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FOREWORD

Climate change is the greatest challenge facing humanity and biodiversity today and represents an existential threat to us and future generations. With efforts to halt temperature rise off-track, ambitions of individual countries lagging, and climate disasters becoming ever more severe, it is increasingly urgent to provide a means and platform for climate research. The *Cambridge Journal of Climate Research*, produced by the Cambridge Climate Society, is playing a role in that endeavour.

The concentration of CO_2 in the atmosphere is increasing (so far ~50% above the pre-industrial level), resulting in warming of the atmosphere, land and ocean. In 2024 the average global temperature reached 1.55°C above pre-industrial levels. This warming is human induced. Warming is already having immediate effects on food security, health, water supplies and biodiversity. The longer-term outlook is even more dire: the latest UN Emissions Gap Report suggests we may be heading for warming of 2.6 to 3.1°C, which will have severe consequences for humanity and all life on this planet.

It is increasingly clear that in order to avoid the worst effects of climate change, the world must reach net zero as soon as possible. Net zero by 2050 requires transformation of our energy portfolio, along with technological transformation of the infrastructure in place to store and transport it. It seems certain that as well as reducing emissions, efforts must also be accelerated to remove carbon from the atmosphere, through a range of carbon capture and storage mechanisms.

I am honoured to have the opportunity to pen this Foreword introducing a collection of impactful articles dealing with the myriad challenges associated with climate change. In this issue, a range of papers explore a number of physical and social science and political topics linked with the impacts of climate change and society's priorities for the future. Climate governance increasingly takes centre stage in multilateral climate discussions and this forms the basis of an article by Saoudy looking at the mechanisms by which less powerful actors, such as those from the Global South, are heard. Specific countries face specific challenges: Asgarian explores how Iran navigates climate change and its impact under the influence of international sanctions. Pacific Small Island Developing States have long been at the forefront of climate change and Tang discusses how they can achieve influence in the global climate debate. More developed countries arguably have a greater responsibility for financing the sustainable development of less developed countries as regards climate change mitigation given their greater historical contribution to global emissions, argues Macleod. Climate injustice is a theme continued by Rice, who shows that information gaps fuel failures in climate-related financial markets. DiSera et al. discuss how climate information is communicated, trusted and used by farmers in Colombia; and León Báez looks back at how Iberian thinkers rationalised climate change in the historical past.

The future will require innovation and investment across the energy sector. Obeng-Akrofi examines the different ways in which countries tackle innovation, with a focus on nuclear fusion. Sikes targets hydropower and the human history behind it in the American West. Pinto and Hritsyshyna discuss

whether hydrogen has a role to play in the delivery of climate objectives. Song examines how the aviation sector will adapt and become climate-sustainable, and the key challenges. The impacts of climate change are many and varied, but one aspect that is increasingly dominant in global news is flooding. Bikakis examines the nature and resilience of the mortgage market in flooding-prone areas, highlighting the role of shadow banking the wake of flood events. Extreme rainfall is becoming more common, and less predictable at the same time. Aladalli tests climate models that aim to describe extreme rainfall events, showing that the complexity of the physics is a key aspect in their success.

As 2025 draws to a close, we mark the end of a remarkable life—that of Dr Jane Goodall, who passed away in October 2025. On Earth Day 2025, Dr Goodall said: "I do believe there is a window of time when we can at least slow down climate change and loss of biodiversity. But only if we get together and take action now. And without hope we will fall into apathy and do nothing. Then we are doomed".

This message of hope is an important one. And 2025 certainly has brought us some measures of hope. Wind, solar and other renewable power sources overtook coal as the world's leading source of electricity this year, largely driven by China, where CO_2 emissions over 12 months fell for the first time. Brazil hosted COP30 this year, in the Amazon rainforest, where an ambitious roadmap to end deforestation by 2030 was announced, supported by 90 countries. Building resilience to climate change is now arguably front and centre of the international agenda, with finance increased for both climate adaptation and the transition to a low carbon economy. The rights of Indigenous peoples in the context of climate impacts are increasingly recognised and valued. However, major unresolved challenges remain that require academe, industry, governments and all of humankind to work together to effect change.

Professor Marie Edmonds, Hon DSc (Plym), PhD, MA Hons (Cantab), FRS

Head of Department and University Professor, Department of Earth Sciences, University of Cambridge
Vice President and Ron Oxburgh Fellow in Earth Sciences, Queens' College, University of Cambridge

PRESIDENT'S LETTER

Volume 2, Issue 2 of the *Cambridge Journal of Climate Research* presents interdisciplinary climate research at a critical moment for global climate action. We are witnessing our collective debates increasingly taking place in an environment where evidence is contested, expertise undermined, and lived realities flat-out denied. In this context, the role of rigorous, student-led, and interdisciplinary climate research becomes essential as the practical enactment of our capacity to rebuild trust and collective efficacy.

From our very beginning, the Cambridge Climate Society has been committed to creating spaces where disciplines, voices, and ideas can meaningfully enter into conversation, forming a collective foundation for educating and empowering students on climate change and climate justice. This commitment reflects a simple but, particularly in today's world, overlooked reality: the overwhelming majority of people recognise the climate crisis for what it is, and meaningful progress depends on organising this shared understanding into joint action. Accordingly, the task at hand is not to manufacture consensus or endlessly persuade the unconvinced, but to turn existing concern into shared capacity. The *Journal*, then, moves beyond its role as a record of research. It becomes an organising infrastructure converting common concern into knowledge, legitimacy, and purpose.

The accomplished and varied contributions in this issue do exactly that and demonstrate that this capacity already exists and is growing. Authors throughout show us how to make sense of the invisible structures that often stall progress: Bikakis, for example, tracks the flows of credit in flood-exposed shadow mortgage markets, while Asgarian identifies the possibilities for justice-centred mitigation efforts in Iran under international sanctions.

We also see a powerful reassertion of narrative leadership. Saoudy and Tang both engage with discursive and normative strategies in the UNFCCC and beyond, highlighting how Global South actors and Pacific Island states are designing the very meaning of key terms like climate security and just transition. Alongside the works by Rice and Macleod on two particular instances of power imbalance in climate finance, one historic and one informational, they demonstrate that a more equitable global community is viable.

Ultimately, this issue proves that our collective agency is revitalised when we integrate every scale of collective knowledge. Between Aladalli's technical engagement with biases in precipitation models and DiSera et al.'s ethnographic account of Colombian farmers' relation to weather and climate information, we witness how expertise is most effective when it is grounded in local reality. Whether exploring the political economy of fusion energy (Obeng-Akrofi), hydrogen (Pinto & Hritsyshyna) and aviation policy (Song), dam construction in the 1930s (Sikes) and historic weather soundings (León Báez), these contributors show that by connecting the possibilities of the future with the lessons of the past, we are moving beyond documenting this crisis to build the intellectual resilience required to dismantle it.

This issue is as much a product of collective effort as it is a call for it: I would like to extend my heartfelt thanks to our exceptional Editorial Board, led by Kaden Pradhan, the *CJCR* Editor-in-Chief and CCS Vice-President for Knowledge and Impact. I would also like to express my profound gratitude to Tamara Zambiasi and Manav Divecha as Senior Editors, and to Isabella Dressel, Lakshmi Rasipuram-Balakrishnan, Md Abu Toha, Siang Ern Lek and Apoorva Aladalli as Associate Editors. My heartfelt thanks also go to the Research Team and the entire CCS Committee for their continued dedication in making climate research and action more accessible. Most importantly, we thank our contributors. Your work is the foundation through which change becomes possible.

Niklas Todt, President, Cambridge Climate Society

VALEDICTORY EDITORIAL

Threats to Climate Research Endanger an Already Imperilled Climate System—We Must Face Them with Hope, Drive, Novelty and Charity

On the 16th December, the US federal government announced it would be breaking up the National Centre for Atmospheric Research as it was "one of the largest sources of climate alarmism" operating in the country.[1] This followed severe personnel and budget cuts across agencies such as the NOAA, NASA, and the EPA; all of which were deeply unpopular with voters.[2] More subtle but equally impactful moves included the termination of NSF funding for more than one hundred climate research projects,[3] as well as the gradual erasure of climate data from public websites.[4] These measures, some scientists worry, will have effects which endure far beyond near-term electoral cycles.[5]

This is not a uniquely American problem, either. Naturally, these US policy shifts have global impacts: on multinational academic projects,[6] on the IPCC,[7] and on downstream users of produced information.[8] Similarly, radical cuts to foreign aid and climate finance put direct adaptation and mitigation programmes at risk,[9] but also affect research institutions elsewhere in the world which rely on external funding.[10]

The connection between well-researched climate science and effective climate policy is clear.[11] This holds true for localised climate research too, wherein the contextualisation of variables, methods, and sampling allows for correspondingly contextualised results and recommendations, and creates wider opportunities for direct engagement with local decision-makers.[12] Sociological, historical, and anthropological studies of the climate are often undervalued against economic, political, legal, and

[1] Volcovici, Valerie. "Trump Administration to Dissolve Key Climate Research Agency." *Reuters*, 17 Dec. 2025.
[2] Kirk, Karin. "Trump's Climate Cuts Are Unpopular, Even with Republican Voters." *Yale Climate Connections*, 3 Jul. 2025.
[3] Temple, James. "The Trump Administration Has Shut Down More than 100 Climate Studies." *MIT Technology Review*, 2 Jun. 2025.
[4] Sethi, Pallavi. "Inside Trump's Campaign to Censor Climate Science." *Grantham Research Institute Commentary*, 5 Aug. 2025.
[5] "Axing Climate Research Endangers Americans, Say Former Officials." *Salata Institute News*, 5 May 2025.
[6] Klotz, Frieda. "The Impact of NIH Cuts Ripples Beyond U.S. Borders." *Undark*, 30 Jun. 2025.
[7] Voosen, Paul. "NASA Cuts Off International Climate Science Support." *ScienceInsider*, 24 Feb. 2025.
[8] Watkins, Andrew, et al. "As US Climate Data-Gathering Is Gutted, Australian Forecasting Is Now at Real Risk." *The Conversation*, 28 Jul. 2025.
[9] Shi, Xuefei, and Magnus Hatlebakk. "Assessment of the Impact of Aid Cuts on Climate and Nature Action." *WWF-CMI Report*, 8 Aug. 2025.
[10] Adepoju, Paul. "Q&A: Aid Cuts Call for African Self-Reliance in Research." *SciDev*, 17 Jun. 2025.
[11] According to the UNEP, bodies such as the IPCC, which synthesises climate research, "have played a vital role in ensuring better informed decisions and actions, with thousands of scientists and knowledge holders … working together to distil the latest research, evidence and policy options into reports accepted by governments around the world": "How Science-Policy Bodies Are Driving Solutions to Planetary Crises." *UN Environment Programme*, 19 Jun. 2024. Some commentators have suggested in the past that a stronger pipeline is needed between scientific outputs and policy recommendations: *see* Neff, Todd. "Connecting Science and Policy to Combat Climate Change." *Scientific American*, 17 Mar. 2009.
[12] Krabbe, Isabella. "Place-Based Approaches to Climate Change." *RTPI Research Paper*, Mar. 2021.

physical-scientific ones,[13] but they play an important role in interrogating the ways in which contemporary actors grapple with the concepts, norms, and principles which inform the production and implementation of climate policy, many of which are discursively or socially constructed.[14] All this is to say that the unprecedented systemic jeopardy which now faces the global climate research environment is not a concern merely for researchers but will have the substantive effect of weakening local, national, and international climate policy, thus enabling the continued deterioration of the climate system itself and the ecological holons which occupy it; it will seriously exacerbate the ongoing suffering of both people and planet.

How, then, is the climate research network to approach this issue?[15] My suggestion is to keep four informing values in mind.

The first is hope. It is easy, alluring even, to slip into defeatism when faced with challenges of this nature. In light of the unhappy but inevitable truth that successful climate research demands a monetary input, and often a very big one,[16] it is no wonder that researchers feel their reliance on institutions and grant bodies (themselves reliant on governments, NGOs, and IGOs) keenly. A disruption to a funding flow can be a disruption not only to a project but to a researcher's life, their control over their work, and their sense of impact and meaning. Optimism, however, is warranted. Notwithstanding the current environment, funding flows have grown over the last decade,[17] and as the public becomes increasingly climate-conscious,[18] there is no reason why in the long run this trend will not continue.

The second is drive. Drive is, I think, the rational operationalisation of hope. It is the ability to recognise where certain hurdles are insurmountable but to confine those hurdles to their proper limits and not allow their effect to escape those limits and prejudice other work programmes: to carefully divide doomed projects from those which can be reworked and continued. It also includes a capacity not to allow immediate obstacles to paralyse action where more distant opportunities remain open. Sometimes there genuinely is only one option, and when it is closed off, that is the end of the story. Climate research, however, is somewhat distinct in that it is undergirded by an array of sources of support which are smaller, community-led, often more difficult to find, but underutilised nonetheless.[19]

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[13] Bjurström, Andreas, and Merritt Polk. "Physical and Economic Bias in Climate Change Research: A Scientometric Study of IPCC Third Assessment Report." *Climatic Change*, vol. 108, 2011, pp. 1-22.
[14] Blue, Gwendolyn. "Framing Climate Change for Public Deliberation: What Role for Interpretive Social Sciences and Humanities?" *Journal of Environmental Policy & Planning*, vol. 18, no. 1, 2016, pp. 67-84.
[15] Perhaps aside from transitioning into politics and advocating on behalf of climate research as a political agent, which might well be an effective way to go about it.
[16] Sovacool, Benjamin, et al. "Critically Examining Research Funding Patterns for Climate Change and Human Health." *NPJ Climate Action*, vol. 3, 2024, 64.
[17] Aleixandre-Tudó, José Luis, et al. "Trends in Funding Research and International Collaboration on Greenhouse Gases: A Bibliometric Approach." *Environmental Science & Pollution Research*, vol. 28, 2021, pp. 32330-32346.
[18] Hamilton, Lawrence. "Public Awareness of the Scientific Consensus on Climate." *SAGE Open*, 2016; Kenny, John, and Stephen Fisher. "Europeans' Climate Consciousness: Increased Yet More Politicised." *Environmental Politics*, 2025.
[19] Creamer, Emily. "The Double-Edged Sword of Grant Funding: A Study of Community-Led Climate Change Initiatives in Remote Rural Scotland." *Local Environment*, vol. 20, no. 9, 2015, pp. 981-999; Cann, Katherine, et al. "Building Equitable Research Partnerships: Learning from a Community Climate Resilience Grant Program." *Community Science*, vol. 3, no. 3, 2024; North, Michelle, et al. "Tracing Primary Sources of Funding for, and Patterns of Authorship in, Climate Change Research in Africa." *Environmental Science & Policy*, vol. 127, 2022, pp. 196-208.

The third is novelty. Without an innovative spirit, climate researchers may be unable to guide their projects through the extraordinary problems created by this extraordinary situation. Without falling, I hope, into grandstanding, I would like to highlight the *CJCR* itself as an example of that kind of innovation. Established at the end of 2023 by a group of postgraduate and undergraduate students in Cambridge as a response to the departmental siloes in our University which prevented interdisciplinary climate research almost entirely, it has grown into a truly international publication whilst retaining the open and critical ethos which motivated its genesis and animated its first issue. We are diamond open-access, meaning that we charge no fees to either authors or readers, such that the process for determining what works are published is based on merit alone, without regard to the affiliation or career stage of the author, their resources, or even the field of study. We are proud to have published exceptional pieces from eminent established professors, first-year undergraduates, and everyone in between. This kind of broad-minded receptivity embodies the reshaped practices which publishers of climate research will have to embrace to adapt to severe financial pressures. It is also a bilateral receptivity: researchers may have to come to terms with publishing in newer, less prestigious, or alternative spaces to ensure that studies are viable and to keep each project lifecycle roughly on track.

The fourth is charity. The current paradigm may require all actors in the climate research environment to make concessions on certain stringent demands so that the environment itself can survive these short-run stresses. In other words, both myopia and ordinarily legitimate self-interest will only lead to self-destruction. To use the *CJCR* as an example once again, we benefit enormously from our partnership with the Cambridge University Library, by virtue of which we host the *Journal* on a DSpace platform loosely based on the University's institutional repository, Apollo. This allows us to run a zero-cost business model for the electronic version of the *Journal*, which in turn enables us to keep it diamond open-access. These partnerships are also becoming more common in other fields. One fascinating case-study is the mass resignation of the Board of *Critical Public Health*, published by Taylor & Francis, to establish the *Journal of Critical Public Health*, hosted by the University of Calgary on a diamond open-access DSpace platform very similar to the Cambridge University Library's.[20] The generosity of these platform hosts cannot be overstated, and it represents exactly the kind of charity which the climate research environment requires now more than ever.

With these four values in mind, I am confident climate research will continue to thrive, even in the face of such profound perils.

A Personal Farewell to the *CJCR*

This is my last issue as Editor-in-Chief of the *CJCR*. I was one of the Founding Editors who came together in the Cambridge Climate Society in December 2023 with a clear ambition in mind. Under the learned guidance of the Founding Editor-in-Chief, Chibuzor Ndubisi, then studying for his MPhil in the Department of Engineering, we established the *Journal* and published our first issue in May 2024, at which point I took over leadership from Chibuzor. Two years on, we have published four

[20] Bunton, Robin, et al. "Manifesto for a New Journal: Safeguarding Critique in Public Health." *Journal of Critical Public Health*, vol. 1, no. 1, 2024, pp. 1-4.

issues, including this one, across two volumes. We have created print versions for the first two, and set up a storefront to sell them, with the other two still to come. We have published excellent and impactful research from all around the world and have seen growing readership and engagement.

This role has been the greatest privilege of my life. I must confess, managing a publication like this is very consuming indeed, and it has occupied much of my free time. Nonetheless, I have been devoted to the *CJCR* from the very start, and I have poured my heart and soul into it. Passing it on to a new Board is a sorrowful moment indeed, but I have the utmost faith in my successors' ability to take the *Journal* to new and exciting heights.

Perhaps unsurprisingly, I have a few acknowledgements I must articulate before inviting you to enjoy this wonderful issue and signing off. First, I am endlessly grateful to the other members of the Editorial Boards which have stewarded the *CJCR* over the past two years. Chibuzor Ndubisi, Liniet Gitonga, Maja Glavin, Kilian Bartsch, Tamara Zambiasi, Manav Divecha, Lakshmi Rasipuram-Balakrishanan, Isabella Dressel, Siang Ern Lek, Apoorva Aladalli, Sara Uddin Nasrat, and Md Abu Toha—I could not have done any of this without your support, expertise, and enormous commitment to this shared endeavour. Special thanks to Tamara and Manav, who served as Senior Editors for the past year, and whose support was invaluable; and to Taylor Edgar, our Cover Illustrator, who is both a dear friend and a talented artist. Second, I must reiterate my immense appreciation for Open Research Systems Team at the Cambridge University Library, particularly Agustina Martínez García and Peter Sutton-Long, without whom this entire project would have been virtually impossible from the get-go. Third, I thank our wonderful Foreword authors, Prof Sir David King, Prof Marie-Claire Cordonier Segger, Prof Mike Hulme and Prof Marie Edmonds, who offered their valuable time and visionary insights to introduce each issue. Fourth, the Cambridge Climate Society, which has officially published the *CJCR* since its inception, and the Society leadership over the years—Aman Vernekar, Beth Doherty, Shreya Patel, Benedetta Radice, Niklas Todt, and Lea Milanini—have been the guardians of our ethos and spirit. Fifth, all of the readers of our articles, to whom we hope we have been of some use. Finally, the most crucial element of any successful periodical: the authors themselves, who have submitted their outstanding contributions, tolerated our exacting and intensive review process, and agreed to entrust their works to a fledgling publication. Thank you all for your indispensable commitment to this collective venture.

My best wishes to my successors, and may climate research continue to thrive, so that we may all retain a spark of optimism that this world can yet be saved.

Kaden Pradhan, Editor-in-Chief, *Cambridge Journal of Climate Research*

CONTRIBUTORS

Apoorva Aladalli is an MPhil Candidate in the Department of Applied Mathematics and Theoretical Physics at the University of Cambridge.

Hoda Asgarian is a PhD Candidate in the Faculty of Law at Bond University.

Thanos Bikakis is a PhD Candidate in the Department of Land Economy at the University of Cambridge.

Laurel DiSera is a Postdoctoral Fellow in the Department of Earth and Environmental Sciences and the International Research Institute for Climate and Society at Columbia University and at the Abdus Salam International Centre for Theoretical Physics.

Carolina Hernández Rodríguez is a PhD Candidate in the Department of Geography at the National University of Colombia and in the Centre de Recherche et de Documentation sur les Amériques at the Sorbonne Nouvelle University.

Maryna Hritsyshyna is a PhD Candidate in the Center for Climate Change, Energy and Environmental Law at the University of Eastern Finland.

Flora Lecomte is a PhD Candidate in the Centre de Recherche et de Documentation sur les Amériques at the Sorbonne Nouvelle University.

Juan Fernando León Báez is a Postdoctoral Teaching Fellow in the Chabraja Center for Historical Studies at Northwestern University.

Molly Macleod is a Law Tripos Student at Emmanuel College in the University of Cambridge.

Eugenia Obeng-Akrofi is a PhD Candidate and a Graduate Teaching Assistant in the Department of Environment and Geography and the Department of Politics at the University of York.

Jaqueline Pinto is a PhD Candidate in the Center for Climate Change, Energy and Environmental Law at the University of Eastern Finland.

James Rice is a PhD Candidate in the Department of Government at the University of Essex.

Melissa Saoudy is an MSt Candidate in the Judge Business School at the University of Cambridge.

Dover Sikes is an MPhil Candidate in the Department of Land Economy at the University of Cambridge.

Qi Song is a Research Associate and the King's Global Sustainability Fellow in Climate Risk in Aviation at the University of Cambridge Institute for Sustainability Leadership.

Siyue (Grace) Tang is an MPhil Candidate in the Department of Land Economy at the University of Cambridge.

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What Drives General Circulation Model Biases in Precipitation Extremes? A Generalised Pareto Distribution (GPD)-Based Diagnostic of CMIP6 Tail Behaviour

Apoorva Aladalli*

* MPhil Candidate (Department of Applied Mathematics and Theoretical Physics), University of Cambridge, UK

KEYWORDS

climate change, extreme rainfall, CMIP6, GCM biases, POT GPD diagnostic

ABSTRACT

This study uses a point-scale Peaks-Over-Threshold (POT) Generalised Pareto Distribution (GPD) framework to evaluate extreme precipitation simulated by 32 CMIP6 models from 2015 to 2024. Daily rainfall exceeding high thresholds is fitted to the GPD using three estimators: Maximum Likelihood Estimation, L-moments, and Bayesian inference. Return levels for 2, 5, 10, 20, 50, and 100 year events are computed. Two climatically distinct sites are analysed, one in tropical South India and one in mid-latitude Northern Italy, with observational benchmarks from IMD4 and E-OBS datasets. Results show systematic model biases. CMIP6 models generally overestimate extreme rainfall in India and underestimate it in Italy. Biases are closely linked to convection parameterisation schemes. Zhang-McFarlane models simulate Indian monsoon extremes within about 30 percent accuracy but underpredict Italian 100-year rainfall by 50 to 65 percent. Gregory-Rowntree scheme models show mixed results. Models with simple bulk convection schemes tend to have the largest errors, often exceeding 100 percent in both regions. Notably, the finely tuned Gregory-Rowntree model KACE-1-0-G performed well in both domains, highlighting the importance of targeted calibration regardless of scheme type. Variability in threshold selection, driven by convection scheme differences and drizzle bias, affects return level estimates more than GPD shape or scale parameter variations. Differences across estimation methods are minor compared to inter-model spread, with Bayesian inference showing the most stable results. Increasing model resolution alone does not guarantee improved simulation of extreme precipitation. Overall, findings underscore that model physics, particularly convection parameterisation, is the primary determinant of extreme precipitation biases, suggesting that advancements in physical processes offer greater potential for reducing biases than resolution enhancements alone.

I. **Introduction**

Extreme weather events such as floods, heatwaves, and storms are statistically infrequent but disproportionately responsible for large-scale social, economic, and ecological disruption. A growing body of evidence, from theoretical thermodynamic reasoning based on the Clausius–Clapeyron relationship, to observational trends and climate model simulations, demonstrates that the variability, intensity, and frequency of precipitation extremes are increasing as global temperatures rise.[1] Events such as cloudbursts, flash floods, and landslides are highly localised, typically occurring at basin or sub-basin scales, and are regulated by topography, land-surface heterogeneity, and mesoscale atmospheric dynamics. Consequently, effective risk assessment and adaptation planning require high-resolution, point-scale diagnostics to inform urban drainage design, early warning systems, and resilient infrastructure planning.

In practice, decision-makers and engineers rely on climate projections from publicly available multi-model ensembles such as the Coupled Model Intercomparison Project Phase 6 (CMIP6) to assess future hydroclimatic risks.[2] Yet a central question remains: to what extent do CMIP6 models accurately reproduce the statistical characteristics of observed precipitation extremes at the spatial scales most relevant for real-world decisions?

Most model evaluation studies to date have been conducted at regional or global scales using spatially aggregated observational products or gridded reanalyses and rely on simplified statistical frameworks, particularly the block maxima method,[3] which fits annual or seasonal maxima to a Generalised Extreme Value (GEV) distribution. Likewise, the Expert Team on Climate Change Detection and Indices (ETCCDI) suite of extreme precipitation indices (for example, Rx1day, R20mm) has become a standard tool for inter-model comparison.[4] Although these methods are widely used for their simplicity and ease of interpretation, they provide limited insight into the tail of the distribution, which is essential for characterising rare, high impact events.[5] The block maxima approach retains only one value per year or season, discarding other extreme events that exceed high thresholds but do not represent the annual maximum.[6] ETCCDI indices are policy-relevant but rely on absolute thresholds (for example, the number of days with precipitation greater than 10 mm or 20 mm), which may not be climatologically meaningful across diverse regions.[7] Moreover, each index

[1] Westra, Seth, et al. "Future Changes to the Intensity and Frequency of Short-Duration Extreme Rainfall." *Reviews of Geophysics*, vol. 52, no. 3, 2013, pp. 522-555; Kharin, Viatcheslav, et al. "Changes in Temperature and Precipitation Extremes in the CMIP5 Ensemble." *Journal of Climate*, vol. 26, no. 23, 2013, pp. 8469-8482; de Vries, I, et al. "Increasing Extreme Precipitation Variability Plays a Key Role in Future Record-Shattering Event Probability." *Nature Communications*, vol. 15, 2024, 7447.

[2] Eyring, Veronika, et al. "Overview of the CMIP6 Experimental Design and Organization." *Geoscientific Model Development*, vol. 9, no. 5, 2016, pp. 1937-1958; O'Neill, Brian, et al. "The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP6." *Geoscientific Model Development*, vol. 9, no. 9, 2016, pp. 3461-3482; IPCC. *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report*. Cambridge University Press, 2021.

[3] Li, Chao, et al. "Changes in Annual Extremes of Daily Temperature and Precipitation in CMIP6 Models." *Journal of Climate*, vol. 34, no. 9, 2021, pp. 3441–3460; Alaya, MA Ben, et al. "An Evaluation of Block-Maximum-Based Estimation of Very Long Return Period Precipitation Extremes with a Large Ensemble Climate Simulation." *Journal of Climate*, vol. 33, no. 16, 2020, pp. 6957–6970.

[4] Alexander, L, et al. "Global Observed Changes in Daily Climate Extremes of Temperature and Precipitation." *Journal of Geophysical Research: Atmospheres*, vol. 111, no. D5, 2006, 2005JD006290; Seneviratne, Sonia, and Mathias Hauser. "Regional Climate Sensitivity of Climate Extremes in CMIP6 Versus CMIP5 Multimodel Ensembles." *Earth's Future*, vol. 8, no. 9, 2020, e2019EF001474.

[5] ibid.

[6] Coles, Stuart. *An Introduction to Statistical Modeling of Extreme Values*. Springer, 2001; Katz, Richard, et al. "Statistics of Extremes in Climate Change." *Climatic Change*, vol. 100, no. 1, 2002, pp. 71-76.

[7] Donat, Markus, et al. "Updated Analyses of Temperature and Precipitation Extreme Indices Since the Beginning of the Twentieth Century: The HadEX2 Dataset." *Journal of Geophysical Research: Atmospheres*, vol. 118, no. 6, 2013, pp. 2098-2118; de Medeiros, Jeferson, et al. "Classification and Definitions of Extreme

isolates a specific attribute such as intensity, frequency, or duration and is thus sensitive to differing statistical and physical assumptions, which limits their diagnostic power for reliable local-scale assessments.

This study addresses these scale and methodological mismatches in two principal ways. First, it adopts a point-scale evaluation framework that analyses individual grid-cell level data rather than spatial aggregates, thereby aligning the spatial resolution of model evaluation with the scale of observed extremes. By selecting two climatically and dynamically distinct grid cells, one in southern India (13° N) and the other in northern Italy (44° N), the study evaluates CMIP6 model performance across fundamentally different latitudinal zones, climate regimes, and precipitation-generating mechanisms. The southern India site lies in the tropical monsoon belt and is governed by the Southwest Monsoon, which delivers over 70% of the annual rainfall between June and September. Events are typically convective, episodic, and high in intensity, and are often associated with synoptic features such as monsoon depressions, low-pressure systems, and break spells. This region is characterised by the combined influence of deep tropical convection and orographic effects, and global models continue to struggle with these processes, largely due to their coarse resolution and reliance on parameterised convection.[8] The northern Italy site lies within a mid-latitude Mediterranean climate zone, where rainfall is modulated by synoptic-scale disturbances, extratropical cyclones, and frontal systems embedded within the westerlies.[9] Seasonal peaks in precipitation in the Mediterranean and adjacent regions often occur in autumn and spring and are substantially associated with frontal uplift and extratropical cyclones, especially cold front systems. Unlike the thermodynamically unstable tropics, precipitation here has historically been linked to more stable, long duration rainfall organised by planetary-scale dynamics, indicating a sharp contrast in both the origin and structure of extremes.

Second, the study employs a Peaks-Over-Threshold (POT) approach, fitting a Generalised Pareto Distribution (GPD) to daily rainfall values exceeding a high threshold. This allows the inclusion of multiple extreme events per year and offers a more data-efficient and tail-sensitive analysis of precipitation extremes than the block maxima framework. The study compares three GPD parameter estimation methods, Maximum Likelihood Estimation, L-moments, and Bayesian inference, each of which differs in its sensitivity to sample size, distributional shape, and inferential assumptions.[10] At its core, the study interrogates systematic model bias, specifically the persistent deviations between return levels estimated from 32 CMIP6-simulated precipitation (SSP5–8.5) and those derived from observational reference datasets (IMD4 and E-OBS). Rather than attempting a full decomposition of projection uncertainty, the analysis evaluates the extent to which statistical inference methods and model structure contribute to bias in the simulation of extremes. By assessing return level sensitivity across estimation techniques and identifying models that systematically overestimate or underestimate extremes at both sites, the study characterises the magnitude and spatial structure of model–observation biases. The goal is not merely to rank models, but to understand the conditions under which some

Indices for Precipitation." *Remote Sensing of Environment*, vol. 279, 2022, 113078.

[8] Villalba-Pradas, Anahí, and Francisco Tapiador. "Empirical Values and Assumptions in the Convection Schemes of Numerical Models." *Geoscientific Model Development*, vol. 15, 2024, pp. 3447-3474; Prein, Andreas, et al. "The Future of Weather Prediction is Convection Permitting." *Bulletin of the American Meteorological Society*, vol. 96, no. 2, 2015, pp. 171-173.

[9] Rüdisühli, Stefan, et al. "Attribution of Precipitation to Cyclones and Fronts Over Europe in a Kilometer-Scale Regional Climate Simulation." *Weather and Climate Dynamics*, vol. 1, no. 2, 2020, pp. 675-699.

[10] Scarrott, Carl, and Andrew MacDonald. "A Review of Extreme Value Threshold Estimation and Uncertainty Quantification." *REVSTAT—Statistical Journal*, vol. 10, no. 1, 2012, pp. 33-60; Lazoglou, Georgia, and Christina Anagnostopoulou. "Comparing Bayesian and Classical Approaches for the Generalized Pareto Distribution in Peak Over Threshold Modeling." *Theoretical and Applied Climatology*, vol. 130, no. 3-4, 2017, pp. 1073-1086.

models outperform others in representing the upper tail of the precipitation distribution. This diagnostic insight has clear implications for improving climate model physics, especially in the treatment of convection and orography, and for enhancing the utility of model-derived information in risk-sensitive decision-making. The study contributes one component toward the broader goal of developing a statistically principled framework for benchmarking climate models and adds to the growing body of work diagnosing the capabilities and limitations of CMIP6 models in simulating precipitation extremes.

The remainder of the paper is organised as follows. Section II provides background on CMIP6 model development and the physical and numerical processes that influence simulated precipitation extremes, including convection parameterisation, resolution and time stepping, orographic representation, cloud microphysics, vertical structure, and the role of large-scale teleconnections, as well as recent advances in convection-permitting models. Section III describes the study design, data sources, and preprocessing steps, and outlines the Extreme Value Analysis framework based on a peaks-over-threshold GPD approach. Section IV presents the results, including biases in GEV parameters, threshold selection and exceedances, return level estimates, and model ranking. Section V discusses the implications of these findings, focusing on method-related biases, model physics bias, the role of resolution, and key limitations. Section VI summarises the main conclusions and highlights priorities for future work.

II. **Model Development and Theoretical Background**

A. *Convection Parameterisation and Model Bias*

Simulating precipitation extremes is strongly constrained by the parameterisation of convection. CMIP6 models, which typically operate at horizontal resolutions of about 100 to 250 km, cannot explicitly resolve convective clouds and mesoscale convective systems and therefore rely on convection parameterisation schemes.[11] These schemes vary widely across models and introduce systematic differences in the frequency, intensity, and spatial structure of simulated extremes, most notably the tendency toward a 'drizzling bias' in which models produce too frequent light rain and underestimate heavy rainfall, especially in tropical regions.[12] Different convection schemes show distinct behaviours. Zhang–McFarlane and Relaxed Arakawa–Schubert schemes, for example, tend to overproduce light rain and underrepresent heavy events, contributing to drizzle bias.[13] Gregory–Rowntree and Tiedtke-type schemes have shown regional improvements, particularly in mid-latitude frontal regimes, while newer hybrid schemes such as those used in TaiESM1 display enhanced precipitation variability and extreme rainfall skill.[14] As a result, model skill in representing extremes is highly sensitive to the choice and tuning of the convection scheme.

B. *Resolution, Time Step, and Orography*

Model skill in simulating extremes also depends on horizontal resolution, time stepping, and orographic representation. Higher horizontal resolutions of about 50 to 100 km can better capture mesoscale organisation and orographic enhancement of

[11] Arakawa, Akio. "The Cumulus Parameterization Problem: Past, Present, and Future." *Journal of Climate*, vol. 17, no. 13, 2004, pp. 2493-2525.

[12] Stephens, Graeme, et al. "Dreary State of Precipitation in Global Models." *Journal of Geophysical Research: Atmospheres*, vol. 115, no. D24, 2010, D24211; Chen, Duoying, et al. "The Convective-To-Total Precipitation Ratio and Degrees of Freedom for Convection." *Journal of Geophysical Research: Atmospheres*, vol. 126, no. 5, 2021, e2020JD034198

[13] Zhang, Mingkui, and Ying Mu. "Understanding the Role of Convective Clouds in the Hydrological Cycle." *Journal of Geophysical Research: Atmospheres*, vol. 110, 2005, D11201; Lin, Y, et al. "Changes in Extreme Precipitation Events in CMIP6 Simulations." *Journal of Climate*, vol. 26, no. 23, 2013, pp. 9469-9482.

[14] Li, Gudongze, et al. "Convection-Permitting Simulation of Persistent Precipitation Events Impacting Eastern China." *Climate Dynamics*, vol. 29, no. 7-8, 2007, pp. 723-741; Walters, David, et al. "The Met Office Unified Model Global Atmosphere 7.0/7.1 and JULES Global Land 7.0 Configurations." *Geoscientific Model Development*, vol. 12, no. 5, 2019, pp. 1909-1963; Wang, Shaocheng, et al. "Metrics and Diagnostics for the Climate Variability Timescale Spectrum." *Journal of Climate*, vol. 34, no. 9, 2021, pp. 3467-3482.

rainfall, although improved physics remains essential.[15] Shorter model time steps help to represent the life cycle of convective systems more realistically and reduce numerical artefacts in heavy precipitation.[16] The representation of orography is particularly important in regions with strong terrain gradients, where coarse grids smooth topographic features and can suppress locally intense rainfall.[17] In point-scale evaluation studies, an additional source of uncertainty arises from the spatial mismatch between observation stations and model grid cells. Even when the nearest grid point is selected, spatial offsets of several tens of kilometres are common and can markedly affect the representation of localised extremes, especially in complex terrain.[18]

C. *Microphysics, Vertical Structure, and Teleconnections*

Cloud microphysics and vertical resolution exert a strong control on simulated precipitation extremes. Many global models still use relatively simple single-moment microphysics schemes that limit raindrop size-distribution variability and evaporation processes, which in turn leads to biases in both the intensity and frequency of extremes.[19] Higher vertical resolution, particularly in the lower troposphere, improves the representation of convective development and short-duration rainfall processes.[20] Model skill is also modulated by large-scale modes of variability such as the Madden–Julian Oscillation, El Niño–Southern Oscillation, and the Quasi-Biennial Oscillation, which influence rainfall variability and extremes across the tropics and subtropics.[21] Persistent limitations in these areas contribute to structured biases in simulated extremes and help explain why models often struggle to reproduce observed tail behaviour.

D. *Advances in Convection-Permitting Models*

Convection-permitting models with grid spacing of about 1 to 4 km explicitly resolve deep convection and have been shown to markedly improve the simulation of short-duration rainfall and local precipitation extremes.[22] However, their high computational cost still limits their application to relatively small domains and shorter simulation periods, and they are not yet standard in global ensembles such as CMIP6. Interim progress has therefore focused on refinements to parameterisation schemes and moderate increases in resolution, including HighResMIP experiments, which reduce some biases in extreme rainfall but do not eliminate them.[23] Overall, current evidence indicates that biases in simulated

[15] Bador, Margot, et al. "Impact of Higher Spatial Atmospheric Resolution on Precipitation Extremes Over Land in Global Climate Models." *Journal of Geophysical Research: Atmospheres*, vol. 125, no. 13, 2020, e2019JD032184.

[16] Barrett, Andrew, et al. "One Step at a Time: How Model Time Step Significantly Affects Convection-Permitting Simulations." *Journal of Advances in Modeling Earth Systems*, vol. 11, no. 3, 2019, pp. 641-658.

[17] Pierce, David, et al. "Future Increases in North American Extreme Precipitation in CMIP6 Downscaled with LOCA." *Journal of Hydrometeorology*, vol. 24, no. 5, 2023, pp. 951-975.

[18] Haerter, Jan, et al. "Comparing Atmospheric Indices of Extreme Precipitation Events Derived From Satellite and Rain Gauge Data." *Journal of Geophysical Research*, vol. 116, 2011, D11107.

[19] Abel, S, and I Boutle. "An Improved Representation of the Raindrop Size Distribution for Single-Moment Microphysics Schemes." *Quarterly Journal of the Royal Meteorological Society*, vol. 138, no. 669, 2012, pp. 2151-2162; Morrison, Hugh, and Jan Milbrandt. "A New Double-Moment Microphysics Parameterization for Application in Cloud and Climate Models. Part I: Description." *Journal of the Atmospheric Sciences*, vol. 72, no. 1, 2015, pp. 287-311.

[20] Jenney, A, et al. "Vertical Resolution Impacts Explicit Simulation of Deep Convection." *Journal of Advances in Modeling Earth Systems*, vol. 15, no. 3, 2023, e2022MS003444.

[21] Ahn, M-S, et al. "MJO Simulation in CMIP5 Climate Models: MJO Skill Metrics and Process-Oriented Diagnosis." *Climate Dynamics*, vol. 49, no. 11-12, 2017, pp. 4023-4045; Richter, Jadwiga, et al. "Progress in Simulating the Quasi-Biennial Oscillation in CMIP Models." *Journal of Geophysical Research: Atmospheres*, vol. 125, no. 8, 2020, e2019JD032362.

[22] Kendon, Elizabeth, et al. "Do Convection-Permitting Regional Climate Models Improve Projections of Future Precipitation Change?" *Bulletin of the American Meteorological Society*, vol. 98, no. 1, 2017, pp. 79-93; Fosser, Geert, et al. "Convection-Permitting Climate Simulations Over Europe: Recent Developments in EURO-CORDEX." *Bulletin of the American Meteorological Society*, vol. 101, no. 8, 2020, pp. E1301-E1315.

[23] Prein et al. (n 8) *supra*; Haarsma, R, et al. "High Resolution Model Intercomparison Project (HighResMIP

precipitation extremes stem mainly from convective parameterisation, orographic representation, microphysics, and structural model differences, underscoring the importance of diagnosing these sources when evaluating extremes in CMIP6 model.[24]

III. **Methodology**

This study evaluates the performance of 32 CMIP6 models in simulating extreme daily precipitation at two sites: one in the Western Ghats, India (13.3°N, 75.9°E), and another in Emilia–Romagna, Italy (44°N, 12°E), for the 2015–2024 hindcast period under the SSP5–8.5 scenario. The methodology employs a point-scale peaks-over-threshold approach, fitting a GPD to daily rainfall values exceeding a high threshold. Return levels for 2-, 5-, 10-, 20-, 50-, and 100-year periods are computed using three parameter estimation methods—maximum likelihood estimation, L-moments, and Bayesian inference—to assess methodological sensitivity. Model performance is evaluated through comparative analysis of GPD parameters, threshold selection, and return level estimates against observational benchmarks.

The analysis is structured around five key methodological components: (A) Study Design and Data Sources, (B) Data Extraction and Preprocessing, (C) Extreme Value Analysis, (D) Goodness-of-Fit and Diagnostics, and (E) Bias Evaluation.

A. *Study Design and Data Sources*

The study focuses on the 2015–2024 period as a hindcast period to evaluate how well models reproduce current precipitation extremes, which is essential for testing before applying them to future risk assessment.[25] Hindcasts also inform bias correction, which depends on models capturing realistic extreme behaviour,[26] and provide insight into model deficiencies. In addition, they help identify whether biases stem from the mean state, sub-daily processes, or variability of extremes;[27] for instance, O'Gorman and Schneider[28] linked CMIP6 biases to convective scheme limitations.

All model data in this study come from the high emissions Shared Socioeconomic Pathway 5–8.5 (SSP5-8.5) scenario runs over 2015–2024. The SSP5-8.5 scenario was chosen in part because it provides available high-forcing pathways across many models, and differences between emissions scenarios remain minimal in the near term up to about 2040.[29] In other words, during 2015–2024, the climate trajectories under various SSPs are very similar, so using SSP5-8.5 does not significantly distort the comparison, and biases in hindcast simulations are primarily attributable to model physics and structural differences rather than scenario divergence.

The best-available high-resolution gridded datasets for each region were used for observed precipitation. For South India, I used the latest version of the IMD4 daily gridded rainfall dataset from the Indian Meteorological Department (IMD), which serves as the benchmark observational

v1.0) for CMIP6." *Geoscientific Model Development*, vol. 9, no. 11, 2016, pp. 4185-4208; Roberts, M, et al. "The Benefits of Global High Resolution for Climate Simulation: Process Understanding and the Enabling of Stakeholder Decisions at the Regional Scale." *Bulletin of the American Meteorological Society*, vol. 99, no. 11, 2018, pp. 2341-2359; Wehner, Michael, et al. "Evaluation of Extreme Sub-Daily Precipitation in High-Resolution Climate Models." *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, vol. 379, no. 2190, 2021, 20190544.

[24] Stephens (n 12) *supra*; O'Gorman, Paul. "Precipitation Extremes Under Climate Change." *Current Climate Change Reports*, vol. 1, no. 2, 2015, pp. 49-59; Bador et al. (n 15) *supra*.

[25] Kharin et al. (n 1) *supra*; Wehner, Michael, et al. "Changes in Extreme Precipitation and Hydrology: A Comparison of Dynamical and Statistical Downscaling Approaches." *Journal of Hydrometeorology*, vol. 21, no. 12, 2020, pp. 2899-2913.

[26] Risser, Mark, et al. "Quantifying the Role of Internal Climate Variability in Future Climate Change: The Importance of the Ramp Function." *Climatic Change*, vol. 156, no. 3-4, 2019, pp. 605-625.

[27] Prein et al. (n 8) *supra*.

[28] O'Gorman, Paul, and Tapio Schneider. "The Physical Basis for Increases in Precipitation Extremes in Simulations of 21st-Century Climate Change." *Proceedings of the National Academy of Sciences*, vol. 106, no. 33, 2009, pp. 14773-14777.

[29] IPCC (n 2) *supra*.

dataset. IMD4 is available over the entire spatial extent of India from 1901 to the present at a resolution of 0.25° × 0.25°.[30] The dataset is constructed using an Inverse Distance Weighted (IDW) interpolation scheme, applied to daily rainfall observations from 6,955 rain gauge stations distributed across India, after stringent quality checks and homogeneity assessments.[31] In southern India, the relatively high density of rain gauge stations improves the ability of IMD4 to represent daily rainfall patterns compared to earlier products.[32] The dense station network in southern India enhances the reliability of IMD4, particularly for regional-scale precipitation features, although interpolation in complex topography such as the Western Ghats remains challenging. Given that our location of interest lies on the lee side of the Ghats, the IMD4 product is expected to offer a better representation than coarser global products, though some residual uncertainty may persist due to sharp spatial rainfall gradients in such terrain.

For Northern Italy, I used E-OBS version 30.0e, a 0.1° gridded daily precipitation dataset based on quality-controlled station data from the European Climate Assessment & Dataset network, produced using thin-plate spline interpolation.[33] E-OBS has been widely used for climate model evaluation and extreme precipitation studies in Europe,[34] and offers high reliability in northern Italy given the dense gauge network, though with known limitations in high-mountain regions.[35] The use of different grid resolutions (0.25° vs 0.1°) for India and Italy reflects that in both cases the observation grid is finer than the typical resolution of the CMIP6 models (which is on the order of 1° or coarser), so the observations are unlikely to be a limiting factor. The higher resolution of E-OBS in Europe is possible due to a very dense station network,[36] whereas IMD4's 0.25° resolution is the highest available in India given the gauge density and interpolation methods.[37] Despite the resolution difference, each dataset is of sufficient grid resolution to capture extreme daily rainfall at the point scale of interest.

All analyses use daily precipitation totals (24-hour accumulated rainfall) for consistency. Model outputs (typically reported as precipitation flux) were converted to daily total rainfall (mm day^{-1}) to match the units of the observational datasets. The target model grid cell nearest to each location coordinate was extracted to represent the model's precipitation at that site.

I chose to evaluate model rainfall at single grid points, since many hydrological applications (e.g., flood risk modelling) and bias correction schemes rely on point-scale relationships between models and observations. Evaluating model skill at the grid-point level provides the most relevant diagnostic for practical use.[38]

Since the study period spans only a decade, I adopt a stationary framework for extreme value analysis, consistent with literature[39] that suggests non-stationarity typically emerges over longer timescales.

B. *Data Extraction and Preprocessing*

[30] Pai, D, et al. "Development of a New High Spatial Resolution (0.25° × 0.25°) Long-Period (1901-2010) Daily Gridded Rainfall Dataset Over India." *Journal of the Meteorological Society of Japan*, vol. 92, no. 1, 2014, pp. 39-65.
[31] ibid.
[32] ibid.
[33] Cornes, Richard, et al. "An Ensemble Version of the E-OBS Temperature and Precipitation Datasets." *Journal of Geophysical Research: Atmospheres*, vol. 123, no. 17, 2018, pp. 9391-9409.
[34] Cornes, Richard, et al. "E-OBS: High-Resolution Gridded Mean/Max/Min Temperature, Precipitation and Sea Level Pressure for Europe & Northern Africa." *Climate Data Guide*, UCAR, 2023.
[35] Prein, Andreas, and Andreas Gobiet. "Impacts of Uncertainties in European Gridded Precipitation Observations on Regional Climate Analysis." *International Journal of Climatology*, vol. 37, no. 1, 2017, pp. 305-327.
[36] Cornes et al. (n 33) *supra*.
[37] Pai et al. (n 30) *supra*.
[38] Teutschbein, Christof, and Jörg Seibert. "Bias Correction of Regional Climate Model Simulations for Hydrological Climate-Change Impact Studies: Review and Evaluation of Different Methods." *Journal of Hydrology*, vol. 456-457, 2012, pp. 12-29.
[39] Singh, Devendra, et al. "Changing Intensification Rate of Precipitation Extremes with Temperature." *Nature Climate Change*, vol. 14, no. 5, 2024, pp. 419-425.

Daily precipitation time series for 2015–2024 were extracted from each model and observation dataset for the two target coordinates. I used nearest-neighbour interpolation to extract daily precipitation values from the climate model grids at each target location. Nearest-neighbour interpolation was prioritised over bilinear interpolation to preserve the peaks of extreme rainfall events, as large model grid cells can dampen extremes through smoothing procedures.

Data were standardised for calendar consistency, units (all converted to mm day^{-1}), and temporal alignment across the entire 10-year period. Quality control checks identified missing values, which were minimal across all datasets. All time series were visually inspected to identify and flag potential data anomalies or discontinuities.

C. *Extreme Value Analysis*

Extreme Value Analysis (EVA) was conducted using a POT approach, fitting a GPD to daily rainfall values exceeding a high threshold. The POT method allows for the inclusion of multiple extreme events per year, offering a more data-efficient and tail-sensitive analysis of precipitation extremes compared to the block maxima framework.

1. Threshold Selection

A fixed percentile threshold at the 99th percentile was applied consistently across all models and observations to ensure comparability. This threshold was validated using Mean Residual Life (MRL) plots, which provide a graphical diagnostic for assessing threshold stability. MRL plots display the mean excess of values above a threshold as a function of the threshold itself; for a valid threshold, this plot should be approximately linear.[40] Thresholds were considered appropriate if the linearity assumption held within a visually acceptable range.

2. Parameter Estimation

Three parameter estimation methods were applied to each dataset to assess methodological sensitivity:

- MLE: Standard likelihood-based approach, numerically optimised using gradient ascent methods. MLE is known for its asymptotic efficiency and is widely used in hydrological applications.
- L-moments: A robust, distribution-free method that uses linear combinations of order statistics. L-moments are particularly useful for small sample sizes and are less sensitive to outliers.[41]
- Bayesian Inference: A fully probabilistic approach that incorporates prior information about parameter values. Bayesian methods were implemented using Markov Chain Monte Carlo (MCMC) sampling with weakly informative priors. This approach provides full posterior distributions and is particularly valuable when sample sizes are limited or when parameter uncertainty needs to be quantified.[42]

Each method estimates the scale (σ) and shape (ξ) parameters of the GPD. These parameters define the tail behaviour: the shape parameter ξ controls whether the tail is bounded (ξ < 0), exponential (ξ ≈ 0), or unbounded (ξ > 0).

3. Return Level Computation

The return level z_T associated is the rainfall magnitude expected to be exceeded on average once every T years given by

$$z_T = \mu + \sigma.ln(T.\lambda) \text{ for } \xi = 0.$$

Using the fitted GPD parameters (σ – scale parameter) along with the threshold (u) and the rate of threshold exceedances (λ), return levels was calculated for return periods of 2, 5, 10, 20, 50, and 100 years for each dataset to provide a comprehensive view of extreme behaviour across multiple timescales.

[40] Coles (n 6) *supra*.

[41] Hosking, J. "L-Moments: Analysis and Estimation of Distributions Using Linear Combinations of Order Statistics." *Journal of the Royal Statistical Society: Series B (Methodological)*, vol. 52, no. 1, 1990, pp. 105-124.

[42] Coles, Stuart, and Jonathan Tawn. "Modelling Extreme Multivariate Events." *Journal of the Royal Statistical Society: Series B (Methodological)*, vol. 58, no. 2, 1996, pp. 377-392.

D. *Goodness-of-Fit and Diagnostics*

Model fits were evaluated using multiple diagnostic plots:

- Quantile–Quantile QQ plots: Compare quantiles of the fitted GPD distribution against empirical quantiles of the data. Points lying along the 1:1 reference line indicate a good fit.
- Probability–Probability PP plots: Compare cumulative probabilities from the fitted distribution against empirical probabilities. Similar to QQ plots, deviations from the 1:1 line indicate poor fit, particularly in the upper tail.
- Mean Residual Life MRL plots: Validate the linearity assumption required for threshold selection, as described above.

These diagnostics were generated for all models and estimation methods to identify cases where the GPD assumption may be violated or where parameter estimates were unstable.

E. *Bias Evaluation*

Model bias was quantified as the average percentage deviation of modelled return levels from observed values using the Percentage Bias (PBIAS) metric:

$$\text{PBIAS}_{avg} = \frac{100}{N} \sum_{i=1}^{N} \left(\frac{RL_i^{mod} - RL_i^{obs}}{RL_i^{obs}}\right)$$

where RL_i^{mod} is the model's estimated return level at return period I, RL_i^{obs} is the observed return level at return period I and N is the number of return levels. Positive PBIAS indicates overestimation and negative values indicate underestimation.

Model performance was interpreted as follows: PBIAS within ±10% was considered good agreement with observations, ±20% as moderate agreement, and biases larger than ±50% as indicative of poor model performance. These thresholds provide benchmarks for identifying models with systematic biases that might limit their utility for decision-making.

The comparative PBIAS across models, grouped by convection scheme and resolution, was used to identify systematic biases and assess model skill in simulating precipitation extremes. Statistical differences between models and estimation methods were evaluated visually through ranking plots and ensemble statistics.

IV. **Results**

A. *GEV Scale and Shape Parameter Biases*

I first compare the fitted GEV scale and shape parameters from each model against the observational benchmarks at the India (IMD4) and Italy (E-OBS) sites (**Figure 1**, below). Across CMIP6 models, MLE and Bayesian estimation produce very similar scale and shape values (even the sign) for a given model, whereas L-moments often diverge substantially. In the Italian (E-OBS) case, for example, as seen in Figure 1(d), most models underestimate the observed scale (≈7.8) derived using L-moments, on the other hand, MLE and Bayesian estimates show a wider spread and generally cluster around their respective, higher observational benchmarks. Only 2 of 15 models at 100 km and 2 of 17 at 250 km resolution are within ~10% of the observed scale in Italy. Higher horizontal resolution offers some improvement for India, as 3 of 15 models at 100 km (and none for 250 km) resolution meet this threshold.

Nevertheless, even at fine resolution, fewer than 25% of models achieve this level of agreement in either region. Only ACCESSCM2 estimates the scale parameter within ~10% of the observed value across all methods for Italy, while no model does so for India. 25% of models overestimate the scale in Italy and 50% do so for India; so the pattern is regionally consistent. It indicates that models tend to under-predict extreme rainfall magnitudes in Italy, but more frequently overestimate them in India.

The GEV shape parameters show analogous trends. For Italy, the observed shape is near zero, and most models (MLE / Bayesian) likewise estimate a small magnitude (positive or negative) shape, with L-moments again

producing a broader range. In Figure 1(c), it is observed that the E-OBS dataset itself yields almost identical shape estimates under MLE and Bayesian fits, indicating that this observational reference is immune to the fitting method. In contrast, at the India site, the observed shape is significantly negative (a bounded tail), and many models (MLE / Bayesian) capture a negative or near-zero shape, but L-moments fails to do so. It returns only small positive shapes for all models and even for IMD4 itself as seen in Figure 1(a).

About one-third of models simulate a negative shape for India, but L-moments produces non-negative shapes across the board. In summary, MLE and Bayesian approaches yield consistent shape estimates (agreeing in sign and magnitude) for each model, whereas L-moments cannot reproduce strongly negative shapes. Only 3–5 models per region match the observed shape within ~10% (e.g., KACE-1-0-G for India, CMCC-ESM2 for Italy) under the Bayesian method.

B. *Extreme Threshold Selection and Exceedances*

The selected thresholds matched well with the inferences from Mean Residual Life (MRL) plots in 94% of models for both regions, confirming the stability of the threshold selection across methods and models. The models' baseline extreme thresholds (e.g. the threshold fora one-in-one-year event or POT threshold) generally differ from observations. As shown in **Figure 2**, below, in the E-OBS analysis (Italy point), the observed extreme rainfall threshold is about 30.7 mm per day. Most models underestimate this value, i.e., 24 out of 32 models have lower thresholds. For example, HadGEM3-GC31-MM matches the observed threshold closely, but EC-Earth3-Veg-LR underestimates it by ≈19% despite a grid point only ≈16 km from the observation point. Geographic proximity influences threshold performance, but proximity alone does not guarantee accuracy. In both regions, several of the better-performing models, such as CMCC-ESM2 and KACE-1-0-G, sample grid points within ~50 km of the gauge.

In contrast to the Italy point, for the Indian point (observed threshold ≈33.4 mm per day), the bias reverses in that 19 of 32 models set higher thresholds than observed, and 13 are lower. KACE-1-0-G and CMCC-CM2-SR5 lie close to the observed value and HadGEM3-GC31-MM underestimates the threshold by ≈52%. Thus, E-OBS thresholds are predominantly underestimated and IMD4 thresholds are predominantly overestimated. 100 km models exhibit a slightly lower mean threshold error (8.82 mm per day) than 250 km models (9.08 mm per day) in Italy, showing a modest improvement with resolution. As shown in Figure 2, across both benchmarks, the great majority of models do not match the observed threshold. These threshold biases are carried forward into the return level estimates.

C. *Return Levels and Estimation Method Sensitivity*

Using each model's GEV fit (with the model-specific threshold), the 100-year return level (RL100) was computed. I compare the three fitting methods and also aggregate model-to model spread. Despite differences in fitted GEV parameters, the 100-year return levels (RL100) predicted by the three methods are generally of the same order for a given model, typically within 10–20% variation among MLE, Bayesian, and L-moments estimates. The average inter-method spread is ≈11–16%. In many cases, MLE and Bayesian estimates are nearly identical, while L-moments sometimes gives lower values, especially for heavy-tailed models. As shown in Figure 3, the three method curves for most models sit close together.

In worst-case outliers, ACCESSCM2 shows a method-driven RL100 variation of ≈33%. KACE-1-0-G is one of the few models performing well in both regions (E-OBS and IMD4), matching both the observed threshold and RL100 within ~10% in each case. However, method differences remain small compared to inter-model spread, which spans several hundred per cent. The ensemble mean reflects systematic biases; in E-OBS, RL100 is underestimated (~77 mm vs 100 mm

observed), and in IMD4, it is overestimated (≈145 mm vs 86 mm observed). As seen in Figure 3, these biases persist across return periods, with L-moments yielding a narrower quantile range, especially in E-OBS.

Certain models also demonstrated strong return level performance despite imperfect GPD parameter estimates. For example, HadGEM3-GC31-MM, despite having a large shape parameter bias (–121%) in E-OBS, reproduced the 100-year return level within 7.8%, likely due to accurate threshold estimation (+0.6%). Although the threshold for extremes is slightly lower in E-OBS (≈30.7 mm vs 33.4 mm for IMD4), the observed extremes in Italy are much larger in absolute terms. The maximum daily rainfall recorded in E-OBS during 2015–2024 reached 141 mm, well above the observed RL100 of ≈100 mm, and IMD4 recorded a maximum of only 78.7 mm, just slightly above its RL100 of ≈77.6 mm. Moreover, E-OBS exceeded its RL100 on two occasions in the past decade, and IMD4 exceeded its RL100 once.

D. *Model Bias and Ranking*

Finally, the models are ranked by their performance in simulating extreme precipitation. Model performance in simulating extreme precipitation return levels showed a clear dependence on the convection scheme (**Figure 4**, below). Zhang–McFarlane models (e.g. CESM2, NorESM2) widely underestimated extremes for Italy; for example, CESM2's 100-year return showed –54% bias. Similarly, NorESM2 and other ZM models showed strong underestimation at high return periods in Europe. However, only CESM2 performed well over India, with biases within ~10% across estimation methods, and other ZM models like GFDL-ESM4 and NorESM2-MM (top performer for India) overestimated Indian extremes by over 100% and 17% respectively.

For Gregory–Rowntree models, HadGEM3-GC31-MM performs reasonably well in Italy with modest RL100 underestimation (–8% to –20%), and UKESM1-0-LL overestimates by ≈30%. However, most Gregory–Rowntree models perform poorly in India, with HadGEM3-GC31-MM and ACCESSCM2 significantly underestimating and UKESM1-0-LL overestimating by up to +100%. Tiedtke-type models (EC-Earth family) were intermediate in that they generally captured large-scale features but still exhibited bias. For example, CNRM-CM6-1-HR's 100-year return level (~107 mm) was very close (+7%) to the observed 99.7mm in E-OBS, whereas other Tiedtke models (e.g. EC-Earth3) tended to under-predict the upper tail. Bulk adjustment schemes (e.g. IPSL-CM6A-LR, BCC-CSM2-MR, FGOALS-g3) showed larger biases.

In E-OBS, several bulk-scheme models had biases well outside ±20%. IPSL-CM6A-LR is a partial exception, delivering moderately accurate estimates in E-OBS (+24%) but severely overestimating extremes in IMD4 (+400%).

Across both regions, models using the Gregory–Rowntree and Tiedtke-type convection schemes generally produced lower biases, particularly in E-OBS. Zhang–McFarlane models showed strong underestimation in Europe but performed better in India. Bulk-adjustment schemes exhibited the highest biases overall, with large deviations observed in both domains. The performance varied across methods and no convection scheme delivered low-bias estimates in both regions. Importantly, KACE-1-0-G, a Gregory-Rowntree model, performed exceptionally well in both regions, ranking in the top 3 across all estimation methods.

Finally, model complexity (GCM vs ESM) was not a reliable predictor of performance. Both high-performing and poorly performing models were found among GCMs (e.g. HadGEM3-GC31-MM vs CESM2) and ESMs (e.g. UKESM1-0-LL vs NorESM2-MM). Instead, convection scheme design emerged as the dominant factor explaining model performance in simulating extreme precipitation return levels.

V. **Discussion and Limitations**

A. *Extreme Value Analysis Method Bias*

This study demonstrates that the methods used in EVA, especially in threshold selection and parameter estimation, exert an influence on return level estimates. E-OBS provides a firmer reference point when assessing model bias and return levels since it produces consistent results of GPD parameters across estimation methods, which could be attributed to a relatively dense underlying rain gauge network and high spatial resolution.[43] In contrast, the greater method sensitivity observed for IMD4 introduces additional uncertainty into the evaluation, particularly for high return periods. This highlights the importance of carefully considering the quality of the observational benchmark when interpreting bias magnitudes because an apparently large model bias against IMD4 may partly reflect uncertainties in the reference itself, whereas biases against E-OBS are likely more robust. POT offers more data points for fitting, improving parameter stability,[44] yet it is equally clear that the method is only as reliable as the data to which it is applied.[45] Any biases or limitations in the observational datasets inevitably propagate into fitted return levels, influencing not just absolute bias estimates but also the relative ranking of model performance.

Perhaps more importantly, threshold selection emerged as the dominant driver of bias in return level estimation. As noted by Coles,[46] the chosen threshold effectively defines what is deemed 'extreme'; and if poorly selected, it will skew the tail fit. In our models, it is found that even where shape and scale parameters were well aligned with observations, a bias in threshold led to substantial errors in return levels. This is particularly pronounced in convective regions like India, where coarse models tend to pre-trigger convection and hence artificially inflate the threshold (the 'drizzle bias' discussed by Stephens et al.[47]). On the other hand, in Italy's more stratiform regime, some models underestimated the threshold due to different triggering mechanisms. In both settings, the threshold effect dominated other sources of bias. This finding validates the literature's concern[48] that threshold choice remains a key uncertainty in POT approaches.

Estimator sensitivity is another issue highlighted by our results, especially when the shape parameter (ξ) approaches zero. Theoretically, as $\xi \to 0$, the GPD tail approaches an exponential form, where small changes in ξ have outsized impacts on long return period estimates.[49] In models where ξ hovered near zero, such as FGOALS-g3 over the India point ($\xi \approx -0.016$), the estimated 100-year return level (RL100) varied by up to 30mm depending on the estimator used. As Lazoglou and Anagnostopoulou[50] and de Zea Bermudez and Kotz[51] observe, likelihood-based methods such as MLE and Bayesian inference are generally more stable in this regime as opposed to L-moments which can become unreliable and fail to produce negative shape values. In my analysis, Bayesian estimates tended to be most reliable across all cases, especially where ξ was small or where sample sizes were limited. The increasing divergence between estimation methods at long return periods[52] exposes the sensitivity of tail estimates to parameter uncertainty, which is useful for diagnosing unstable model behaviour and emphasising that method

[43] Haylock, Malcolm, et al. "A European Daily High-Resolution Gridded Data Set of Surface Temperature and Precipitation for 1500-2100." *Journal of Geophysical Research*, vol. 113, D20119, 2008; Cornes (n 34) *supra*.
[44] Coles (n 6) supra; Scarrott & MacDonald (n 10) *supra*.
[45] Coles (n 6) *supra*; Beguería, Santiago, and Sergio Vicente-Serrano. "Mapping the Hazard of Extreme Rainfall by Peaks over Threshold Extreme Value Analysis and Spatial Regression Techniques." *Journal of Applied Climatology*, vol. 45, no. 1, 2006, pp. 108-124.
[46] Coles (n 6) *supra*.
[47] Stephens (n 13) *supra*.
[48] Scarrott & MacDonald (n 10) *supra*; Roth, M, et al. "Threshold Selection for Regional Peaks-Over-Threshold Data." *Journal of Applied Statistics*, vol. 43, no. 7, 2016, pp. 1291-1309.
[49] Katz, Richard. "Extremes of Daily Precipitation in Global Climate Models." *Journal of Climate*, vol. 12, no. 7, 1999, pp. 2067-2078.
[50] Lazoglou & Anagstopoulou (n 10) *supra*.
[51] de Zea Bermudez, Paolo, and Samuel Kotz. *Extreme Value Distributions: Theory and Applications*. Imperial College Press, 2010.
[52] Katz (n 49) *supra*.

choice is critical when extrapolating extremes for decision-making.

It should be noted, however, that even though methodological choices clearly affect return levels, the spread between models is substantially larger than the spread between estimation methods. This suggests that the dominant uncertainties in extreme precipitation projections arise from model physics, not statistical estimation per se. Nonetheless, good practice in EVA remains essential. Poor threshold selection or inappropriate estimators can easily confound results, as has been warned in numerous prior studies.[53] Since threshold selection often relies on judgment (e.g., 95th or 99th percentile), there is a need for more principled methods that reduce arbitrariness and promote consistency across studies.

B. *Model Physics Bias*

It is observed that model biases in extreme precipitation align strongly with convection scheme families. These biases remain consistent across estimation methods and reinforce the importance of parameterisation in shaping return-level behaviour.

Zhang–McFarlane (ZM) models such as CESM2, NorESM2-LM, and NorESM2-MM perform well in India, with RL100 biases generally within ±30%, consistent with their capacity to simulate deep convection during the monsoon. However, all three substantially underestimate extremes in Italy, with RL100 values falling short by 50–65%. This behaviour reflects known weaknesses in ZM schemes under midlatitude conditions, where premature convection stabilises the atmosphere and suppresses extreme rainfall. These findings support earlier results by Wang et al.[54] and Zhang and Mu[55], which highlight the latitude sensitivity of the ZM family.

Models using the Gregory–Rowntree (GR) scheme show more mixed results. HadGEM3-GC31-MM matches observations fairly well in E-OBS, with RL100 bias under 20%, but underestimates Indian extremes by ≈30%. UKESM1-0-LL performs less reliably, overestimating RL100 by ≈30% in Italy and by more than 80% in India. The GR approach, which delays deep convection through convergence-based triggers, captures European midlatitude extremes more effectively than tropical ones. Nonetheless, performance varies significantly within the family, and no GR model shows strong agreement across both regions.

Mass-flux lineage schemes exhibit a broader spread. CNRM-CM6-1-HR delivers the most accurate result in E-OBS, with RL100 bias under 3% and threshold error below 8 mm. In contrast, its performance deteriorates over India, where it overestimates the 100-year return level by more than 50%. CNRM-ESM2-1 shows moderate underestimation in Italy but strongly overestimates extremes in India, with a bias exceeding 65%. EC-Earth models, also part of the Tiedtke family, show mixed performance. EC-Earth3-CC performs reasonably in both domains (bias within ±20%), while EC-Earth3-Veg-LR overestimates RL100 in India by ≈23%. These inconsistencies likely arise from differences in tuning, such as entrainment rates or trigger thresholds.

Models that retain relatively simple single-moment microphysics and mass-flux convection (e.g., FGOALS-g3, BCC-CSM2-MR, IPSL-CM6A-LR) perform poorly across both regions. FGOALS-g3 underestimates RL100 by 40% in Italy and overshoots it by more than 100% in India. BCC-CSM2-MR shows extreme overestimation in India (bias over 400%) and severe underestimation in Europe. IPSLCM6A-LR, although slightly more accurate in E-OBS (bias ≈+20%), ranks among the worst

[53] Beguería, Santiago, et al. "Mapping the Hazard of Extreme Rainfall by Peaks over Threshold Extreme Value Analysis and Spatial Regression Techniques." *Journal of Applied Statistics*, vol. 43, no. 7, 2005, pp. 1291-1309.

[54] Wang, Yun, et al. "Latitudinal Differences in the Response of Temperature Extremes to Anthropogenic Forcing." *Nature Climate Change*, vol. 12, no. 5, 2022, pp. 406-412

[55] Zhang & Mu (n 13) *supra*.

performers in IMD4, with RL100 bias exceeding 300%. These models lack explicit cloud microphysics and rely on simplistic moisture-to-rain conversion rules, which leads to sharp threshold errors and unstable tail behaviour.

IPSL-CM6A-LR, though somewhat more advanced, still exhibits bulk-like behaviour. Its good performance in Italy may partly reflect both chance and the model's coarse resolution, which aligns better with the large-scale orographic and synoptic extremes (cyclones) typical of the region, but it fails in India, where capturing small-scale, intense convective bursts is critical. KACE-1-0-G demonstrates consistently strong performance across both regions, despite using a conventional Gregory–Rowntree model. Its effective tuning appears to support realistic tail behaviour in both tropical and mid-latitude regimes, which underlines the importance of targeted calibration, even within standard parameterisation frameworks. The ensemble mean is biased relative to observations but displays consistent and spatially coherent errors, making it amenable to statistical bias correction.

Overall, the structured model biases observed are fully consistent with prior literature. As Rio et al. and Emmenegger et al.[56] argued, model physics, particularly the handling of deep convection, remains the primary driver of biases in simulated precipitation extremes. My two-region comparison added the idea that these biases are systematic and region-dependent. The same model can perform well in one region (Italy) but poorly in another (India), highlighting the challenges of achieving universal skill across different climate regimes.[57] It is also worth noting the role of latitude and large-scale dynamics. Tropical extremes are dominated by deep convection, modulated by phenomena such as the Madden–Julian Oscillation (MJO) and equatorial wave[58] in contrast with midlatitude extremes that depend more on frontal systems and orographic forcing. Unsurprisingly, no single convection scheme performed equally well across both latitudes, which echoes the findings of Norris et al.[59] and Hohenegger and Bretherton.[60] Hybrid schemes, such as the one used in TaiESM1, may offer a more flexible approach, though this remains an area for future model development.

Convection-permitting models offer a promising path forward, but their high computational costs mean that for the foreseeable future, progress in CMIP-class models will depend on more sophisticated parameterisations and targeted improvements in microphysics and dynamics. Investment in these areas is likely to yield meaningful gains in extreme precipitation projections, with clear benefits for downstream risk applications.

C. *Resolution*

In this analysis, an interesting latitude-dependent pattern emerges where finer grid models tend to perform better for IMD4 (India) and some coarser-grid models still perform well for E-OBS (Italy). Finer resolution is important, particularly for convection-dominated regions, but it is not

[56] Rio, Catherine, et al. "Ongoing Breakthroughs in Convective Parameterization." *Current Climate Change Reports*, vol. 5, no. 2, 2019, pp. 95-111; Emmenegger, Laurent, et al. "Observational Constraints on Aerosol-Cloud-Convection Interactions." *Nature Reviews Earth & Environment*, vol. 4, no. 7, 2023, pp. 440-455.

[57] Zhang, Xuebin, et al. "Understanding the Causes of Climate Change Impacts on Precipitation Extremes in the Future." *Bulletin of the American Meteorological Society*, vol. 106, no. 3, 2025, pp. 423-437; Iturbide, Maialen, et al. "An Update of IPCC Climate Reference Regions for Subcontinental Analysis of Climate Model Data: Definitions and Aggregated Datasets." *Earth System Science Data*, vol. 12, no. 4, 2020, pp. 2959-2970.

[58] Mayta, V, et al. "Modulation of Intraseasonal Convective Activity by the MJO over the Central Andes." *Climate Dynamics*, vol. 62, no. 5, 2024, pp. 3475-3492.

[59] Norris, Jesse, et al. "Evaluation of the Tail of the Probability Distribution of Daily and Subdaily Precipitation in CMIP6 Models." *Journal of Climate*, vol. 34, no. 7, 2021, pp. 2657-2678

[60] Hohenegger, Cathy, and Christopher Bretherton. "Microphysics and Turbulence in Simulations of Deeper Convection." *Journal of the Atmospheric Sciences*, vol. 68, no. 8, 2011, pp. 1854-1873.

sufficient by itself, as noted by Prein et al.[61] Models like MRI-ESM2-0 demonstrate that even at finer scales, biases can persist if the convection scheme or time-stepping poorly represents storm evolution. Similarly, orographic smoothing and point–grid mismatch continue to introduce structural uncertainties.[62] Overall, these results align with Chen et al. and Bador et al.[63] in showing that increasing resolution improves the potential for realistic extremes, but model physics and temporal precision remain equally essential. Future model development could involve hybrid approaches that combine advanced physics with regionally adaptive resolution, for example, using variable-resolution grids or embedding convection-permitting nests in key regions. Such strategies may improve the global simulation of precipitation extremes without prohibitive computational costs.

Since this study evaluates extremes at the point scale, some bias arising from the distance between the model grid point and the observation site is unavoidable, particularly in regions with complex terrain or sparse station networks. Even when selecting the nearest grid point, spatial mismatches of several tens of kilometres can occur, which can influence the representation of localised extremes.

A further challenge for CMIP6 models is capturing internal climate variability, which modulates extreme rainfall on interannual to decadal timescales. At the Italy point, two events exceeding the 100-year return level occurred in the past decade, which were attributed to internal variability rather than climate change.[64] Most models struggled to reproduce this behaviour;[65] only KACE-1-0-G (for both regions) and HadGEM3-GC31-MM (for Italy) produced return level structures consistent with observed event frequency. CMIP6 models can represent mean trends in extremes but lack the ability to simulate the clustering and timing of rare, variability-driven events.

D. *Implications for Climate Model Users and Climate-Sensitive Decision-Making*

The magnitude of inter-model spread in return level estimates—spanning several hundred percent in extreme cases—raises important questions about the credibility and utility of CMIP6 ensemble predictions for decision-makers. Whilst multi-model ensembles are often presented to stakeholders as a means of quantifying uncertainty, the spread documented here reflects primarily differences in model physics rather than a principled sampling of genuine uncertainty. Citizens, water utilities, and civil protection agencies who rely on ensemble summaries (ensemble means or percentile ranges) may be misled about the true range of plausible future extremes if the ensemble is composed of models with widely divergent convection schemes and calibration choices. If biases are systematic and scheme-dependent, then claims of consensus or high confidence in ensemble predictions become contingent on the composition of the ensemble.

The literature on climate change adaptation economics indicates that uncertainty in precipitation extremes is a primary driver of infrastructure planning risk.[66] World Bank estimates place the cost of water sector adaptation globally at approximately USD 20 billion per year by 2050, and failures in climate-informed infrastructure planning can result in losses ranging from 5% to 60% in hydropower revenue alone, depending on the basin and the accuracy of precipitation projections.[67] When model-derived

[61] Prein et al. (n 8) *supra*.
[62] Barrett et al. (n 16) *supra*; Pierce et al. (n 17) *supra*.
[63] Chen, Xiuhong, et al. "Changes in Annual Extremes of Daily Temperature and Precipitation in CMIP6 Models." *Journal of Climate*, vol. 38, no. 9, 2025, pp. 3441-3460; Bador et al. (n 15) *supra*.
[64] Barnes, Clair, et al. "Limited Net Role for Climate Change in Heavy Spring Rainfall in Emilia-Romagna." Imperial College London Working Report, 2023.
[65] Wu, Yuanxin, et al. "Understanding the Contribution of Extreme Heat to the June 2021 Pacific Northwest Heat Wave." *Journal of Geophysical Research: Atmospheres*, vol. 127, no. 15, 2022, e2022JD036873.
[66] Hughes, Gordon, et al. "The Costs of Adapting to Climate Change for Infrastructure." World Bank Development and Climate Change Discussion Paper 2, 2010.
[67] ibid.

precipitation projections are significantly biased, the risk calculus underlying infrastructure investment decisions becomes distorted. Policymakers and water utilities may either fail to invest adequately in resilience measures (if models underestimate future extremes) or invest excessively in over-designed infrastructure (if models overestimate extremes), both outcomes representing economic inefficiency and misallocation of resources in constrained adaptation budgets.

Furthermore, the finding that threshold selection in extreme value analysis exerts greater control over return-level bias than variations in parameter estimation methods suggests that uncertainty in return-level projections is as much a function of methodological choices made downstream of the model output as it is a reflection of model physics.

From a decision-support perspective, these findings suggest that ensemble-based projections will be more useful to practitioners if they are stratified by convection scheme family and if scheme-specific biases are communicated alongside ensemble statistics. Rather than presenting a single multi-model mean return level to an urban planner or water utility engineer, it may be more honest and more useful to present: (i) the range of scheme-specific biases documented from evaluation against observations; (ii) the envelope of model projections annotated with scheme family and bias magnitudes; and (iii) explicit recommendations about which models are most appropriate for specific regions and applications. Such an approach would improve the scientific integrity of climate-informed adaptation planning by ensuring that decision-makers have clear insight into the physical drivers of model divergence and the likely accuracy of projections in their region of interest.

E. *Limitations*

I did not formally quantify the statistical uncertainty of my return-level estimates (e.g. via confidence or credible intervals). This was a deliberate choice to concentrate on bias structure, but it means uncertainties for any single model's 100-year event are not reported. Had I included bootstrapped confidence intervals or full Bayesian posteriors, it would have been more complete uncertainty information, but the central conclusions (regarding relative biases) would likely remain similar. In effect, by focusing on relative differences among models and methods, I have somewhat sidestepped the sampling noise issue in that the biases that persist across methods are unlikely to be purely due to random variability. Future work should incorporate formal interval estimation to check whether the observed bias magnitudes are statistically significant.

Another limitation of this study is its relatively narrow spatial and variable scope. The analysis focuses on only two locations in the tropics and mid-latitudes, without testing model skill in other important climate regimes, such as high latitudes or in the mountains, where different physical processes dominate the generation of extremes. As a result, the findings may not capture the full diversity of regional climate behaviours or model responses. Furthermore, this study evaluates precipitation extremes only using daily precipitation data, whereas other studies have used dynamical fields such as 500 hPa geopotential height, mean sea-level pressure, or wind anomalies to investigate the atmospheric conditions associated with extreme events. Including such diagnostics could offer a less siloed assessment of model skill and help attribute observed biases to circulation features or synoptic-scale drivers.

VI. **Conclusion**

This study was designed with three primary objectives: to quantify systematic biases in extreme daily precipitation simulated by 32 CMIP6 models at the point scale; to identify the dominant sources of these biases, distinguishing between contributions from statistical methodology versus model physics; and to assess the extent to which model characteristics, particularly convection

parameterisation, influence the fidelity of simulated extreme precipitation.

To address these objectives, a POT framework was employed, fitting a GPD to daily rainfall values exceeding the 99th percentile threshold. Three parameter estimation methods (Maximum Likelihood Estimation, L-moments, and Bayesian inference) were applied to quantify estimator sensitivity. Return levels for return periods ranging from 2 to 100 years were computed, and model performance was evaluated against observational benchmarks from IMD4 (India) and E-OBS (Europe) using the PBIAS metric.

The analysis revealed several key findings. First, CMIP6 models exhibit systematic and geographically divergent biases as they tend to overestimate extreme precipitation in the tropical Indian monsoon domain and underestimate it in the mid-latitude Mediterranean climate of northern Italy. Second, these biases are strongly organised by convection scheme family, with Zhang–McFarlane models performing reasonably well in monsoon regimes but substantially underestimating mid-latitude extremes, whilst Gregory–Rowntree and Tiedtke-type schemes show contrasting regional strengths and weaknesses. Third, threshold selection emerges as a critical source of uncertainty in return level estimation, with considerable variability observed across models driven by differences in convection parameterisation and drizzle bias. This variability underscores the necessity for more objective and standardised threshold selection procedures; subjective or ad hoc threshold choices introduce systematic biases that can substantially exceed variations attributable to fitted shape and scale parameters, highlighting the imperative for principled, reproducible methodologies in extreme value analysis. Finally, whilst differences among the three estimation methods are non-negligible, they remain modest relative to inter-model spread, with Bayesian inference demonstrating the most robust behaviour in edge cases where the shape parameter approaches zero.

This study contributes to the field by establishing a tailored, point-scale diagnostic framework that explicitly links CMIP6 tail behaviour to underlying model physics. By demonstrating that convection parameterisation is the primary driver of return-level bias more so than model resolution or choice of extreme value estimator the work underscores the value of physics-oriented model development over computational refinement alone. Moreover, by highlighting the dominant role of threshold selection, the analysis provides practical guidance for practitioners conducting extreme value analyses on climate model output.

On the basis of these results, the following recommendations are offered. First, efforts to improve CMIP6 skill in extreme precipitation should prioritise refinement of convection parameterisation schemes and associated microphysics and moisture treatments, particularly in convection-dominated regimes. Second, systematic and physically grounded tuning of model parameters which is evidenced by the exceptionally strong performance of KACE-1-0-G across both regions, offers a promising pathway to reducing tail biases. Third, extreme value analyses intended for impact-relevant applications should document and justify choices regarding threshold selection, percentile definition, and estimator selection, given the demonstrated sensitivity of return levels to these methodological decisions.

Future investigations could extend this diagnostic approach in several directions. Application to additional climate regions and to multi-site or spatially aggregated configurations would clarify the generality of the identified bias patterns. Integration of convection-permitting models or variable-resolution simulations, where computationally feasible, would enable systematic assessment of whether explicit convection reduces tail biases relative to parameterised approaches. Finally, formal attribution of model biases to specific parameter or process choices would support

targeted model development aimed at enhancing the utility of precipitation extremes projections for adaptation and risk-management applications.

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Figure 1: Comparison of GEV Shape Parameter Estimates for Each Model under Three Methods (MLE, L-moments, Bayesian) at 100km (Left) and 250km (Right) Nominal Resolutions. *Notes: Dashed lines indicate the shape and scale value from observation data (IMD4 – Fig 1(a), (b), E-OBS – Fig 1(c), (d)) for each method. Models are arranged in increasing distance from the model data point to observation data point. MLE and Bayesian generally produce similar shape values (often of the same sign), while L-moments shows greater divergence and fails to capture negative shapes, tending to stay positive.*

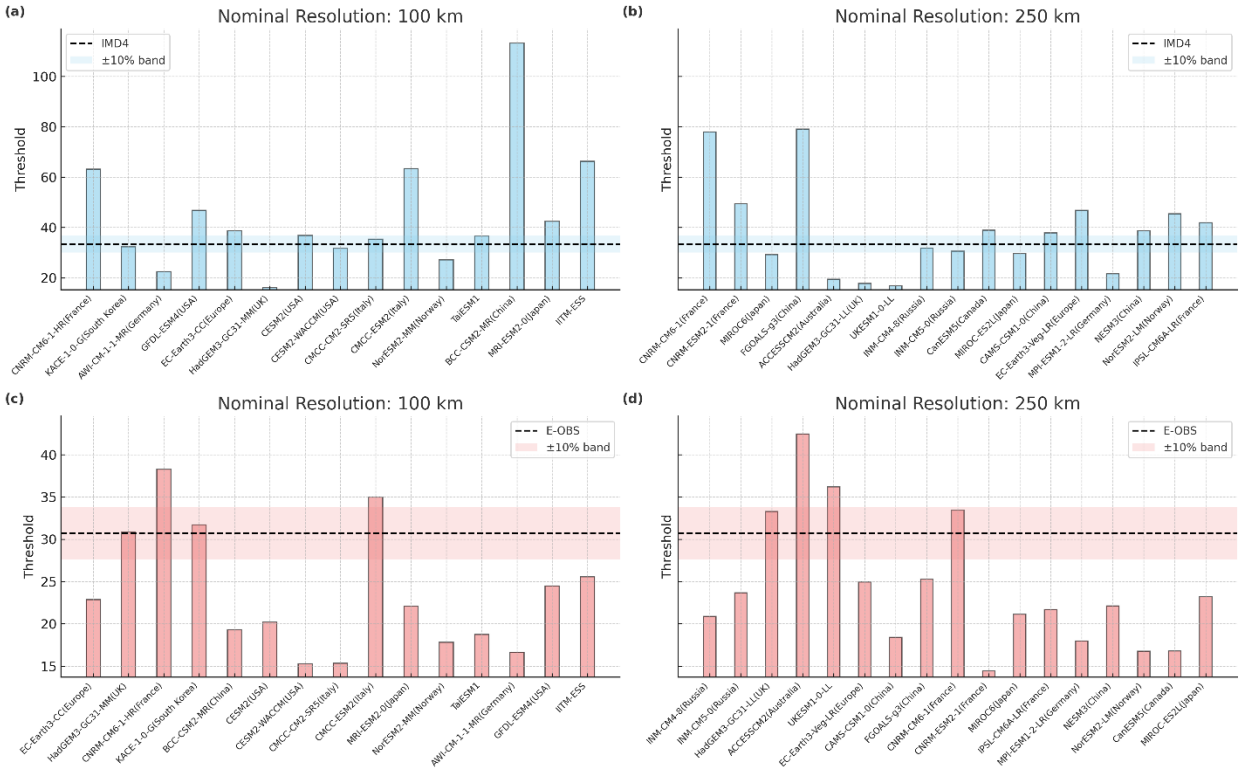


Figure 2: Comparison of 99th Percentile Threshold Value for Each Model at 100km and 250km Resolution. *Notes: Horizontal dashed lines indicate the threshold for an observation dataset (IMD4- Fig 2(a), 2(b), E-OBS- Fig 2(c),4.2(d)) and the shaded ~10% band provides a visual guide to identify models that closely match the observed value. Models are arranged in increasing distance from model data point to observation data point. Threshold value for IMD4 is often more than for observed data and vice versa for E-OBS case.*

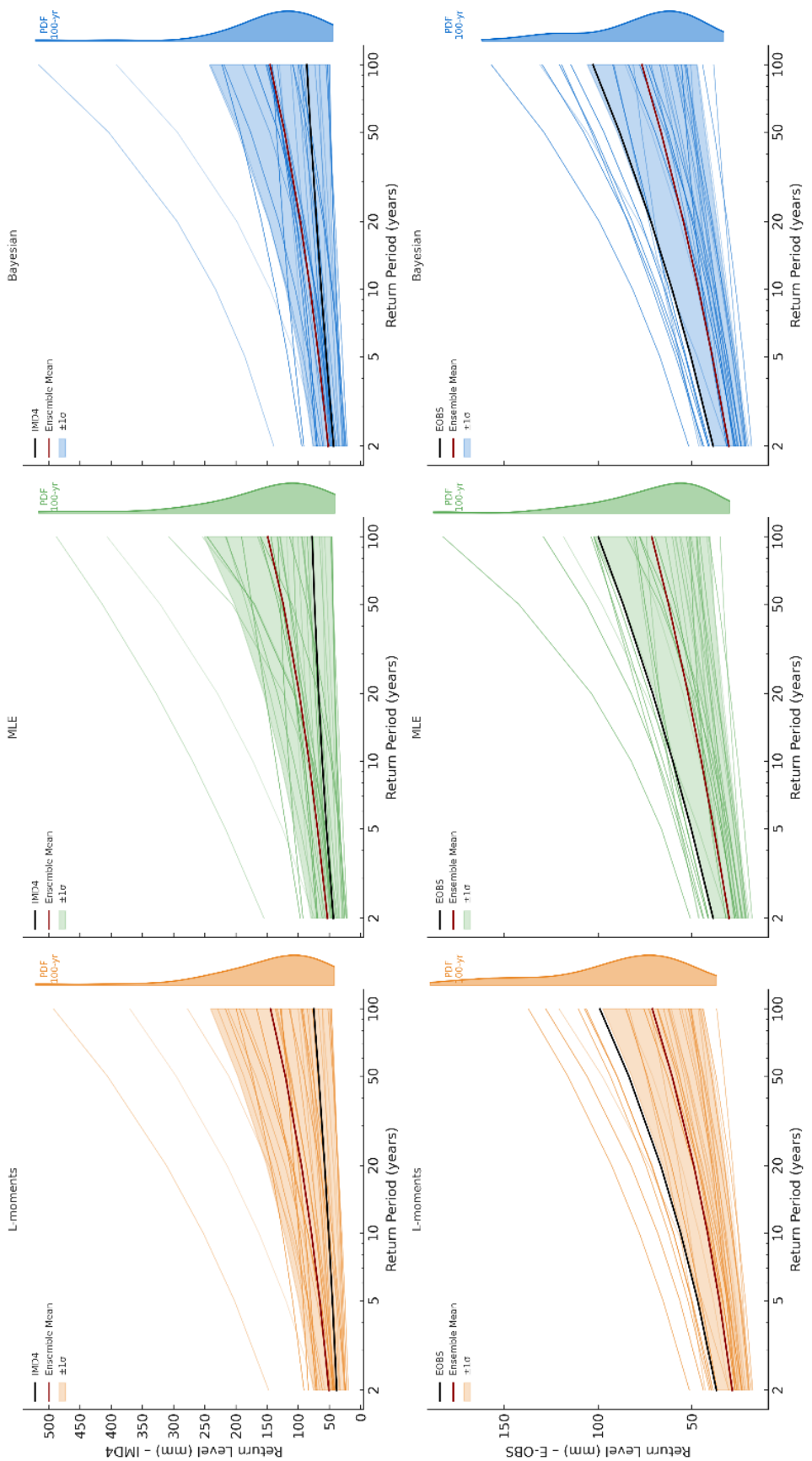


Figure 3: Return Level Estimates for Different Return Periods Using Three Parameter Estimation Methods—L-moments (a, d), Maximum Likelihood Estimation (b, e), and Bayesian Inference (c, f) for IMD4 (Top Row) and E-OBS (Bottom Row). Notes: Each panel shows return levels from individual CMIP6 models (light lines), the ensemble mean (red), and observational values (black). Shaded bands around the ensemble mean represent ~1 standard deviation. On the right of each plot is a probability density function (PDF) of the 100-year return level across models, showing ensemble spread. Return periods are shown on a log scale.

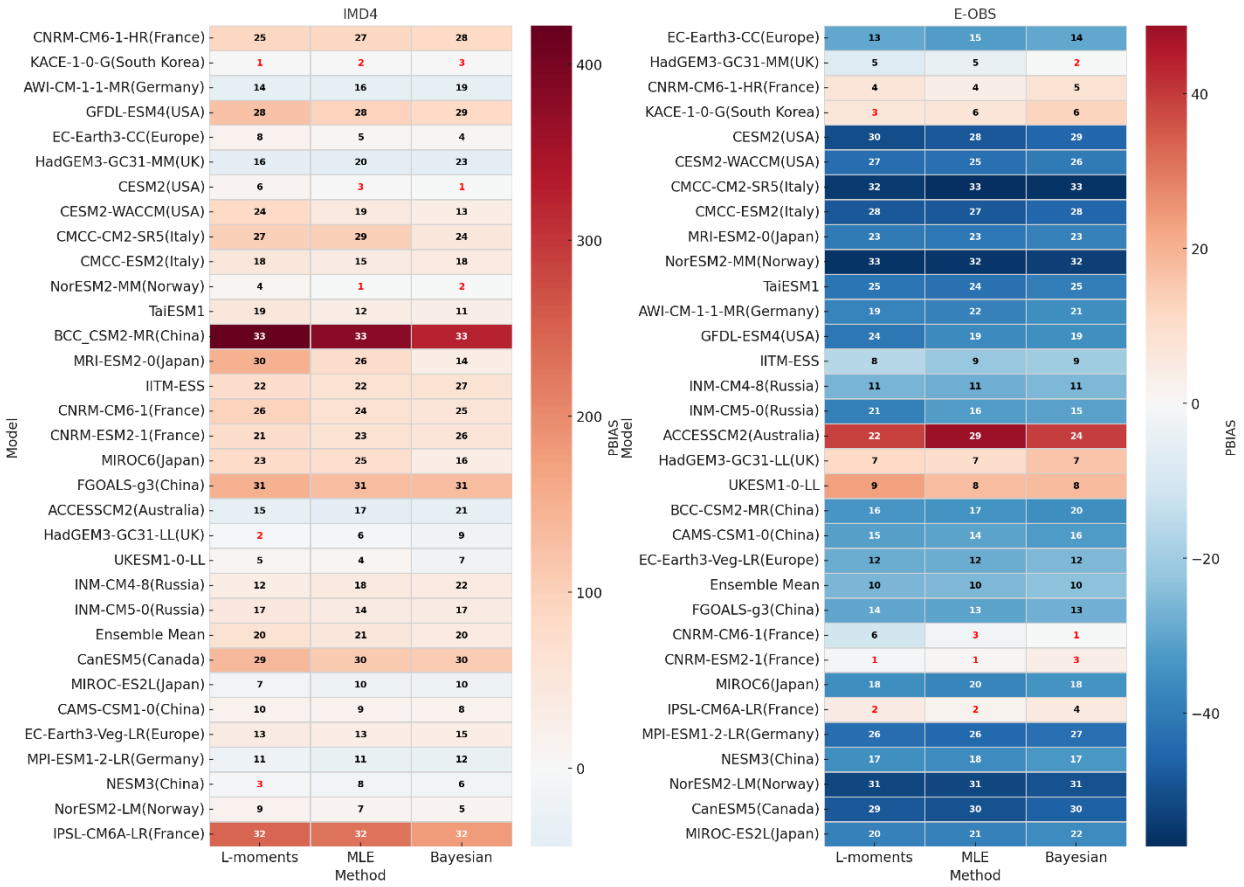


Figure 4: Model Biases in Simulating Daily Precipitation Extremes at India Site (Fig 4(a)) and Italy Site (Fig 4(b)). Notes: CMIP6 models ranked by the absolute value of Mean PBIAS (%), including the ensemble mean, grouped by resolution (100km/250km) and ordered by distance. Top three ranks for each site are written in red. Models mostly show positive bias (red shade) for the India site and mostly negative bias for the Italy site (blue shade).

Delineating the Skyscape: Mapping Sustainable Aviation Policy Levers for Climate Risk

Qi Song*

* Research Associate & The King's Global Sustainability Fellow in Climate Risk in Aviation, University of Cambridge Institute for Sustainability Leadership, UK

KEYWORDS

sustainable aviation, climate risk, policy levers, transition pathways, decarbonisation strategies

ABSTRACT

The aviation sector faces a growing risk of failing to meet international climate targets, as current mitigation efforts fall short of the scale and pace required. Closing this gap demands the aligned mobilisation of technical, societal, and operational solutions across emerging transition pathways, underscoring the need for coherent and timely policy intervention. This viewpoint article provides a stocktake of sustainable aviation policy levers across five key impact domains identified in recent academic literature and research reports: system efficiency improvements, sustainable aviation fuels, alternative aircraft design, air travel demand management, and the mitigation of non-carbon dioxide climate effects. Together, these domains shape the sector's transition towards a climate-neutral future, offering an integrated perspective on how strategic and well-sequenced policy design can accelerate change. The article outlines key policy mechanisms for addressing aviation-related climate risk and introduces a heuristic framework for rethinking system-level governance. It highlights the need for the effective and coordinated deployment of regulatory, economic, voluntary, and capacity-building instruments across multiple stakeholder groups in the sector. Collectively, the design of policy strategy, the choice of instruments, and the styles of policy processes warrant greater attention from this cross-cutting scoping viewpoint.

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I. **Introduction**

The climate impact of aviation demands rapid and fundamental systemic transitions. The sector accounted for approximately 2.5% of global carbon dioxide emissions in 2023, with emissions growing at a faster rate than rail, road or shipping over recent decades.[1] Beyond carbon dioxide (CO_2), non-CO_2 emissions from aviation—including nitrogen oxides, water vapour, sulphur oxides, aerosols, contrails and contrail-induced cirrus clouds—contribute substantially to aviation's overall radiative forcing, with a warming impact of similar magnitude to that of aviation's CO_2 emissions.[2] Whilst CO_2 acts as a long-lived climate forcer operating over decades to millennia, non-carbon-dioxide emissions influence the climate over shorter timescales

[1] *European Aviation Environmental Report 2025*. European Union Aviation Safety Agency, 2025.

[2] Aviation Impact Accelerator. *Five Years to Chart a New Future for Aviation*. University of Cambridge, 2024.

ranging from weeks to decades.[3] Taken together, the cumulative climate impact of aviation underscores both the challenges of unlocking timely change in a complex sector and the need for a whole-system approach to transforming the sector toward climate neutrality.[4]

Although progress toward net zero remains deeply uncertain, emerging solutions offer promising pathways. In 2021, the International Air Transport Association (IATA) announced an industry target to achieve net zero carbon emissions from operations by 2050, aligned with the temperature goals of the Paris Agreement. By 2025, however, IATA warned that the sector is already off track.[5] Aviation is widely regarded as a hard-to-abate sector, where meaningful emissions reductions require the well-aligned development of technological, operational, business and financial levers across the whole aviation ecosystem.[6] Collective action among airlines, regulators, air traffic control, airports, airframe manufacturers, the financial sector and governments is essential for overcoming structural barriers and achieving timely decarbonisation.[7] In this context, sustainable aviation fuels, hydrogen and electrified propulsion, operational efficiency improvements, demand-management strategies, and the mitigation of non-CO_2 emissions are increasingly recognised as promising avenues for leveraging the transformative power of policy action. Recent system-modelling assessments indicate that several of these solutions are technically feasible and economically viable under appropriate policy conditions for the near-term window, provided that supportive policy frameworks in place.[8] Yet the sector's complexity and diversity of technologies, stakeholders and governance levels require policy levers to be clearly differentiated and strategically sequenced within an integrated sectoral policy roadmap. Identifying, integrating and coordinating policy levers is therefore crucial for overcoming bottlenecks, unlocking system-wide benefits and accelerating the transition toward climate neutrality.

Given the analytical complexity of the aviation system, mapping sustainable aviation policy levers to address climate risk requires a degree of disaggregation to enable effective operationalisation and to identify key intervention points. As a pre-analytical framing, five key impact domains are identified through recent academic literature and research reports:[9] system efficiency improvement, sustainable aviation fuel, alternative aircraft design, air travel demand management and the mitigation of non-CO_2 emissions. Building on recent scholarship that conceptualises sustainable transition policy mixes as combinations of strategic elements and policy instruments,[10] these impact domains, defined as areas affected by a mix of policy instruments that pursue one common or different strategies,[11] serve as a focusing device that enables a comprehensive examination of the policy levers across different sustainable aviation transition pathways. This approach is adopted because there is currently no widely recognised set of

[3] Significant scientific uncertainty remains, however, regarding the precise magnitude and temporal dynamics of these effects.
[4] Kallbekken, Steffen, et al. "Transforming Aviation's Impact on the Climate: Rethinking the Research Strategy." *Environmental Science & Technology*, vol. 58, no. 47, 2024, pp. 20849-20858.
[5] *ICAO Environmental Report 2025*. International Civil Aviation Organization, 2025.
[6] *ICAO Environmental Report 2022*. International Civil Aviation Organization, 2022.
[7] Aviation Impact Accelerator (n 2) *supra*.
[8] ibid.
[9] Aviation Impact Accelerator (n 2) *supra*; Kallbekken et al. (n 4) *supra*; Muehlberger, Clara-Marie, et al. "Socio-Technical Imaginaries of Climate-Neutral Aviation." *Energy Research & Social Science*, vol. 114, 2024, 103595.
[10] Rogge, Karoline, and Kristin Reichardt. "Policy Mixes for Sustainability Transitions: An Extended Concept and Framework for Analysis." *Research Policy*, vol. 45, no. 8, 2016, pp. 1620-1635; Rogge, Karoline, and Qi Song. "Policy Mixes for Addressing Environmental Challenges." *Routledge Handbook of Environmental Policy*, edited by Helge Jörgens et al., Routledge, 2023, pp. 327-346.
[11] Ossenbrink, Jan, et al. "Delineating Policy Mixes: Contrasting Top-down and Bottom-up Approaches to the Case of Energy-Storage Policy in California." *Research Policy*, vol. 48, no. 10, 2019, 103582.

strategic intentions at the sector level, and policy debates remain fragmented. Instead, discussions in both academic and policy arenas tend to cluster around a set of emerging solution pathways. Although there is some conceptual overlap among these domains, each comprises a distinct mix of regulatory, economic, and voluntary instruments, complemented by capacity-building measures that strengthen the skills, resources, infrastructure, and broader enabling conditions needed to deliver policy outcomes. The five impact domains identified here are not intended to be exhaustive, but rather to serve as an illustrative and analytically tractable framing of a complex policy landscape. Other domains—such as airport infrastructure, supply-chain decarbonisation or international governance reform—are recognised as important but are either subsumed within these categories or addressed indirectly through the policy levers considered.

This work aims to delineate the landscape of policy levers for navigating climate risk across the aviation ecosystem. Drawing on a scoping review of the existing literature on sustainable aviation policy,[12] it takes a first step toward system-wide thinking that helps reweave currently fragmented and isolated policy actions. It is worth noting that this exercise provides a stocktaking of possible policy levers rather than a deep dive into real-world implementation, which is shaped by a range of barriers and contextual factors, as discussed in the concluding Section. In doing so, this article contributes to the current debate by connecting sectoral ambitions and targets with specific policy levers through a focus on meso-level impact domains. The following sections examine each of these domains in turn, and the conclusion summarises the overarching policy takeaways.

II. **Impact Domain I: System Efficiency Improvement**

As the first impact domain, system-level efficiency improvements within the existing aviation architecture represent one of the most immediate and scalable avenues for achieving cascading emissions reductions across the whole sector. Realising these gains, however, requires well-aligned action across a wide range of industrial stakeholders, including airline operators, aircraft and engine manufacturers and suppliers, airport and ground service providers, and airspace navigation and traffic management authorities. Discussions of potential policy instruments in this impact domain generally centre on at least four main intervention areas: fleet and technology efficiency; operational efficiency; airspace and network efficiency; and airport and ground infrastructure efficiency (as outlined in **Table 1**, below).

Improvements in fleet and technology efficiency undertaken by airline operators and technology manufacturers represent a complex but essential element of maximising the emissions-reduction potential of the sector's current technological architecture. Regulatory instruments form the foundation for progress in this area. These include fuel-efficiency standards, carbon dioxide and greenhouse-gas performance requirements, and baseline design criteria that apply to the technology supply side.[13] Complementary guidance and information tools—such as sustainability programmes, green fleet-management frameworks and voluntary aircraft-replacement schemes—can further support the adoption of more efficient technologies and fleet-planning practices. These voluntary approaches can mobilise the transformative potential of corporate actors and strengthen their leadership in addressing climate change. Economic instruments also play a crucial role. Emissions taxes or

[12] The review is based on keyword-based Scopus literature searches on sustainable aviation policy—which yielded 609 documents as of 14 Oct. 2025—as the primary dataset, alongside complementary internet searches.

[13] Proost, Stef. "Looking for Winning Policies to Address the Climate Issue in EU-Aviation." *Journal of Air Transport Management*, vol. 115, 2024, 102534.

subsidies that encourage investment in modern, fuel-efficient aircraft create financial signals that influence decisions on fleet renewal and technological upgrading.[14] Revenue generated from emissions-related taxation can be reinvested in the research, development and deployment of cleaner technologies, helping to create a positive innovation cycle.[15] The strategic relationship between technology providers and their major customers, particularly commercial airlines, is especially significant in this context. Targeted capacity-building measures, including support for technology road-mapping and fleet-efficiency planning, can help accelerate the deployment of higher-efficiency aircraft across existing fleets.

Operational efficiency forms another strategically important avenue for reducing the climate impacts of air travel. Here, airline and fleet operators have direct, day-to-day influence. Regulatory frameworks addressing operational practices can include provisions on weight and load optimisation, fuel-management procedures and slot utilisation. Reforms to slot-allocation rules (such as grandfather rights), for example, can discourage inefficient operations and foster more rational scheduling.[16] These regulatory tools can be strengthened through economic levers such as differential carbon taxes on various routes and environmental landing charges.[17] Alongside mandatory requirements, voluntary initiatives led by airlines often offer some of the most promising avenues for climate-oriented operational improvements, especially in areas where regulation is not yet feasible. Policy support for such initiatives can generate early-mover momentum and help identify best practices that may later be codified into formal regulation. Given the regulatory complexity of the aviation sector, clear operational guidance is also essential. Manuals and best-practice standards issued by organisations including the International Civil Aviation Organization (ICAO) and IATA provide authoritative reference points, while targeted capacity-building is required at both institutional and individual levels. Flight crews and ground-operations staff play a decisive role in determining the practical effectiveness of operational-efficiency measures.[18]

Adaptive regulatory coordination at the system and network level is central to advancing airspace modernisation and shaping international technical and operational standards that increasingly integrate climate considerations. This includes incorporating carbon-related performance requirements into international standards and implementing national airspace-redesign and restructuring frameworks. Large-scale initiatives such as the Single European Sky demonstrate how coordinated cross-border governance can contribute to emissions reductions by improving flight-path planning, reducing delays and enabling more efficient air traffic management.[19] Economic measures—such as differential carbon taxes that motivate airlines to adjust their route choices at the operational level, as discussed above—can complement these regulatory efforts by supporting improvements in network-level efficiency. System and network-efficiency

[14] Ovaere, Marten, and Stef Proost. "Strategic Climate Policy in Global Aviation: Aviation Fuel Taxes and Efficiency Standards with Duopolistic Aircraft Producers." *Economics of Transportation*, vol. 41, 2025, 100397.

[15] Wild, Peter, et al. "Impact of Political and Market-Based Measures on Aviation Emissions and Passenger Behaviors (a Swiss Case Study)." *Transportation Research Interdisciplinary Perspectives*, vol. 10, 2021, 100405.

[16] Kösters, Till, et al. "Effects of the Use-It-or-Lose-It Rule on Airline Strategy and Climate." *Transportation Research Part D: Transport and Environment*, vol. 115, 2023, 103570.

[17] Dray, Lynnette, and Khan Doyme. "Carbon Leakage in Aviation Policy." *Climate Policy*, vol. 19, no. 10, 2019, pp. 1284-1296; Rathore, Himanshu, and Suresh Kumar Jakhar. "Differential Carbon Tax Policy in Aviation: One Stone That Kills Two Birds?" *Journal of Cleaner Production*, vol. 296, 2021, 126479.

[18] Maleviti, Eva, and Sarah Talley. "Integrating Sustainability into Aviation Training." *International Journal of Aviation Research*, vol. 17, no. 1, 2025.

[19] Franchina, Federico, and Cinzia Ingratoci. "The Single European Sky and Aviation Sustainability." *Transport Transitions: Advancing Sustainable and Inclusive Mobility*, edited by Ciaran McNally et al., Springer, 2025, pp. 212-218.

measures yield the greatest benefits when combined with improvements in operational efficiency and enhanced voluntary collaboration across the sector. Examples include shifting from hub-and-spoke patterns to more direct routes, expanding joint programmes between airlines and air-navigation service providers, and fostering cross-operator coordination to streamline flows across the network.[20] Sustained improvements of this scale require substantial investment in capacity-building, including clearer guidance on airspace management, traffic-flow optimisation and network planning, alongside strengthened institutional capabilities in areas such as airspace design, controller training and integrated network-management systems. These coordinated efforts allow airspace modernisation and climate objectives to advance together within a coherent system-wide policy framework.

Efficiency opportunities also extend to airport and ground-infrastructure systems. Regulatory and policy instruments can require sustainable terminal design, optimised surface operations, green taxiing systems and efficient pushback procedures, drawing on innovations such as electrified shuttle buses and electric taxiing technologies.[21] Implementing these measures necessitates robust life-cycle environmental assessment, comprehensive monitoring frameworks and clear operational guidance for all airport and ground-infrastructure actors. Smart-infrastructure investments and sustainable hub-design principles further strengthen the emissions-reduction potential of this domain.[22] Economic tools available to airports, including green bonds and targeted subsidies, can help finance sustainable infrastructure, electrified ground-support equipment and energy-efficient terminal upgrades.[23] Economy-wide instruments such as carbon taxes, green airport charges and incentives linked to sustainable aviation fuel can support the reorientation of long-term investment patterns towards low-carbon innovation.

As discussed above, a set of policy levers spans the full spectrum of system efficiency opportunities, ranging from improvements in aircraft and engine performance to enhanced operational practices, more efficient airspace management, and more sustainable airport and ground-based systems. Although each specific efficiency sub-domain encompasses distinct opportunities for deploying policy instruments, it must be noted that their overlap and interconnectedness often generate cascading benefits across domains, amplifying their contribution to sector-wide climate mitigation. With this in mind, a system-level roadmap for coordinated efficiency improvements should be central to near-term sustainable policy planning.

III. **Impact Domain II: Sustainable Aviation Fuel**

As the second impact domain, Sustainable Aviation Fuel (SAF) represents an incremental yet potentially transformative pathway for reducing the climate impacts of aviation. Its significance lies in its compatibility with existing aircraft, engine and fuel-distribution architectures, positioning SAF as one of the few technologically viable mitigation options available in the short and medium term, particularly for long-haul, high-density and other mission profiles where electrification and hydrogen propulsion remain commercially and operationally distant. The scalable phase-in of high-integrity SAF is

[20] Jamin, Solomon, et al. "Aviation Emissions and Abatement Policies in the United States: A City-Pair Analysis." *Transportation Research Part D: Transport and Environment*, vol. 9, no. 4, 2004, pp. 295-317.
[21] Avogadro, Nicolò, and Renato Redondi. "Pathways toward Sustainable Aviation: Analyzing Emissions from Air Operations in Europe to Support Policy Initiatives." *Transportation Research Part A: Policy and Practice*, vol. 186, 2024, 104121.
[22] Vinisha, Poornima, et al. "Sustainable Design Strategies for the Future of Aerospace Hubs: Integrating Green Technologies and Smart Infrastructure." *Proceedings of the 10th International Conference on Applying New Technology in Green Buildings (ATiGB)*, IEEE, 2025, pp. 854-863.
[23] Kumar, Bhavesh, et al. "Sustainable Aviation Finance: Integration of Environmental Impact Mitigation and Green Investment Strategies." *Research in Transportation Business & Management*, vol. 61, 2025, 101410.

intrinsically linked to the managed phasedown of conventional kerosene; treating these processes in isolation risks an analytically incomplete understanding of the transition dynamics. Accordingly, effective SAF policy must combine mutually reinforcing demand-side and supply-side measures that operate in parallel (as summarised in **Table 2**, below), while ensuring robust lifecycle sustainability across the entire value chain, from feedstock production and fuel processing to airline procurement, operational integration and environmental certification.

On the demand side, regulatory instruments such as blending mandates, minimum-use requirements and quota systems create guaranteed markets for sustainable aviation fuel and provide the long-term investment signals necessary for producers to scale. Recent policy initiatives such as the European ReFuelEU agenda and the United Kingdom's Sustainable Aviation Fuel Mandate exemplify the underlying design logic whereby compulsory market-creation instruments facilitate the early-stage deployment of alternative fuels that still require time to mature.[24] These measures increasingly sit within wider policy architectures shaped by the EU Green Deal and by existing and emerging international and regional carbon-pricing frameworks (e.g., EU Emissions Trading System),[25] which are intended to improve the market competitiveness of sustainable energy carriers.[26] In this context, economic instruments such as carbon pricing, differential fuel taxation and financial incentives encourage airlines and airports to procure SAF despite current price premiums.[27] The role of airline-airport partnerships is especially vital in this case, as they are instrumental in delivering the deployment of early niche markets for SAF.[28] Information and guidance tools assist airlines in complying with mandates, understanding blending logistics and planning for operational integration through compliance support measures, policy guidance on SAF adoption and frameworks clarifying blending strategies. Voluntary airline commitments, often exceeding regulatory requirements, contribute further by signalling corporate climate ambition, supporting early niche markets and strengthening reputational incentives for early action. Capacity-building instruments on the demand side are increasingly important, involving training programmes for airlines, airports and regulators on blending procedures, sustainability criteria and safety standards, and the strengthening of institutional capabilities for implementing conditional bailouts tied to emissions performance, which often include provisions promoting SAF uptake. A particularly notable measure is the progressive reduction of fossil fuel subsidies in aviation,[29] which helps correct existing price distortions and narrow the differential between SAF and conventional jet fuel.

On the supply side, scaling SAF production also depends on an integrated mix of regulatory, economic, voluntary and capacity-building instruments. Regulatory frameworks such as national and regional blending obligations create policy drivers not only for demand but also for supply, while certification schemes and harmonised technical standards provide predictable demand signals for producers and ensure consistency across

[24] Maulet, Nicolas. "UK Policy Instruments for Aviation Decarbonisation: The Sustainable Aviation Fuel Mandate and Policymaking Approach Underlying the Future UK Framework." *Global Energy Law and Sustainability*, vol. 5, no. 2, 2024, pp. 182-197.

[25] Reisdorf, Andrea, et al. "Opportunities and Challenges Arising from European Sustainable Aviation Fuel Regulations: A Case Study Approach." *Journal of the Air Transport Research Society*, vol. 5, 2025, 100085.

[26] Valdés, Rosa María Arnaldo, and Victor Fernando Gómez Comendador. "Strategies and Economics for Decarbonizing Aviation by 2050." *Sustainable Aviation*, 2025, pp. 227-265.

[27] Watson, M, et al. "Sustainable Aviation Fuel Technologies, Costs, Emissions, Policies, and Markets: A Critical Review." *Journal of Cleaner Production*, vol. 449, 2024, 141472.

[28] Varadarajan, Venugopal, et al. "Carbon Remediation for the Airline Industry via ATF Drop-in Substitution: Strategic and Operational Perspective." *SAE International Journal of Aerospace*, vol. 5, no. 1, 2012, pp. 1-10.

[29] Posada, Eduardo, et al. *Fossil Fuel Subsidy Reform in Aviation and Shipping*. International Institute for Sustainable Development, Feb. 2025.

production pathways.[30] Economic and financial instruments remain essential for overcoming the high capital and operating costs associated with early-stage SAF facilities.[31] Public funding through tax credits, capital grants, feedstock subsidies, output-based credits, support for carbon capture integration and green finance mechanisms significantly reduce financial risk and accelerate novel projects. Additional financial support for enabling technologies, such as renewable hydrogen for power-to-liquid pathways or carbon capture at biorefineries, further strengthens investor confidence. Knowledge sharing and voluntary initiatives, including pilot plants, collaborative research and development programmes, regional SAF demonstration projects, techno-economic modelling and cross-industry experimentation platforms help derisk innovation, build legitimacy and ensure knowledge transfer across SAF pathways. Capacity-building measures for supply chain scale-up are equally important, requiring strengthened research institutions, new centres of excellence, more effective technology transfer arrangements and deeper expertise in supply chain coordination. This includes strengthening national and international certification bodies, expanding institutional capacity for lifecycle reporting and supporting research networks that underpin the expansion of the SAF ecosystem.

Ensuring the environmental integrity of SAF constitutes a third and indispensable dimension of the transition. Robust sustainability regulations, harmonised fuel quality standards and lifecycle carbon accounting frameworks protect against indirect land use change, unsustainable feedstock sourcing and inconsistent environmental credentials.[32] Renewable fuel standards, harmonised sustainability protocols for alternative jet fuels and international certification frameworks help set clear requirements for environmental and social safeguards. At the same time, robust governance and transparency are required to prevent SAF research and deployment from being instrumentalised to delay near-term emissions reductions, dilute regulatory ambition or enable greenwashing through overstated climate benefits or selective lifecycle accounting. Economic instruments can reinforce sustainability by rewarding high integrity fuels through differentiated crediting systems, multiplier mechanisms, certified feedstock premiums and green taxation frameworks. Information and guidance tools such as lifecycle assessment methodologies, feedstock sustainability guidelines, best practice documents for low-carbon production and emerging global SAF sustainability frameworks support producer compliance and improve transparency. Strong institutional capacity is essential for monitoring lifecycle emissions, verifying sustainability criteria and administering certification systems. This requires the strengthening of data infrastructures, improvements in biofuel certification usability, training for auditors, harmonisation of regional sustainability protocols and alignment with global disclosure frameworks that shape reporting requirements for fuel lifecycle impacts. Moreover, recent literature has indicated the potential of SAF allocation strategies to reduce non-CO_2 climate impacts from aviation.[33]

In this vein, the policy levers shaping the deployment of sustainable aviation fuel constitute an integrated architecture spanning demand creation, supply-side scale-up and sustainability governance. Their effectiveness depends on coherent implementation across all three dimensions, supported by aligned

[30] Prussi, Matteo. "The Sustainability Dimension for Sustainable Aviation Fuels (SAF): Comparing Regional and International Approaches." *Sustainability*, vol. 17, no. 18, 2025, 8401.
[31] Zheng, Shiyuan, et al. "Carrot or Stick? Environmental and Welfare Implications of Sustainable Aviation Fuel Policies." *Transportation Research Part B: Methodological*, vol. 188, 2024, 103062.
[32] Prussi (n 30) *supra*.
[33] Woeldgen, Elisabeth, et al. "Sustainable Aviation Fuel Deployment Strategies in Europe: Supply Chain Implications and Climate Benefits." *Environmental Science & Technology*, vol. 59, no. 25, 2025, pp. 12447-12457.

regulatory signals, targeted economic incentives, clear technical guidance, voluntary action and robust institutional capacity. When deployed in a coordinated manner, these instruments enable SAF to contribute meaningfully to climate mitigation while supporting a credible, scalable and environmentally sound transition for the global aviation sector.

IV. **Impact Domain III: Alternative Aircraft Design**

Alternative aircraft design represents the most transformative yet also the most uncertain impact domain in aviation's transition toward deep decarbonisation. Whilst system efficiency improvements and sustainable aviation fuels can deliver substantial near and mid-term emissions reductions, long-term climate neutrality ultimately depends on reshaping the technological foundations of aircraft itself. Hydrogen-powered aircraft, battery-electric propulsion, hybrid-electric platforms and emerging electric vertical take-off and landing (eVTOL) aircrafts offer the prospect of zero or near-zero operational emissions. Yet each remains constrained by technological immaturity, infrastructure and energy system requirements, safety certification challenges and uncertain early markets. Effective policy therefore requires a balanced mix of technology push instruments that accelerate research and development and reduce innovation risk, and market-pull instruments that create credible early demand signals, encourage commercial uptake and support the emergence of viable markets for next-generation aircraft (**Table 3**, below).

Technology-push instruments form the foundation for advancing disruptive propulsion technologies by reducing early-stage risk and enabling scientific and industrial progress.[34] Regulatory instruments provide direction and legitimacy by establishing innovation roadmaps, technical standards and legal frameworks for hydrogen, electric and eVTOL aircraft, including rules for certifying new propulsion systems and aircraft categories. Economic instruments reinforce this by delivering large public investments in hydrogen and electric propulsion alternatives, offering financial support for prototype development and reinvesting environmental revenues into clean aircraft research and development.[35] Information and guidance instruments such as foresight studies, long-term innovation strategies and policies promoting technological partnerships help align research ecosystems and support the exchange of emerging knowledge. Voluntary instruments, including collaborative research programmes led by academic institutions, joint testing initiatives, and industry-driven innovation efforts, enhance experimentation and risk sharing among manufacturers, airports, and energy providers. Examples include the Bennett Innovation Lab hosted by the Whittle Laboratory at the University of Cambridge. Capacity-building instruments complement these measures by expanding research facilities, specialised skills and institutional capabilities, including support for high-risk technological alternatives, public-private research frameworks and work on integrating eVTOL technologies into the wider aviation system. Taken together, these technology-push instruments lay the groundwork for sustained progress across the aviation innovation pipeline.[36]

Market-pull instruments complement the supply side efforts by creating early demand, reducing commercial uncertainty and preparing aviation markets for the wider adoption of transformative aircraft technologies. Regulatory instruments such as clean aircraft deployment targets, performance-based certification rules and policies enabling the commercial use of new

[34] Kallbekken, Steffen, and David Victor. "A Cleaner Future for Flight—Aviation Needs a Radical Redesign." *Nature*, vol. 609, no. 7928, 2022, pp. 673-675.
[35] Huete, Jon, et al. "A Strategy to Decarbonize Civil Aviation: A Phased Innovation Approach to Hydrogen Technologies." *IEEE Electrification Magazine*, vol. 10, no. 2, 2022, pp. 27-33.
[36] Victor, David, et al. "Mobilizing Capital and Technology for a Clean Aviation Industry." *Science*, vol. 390, no. 6770, Oct. 2025, pp. 242-245.

propulsion systems help guarantee early market access and provide predictable signals to investors and manufacturers. Economic instruments including support for early adopters, preferential financing schemes and the allocation of environmental revenues to zero-emission aircraft deployment help bridge cost gaps and stimulate first-mover activity.[37] Information and guidance instruments aimed at passengers, operators and the wider public build social acceptance by increasing familiarity with hydrogen, electric and eVTOL technologies and communicating their operational and environmental benefits. Voluntary instruments including airline, manufacturer and airport partnerships, pilot testing programmes and collaborative innovation initiatives create participatory networks that accelerate early operational learning. Capacity-building instruments prepare markets and institutions for long-term diffusion by strengthening certification capabilities, developing supply chains, expanding workforce skills and investing in the infrastructure needed to support the introduction of hydrogen, methane, electric or alternative innovative aircraft.

Overall, radical innovation in aviation emerges not as a spontaneous outcome but as the product of sustained and coordinated policy intervention. It requires deliberate, long-term governance capable of stimulating technological discovery, supporting early markets and cultivating the institutional and industrial capacity needed for widespread adoption.

By balancing technology-push and market-pull approaches, policymakers can nurture an innovation ecosystem that accelerates the development, demonstration and diffusion of transformative aircraft technologies and places aviation on a credible pathway toward deep decarbonisation.

V. **Impact Domain IV: Air Travel Demand**

Travel and demand efficiency represents a critical yet politically sensitive impact domain of aviation decarbonisation. Even with substantial efficiency gains, large-scale adoption of alternative fuels and the emergence of radical technological innovations, long-term climate goals cannot be achieved without moderating growth in air travel demand. Demand management therefore spans systemic measures affecting all travellers, targeted interventions focused on high-emitting groups, and policies that address the specific patterns of business and organisational travel. Effective policy design must balance the societal value of air connectivity with the urgent need to reduce emissions, while recognising that a relatively small proportion of travellers accounts for a disproportionate share of total demand. Conceptually, as summarised in **Table 4** below, policy instruments operate across three levels: system-wide measures that affect all passengers, measures directed at individual travellers, and measures tailored to business and organisational travel.

System-wide measures affecting all passengers aim to reshape aggregate travel behaviour by altering regulatory, economic and informational conditions across the aviation system. Regulatory instruments include capacity limits at congested airports, restrictions on super short-haul flights, distance-based travel thresholds, and international agreements that incorporate sufficiency principles.[38] Economic instruments influence overall demand by internalising environmental costs through aviation carbon taxes, distance-based passenger charges and harmonised global air travel levies.[39] Voluntary instruments include airline-wide offset programmes and broad climate-responsibility schemes that invite passengers to engage proactively with their

[37] Wild et al. (n 15) *supra*.

[38] Dobruszkes, Frédéric, et al. "Banning Super Short-Haul Flights: Environmental Evidence or Political Turbulence?" *Journal of Transport Geography*, vol. 104, 2022, 103457.

[39] Fouquet, Roger, and Tanya O'Garra. "In Pursuit of Progressive and Effective Climate Policies: Comparing an Air Travel Carbon Tax and a Frequent Flyer Levy." *Energy Policy*, vol. 171, 2022, 113278.

environmental impact.[40] Capacity-building instruments operate at the systemic level by integrating sustainability and sufficiency considerations into national tourism and mobility planning, and by developing monitoring, evaluation and coordination frameworks capable of supporting long-term demand management.

Discussions of possible measures directed at individual travellers focus on specific passenger segments, particularly high-emitting and frequent luxury passengers whose behaviour disproportionately drives aviation emissions. Regulatory instruments include mandatory reporting of individual travel emissions and measures that promote modal substitution, particularly through the expansion and integration of high-speed rail networks. Economic instruments can apply either flat incentives or progressive responsibilities to the highest-emitting individuals, for example through frequent-flyer levies, premium-class taxes and surcharges for long-distance or luxury travel.[41] Voluntary instruments support behavioural change through personal carbon budgets, participation in sustainability programmes and greater uptake of low-carbon alternatives. Capacity-building instruments help individuals reduce carbon-intensive travel through support for videoconferencing in professional contexts, guidance on low-carbon mobility for short trips, and tools that allow travellers to monitor and reduce their flight frequency. It is worth noting that debates over the distribution of climate responsibilities between frequent flyers and ordinary users are ongoing, underscoring the need for a fair transition solution in the future.

Measures tailored to business and organisational travel target a segment historically responsible for a significant share of emissions within the organisational setting. Regulatory instruments include mandatory emissions reporting for corporations and public institutions, as well as compliance requirements that limit non-essential travel within organisational sustainability strategies. A prime case discussed is academic travel, which offers promising avenues to reduce emissions.[42] Economic instruments such as internal carbon pricing, corporate air travel levies and the redirection of aviation tax revenues toward low-carbon mobility alternatives reshape organisational incentives. Voluntary instruments include institutional travel-reduction pledges, organisational offset programmes and partnerships with airlines to explore lower-emission travel options, often reinforced by reputational competition through green-branding initiatives. Capacity-building instruments strengthen organisational transitions by establishing robust travel-reporting systems, training staff in sustainable mobility planning and investing in infrastructure and service integration that supports a shift from air to rail, particularly for business travel.

As shown above, aviation demand management relies on a combination of systemic action, targeted interventions and institutional transformation. The emphasis is not solely on constraining air travel but on creating supportive conditions that enable behavioural, cultural and structural changes towards a low-carbon mobility system.[43]

With coordinated governance, socially equitable policies and integrated multi-modal planning, it is possible to reduce aviation demand while preserving essential connectivity and promoting sustainable alternatives.

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[40] Becken, Susanne. "Tourists' Perception of International Air Travel's Impact on the Global Climate and Potential Climate Change Policies." *Journal of Sustainable Tourism*, vol. 15, no. 4, 2007, pp. 351-368.

[41] Kogler, Marie, et al. "Short-Term Emission Reductions in Leisure and Business Air Travel: Assessment of Taxation, Regulations, Sustainable Aviation Fuels and Personal Intentions." *Journal of Sustainable Tourism*, 2025, pp. 1-23.

[42] Ben-Ari, Tamara, et al. "Flight Quotas Outperform Focused Mitigation Strategies in Reducing the Carbon Footprint of Academic Travel." *Environmental Research Letters*, vol. 19, no. 5, 2024, 054008.

[43] Muehlberger et al. (n 9) *supra*.

VI. **Impact Domain V: Non-CO_2 Climate Effects**

As primary non-CO_2 climate forcers in aviation, contrails including contrail cirrus and nitrogen oxides (NOx),[44] represent an impact domain that highlights both the scientific complexity and the operational challenges involved in managing aviation's climate effects.[45] Specifically, a growing body of research indicates that contrails account for a substantial share of aviation's short-term climate impact, particularly when an aircraft passes through ice supersaturated regions.[46] Persistent gaps in atmospheric measurement, modelling capacity, and data infrastructure continue to limit the production of consistent real-world evidence.[47] At the same time, the processes through which emerging scientific understanding feeds into regulatory design, operational decision-making and market-based instruments are still evolving (**Table 5**, below). Acting on the best available evidence now can help break cycles of policy inaction, generate real-world implementation experience and, in turn, provide critical feedback that enables scientific understanding and policy frameworks to co-evolve within this rapidly developing governance space.

Contrail avoidance can be broadly divided into two parts: pre-tactical mitigation and tactical mitigation. Pre-tactical mitigation focuses on planning measures incorporated before a flight departs. Regulatory instruments shape this stage by requiring airlines and air navigation service providers to integrate contrail considerations into route scheduling and design, altitude and speed planning, and the strategic avoidance of ice-supersaturated regions, alongside technical requirements for new engine designs and energy carriers that reduce contrail formation across the fleet. Economic instruments reinforce these rules through funding for measurement campaigns and by shaping multi-species market signals, such as proposals to include all climate-relevant emissions in the European Emissions Trading System (ETS),[48] or to impose "climate charges" on airlines operating in certain airspace areas.[49] However, it must be acknowledged that such measures remain subject to ongoing debate and that multiple options are still under consideration, requiring close communication with the industry. Information and scientific standardisation instruments support the evidence base, including international methods for measuring particle size distribution and non-volatile particulate matter. Capacity-building instruments, including public support for data acquisition and modelling infrastructure, help operators embed contrail-aware planning in routine practice.

Tactical mitigation concerns real-time operational adjustments made during the flight. Regulatory instruments influence this phase through requirements or permissions for in-flight altitude changes, heading adjustments, and dynamic re-routing to avoid atmospheric conditions conducive to

[44] Further detailed technical discussion of the mechanisms through which aviation-induced contrail cirrus and NO_x emissions impact climate can be found here: Burkhardt, Ulrike, and Bernd Kärcher. "Global Radiative Forcing from Contrail Cirrus." *Nature Climate Change*, vol. 1, no. 1, 2011, pp. 54-58; Gilmore, Christopher, et al. "Temporal and Spatial Variability in the Aviation NOx-Related O_3 Impact." *Environmental Research Letters*, vol. 8, no. 3, 2013, 034027.

[45] *Contrails and Contrail Management: A Royal Aeronautical Society Briefing Paper*. RAS, Apr. 2023.

[46] Petzold, Andreas, et al. "Most Long-Lived Contrails Form within Cirrus Clouds with Uncertain Climate Impact." *Nature Communications*, vol. 16, no. 1, 2025, p. 9695; Singh, Dharmendra Kumar, et al. "Understanding the Role of Contrails and Contrail Cirrus in Climate Change: A Global Perspective." *Atmospheric Chemistry and Physics*, vol. 24, no. 16, 2024, pp. 9219-9262.

[47] Pushparaj, Nishanth, et al. "Real-Time Contrail Monitoring and Mitigation Using CubeSat Constellations." *Atmosphere*, vol. 15, no. 12, 2024, p. 1543; Sarna, Aaron, et al. "Benchmarking and Improving Algorithms for Attributing Satellite-Observed Contrails to Flights." *Atmospheric Measurement Techniques*, vol. 18, no. 14, 2025, pp. 3495-3532.

[48] Scheelhaase, Janina D. "How to Regulate Aviation's Full Climate Impact as Intended by the EU Council from 2020 Onwards." *Journal of Air Transport Management*, vol. 75, 2019, pp. 68-74.

[49] Niklaß, Malte, et al. "Concept of Climate-Charged Airspaces: A Potential Policy Instrument for Internalizing Aviation's Climate Impact of Non-CO_2 Effects." *Climate Policy*, vol. 21, no. 8, 2021, pp. 1066-1085.

persistent contrails. Voluntary instruments are particularly influential here, as demonstration flights and industry-led trials provide empirical evidence of feasibility under operational constraints. Economic instruments play a smaller but growing role in encouraging airlines to trial climate-friendly trajectories. Capacity-building instruments are essential, including Living Lab Airspace Trials for real-world experimentation, scientific programmes that improve measurement and modelling, and training for pilots, controllers, and dispatch teams to ensure safe and consistent implementation of tactical contrail mitigation. Many of these considerations apply to both pre-tactical and tactical avoidance, underscoring the need for a coherent policy framework that aligns planning-stage decisions with real-time operational practices.

Nitrogen oxides represent a separate non-CO_2 impact pathway shaped by complex atmospheric chemistry. Regulatory instruments include engine emission standards, combustor design requirements, and emerging multi-species climate governance frameworks. Economic instruments provide incentives for research, development, and efficiency improvements, and may eventually include pricing signals that reflect NO_x-related climate impacts. Voluntary instruments support operational experimentation, such as trials of altitude optimisation to influence net NO_x climate effects. Capacity-building instruments strengthen atmospheric modelling, monitoring systems, and reporting standards, enabling operators and regulators to make decisions that reflect the full climate consequences of NO_x emissions.

Overall, non-CO_2 climate impacts, particularly contrail and contrail-induced cirrus formation, offer a near-term mitigation opportunity for aviation policy. Initiatives such as contrails.org suggest that targeted contrail avoidance could deliver meaningful climate benefits at relatively low cost through operational adjustments rather than major technological change. Compared with deep CO_2 mitigation measures, such as large-scale deployment of sustainable aviation fuels, non-CO_2 options like contrail avoidance require less system-wide transformation and therefore represent an attractive complementary pathway within a broader aviation decarbonisation strategy.

VII. **Concluding Remarks**

To address the climate risk in the aviation sector, a comprehensive policy mix approach that covers a wide set of impact domains is required in today's sustainable aviation policymaking, as shown in the preceding analysis. This spans incremental improvements in system-wide efficiency and the development of SAFs, ambitious moonshot projects laying the foundation for transformative innovation breakthroughs, fundamental rethinking of demand-side travel behaviours in the coming decades, and attention to often-overlooked non-CO_2 climate impacts. Achieving the Paris Agreement targets requires the effective deployment of regulatory, economic, voluntary, and capacity-building instruments for multiple stakeholder groups across the whole sector, and across all five key impact domains, in a coherent and consistent manner. Collectively, the design of policy strategy, the choice of instruments, and the styles of policy processes merit greater attention from this cross-cutting scoping viewpoint. When re-weaving currently fragmented sustainable aviation policy levers to address climate risk, it is critical that policy actions align with overarching, credible system pathways for each impact domain, guided by a well-defined policy strategy. To achieve this, a set of actionable principle plans with well-defined policy objectives for each impact domain needs to be developed and packaged as top-level guiding frameworks. This will inform strategic ambitions for a climate-friendly aviation future.[50] This builds

[50] Rogge, Karoline, and Qi Song. "Policy Mixes for Addressing Environmental Challenges." *Routledge Handbook of Environmental Policy*, edited by Helge Jörgens et al., Routledge, 2023, pp. 327-346; Nemet, Gregory, et al. "Addressing Policy Credibility Problems

a traceable and credible chain of system thinking that helps integrate currently isolated policy actions, moving from high-level targets with quantified ambition levels, to principled plans outlining the general pathway for each impact domain, to policy levers addressing various intervention points related to climate risk. As shown in this stocktaking exercise, interactions between measures such as innovative aircraft design, SAF deployment and contrail avoidance point to the need for a whole-system approach that addresses within-domain goals while recognising cross-domain linkages. While individual impact domains may deliver substantial emissions reductions if pursued aggressively, none is sufficient on its own to deliver a robust, system-wide transformation of aviation. Each domain faces inherent constraints, uncertainties and implementation risks—whether related to technological maturity, feedstock availability, operational feasibility or governance—which limit the reliability of single-track strategies. Over-reliance on one domain therefore risks delaying progress, creating lock-in or amplifying failure if expected gains do not materialise at scale. A diversified portfolio of aligned policy levers across impact domains reduces these risks, enables complementarities between solutions with different temporal profiles and increases the likelihood of achieving sustained and credible climate outcomes. This systems logic should be reflected in forthcoming top-level strategy discussions and roadmap development, guiding resource allocation and priority-setting over time.

The choice, implementation, and assessment of policy instruments—from regulatory and economic to voluntary and capacity-building—and their mixes, should be reconsidered case by case, based on each impact domain, target group, and governance level.[51] As discussed, the nature of climate-risk problems differs substantially across impact domains. Likewise, sustainable aviation solution developers vary across stakeholder groups, as does the potential for resistance. Governance resources and legislative authority also differ across international, national, and regional levels, all of which will require greater attention in the future. The contextual conditions must be considered when developing coherent policy processes, particularly in deliberately sequencing policy levers in a time-wise approach over the coming years. In particular, attention is needed to exploit near-term opportunities that can open windows for cascading transformation.[52] The hard-to-abate nature of aviation should not serve as an excuse for delaying transformative action; instead, it should motivate the identification and prioritisation of policy levers that can create positive feedback loops and accelerate the transition.[53] Future inquiries should focus on nuanced analyses of specific policy levers within particular impact domains, taking account of techno-economic viability, socio-political feasibility, resource constraints and governance arrangements, alongside their effectiveness in delivering both short-term and long-term climate benefits. In doing so, such analyses will support the development of a time-sequenced approach to selecting and sequencing policy mixes, with potential feedback loops taken into account, enabling cascading system changes toward a sustainable aviation future.

Finally, regarding the styles of policy processes, it is important to acknowledge the

for Low-Carbon Investment." *Global Environmental Change*, vol. 42, 2017, pp. 47-57.

[51] Howlett, Michael, and Pablo del Rio. "The Parameters of Policy Portfolios: Verticality and Horizontality in Design Spaces and Their Consequences for Policy Mix Formulation." *Environment and Planning C: Government and Policy*, vol. 33, no. 5, 2015, pp. 1233-1245; Mavrot, Céline, et al. "Mapping the Mix: Linking Instruments, Settings and Target Groups in the Study of Policy Mixes." *Research Policy*, vol. 48, no. 10, 2019, 103614.

[52] Meckling, Jonas, et al. "Winning Coalitions for Climate Policy." *Science*, vol. 349, no. 6253, 2015, pp. 1170-1171.

[53] Geels, Frank, and Martina Ayoub. "Policy Feedbacks and Socio-Technical Feedbacks in Accelerated Low-Carbon Transitions: An Integrated Conceptual Framework Illustrated with Case Studies of Lighting and Smart Meters." *Research Policy*, vol. 54, no. 8, 2025, 105294.

high complexity and uncertainty inherent in the aviation transition, which will persist over time.[54] Uncertainties span incomplete scientific understanding of certain climate-risk mechanisms, such as contrail effects, long development timelines and performance risks associated with radical aircraft technologies, and evolving socio-economic drivers of air travel demand. These conditions limit the effectiveness of static or prescriptive policy approaches and instead call for experimental, adaptive and learning-oriented policy styles.[55] Policy strategies should therefore embed mechanisms for iterative learning, evidence generation and adjustment over time, supported by capacity-building instruments that strengthen analytical capability, transparency and stakeholder participation. Progress toward climate-friendly aviation will depend less on predetermined technological fixes than on governance systems capable of operating under uncertainty, testing interventions in real-world contexts and recalibrating pathways as knowledge evolves. Under these conditions, transformative leadership is required to sustain commitment, accelerate implementation where transformative potential has been demonstrated, enable the timely deployment of emerging solutions, and remain responsive to new evidence and changing circumstances.

To conclude, this viewpoint article has provided a stocktaking overview of sustainable aviation policy levers for addressing climate risk across key impact domains in the entire aviation sector. In doing so, it offers a more granular perspective and a heuristic framework for rethinking the system-level deployment of policy levers. The variety, complementarity, and cascading synergies across instruments showcased in the analysis highlight promising avenues for future research to deepen inquiry into specific policy interactions and implementation pathways. Acknowledging policy complexity is the first step toward navigating it. Now is the time to chart a clear course for take-off.

Impact Domain I: System Efficiency Improvement	**Instrument Type**			
	Regulatory	**Economic**	**Voluntary**	**Capacity-building**
Fleet & Technology Efficiency	Fuel efficiency standards, carbon and greenhouse gas performance requirements, baseline aircraft design criteria.	Emissions taxes, subsidies and incentives supporting fleet renewal and efficient aircraft investment.	Sustainability programmes, green fleet management schemes, voluntary aircraft replacement initiatives.	Technology road mapping, fleet planning support, institutional capability for evaluating efficiency gains.
Operational Efficiency	Rules on flight age, weight and load optimisation, fuel management procedures, slot allocation and utilisation reforms.	Differential carbon taxes, environmental landing charges, delay-based pricing.	Airline-led operational improvement initiatives and best-practice demonstration projects.	Training for flight crews and ground staff, operational guidance from international bodies such as ICAO and IATA.
Airspace & Network Efficiency	Airspace redesign frameworks, international performance standards, cross-border coordination mechanisms such as Single European Sky.	Route-linked carbon pricing, incentives for optimised routing and network-level planning.	Collaborative programmes between airlines and air navigation service providers to improve routing.	Institutional capacity for airspace design, controller training, traffic-flow optimisation and integrated network-management systems.

[54] Peeters, Paul, et al. "Are Technology Myths Stalling Aviation Climate Policy?" *Transportation Research Part D: Transport and Environment*, vol. 44, 2016, pp. 30-42.

[55] Kallbekken et al. (n 4) *supra*.

Airport & Ground Infrastructure Efficiency	Requirements for sustainable terminal design, surface operations optimisation, electric taxiing and ground-mobility standards.	Green bonds, targeted subsidies, carbon taxes and green airport charges supporting low-carbon infrastructure.	Airport-led sustainability initiatives and cooperation with operators to improve ground-efficiency practices.	Infrastructure planning support, lifecycle assessment capability, staff training and monitoring systems for sustainable ground operations.

Table 1: Impact Domain I—Summary of Policy Levers for System Efficiency Improvement.

Impact Domain II: Sustainable Aviation Fuel	**Instrument Type**			
	Regulatory	**Economic**	**Voluntary**	**Capacity-building**
Demand-Side	Blending mandates, minimum use requirements, quota systems, harmonised regional rules, lead market initiatives (e.g., Fit for 55), conditional bailouts tied to emissions performance.	Carbon pricing, differential fuel taxation, carbon credits for e-fuels, green financing mechanisms such as green bonds and sustainability linked loans, joint procurement models.	Airline commitments to exceed mandate levels, corporate SAF purchase agreements.	Training on blending procedures and sustainability criteria, institutional capacity for mandate implementation and emissions linked conditions.
Supply-Side	Certification schemes such as ASTM D7566, harmonised technical standards, dedicated alternative jet fuel regulations, EU Green Deal frameworks for scale up.	Tax credits, capital grants, feedstock subsidies, output based credits, green finance for innovative facilities and wider infrastructure development, support for enabling technologies such as renewable hydrogen and carbon capture.	Pilot plants, collaborative research and development, industry led demonstration projects and experimentation platforms.	Expansion of research institutions and centres of excellence, technology transfer systems, strengthened certification bodies and supply chain coordination expertise.
Lifecycle Sustainability	Sustainability protocols, renewable fuel standards, harmonised lifecycle carbon accounting, international certification frameworks and safeguards.	Differentiated crediting schemes, multiplier mechanisms, certified feedstock premiums, green taxation aligned with lifecycle integrity.	Sustainability guidelines, lifecycle assessment methodologies, best practice frameworks for low-carbon production.	Data infrastructures for lifecycle monitoring, auditor training, usability improvements in certification systems, harmonisation of regional sustainability protocols and global disclosure frameworks.

Table 2: Impact Domain II—Summary of Policy Levers for Sustainable Aviation Fuel.

Impact Domain III: Alternative Aircraft Design	**Instrument Type**			
	Regulatory	**Economic**	**Voluntary**	**Capacity-building**
Technology-Push	Innovation roadmaps and technical standards for hydrogen, electric, hybrid electric and eVTOL systems; certification frameworks for new propulsion and aircraft categories.	Public investment in early-stage R&D, prototype development and demonstration projects; financial support for high-risk technological alternatives.	Collaborative research programmes, joint testing initiatives and industry led innovation partnerships.	Expansion of research facilities, specialised skills and institutional capabilities supporting early-stage innovation.

Market-Pull	Clean aircraft deployment targets and performance linked certification rules; policies enabling commercial operation of new propulsion technologies.	Incentives for early adopters; preferential financing and allocation of environmental revenues to support zero-emission aircraft uptake.	Airline, manufacturer and airport alliances for pilot testing and early market trials.	Development of supply chains, workforce skills, certification capacity and infrastructure enabling large scale adoption.

Table 3: Impact Domain III—Summary of Policy Levers for Alternative Aircraft Design.

Impact Domain IV: Air Travel Demand	**Instrument Type**			
	Regulatory	**Economic**	**Voluntary**	**Capacity-building**
System-Wide Measures	Flight taxes and levies, capacity limits, restrictions on super short-haul flights, distance thresholds, international sufficiency agreements.	Aviation carbon taxes, distance-based passenger charges, global or regional travel levies.	Airline-wide offset schemes, general climate-responsibility programmes.	Integration of demand management into tourism and mobility planning, system-wide monitoring and coordination frameworks.
Individual Travellers	Mandatory travel-emissions reporting, policies promoting modal shift, especially high-speed rail.	Frequent-flyer levies, premium-class surcharges, additional charges on long-distance or luxury travel.	Personal carbon budgets, participation in sustainability programmes, voluntary flying reduction.	Support for videoconferencing, guidance on low-carbon mobility, tools for tracking and reducing flight frequency.
Business and Organisational Travels	Mandatory reporting for corporations and public institutions (including universities), organisational travel-compliance requirements.	Internal carbon pricing, corporate travel levies, redirected revenues for low-carbon mobility.	Institutional travel-reduction pledges, organisational offset initiatives, partnerships for lower-emission travel options.	Travel-reporting systems, training in sustainable mobility planning, investments in rail-air integration for business travel (e.g. internet access).

Table 4: Impact Domain IV—Summary of Policy Levers for Air Travel Demand.

Impact Domain V: Non-CO_2 Climate Effects	**Instrument Type**			
	Regulatory	**Economic**	**Voluntary**	**Capacity-building**
Contrail	Altitude, time, speed and trajectory planning requirements, avoidance of ice-supersaturated regions, integration of contrail impacts into multi-species regulation and emissions trading, standardised measurement protocols for nvPM and PSD, contrail-aware aircraft or fuel-based technical requirements.	Funding for measurement campaigns and modelling, financial incentives for contrail-aware routing, adjustments to market signals within ETS.	Demonstration flights testing altitude adjustments, optimal routing, and real-time avoidance of climate-sensitive regions.	Development of measurement standards, Living Lab Airspace Trials, operational training for pilots, dispatchers, and air traffic controllers.
NOx	Emission standards for engines and combustors, integration of NO_x into multi-species climate governance frameworks.	R&D funding supporting engine efficiency and combustor innovation, potential multi-species pricing signals.	Operational experimentation with altitude optimisation and routing strategies to reduce climate-sensitive NO_x effects.	Advances in atmospheric chemistry modelling, improved monitoring and reporting systems, training to interpret multi-species climate metrics.

Table 5: Impact Domain V—Summary of Policy Levers for Non-CO_2 Climate Effects.

The Role of Climate Policy in the Hydrogen Economy: An Analysis of the EU and the US

Jaqueline Pinto,* Maryna Hritsyshyna†

* PhD Candidate (Center for Climate Change, Energy and Environmental Law), University of Eastern Finland

† PhD Candidate (Center for Climate Change, Energy and Environmental Law), University of Eastern Finland

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climate policy, hydrogen economy, comparative regulatory analysis, RFNBO

ABSTRACT

Globally, renewable and low-carbon hydrogen is attracting popularity for reducing greenhouse gas emissions in hard-to-abate sectors. This article employs comparative legal analysis to examine regulatory frameworks governing hydrogen in the EU and the US over the past five years, interrogating climate goals as drivers for hydrogen sector development. Initially characterised by divergent approaches, with the EU emphasising renewable hydrogen through its RFNBO framework and the US adopting technology-neutral definitions, both jurisdictions are now converging towards broader low-carbon pathways, reflecting shifting priorities driven by amongst others political and geopolitical pressures.

The article investigates whether, inter alia, (i) climate goals drive hydrogen market creation; (ii) renewable-only hydrogen can emerge absent climate targets; and (iii) current low-carbon hydrogen frameworks can deliver on climate objectives whilst balancing energy security and geopolitical considerations. It also looks at the possible effect of the ICJ Advisory Opinion on Climate Change on the hydrogen economy. The findings contribute to a more comprehensive understanding of the relationship between climate policy and hydrogen regulation, demonstrating that climate goals are catalysts for renewable and low-carbon hydrogen market development.

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I. **Introduction**

The trajectory of hydrogen policy in the European Union (EU) and the United States (US) over the past half-decade (2019-2025) reveals a rapidly developing, if at times fragmented, legal framework emerging at the intersection of energy transitions and climate mitigation. Hydrogen[1] is seen to play a role in strategies for decarbonising sectors that are most resistant to conventional electrification. Yet this shift has been neither linear nor uncontested. Rather, it reflects a confluence of

[1] Hydrogen is not often found in its natural form, so that it needs to be produced using another power source. For purposes of this article, where the term hydrogen is used, it refers to renewable and / or low-carbon forms of hydrogen, unless the context indicates otherwise.

motivations, such as climate mitigation, industrial competitiveness, job creation, energy security, and technological leadership, mediated through legal frameworks that embed hydrogen within broader economic, climate and geopolitical strategies.

Industrial processes requiring extreme heat, long-distance aviation and maritime transport, and the provision of seasonal energy storage all present challenges that direct electrification cannot readily address. Hydrogen offers a potential solution to these hard-to-abate sectors, whilst simultaneously serving functions in grid balancing and system integration[2] that become more critical as renewable electricity generation expands. Consequently, the legal instruments governing hydrogen have a role as mechanisms for implementing broader climate commitments.

The European Climate Law's[3] binding commitment to a 55% net greenhouse gas (GHG) reduction by 2030, alongside the proposed 90% net GHG emission reduction for 2040[4] (both compared to 1990 levels), creates direct legal pressure that permeates sectoral instruments. The US, on the other hand, articulated climate ambitions, including the aim to achieve net-zero by 2050, through Nationally Determined Contributions (NDC),[5] Executive Orders[6] and the US' 2021 Long-Term Strategy,[7] rather than binding statutory obligations. However, these climate ambitions were all drafted under the previous Biden administration. The recent start of the process of withdrawal from the Paris Agreement[8] under the new administration introduces considerable uncertainty regarding the durability of federal climate commitments, even as the underlying legislative architecture of hydrogen support remains, to some extent, nominally intact.

The legal treatment of hydrogen in these two jurisdictions has followed different trajectories. The EU initially adopted what might be characterised as a renewables-first approach, focusing regulatory attention on renewable fuels of non-biological origin (RFNBOs), discussed below. This framework reflects a commitment to ensuring that hydrogen production contributed to decarbonisation moving away from demand for fossil-generated electricity. More recently, however, EU policy has exhibited a notable shift towards accommodating a broader category of 'low-carbon' hydrogen. This evolution reflects, in certain respects, the technologically neutral approach that has characterised US hydrogen policy from the outset, particularly through the section 45V clean hydrogen production tax credit (the "S45V Credit") established under the Inflation Reduction Act (IRA).[9] The US framework employs a lifecycle GHG emissions approach.

This article examines hydrogen policy development in the EU and US at a federal and supranational level,[10] over the period 2019-2025, through a climate-focused analytical lens. It adopts a comparative legal methodology, analysing the intersection of hydrogen and climate goals, examining how climate objectives are a driver for and how

[2] Pinto, Jaqueline. "Framework Conditions for Hydrogen Valleys in the EU: Understanding Legal Barriers to Cross-Sectoral Regulation." *Global Energy Law and Sustainability* (forthcoming).
[3] Regulation (EU) 2021/1119 [2021] OJ L243, pp. 1-17.
[4] European Commission Proposal COM(2025) 524 Final, 2 Jul. 2025.
[5] *US 2035 Nationally Determined Contribution*. Report Submitted to the United Nations Framework Convention on Climate Change, Dec. 2024.
[6] Executive Order No. 14008, *Tackling the Climate Crisis at Home and Abroad*, 27 Jan. 2021.
[7] *The Long-Term Strategy of the United States: Pathways to Net-Zero Greenhouse Gas Emissions by 2050*. The White House, 2021.
[8] *U.S. Withdrawal from the Paris Agreement: Process and Potential Effects*. Congressional Research Service Report, Library of Congress, 2025.
[9] *Inflation Reduction Act of 2022 (IRA): Provisions Related to Climate Change*. Congressional Research Service Report, Library of Congress, 2025.
[10] The EU is neither a State nor a traditional international organisation; rather, it is a unique legal framework in which Member States relinquish specific aspects of their sovereignty to the EU through treaties: *see* Penttinen, Sirja-Leena, et al. "Creating the Hydrogen Market from Scratch in the EU and Australia: How Legislative Authority Shapes the Regulatory Choices." *OGEL*, vol. 3, 2024.

they have been operationalised in the hydrogen sector (for example in funding mechanisms and definitional elements including GHG emissions thresholds). It addresses three interrelated questions that probe the relationship between climate goals and hydrogen sector development. First, it considers whether binding or anchored climate goals constitute the primary legal driver for hydrogen market creation. Second, it interrogates whether a renewable-only hydrogen sector can emerge and sustain itself absent robust climate goals, examining the political economy of hydrogen technology development and the role of climate commitments. Third, it assesses whether the low-carbon hydrogen frameworks, as distinct from purely renewable pathways, can credibly achieve the climate targets that ostensibly justify, to some extent, the recognition of the burgeoning hydrogen economy.

The article proceeds in six Sections. Following this introduction, Section II surveys the evolution of successive waves of hydrogen enthusiasm over the past five decades, contextualising current policy developments within longer cycles of technological optimism and disappointment. Section III analyses the climate goals enshrined in EU and US law and policy, examining how these legally binding or policy-articulated targets create the normative foundation for hydrogen sector regulation. Section IV distinguishes between renewable and low-carbon hydrogen within the respective legal frameworks. Section V addresses each of the aforementioned three guiding questions of the article in turn, drawing on the foregoing analysis to evaluate the causal relationship between climate goals and hydrogen policy evolution. Section VI considers the significance of the International Court of Justice's 2025 advisory opinion for the future trajectory of hydrogen regulation, and the concluding Section reflects on the nexus between climate goals and hydrogen.

II. **Hydrogen 'Hype' Cycles Throughout History**

Detractors of hydrogen often characterise interest in hydrogen through the language of 'hype'. Although the term is frequently used in a somewhat dismissive manner, it can be understood more precisely as "extravagant or intensive publicity or promotion".[11] More specifically, in relation to hydrogen, it refers to periods of intensified attention and expectation in which projected technological potential outpaces demonstrable results, use or readiness. To determine whether the present phase of interest in hydrogen reflects a similar inflation of expectations or a more durable shift, it is necessary to trace the historical evolution of these periods of heightened attention on hydrogen and identify the catalysts that shaped them over the last five decades.

As set out by Yap and McLellan,[12] there could be said to be three main hype bubbles in the last 50 years.[13] During the Slow Growth Phase (1972–1979), hydrogen was initially understood solely as a fuel rather than as part of a broader energy system. The 1973 oil crisis and 1979 energy crisis catalysed searches for alternative energy solutions, bringing hydrogen into focus. Interest peaked in 1974 with the establishment of both the International Energy Agency (IEA) and the International Association for Hydrogen Energy (IAHE). Given that nuclear power was experiencing its 'golden age' in the late 1970s, nuclear energy was considered one of the primary means of hydrogen production. Notably, environmental or climate concerns were not the primary driver behind early hydrogen economy 'hype'.

Then came the Stagnant Growth Phase (1980-1999) which saw growing interest in clean energy constrained by persistently low oil prices. The 1986 Chernobyl disaster diminished nuclear energy's appeal, while mounting concerns about climate change led

[11] "Hype." *Oxford Reference Online*, Oxford University Press.
[12] Yap, Jiazhen, and Benjamin McLellan. "A Historical Analysis of Hydrogen Economy Research, Development, and Expectations, 1972 to 2020," *Environments*, vol. 10, no. 1, 2023, p. 11.
[13] ibid.

to the adoption of the United Nations Framework Convention on Climate Change (UNFCC) in 1992 and the Kyoto Protocol in 1997, both of which significantly influenced interest in hydrogen.

Then came the last 'bubble', the Rapid Growth Phase (2000-2019) which began with what has been termed the era of renewable energy. Hydrogen emerged as a mechanism for enhancing power system flexibility as renewable penetration increased. The 2015 adoption of the Paris Agreement[14] then reinvigorated interest in hydrogen. This period's enthusiasm for hydrogen differed from earlier cycles in its broader scope, moving beyond specific technological applications to encompass wider systemic considerations.[15]

The EU's response to the COVID-19 in 2020 crisis has had a positive impact on the pace of the EU's transition to more sustainable energy, by stimulating the development of instruments to support the deployment of renewable energy sources and hydrogen.[16]

Following the Russian invasion of Ukraine in 2022, the European Commission adopted the REPowerEU Plan, including plans for domestic hydrogen production and imports totalling 20 Mt of hydrogen in 2030.[17] Significant progress in the EU was also made with the development of the regulatory framework for renewable hydrogen in 2023 in the amendments to the Renewable Energy Directive (RED III) and the Delegated Acts related to renewable hydrogen.

III. **What Climate Goals Drive the Current Hydrogen Economy?**

The contemporary focus on the hydrogen economy[18] could be said to be, at least in large part, as a result of binding or aspirational climate targets.[19] This shift reflects a growing recognition that, given the persistently high costs of renewable and low-carbon hydrogen production relative to fossil-derived alternatives,[20] decarbonisation imperatives constitute the primary economic rationale for public investment and regulatory intervention in hydrogen markets. Indeed, absent the legal and policy architecture designed to achieve net-zero emissions, the business case for scaling renewable and low-carbon hydrogen production and distribution infrastructure would remain marginal at best.

Climate goals, in this article, refer to commitments or aspirations to reduce GHG emissions over specified timeframes, typically articulated as percentage reductions against a baseline year or as absolute emission limits. These goals may take various legal forms such as binding statutory obligations enacted through domestic or supranational legislation, commitments articulated in policy documents, or internationally pledged targets submitted as NDCs under the Paris Agreement.[21] The Paris Agreement has catalysed the development of domestic legal frameworks designed to operationalise its international commitments into enforceable or aspirational targets.[22]

A. *EU Climate Goals and Hydrogen*

The EU's ambition to reach climate neutrality by 2050 was defined in the European Green

[14] UN Doc FCCC/CP/2015/L.9/Rev.1.
[15] Yap & McLellan (n 12) *supra*.
[16] Crnčec, Danijel, et al. "The COVID-19 Pandemic and the EU: From a Sustainable Energy Transition to a Green Transition?" *Energy Policy*, vol. 175, 2023, 113453.
[17] European Commission Communication COM(2022) 230 Final, 18 May 2022.
[18] The term hydrogen economy in defined according to Yap & McLellan (n 12) *supra*, namely as "the utilization of hydrogen as an energy carrier for different sectors complementing electricity".
[19] Yap & McLellan (n 12) *supra*.
[20] Whilst precise cost comparisons vary by geography and feedstock, renewable hydrogen production costs in 2024 were substantially above grey hydrogen: *see Global Hydrogen Review 2024*. OECD / IEA, 2024.
[21] Article 4.2 of the Paris Agreement mandates that each Party "shall prepare, communicate and maintain successive nationally determined contributions that it intends to achieve. Parties shall pursue domestic mitigation measures, with the aim of achieving the objectives of such contributions".
[22] Voigt, Christina. "The Power of the Paris Agreement in International Climate Litigation," *Review of European, Comparative & International Environmental Law*, vol. 32, no. 2, 2023, pp. 237-249.

Deal,[23] a set EU policy initiatives with the overarching aim of making the EU climate neutral by 2050. This ambition was followed by the European Climate Law which set an intermediate target of at least 55% net GHG emission reductions by 2030 compared to a 1990 baseline. In July 2025, an amendment to the Climate Law, introducing a 2040 target of 90% net GHG emission reductions, was proposed.[24] The Green Deal is directly related to the Paris Agreement,[25] it serves, together with the 'Fit for 55' Package, which implements the Green Deal,[26] as the EU's main policy instrument for fulfilling its commitments under the Paris Agreement by aiming for climate neutrality by 2050, with legally binding targets for emission reductions and comprehensive climate action across sectors.

These economy-wide targets create direct legal pressure that permeates sectoral instruments, including those specifically relevant to hydrogen deployment. To avoid prolixity, these instruments are not discussed in depth at this stage, save to state that RED III,[27] the FuelEU Maritime Regulation[28] and the ReFuel Aviation Regulation[29] spell out particular sectoral targets for RFNBOs (defined below) specifically relevant to the hydrogen sector. RED III sets a percentage target of renewable energy in the EU's total energy use to 42.5% by 2030, with an extra 2.5% that would bring the total to 45%.[30] The cumulative effect of these instruments is to generate binding legal pressure to decarbonise industry and transport through hydrogen deployment. The sectoral RFNBO sub-targets establish a comprehensive regulatory ecosystem designed to stimulate both supply and demand for renewable hydrogen. Thus, for the climate-hydrogen nexus, the EU has a broader regulatory philosophy of using legally binding targets and sectoral obligations to drive market transformation.

B. *US Climate Goals and Hydrogen Policy Direction*

The US approach to climate policy differs in its legal form, relying on a combination of executive commitments, NDCs under the Paris Agreement, and, in respect of hydrogen, relying on legislative fiscal incentives rather than binding statutory obligations comparable to EU law.

In April 2021, the Biden administration, after rejoining the Paris Agreement, submitted an updated NDC setting an economy-wide target to reduce net GHG emissions by 50-52% below 2005 levels by 2030. This target was subsequently bolstered by a December 2024 update establishing a 2035 milestone of 61-66% reductions.[31] The administration also articulated in an Executive Order an objective of achieving net-zero emissions economy-wide by 2050[32] elaborated in the November 2021 Long-Term Strategy.[33]

The US approach in relation to hydrogen has been to incentivise it through federal grants for hydrogen hubs and technologically neutral tax credits. These are discussed later in this article and thus no detail is set out here, save to state that the US approach has been dominated by fiscal incentives, although its fiscal support for renewable hydrogen has changed since the new administration has come to power, with less of a focus on climate.

The divergent legal character of climate commitments in the EU and the US illustrates

[23] For more on the Green Deal, see "The European Green Deal: Striving to the First Climate-Neutral Continent." *European Commission Webpage*.
[24] European Commission (n 4) *supra*.
[25] European Commission Communication COM(2019) 640 Final, 11 Dec. 2019.
[26] Fetting, Constanze. *The European Green Deal*. ESDN Report, Dec. 2020.
[27] Directive (EU) 2023/2413 [2023] OJ L2023/2413 (RED III).
[28] Regulation (EU) 2023/1805 [2023] OJ L234/48 (the FuelEU Maritime Regulation).
[29] Regulation (EU) 2023/2405 [2023] OJ L2023/2405 (the ReFuelEU Aviation Regulation).
[30] RED III, Art. 3(1).
[31] "Fact Sheet: President Biden Sets 2035 Climate Target Aimed at Creating Good-Paying Union Jobs, Reducing Costs for All Americans, and Securing U.S. Leadership in the Clean Energy Economy of the Future." *The White House*, 19 Dec. 2024.
[32] Executive Order 14008 (n 6) *supra*.
[33] The White House (n 7) *supra*.

a fundamental distinction in regulatory approach. Nonetheless, both jurisdictions have established hydrogen as one piece of the puzzle in achieving their respective climate targets or aspirations, with legal and policy instruments explicitly designed to channel investment towards low-emission production pathways.

The extent to which these frameworks will successfully scale hydrogen deployment remains unknown and contested and forms the subject of subsequent analysis in this article.

IV. **Defining Hydrogen: EU and US Hydrogen Classifications**

A. *Renewable Hydrogen in the EU*

To reduce GHG emissions and achieve climate goals, EU regulation distinguishes between two 'types' of hydrogen: renewable and low-carbon hydrogen. However, the definitions and requirements for these types of hydrogen are located in different legal documents and were adopted at different times, making the system fragmented and complicated to some degree.

The main requirements for renewable hydrogen are defined in the RED III together with the Delegated Acts on renewable hydrogen production and GHG emission calculation, adopted in 2023.[34] However, none of these acts include a comprehensive definition of renewable hydrogen. Instead, RED III uses the term 'renewable fuel of non-biological origin' (RFNBO) for hydrogen produced from renewable electricity.[35]

To classify hydrogen as an RFNBO, the Delegated Act on renewable hydrogen production imposes the following main criteria:

- Additionality: Renewable electricity for hydrogen production should be used from new power plants without incentives based on power purchase agreements (PPAs) concluded after 2028; and
- Geographic and Temporal Correlation: Renewable electricity should be produced in the same bidding zone as the electrolyser or interconnected bidding zones in compliance with the requirements for electricity prices, and taking into account the renewable electricity production within a month and later within hours.[36]

Additionally, RFNBO hydrogen must demonstrate 70% GHG emission savings based on lifecycle assessment under the methodology defined in the Delegated Act.[37]

All these criteria apply together as the main preconditions for certification of hydrogen as RFNBO. In the case of non-compliance with these criteria for RFNBO, hydrogen can be classified as low-carbon, provided it meets the 70% GHG emission savings criteria. This GHG emission threshold is based on a 'well-to-wheel' assessment methodology which encompasses the complete lifecycle of hydrogen production, from feedstock extraction to an end-user. During project realisation, the same electrolyser can produce renewable and low-carbon hydrogen depending on the compliance of the electricity with the requirements for renewable electricity and the GHG emission reduction threshold in a certain production period.[38]

Specific requirements for the application of the mentioned criteria for hydrogen production depend on the type of connection of electrolysers, a direct connection with a renewable power plant or through the grid. For hydrogen production with connection to

[34] Commission Delegated Regulation (EU) 2023/1184 [2023] OJ L158/1; Commission Delegated Regulation (EU) 2023/1185 [2023] OJ L158/14.
[35] European Commission Directorate-General for Energy. "Q&A Implementation of Hydrogen Delegated Acts." CIRCABC, 26 Jul. 2023.
[36] Commission Delegated Regulation (EU) 2023/1184 (n 34) *supra*.
[37] Commission Delegated Regulation (EU) 2023/1185 (n 34) *supra*.
[38] Holl, Michaela, et al. *Low-Carbon Hydrogen in the EU: Towards a Robust Definition in View of Costs, Trade and Climate Protection*. Agora Energiewende and Agora Industry, 2024.

the grid, it is necessary to have concluded PPAs with renewable electricity producers. However, in the case of direct connection, PPAs are not required. Notwithstanding the fact that the Delegated Act provides insufficient details regarding PPAs,[39] one of the main purpose of PPAs (in respect of RFNBOs) is confirmation of the use of renewable electricity from installations complying with the requirements of additionality and correlation. These requirements prevent the displacement of existing renewable electricity supply to hydrogen production and instead accelerate the deployment of new renewable energy capacity for the hydrogen sector.

In other words, PPAs are a tool for supporting new renewable capacity deployment without financial incentives (given that such renewable energy cannot be subsidised).[40] Besides this, according to RED III, facilitating PPA uptake is required to deploy renewable energy capacity and ensure compliance with the Member State's national contributions to the binding overall EU target for the share of renewable energy consumption as part of their integrated national energy and climate plans.[41] This means that, further to their role in RFNBO production, PPAs are also an important tool in achieving binding RED III targets for climate goals.

Renewable hydrogen is an RFNBO, but not all RFNBOs are renewable hydrogen,[42] especially given the lack of a comprehensive legally binding definition for the term 'renewable hydrogen'. Simply having energy from renewable sources as a feedstock does not make the hydrogen produced an RFNBO. That is to say, if the electricity produced from renewable sources does not comply with the requirements in the Delegated Act regarding additionality and correlation, then whilst the source of the electricity in practice is still 'renewable', it is not considered 'renewable' for the purposes of compliance with the requirements for production of RFNBO. Therefore, there is a lacuna in that hydrogen produced from renewable energy sources outside the RFNBO framework is not clearly articulated in EU legislation. For example, the RFNBO framework explicitly excludes biomass. Further, hydrogen could be produced from solar or wind power but not satisfy the RFNBO criteria (for example it could not comply with additionality or it could be subsidised) and thus, as a result of this, not have access to the RFNBO market.

The classification of renewable hydrogen is based on its certification according to the voluntary schemes to confirm GHG emissions through the whole supply chain from the place of production of hydrogen to the end-user (well-to-wheel). For purposes of renewable hydrogen certification the European Commission has, to date, recognised three certification schemes for RFNBO certification namely (i) the CertifHy voluntary scheme;[43] (ii) the International Sustainability & Carbon Certification voluntary scheme;[44] and (iii) the REDcert-EU voluntary scheme.[45] The certification of renewable hydrogen in the EU (or for purposes of use in the EU) provides an avenue to confirm the GHG emission in furtherance of achieving RFNBO targets.

Thus, renewable hydrogen is classified as an RFNBO under the EU regulatory framework with specific requirements for renewable electricity and GHG emission savings.

B. *Low-Carbon Hydrogen in the EU*

Low-carbon hydrogen is defined in Directive (EU) 2024/1788 on common rules for the

[39] Scheyl, Jan-Hendrik, et al. *Frequently Asked Questions on EU Requirements for Renewable Hydrogen and Its Derivatives*. International PtX Hub, 2023, at p. 9.
[40] Commission Delegated Regulation (EU) 2023/1184 (n 34) *supra*.
[41] RED III, Art. 3.
[42] The term RFNBO is wide enough to include certain hydrogen derivatives; inter alia, e-methanol and e-kerosene.
[43] Commission Implementing Decision (EU) 2024/3180 [2024] OJ L.
[44] Commission Implementing Decision (EU) 2024/3176 [2024] OJ L.
[45] Commission Implementing Decision (EU) 2024/3194 [2024] OJ L.

internal markets for renewable gas, natural gas and hydrogen (the "Gas Directive").[46] Based on this definition, hydrogen is classified as low-carbon if the energy used for its production comes from non-renewable sources and it complies with the 70% threshold for GHG emission reduction compared to the fossil fuel standard for RFNBO.[47]

In 2025, the European Commission adopted a Delegated Act for low-carbon hydrogen and fuels.[48] The Delegated Act for low-carbon hydrogen identifies two approaches for its production: (i) electrolysis using low-carbon electricity or (ii) natural gas reforming with carbon capture.[49] The calculation of GHG emissions under the Delegated Act for low-carbon hydrogen is based on a similar lifecycle approach throughout the entire supply chain, as for renewable hydrogen.[50]

Notwithstanding a similar approach for GHG emission calculation for renewable and low-carbon hydrogen, they have a significant difference regarding the requirements for electricity. For renewable (RFNBO-compliant) hydrogen, producers need PPAs with renewable electricity producers in the case of connection to the grid, as set out above, whereas for low-carbon hydrogen, the electricity can be sourced from the grid without any renewable PPAs.[51] The Delegated Act for low-carbon hydrogen allows hydrogen production using non-renewable electricity. There remains a lacuna in respect of nuclear energy, and use of nuclear electricity and nuclear PPAs for low-carbon hydrogen production will be subject to assessment by the European Commission in 2028.[52]

In the EU, hydrogen can be classified as renewable or low-carbon hydrogen depending on the feedstock (renewable energy, fossil fuel or low-carbon electricity from the grid with e.g. nuclear energy), the production process (electrolysis or natural gas reforming), and the emission threshold of less than 70% GHG emission reduction (using well-to-wheel lifecycle accounting). Given that this criterion is defined across different legislative instruments, adopted at different times, with differing scopes, the resulting framework can be difficult to navigate, particularly for producers who are seeking to import hydrogen into the EU.

C. *Clean Hydrogen Technology-Neutral Definition in the US*

Two federal government standards delineate 'clean' hydrogen in the US: (i) the IRA's S45V Credit, which has a GHG emissions linked definition, as assessed by the GREET model, in order to be eligible for the credit,[53] and (ii) the Department of Energy's Clean Hydrogen Production Standard (CHPS), established under the Infrastructure Investment and Jobs Act (IIJA), utilised in federal hydrogen initiatives.[54] Whilst the two definitional standards align in important ways, they use different legislative bases and accounting boundaries.

The IIJA[55] defines clean hydrogen[56] as "hydrogen produced in compliance with the GHG emissions standard established under section 822(a), including production from any fuel source". Thus, this definition must be read with section 822(a) which defines clean hydrogen as "hydrogen produced with a carbon intensity equal to or less than 2 kilograms of carbon dioxide-equivalent

[46] Directive (EU) 2024/1788 [2024] OJ L1788 (the Gas Directive).
[47] Art. 2(11) of the Gas Directive.
[48] Commission Delegated Regulation (EU) 2025/2359 [2025] OJ L2359/1.
[49] "Questions and Answers on the Delegated Act Defining Low-Carbon Hydrogen and Fuels." European Commission Press Corner Q&A No 25/1744.
[50] ibid.
[51] Tovar, Magnolia, et al. *Methodology for Assessing Greenhouse Gas Emissions Savings from Low-Carbon Fuels*. ITRE, European Parliament, 2025, at p. 18.
[52] ibid at p. 12.
[53] de Marigny, Barbara, et al. "Final Section 45V Clean Hydrogen Production Tax Credit Regulations: A Closer Look." *Baker Botts Client Updates*, 3 Feb. 2025.
[54] *Clean Hydrogen Production Standard Guidance.* US Department of Energy, Jun. 2023.
[55] Infrastructure Investment and Jobs Act, HR 3684, 2021 (the IIJA).
[56] Sections 40312 and 40315 with section 822 of the IIJA.

produced at the site of production per kilogram of hydrogen produced". In the IRA, 'qualified' clean hydrogen is defined as "hydrogen produced through a process that results in a lifecycle greenhouse gas emissions rate of not greater than 4 kilograms of CO2e per kilogram of hydrogen".[57]

The CHPS, developed pursuant to the IIJA, released in updated guidance in June 2023,[58] establishes a target of 4 $kgCO_2e/kgH_2$ for lifecycle GHG emissions. It employs a 'well-to-gate' assessment methodology, which means that it encompasses the complete lifecycle of hydrogen production, from feedstock extraction through the point of production at the facility gate. This approach excludes downstream activities. The CHPS is explicitly technology neutral, permitting diverse feedstocks, including fossil fuels with carbon capture, biomass, renewable and nuclear energy provided they meet the emissions threshold.[59] CHPS is not a regulatory standard. Despite this, Regional Clean Hydrogen Hubs supported by the IIJA are required to "demonstrably aid achievement" of CHPS by minimising emissions to the greatest extent practicable. Thus, we see that Biden administration framed clean hydrogen as an integral factor in enabling decarbonisation goals.[60]

The IRA's S45V Credit, on the other hand, constitutes a tax credit. The S45V Credit offers a tax credit calculated as a fixed dollar amount for each kilogram of clean hydrogen generated over a 10-year period. The credit is also technology neutral and does not stipulate the feedstock required for hydrogen production.[61] The credit amount is contingent upon the lifecycle GHG emissions of the production process and the facility's adherence to specific prevailing wage and apprenticeship standards (not discussed in this article). Hydrogen can earn up to a credit of $3 per kilogram if its lifecycle GHG emissions are below 0.45 kilogrammes of CO2 equivalent per kilogram of hydrogen produced.[62]

The standards that would be applied to determine the lifecycle GHG emissions for the hydrogen production technique utilised have received a lot of attention because the credit amount is dependent on the carbon intensity of the production process.[63] To run electrolysers on the grid and to claim that your electrons came from a particular plant—instead of taking the grid-average factor baked into the GREET (Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies) model—it is necessary to buy and retire qualifying Energy Attribute Certificates (EACs) that meet three pillar requirements of (i) incrementality, (ii) temporal matching, and (iii) deliverability. Otherwise, the rules default your electricity to the regional grid average in the model.

This 'three pillars' approach, for which final guidance was released in January 2025,[64] is akin to the EU's three pillar framework for RFNBO's and consists of the following:[65]

- Incrementality: The rules established three qualifying pathways: (i) electricity from generation facilities with carbon capture and sequestration technology commissioned within 36 months of the hydrogen facility's operation; (ii) electricity from qualifying nuclear power plants; (iii) and clean electricity from existing facilities in California and Washington.[66]
- Temporal Matching: The transition period for annual matching between electricity

[57] CRSR (n 9) *supra*.
[58] US Department of Energy (n 54) *supra*.
[59] *Hydrogen Production: Overview and Issues for Congress*. Congressional Research Service Report, Library of Congress, 3 Oct. 2024.
[60] Eicke, Laima. "US Hydrogen Policy Paving the Way for Energy Independence, Technology Leadership and Decarbonization." RIFS Discussion Paper, Dec. 2023.
[61] de Marigny et al. (n 53) *supra*.
[62] ibid.
[63] ibid.
[64] Credit for Production of Clean Hydrogen and Energy Credit, Final Regulations, 26 CFR Part 1 (TD 10023), 90 FR 2224, 10 Jan. 2025.
[65] "Treasury and IRS Issue Final Regulations Implementing Section 45V Clean Hydrogen Production Tax Credit." *King & Spalding*, 13 Jan. 2025; "Final Hydrogen Regulations Provide Multiple Paths for Production, But the Three Pillars and Other Obstacles Remain." *Vinson & Elkins*, 15 Jan. 2025.
[66] ibid.

generation and hydrogen production was extended by two years, with mandatory hourly matching commencing in 2030. Existing hydrogen facilities received no grandfathering protections. Once hourly matching becomes mandatory, producers may calculate lifecycle greenhouse gas emissions hourly, provided annual emissions remain below 4 $kgCO_2e/kgH_2$.[67]

- Deliverability: While maintaining the regional boundary framework for electricity sourcing, the rules introduced flexibility for demonstrating viable electricity transfers between regions, including Canadian and Mexican imports.[68]

The adoption of the three pillars and their stringency illustrate the link to climate goals, and various environmental groups have expressed the view that a strong three pillar framework is the only way in which 'clean' hydrogen can demonstrably add to climate mitigation and avoid greenwashing.[69]

V. **Addressing the Hydrogen-Climate Nexus**

This Section of the article evaluates the extent to which climate goals have shaped the development of hydrogen policy frameworks in the EU and US. It addresses the article's three guiding research questions in turn: (i) whether climate goals function as drivers of hydrogen market creation; (ii) whether a renewable-only hydrogen sector can emerge in the absence of climate commitments; and (iii) whether current low-carbon hydrogen frameworks can credibly deliver on climate objectives. The analysis uses legal and policy materials to elucidate the links between climate ambition, regulatory design, and hydrogen pathway selection.

A. *Do Climate Goals Function as Drivers of Hydrogen Market Creation?*

Climate goals are a prominent driver of renewable (and to some extent low-carbon hydrogen) development globally. Analysing the adoption of climate goals in the EU and the US from 2019 to 2025, support for renewable hydrogen in both regions started, to some extent, as a result of the Paris Agreement goals. This can be observed through explicit references to the Paris Agreement and climate change in strategic documents, the incorporation of GHG thresholds methodologies for calculating 'clean' hydrogen (in the US), low-carbon hydrogen and RFNBOs (in the EU), and the sequencing of policy reforms that follow the strengthening and / or weakening of climate commitments.

1. Climate Goal Drivers in the EU

The EU ratified the Paris Agreement in October 2016.[70] With the entry into force of the Paris Agreement in 2016,[71] in 2020, the EU adopted the EU Hydrogen Strategy, which considers hydrogen as an essential element to achieve EU climate neutrality by 2050 and, from a global perspective, an effort to implement the Paris Agreement.[72] This link between climate goals and hydrogen is clear from the EU Hydrogen Strategy where it states that "hydrogen [is] essential to support the EU's commitment to reach carbon neutrality by 2050 and for the global effort to implement the Paris Agreement while working towards zero pollution".[73] It goes on to describe how both the EU Hydrogen Strategy and the Strategy for Energy System Integration "contribute towards the achievement of the Sustainable Development Goals and the objectives of the Paris Agreement"[74] and states that renewable hydrogen is a "key building block towards a climate-neutral and zero

[67] ibid.
[68] ibid.
[69] "Treasury and IRS Finalise Clean Hydrogen Tax Credit." *The Sierra Club*, 2025; "Three-Pillar Rule Is Essential to Safely Grow the U.S. Clean Hydrogen Economy." *Environmental Defence Fund*, 2024; Esposito, Dan. "Evidence Shows Three Pillars Remain Crucial for 45V Hydrogen Tax Credit to Protect Climate, Consumers, Industry." *Energy Innovation Policy & Technology*, Jul. 2024.
[70] Council Decision (EU) 2016/1841 [2016] OJ L282.
[71] ibid.
[72] European Commission Communication COM(2020) 301 Final, 8 Jul. 2020.
[73] ibid at p. 1.
[74] ibid at p. 3.

pollution economy in 2050".[75] One telling indication of the clear link between low-carbon and renewable hydrogen and in the EU Hydrogen Strategy is the statement that "[f]or hydrogen to contribute to climate neutrality, it needs to achieve a far larger scale and its production must become fully decarbonised".[76]

From a reading of the EU Hydrogen Strategy, the initial guiding hydrogen policy document in the EU, it is clear that climate goals were a driver and catalyst for hydrogen market creation. From 2021 to 2023, the EU clarified its climate goals in the Climate Law and defined the RED III targets for renewable hydrogen, together with the legal framework for renewable and low-carbon hydrogen.

What emerges from these documents is a praxeological connection, in which climate goals exert direct influence on EU hydrogen policymaking. First, legally binding climate targets create regulatory pressure to identify decarbonisation technologies capable of displacing fossil fuels in hard-to-abate sectors (with hydrogen expressly designated as one such technology). Second, climate objectives shape the EU's funding architecture to some extent, with mechanisms such as the European Hydrogen Bank initially excluding low-carbon hydrogen and now only including electrolytic low-carbon hydrogen (not steam methane reforming). One can infer that this is, at least in some part, in order to meet emissions-reduction obligations. Third, GHG emission methodology and a defined emissions threshold for renewable and low-carbon hydrogen as a fuel to decrease GHG emissions complete the picture of the interaction between hydrogen and climate targets in the EU.

(α) Climate Targets

With respect to the targets, as set out above, RED III, the FuelEU Maritime Regulation and the ReFuelEU Aviation Regulation set sectoral targets for RFNBOs specifically relevant to the hydrogen sector. Some examples of these specific sectoral targets include: for industry, by 2030, 42% of hydrogen used in industrial processes should be RFNBOs (there are certain derogations available to reduce this);[77] in transport, a target of 1% of RFNBOs (of 5.5% target of advanced biofuels and RFNBOs) is set by 2030;[78] for aviation 6% of sustainable aviation fuels must be mixed with jet fuel (RFNBOs are included in synthetic aviation fuels meeting RED III requirements).[79]

These targets reflect deliberate policy design, and in the Commission Staff Working Document Impact Assessment Report accompanying the proposal to amend RED II, it is explicitly stated that one of the objectives to amend RED II was to "increase sufficiently the renewables share in final energy consumption. This will ensure that the overall and sectoral deployment of renewable energy in 2030 is in line with the CTP [Climate Target Plan] findings, thus contributing cost-effectively to the increased 2030 climate target of at least 55% as well as climate neutrality objective in 2050 (which requires the large scale rollout of innovative technologies including RFNBOs and advanced biofuels after 2030)".[80]

Thus, the EU was clearly of the view that RFNBOs were needed to achieve the legally binding 55% climate target. It follows axiomatically that the RFNBO targets were, at least to a large extent, catalysed by climate goals. Progress on the assessment of the climate targets in the EU is subject to an annual review by the European Commission under the Governance Regulation.[81] The Commission Staff Working Document for the Climate Action Progress Report 2025 considers hydrogen for the decarbonisation of different sectors and, at the same time, sets

[75] ibid at p. 21.
[76] ibid at p. 1.
[77] RED III, Art. 22(a) & 22(b); Talus, Kim, et al. "Realism at the End of the Rainbow? An Argument towards Diversifying Hydrogen in EU Regulation." *Journal of World Energy Law & Business*, vol. 17, no. 4, 2025, p. 217.
[78] RED III, Art. 25; Talus et al. (n 77) *supra*.
[79] Talus et al. (n 77) *supra*.
[80] European Commission Staff Working Document SWD(2021) 620 Final.
[81] Regulation (EU) 2018/1999 [2018] OJ L 328/1 (the Governance Regulation).

out challenges associated with hydrogen production.[82]

(β) EU Funding: Hydrogen Bank

Further to binding targets, the EU has funding mechanisms to assist in establishing a hydrogen economy. One of the most notable of these is the European Hydrogen Bank (EU-HB). In its first two rounds, the EU-HB was limited to renewable hydrogen production methods, illustrating its role as a funding mechanism contributing to the achievement of climate neutrality. The EU-HB, discussed more fully later in this article, aims to cover the investment gap and connect the supply and demand sides of renewable hydrogen.[83] The EU-HB is funded by the Innovation Fund, formed from revenue from the EU Emission Trading System (ETS).[84] Thus, the EU-HB illustrates that funding options for hydrogen in the EU are, to some extent, based on climate objectives.

(γ) GHG Thresholds and Methodology

This link between hydrogen and climate is further illustrated in the specific GHG thresholds and methodologies established for RFNBOs and low-carbon hydrogen. As set out above in this article, for RFNBOs, two Delegated Acts adopted in June 2023 set out the climate-driven requirements namely: the Delegated Act on renewable hydrogen production[85] established the production methodology, defining when hydrogen can qualify as an RFNBO through criteria such as additionality, temporal correlation, and geographical correlation as described earlier in this article. These requirements are stringent and ensure that the RFNBOs achieve the strictest renewable level. The Delegated Act on GHG Methodology[86] sets the calculation methodology for lifecycle GHG emissions and establishes the binding 70% GHG emissions savings threshold (maximum 28.2 gCO_2e/MJ). The Delegated Act on low-carbon hydrogen defines the same emission threshold of 28.2 gCO_2e/MJ for the full life-cycle emissions, and the methodology for GHG emission calculation is aligned with that for renewable hydrogen.[87] These methodologies and requirements translate the EU's emissions reduction target into concrete, enforceable production standards to ensure hydrogen deployment contributes its required share to sectoral decarbonisation.

On 26 February 2025, the European Commission launched a new initiative, the Clean Industrial Deal, outlining decarbonisation actions for European industries. The Clean Industrial Deal confirms the EU's commitment to achieving its climate goals by offering clear business incentives for industry to decarbonise across Europe. At the same time, the Clean Industrial Deal shows the confluence of differing priorities including climate and competitiveness development and includes actions to promote the uptake of not only renewable, but also low-carbon hydrogen.[88]

To further support the climate goals, on 16 October 2025, the European Commission published the EU Global Climate and Energy Vision. This strategic document is based on the global changes that followed the Paris Agreement and considers investment in renewable electricity and hydrogen as an alternative path to eliminate dependence on fossil fuel producers.[89] This document states explicitly that "[o]ur vision builds on the major global shifts that have taken place since the Paris Agreement in 2015. Back then, a global clean transition was only a possibility. Today, it is a reality. Clean investments have overtaken fossil fuel funding … However,

[82] *Climate Action Progress Report 2025: Technical Information*. European Commission, Nov. 2025.
[83] European Commission Communication COM(2023) 156 Final.
[84] ibid.
[85] Commission Delegated Regulation (EU) 2023/1184 (n 34) *supra*.
[86] Commission Delegated Regulation (EU) 2023/1185 (n 34) *supra*.
[87] Butorac, Saša Butorac. *Briefing: Delegated Act on Low-Carbon Hydrogen*. European Parliamentary Research Service, Sept. 2025.
[88] European Commission Communication COM(2025) 85 Final, 26 Feb. 2025.
[89] European Commission and High Representative of the Union for Foreign Affairs and Security Policy Joint Communication JOIN(2025) 25 Final, 16 Oct. 2025.

limiting global warming to 1.5°C requires deeper, more rapid and sustained global greenhouse gas emission cuts: 43% by 2030 and 60% by 2035 compared to 2019 levels before reaching net-zero CO_2 emissions by 2050. This requires a managed and accelerated transition away from fossil fuels, a massive expansion of renewable energy, becoming more energy efficient in all sectors, promoting resource efficiency and the circular economy, and accelerating the deployment of zero- and low-carbon technologies".[90]

We see therefore that the EU's push for technologies such as hydrogen is not simply concurrent with climate policy in the EU but developed in response to it (alongside energy security). Climate goals in the EU have generated legal obligations, fiscal architecture, and sectoral targets in which hydrogen has become a necessary instrument.

2. Climate Goal Drivers in the US

In contrast, the US withdrew from the Paris Agreement in 2019,[91] rejoined it in 2021,[92] and again started withdrawal processed in 2025.[93] The first withdrawal in 2019 did not lead to any notable consequences for the hydrogen sector, but this is largely due to the fact that it was not as prominent in energy discourse at the time. The active development of a supportive framework for clean energy including hydrogen in the US coincided with the rejoining of the Paris Agreement from 2021 to 2024 and the adoption of the IRA and other strategic documents supporting clean energy including hydrogen supply chain development. The initiation of the withdrawal to the Paris Agreement in 2025 was a marker of significant changes in the US framework for hydrogen support. Soon thereafter, the One Big Beautiful Bill Act (OBBBA) was enacted, as discussed later in this article.

After rejoining the Paris Agreement under the Biden administration, the US established climate objectives, as well as funding mechanisms, and GHG methodologies for hydrogen, embedded within a broader framework that prioritised economic competitiveness and job creation from the outset.

(α) US Climate Objectives

The US National Clean Hydrogen Strategy and Roadmap starts by stating that "[g]iven its potential to help address the climate crisis, enhance energy security and resilience, and create economic value, interest in producing and using clean hydrogen is intensifying both in the United States and abroad".[94] It goes on to state that "[z]ero- and low-carbon hydrogen is a key part of a comprehensive portfolio of solutions to achieve a sustainable and equitable clean energy future".[95] This framing reflects the way in which hydrogen policy in the US has been shaped, including in part by the climate imperative. This is seen throughout the definition of 'clean' hydrogen in the US, especially at earlier stages, with a focus on emissions reduction.

While climate objectives formed an important part of the federal narrative underpinning hydrogen policy during the 2021-2024 period, they were embedded within a broader set of political and economic motivations. Given the political backdrop of the US, hydrogen was deliberately framed not only as a tool for decarbonisation but also as a means of strengthening domestic manufacturing capacity and generating local employment.[96] For example, then Secretary of Energy Jennifer Granholm stated that "[c]lean hydrogen is key to cleaning up American manufacturing and slashing emissions from carbon-intensive materials like steel and cement while creating good-paying jobs for American workers".[97] This illustrates how the

[90] ibid.
[91] "On the US Withdrawal from the Paris Agreement." *US Department of State*, 4 Nov. 2019.
[92] "The United States Officially Rejoins the Paris Agreement." *US Department of State*, 19 Feb. 2021.
[93] "Putting America First in International Environmental Agreements." *The White House*, 15 Jan. 2025.
[94] *National Clean Hydrogen Strategy and Roadmap*. US Department of Energy, Jun. 2023, at p. 1.
[95] ibid.
[96] Eicke (n 60) *supra*.
[97] "DOE Establishes Bipartisan Infrastructure Law's $9.5 Billion Clean Hydrogen Initiatives." *Fuel Cell Works*, 15 Feb. 2022.

IIJA, requiring bipartisan support, emphasised hydrogen not only as a decarbonisation tool but as a lever for infrastructure investment. As a result, climate goals operated alongside, and were at times mediated by, economic and strategic considerations from the outset.

(β) US Funding: Tax Credits
The climate catalyst is evident in the S45V Credit Treasury Guidance, which is more fully explored earlier in this article. As discussed, the credit amount is contingent upon inter alia the lifecycle GHG emissions of the production process.[98] However, the sequencing reveals how political shifts can constrain climate policy. Treasury Regulations established the three pillar requirements for clean hydrogen, set out above, but the subsequent compression of construction timelines through the OBBBA, reflecting changing national climate priorities, creates conditions affecting the deployment scales those same tax credits were designed to enable. The climate-driven policy design thus remains in place whilst political commitment to its implementation has weakened.

(γ) GHG Emission Methodology
The evolution of the GREET model further illustrates this policy orientation. The model plays a pivotal role in determining both eligibility and credit amounts under the S45V Credit, discussed earlier. In short, hydrogen producers must demonstrate that their hydrogen meets specific lifecycle emissions thresholds to qualify for the credit. There was more than one revision in the first half of 2025, with the May 2025 revision introducing facility-specific methane loss tracking, which has the possibility of allowing low-carbon (natural gas) hydrogen producers to use lower, project-specific upstream methane leakage rates rather than national averages, a change conceivably designed to help fossil-based projects qualify for higher tax credit tiers. This selective tightening of renewable pathways whilst simultaneously relaxing methodological constraints on fossil-based routes reveals a systematic bias embedded within ostensibly technical modelling choices.[99] This systematic bias can be linked with moving away from the Paris Agreement and climate ambitions.

In the US context, hydrogen policy thus emerged through the alignment of several priorities, including climate change, industrial revival and the creation of high-quality employment. This was particularly apparent in the design of the IIJA, which required bipartisan support (seen by the name it was initially known as, the Bipartisan Infrastructure Law). As a result, climate goals were influential, but they operated alongside, and at times were mediated by, these economic and strategic considerations from the outset.[100]

Thus, there is a correlation between decarbonisation goals and hydrogen sector development. This is as a result of hydrogen, more specifically, renewable (and to some extent low-carbon) hydrogen's ability to aid in decarbonisation efforts. However, there is a variance in the extent of the relation between climate goals and hydrogen in the EU and US.

B. *Can a Renewable-Only Hydrogen Sector Emerge without Climate Goals?*
Despite variances, a viable renewable hydrogen market is unlikely to emerge or scale in the absence of climate-policy commitments. Renewable hydrogen currently remains significantly more expensive than fossil-derived alternatives, and without the climate-policy rationale for subsidising and regulating its production, it has little economic foundation.[101] However, from a climate perspective, renewable hydrogen does not have direct CO2 emissions[102] in the process of production and is thus favourable.

[98] ibid.
[99] Currie, Charlie. "DOE Backs Flexibility for Blue Hydrogen Credits as 45V Hangs in the Balance." *H2View*, 29 May 2025.
[100] ibid.
[101] ibid.
[102] Incer-Valverde, Jimena, et al. "'Colours' of Hydrogen: Definitions and Carbon Intensity." *Energy Conversion and Management*, vol. 291, 2023, 117294.

A widespread opinion among industry,[103] scientists[104] and policymakers[105] confirms the importance of renewable hydrogen for GHG emission reduction in the hard-to abate sectors that cannot be electrified.[106] Moreover, despite the important role of renewable electricity for emission reduction, the Net Zero Emissions by 2050 Scenario of the IEA confirms a vital supplementary role of hydrogen to electricity for reaching climate neutrality by 2050.[107]

The EU and US trajectories both reveal that renewable-hydrogen deployment has advanced where climate policy created either binding obligations (in the EU) or where strong fiscal incentives were bolstered and layered with requirements linked to climate (i.e. in the US, where fiscal Section 45V incentives were linked to the 'three pillars' and hydrogen hubs linked to CHPS emissions accounting requirements). We have also seen, in turn, the weakening of climate ambition in the US altering the policy environment for renewable-hydrogen investment, illustrating the sensitivity of the sector to climate-policy signals.

As set out above, one area in which the climate-hydrogen nexus is illustrated is in financial support mechanisms. The most important supportive mechanism for hydrogen production in the EU is the EU-HB. The status of the EU-HB and the auction design for a fixed premium were defined in the Communication of the European Commission on the European Hydrogen Bank.[108] The EU-HB consists of auctions, with specific terms and conditions that are subject to revision for each auction and a predetermined budget. In the Communication from the EU-HB[109] there are clear links to climate for example, stating that "[t]he European Hydrogen Bank will facilitate both renewable hydrogen production within the EU and imports, contributing to the RePowerEU objectives and to the transition to climate-neutrality"[110] and "the development of renewable hydrogen economies in EU Partner countries will help accelerate their transition towards climate neutrality".[111]

Since 2023, the EU-HB has held two auctions for domestic production of renewable hydrogen. In December 2025, the EU-HB announced the third auction for domestic production of hydrogen.[112] For the first two auctions of the EU-HB, only RFNBO with the emission threshold of 3.4 $kgCO_2e/kgH_2$ was eligible. As has been shown above in this article, the RFNBO methodology is linked to climate change goals, and so limiting funding to RFNBOs is axiomatically a way to bolster the RFNBO industry and provide support for it, in turn providing support for climate ambitions.

However, for the third auction, the call for proposals also includes electrolytic low-carbon hydrogen.[113] At the same time, the call for proposals emphasises that projects funded within the call will contribute to achieving climate neutrality in 2050 and to meeting the 55% emissions reduction target by 2030 under the Climate Law and the European Green Deal.[114] This sequential shift shows the evolution from more climate only focused

[103] *Hydrogen Insights 2023: The State of the Global Hydrogen Economy*. Hydrogen Council / McKinsey, Dec. 2023.
[104] *Global Hydrogen Review 2023*. International Energy Agency, 2023; *World Energy Transitions Outlook 2023: 1.5°C Pathway*. International Renewable Energy Agency, 2023; Davis, Steven, et al. "Net-Zero Emissions Energy Systems." *Science*, vol. 360, no. 6396, 2018, eaas9793; Wolfram, Paul, et al. "The Hydrogen Economy Can Reduce Costs of Climate Change Mitigation by up to 22%." *One Earth*, vol. 7, no. 6, 2024, pp. 885-895.
[105] *Comparative Analysis of International Hydrogen Strategies: Country Analysis 2023*. DECHEMA & acatech, 2024.
[106] Odenweller, Adrian, and Falko Ueckerdt. "The Green Hydrogen Ambition and Implementation Gap." *Nature Energy*, vol. 10, no. 1, 2025, pp. 110-123.
[107] *IEA World Energy Outlook 2025*. International Energy Agency, 2025.
[108] European Commission (n 83) *supra*.
[109] ibid.
[110] ibid at p. 2.
[111] ibid at p. 9.
[112] "€5.2 Billion of EU Emissions Trading Revenues Earmarked for Clean Transition Technologies under the Innovation Fund." *European Commission Webpage*, 4 Dec. 2025.
[113] European Commission, Innovation Fund INNOVFUND-2025-AUC-H2, Version 1.0, 4 Dec. 2025.
[114] ibid.

funding to funding which also considers other imperatives, although still with a strong climate focus (given that only electrolytic low-carbon hydrogen is proposed to be added).

Table 1 below provides an overview of the EU-HB auctions, illustrating the different approaches to the amounts of available funds, ceiling prices, and eligible types of hydrogen.
In contrast to the EU-HB, the S45V Credit provides support in the form of a fixed production tax credit (PTC) when the project is operational. Hydrogen producers in the US, in comparison with the EU, do not have direct auction type competition for the PTC and can rely on an administered price depending on the carbon content of the hydrogen, as illustrated in **Table 2** below. Whilst technologically neutral, the inclusion of carbon content still points to a climate nexus.

In contrast to the EU, the US supportive scheme in the IRA is technologically neutral and can be provided to 'clean' hydrogen without restriction on feedstock, unlike the EU's approach regarding fossil-based production. Table 3 illustrates the differences between the EU-HB in the EU and S45V Credit in the US.

Notwithstanding differences between Section 45V Credit and the EU-EHB, they also have similarities in respect of the three pillar rules for additionality, geographic correlation, and temporal correlation.[115] However, even within these rules, there is divergence, as shown in **Table 3** below.

In sum, climate policy has not simply coincided with hydrogen policy; it has provided a legal, economic, and technical rationale for renewable-hydrogen market creation, albeit to differing degrees in different jurisdictions. Absent that rationale, it is difficult to identify any alternative basis upon which the market could plausibly develop economically at scale. Once the market matures, this may not remain true but as a catalyst and driver climate goals play an important role.

C. *The EU Low-Carbon Evolution*

Following the announcement of the European Green Deal in 2019, the EU's initial focus centred almost exclusively on renewable hydrogen. The adoption of the Delegated Acts[116] in 2023 established the legal framework for an RFNBO with corresponding targets and the launch of the EU-HB auction provided RFNBO only financial support mechanisms.[117]

However, by late 2024 and early 2025, the policy stance began to recalibrate in response to economic constraints, slow infrastructure deployment, and concerns about European industrial competitiveness. The era of the Clean Industrial Deal[118] marks a departure from the previous renewable-only emphasis. This shift is illustrated by the following actions: (i) the 2025 Delegated Act concerning low-carbon hydrogen establishing the regulatory framework for this broader category,[119] and (ii) perhaps most tellingly, the Auction call for proposals for the third EU-HB auction including provisions for electrolytic low-carbon hydrogen, a clear extension of eligible production pathways.[120] This evolution has occurred despite the proposal to amend the European Climate Law to define a 2040 climate target of 90% reduction in GHG emissions,[121] demonstrating that the incorporation of low-carbon hydrogen is not

[115] Guillotin, Arnauld, et al. "Hydrogen Subsidies Under Three Pillar-Frameworks: A Europe–United States Multi-Stakeholder Comparison." *Renewable and Sustainable Energy Reviews*, vol. 211, 2025, 115284.
[116] Commission Delegated Regulation (EU) 2023/1184 (n 34) *supra*; Commission Delegated Regulation (EU) 2023/1185 (n 34) *supra*.
[117] "European Hydrogen Bank." *European Commission Webpage*, 2025.
[118] European Commission (n 88) *supra*.
[119] Commission Delegated Regulation (EU) Ares (2024) 6848064.
[120] INNOVFUND (n 113) *supra*.
[121] European Commission (n 4) *supra*. On 10 December 2025, the Council and Parliament agreed on the 90% emissions reduction climate target so that it appears that this proposal will soon be adopted: *see* "2040 Climate Target: Council and Parliament Agree on a 90% Emissions Reduction." *Council of the EU Webpage*, 10 Dec. 2025.

perceived as incompatible with ambitious climate objectives.

D. *The US Low-Carbon Evolution*

The transition to the Trump administration in January 2025 marked a decisive shift in US climate policy, with knock on effects for hydrogen. The notice of withdrawal[122] from the Paris Agreement indicated a significant shift from globally coordinated climate initiatives to a focus on national energy autonomy and economic competitiveness. This came after the nation's nationally determined contribution was made more stringent in 2024 by the Biden administration.[123] This early stage of the Trump presidency also saw the suspension of IRA fund pay-outs, generating uncertainty in the hydrogen sector.[124]

In July 2025, the OBBBA was enacted.[125] The OBBBA substantially alters clean energy tax incentives established by the IRA.[126] For hydrogen, the OBBBA accelerates the sunset of the S45V Credit, i.e. projects must now begin construction by 31 December 2027, in order to qualify for the credit. Thus, projects must be sufficiently progressed to qualify for the applicable incentives.[127] Whilst the OBBBA retained the section 45Q carbon capture credit for facilities that start construction prior to 2033, its treatment of other clean energy credits compound challenges for renewable electrolytic hydrogen.[128] As the US Energy Information Administration noted in a 2025 report, even under favourable regulatory conditions, SMR from natural gas remains the predominant hydrogen generation method in the majority of scenarios, with electrolyser-based production accounting for less than 1% of total hydrogen generation in the US.[129]

The outcome of these policy developments is a framework that continues to support hydrogen development but under substantially revised conditions. Projects relying on natural gas with carbon capture and storage face fewer near-term obstacles than electrolytic alternatives. This outcome, whilst perhaps less supportive of renewable hydrogen than many advocates had hoped, reflects the political and economic constraints within which hydrogen policy must operate in the US. In practice, viable projects will be those that can swiftly align clean energy, offtake agreements, and financing, and those which rely on gas with carbon capture and storage.

E. *What Does Low-Carbon Hydrogen Mean for Climate Goals?*

The key challenge raised by this trend towards policy frameworks that support diverse hydrogen production pathways is whether or not this is compatible with reaching climate targets. The answer depends substantially on how one sees compatibility. If the standard is whether low-carbon hydrogen can fully replace renewable hydrogen as the primary decarbonisation pathway whilst still achieving net-zero emissions by 2050, considerable scepticism is warranted.[130] Low-carbon hydrogen raises questions of methane leakage and continued reliance on natural gas infrastructure could lead to path dependencies that are hard to break, locking in the use of

[122] The process takes a year and commences with notification.

[123] The White House (n 31) *supra*.

[124] "Unleashing American Energy." The White House, 20 Jan. 2025; Allsup, Maeve. "What a 'Pause' on IRA Funds Really Means." *Latitude Media,* 22 Jan. 2025.

[125] One Big Beautiful Bill Act (OBBBA) of 2025, PL 119-21; *see* Clean Hydrogen Incentives in the One Big Beautiful Bill Act of 2025: Section 45V Clean Hydrogen Production Tax Credit.

[126] Cavanaugh, Jack Andreasen, et al. "Assessing the Energy Impacts of the One Big Beautiful Bill Act." *Center on Global Energy Policy,* 14 Jul. 2025.

[127] Corbeau, Anne-Sophie, and Drake Hernandez. "Analysis: Trump's One Big Beautiful Bill Act Has Given the US Hydrogen Industry Certainty—But Where Will the Green Energy Come From?" *Hydrogen Insight,* 29 Jul. 2025.

[128] For example, the OBBBA saw the cessation of technology-neutral tax credits, namely the Section 45Y Clean Electricity Production Credit and the Section 48E Clean Electricity Investment Credit for wind and solar projects that commence service post 2027, with an exception for projects where construction initiates on or before July 4 2026: *see* "The 'One Big Beautiful Bill' Act– Navigating the New Energy Landscape." *Sidley Austin,* 15 Jul. 2025.

[129] "Natural Gas Remains the Largest Source of Hydrogen in Our Long-Term Projections." *Today in Energy,* 4 Aug. 2025.

[130] "Hydrogen for Decarbonization: A Realistic Assessment." *Clean Air Task Force*, 21 Nov. 2023.

fossil fuels.[131] Thus, the climate benefits of low-carbon hydrogen will be dependent on inter alia the reporting and measurement of methane emissions.[132] Therefore, low-carbon hydrogen could also have significant climate mitigation benefits dependent on production processes and leakage.[133] Thus, so long as there are the necessary guardrails in place, low-carbon hydrogen could still have significant benefits to reaching climate goals, albeit not as large as renewable hydrogen.[134] However, this requires stringent guardrails and proven technologies throughout the entire hydrogen value and supply chain.[135]

Further, if the question is whether the inclusion of low-carbon hydrogen in the transitional energy mix can accelerate the overall development of hydrogen markets and thereby facilitate the eventual ascendancy of renewable hydrogen technology, a more nuanced analysis is necessary. The hydrogen question cannot be stated simply in binary terms (renewable or low-carbon hydrogen).

The infrastructure developed for low-carbon hydrogen can also be used for renewable hydrogen as production scales.[136] The hydrogen molecule itself does not differ, merely the production pathway. Barriers to the later adoption of renewable hydrogen may be lessened by the market mechanisms, and industry expertise obtained from the deployment of low-carbon hydrogen. Renewable hydrogen will eventually require larger expenditures in hydrogen infrastructure, which may be justified in part by the revenue streams and demand certainty offered by low-carbon hydrogen projects.[137] Thus, low-carbon hydrogen can play an important part in reaching climate goals, albeit not directly.

F. *Concluding Remarks on the Hydrogen-Climate Nexus*

The emergence and evolution of hydrogen policy in both the EU and the US cannot be understood independently of the broader climate-policy frameworks within which it developed and continues to develop. In the EU, legally enforceable climate goals put direct regulatory pressure on finding solutions to reduce GHG emissions in hard-to-abate industries. Hydrogen was identified from the start. This forms a praxeological relationship. The EU's decision to more explicitly incorporate low-carbon hydrogen in its regulatory framework later is not a sign that it is giving up on its climate goals. Instead, it constitutes an attempt to balance decarbonisation with energy security and industrial competitiveness. The pattern that emerges is that climate commitments were the first driver and then became a limit on which hydrogen pathways could be recognised without putting long-term emission-reduction goals at risk.

In the US, the relationship is also present, although given the political backdrop in the US, climate has always been seen and couched alongside other drivers. There was a big increase in investment and policy action related to hydrogen between 2021 and 2024. This was in line with the Biden administration's renewed federal climate pledges. However, at the same time, industrial, and employment-related concerns also affected hydrogen policy, which limited how much climate aims propelled the sector. The 2025 administration's less ambitious climate goals and the ensuing OBBBA illustrate keenly how sensitive the sector is to changes in climate policy. Although the connection between climate goals and hydrogen development in the US is influenced by other

[131] "Hydrogen Reality Check: All 'Clean Hydrogen' Is Not Equally Clean." *Rocky Mountain Institute*, 4 Oct. 2022.
[132] Tovar et al. (n 51) *supra* at 9.
[133] Hauglustaine, Didier, et al. "Climate Benefit of a Future Hydrogen Economy." *Communications Earth & Environment*, vol. 3, 2022, 295; Ocko, Ilissa, and Steven Hamburg. "Climate Consequences of Hydrogen Emissions." *Atmospheric Chemistry & Physics*, vol. 22, no. 14, 2022, pp. 9349-9368; Hydrogen leakage means leak of hydrogen molecules into the atmosphere.
[134] Ocko & Hamburg (n 133) *supra*.
[135] Esquivel-Elizondo, Sofia, et al. "Wide Range in Estimates of Hydrogen Emissions from Infrastructure." *Frontiers in Energy Research*, vol. 11, 2023, 1207208.
[136] "Building a Low Carbon Hydrogen Market in Europe." *Strategy&*, 2025.
[137] ibid.

strategic factors, it is still true that stronger climate commitments lead to stronger policy support for renewable hydrogen, while weaker commitments lead to a corresponding adjustment.

It could thus be said that in both jurisdictions, climate goals serve three causal functions: (i) they make hydrogen a desirable tool for decarbonisation, (ii) they shape the design of regulatory and fiscal tools that set up hydrogen markets, and (iii) they affect which production methods and / or emissions thresholds are seen as reliable ways to help meet long-term climate goals. The connection between hydrogen policy and climate strategy was and is not coincidental. Climatic goals have created legal, economic, and political reasons that make hydrogen a part of the energy transition landscape, even though different regions had different priorities.

The comparative timeline below set out in **Table 4** below illustrates how climate targets, geopolitical shocks and political transitions are reflected in hydrogen-specific regulatory developments in each jurisdiction.

It reveals that when climate goals are high, hydrogen policy grows; when climate goals are low, and when the balance between climate, industrial policy, and energy security is amended, hydrogen policy changes.

It illustrates that while the EU maintains tight integration between climate and hydrogen policy, the US demonstrates that hydrogen incentives (which support certain 'types' of hydrogen) can persist even as climate commitments fluctuate.

VI. **The Effect of the ICJ Advisory Opinion: Significance for Hydrogen Policy**

On 23 July 2025, the International Court of Justice (ICJ) issued its Advisory Opinion on States' legal obligations in respect of climate change.[138] Although Advisory Opinions are not binding on States, they are authoritative statements from the United Nations' highest court and carry significant legal and political weight.[139]

In summary, the ICJ held that: (i) States have binding obligations to prevent significant environmental harm from climate change and to cooperate in good faith to address it; (ii) these duties arise not only from climate treaties (such as the United Nations Framework Convention on Climate Change (UNFCCC), Kyoto, the Paris Agreement) but also from customary international law and other branches (e.g. laws relating to the sea); (iii) climate obligations require "appropriate", "deep, rapid and sustained" measures aligned with the best available science; and (iv) violations can entail State responsibility, including reparations in certain circumstances.[140]

The Opinion also clarifies that climate treaties are not *lex specialis* that displace other primary rules of international law. In other words, treaty participation (or non-participation) does not exhaust a state's climate obligations. States remain bound by general duties, such as the no-harm rule, due diligence, and human rights, independently of for example, the Paris Agreement.[141] This is particularly notable in light of the US withdrawal from the Paris Agreement. The ICJ also held that the need to prevent significant transboundary harm under customary international law, are obligations *erga omnes*;

[138] *Obligations of States in Respect of Climate Change*. ICJ Advisory Opinion, 23 Jul. 2025.
[139] Bookman, Sam. "The International Court of Justice's Climate Opinion and What It Means for the U.S." *Emmett Environmental Law & Policy Review*, Sept. 2025; Sthoegher, Eran. "How Do States React to Advisory Opinions? Rejection, Implementation, and What Lies in Between." *American Journal of International Law Unbound,* vol. 117, 2023, pp. 292-297.
[140] "Defining State Obligations in a Warming World: The ICJ's Advisory Opinion on Climate Change." *Herbert Smith Freehills Kramer*, 21 Aug. 2025; "Climate: Historic ICJ Opinion on the Obligations of States," *UN Regional Information Centre for Western Europe*, 24 Jul. 2025.
[141] ICJ Advisory Opinion (n 138) *supra* [411]ff; Bookman (n 139) *supra*.

that is to say, they are duties owed to the entire international community.[142]

A. *Why This Matters for Hydrogen*

Hydrogen sits at the intersection of climate mitigation, energy security, and industrial policy. The ICJ's Opinion doesn't mention hydrogen directly, but it speaks to the legal environment in which hydrogen policy is designed and financed. If hydrogen is seen through a climate lens, then it is seen as constituting a decarbonisation pathway in order to reach net zero.

One of the ways that the Opinion may affect hydrogen is in relation to the 'type' of hydrogen which is bolstered in policy. The ICJ explicitly recognised that states must phase out fossil fuel dependency, stating that State failure "to take appropriate action to protect the climate system from GHG emissions—including through fossil fuel production, fossil fuel consumption, the granting of fossil fuel exploration licenses or the provision of fossil fuel subsidies—may constitute an internationally wrongful act".[143] This could create barriers for low-carbon hydrogen strategies that rely on SMR with carbon capture and storage (CCS),[144] given their continued dependence on fossil fuel feedstocks and associated upstream methane emissions.[145] However, it may also bolster other types of hydrogen which are not renewable such as hydrogen from nuclear energy. The Opinion's discussion of the "best available science" as a standard for evaluating climate measures could mean that nuclear hydrogen could gain regulatory advantages. This is because the SMR with CCS pathway remains structurally tied to fossil-fuel extraction, thereby exposing states to greater scrutiny when assessed against the ICJ's reasoning concerning fossil-fuel dependency. There are criticisms against SMR with CCS hydrogen in respect of methane leakage and assumptions regarding long-term CCS performance that remain technically and legally uncertain.[146] These factors may raise questions about whether hydrogen derived from natural gas with CCS can deliver the consistent and durable emissions reductions required under climate obligations. By contrast, hydrogen produced using nuclear electricity does not rely on fossil inputs and thus, avoids many of the related concerns.[147] Whilst not without criticism,[148] it may hold regulatory advantages in frameworks that place importance on certainty, and the avoidance of fossil-fuel lock-in.

Whilst only authoritative and not binding, States may feel pressure to give priority to hydrogen policies that reduce GHG emissions quickly and sustainably and avoid fossil fuels. This may have the effect of increasing regulatory scrutiny on low-carbon hydrogen routes while giving preference to production pathways that can be shown to meet strict lifecycle thresholds. Governments may want to show that their investments in hydrogen significantly contribute to the "deep, rapid, and sustained"[149] emissions mentioned by the ICJ. This climate lens may highlight the need to address upstream methane emissions in the low-carbon hydrogen value chain, increase carbon capture and storage where no other

[142] González, Fernanda, et al. "The ICJ Rules That Failing to Combat Climate Change Could Violate International Law." *WIRED,* 24 Jul. 2025.
[143] Schaugg, Lukas, et al. "Historic International Court of Justice Opinion Confirms States' Climate Obligations." *International Institute for Sustainable Development,* 28 Jul. 2025; ICJ Advisory Opinion (n 138) *supra* [427].
[144] Hydrogen produced through SMR without CCS is currently the most widely produced form of hydrogen, often called 'grey' hydrogen and is not in discussion here, although it would similarly be disadvantaged, probably to a larger degree.
[145] Khan, Muhammad Haider Ali, et al. "A Framework for Assessing Economics of Blue Hydrogen Production from Steam Methane Reforming Using Carbon Capture Storage & Utilisation." *International Journal of Hydrogen Energy,* vol. 46, no. 44, 2021, pp. 22685-22706.
[146] Howarth, Robert, and Mark Jacobson, "How Green Is Blue Hydrogen?" *Energy Science & Engineering*, vol. 9, 2021, p. 1676 at p. 1680; Maniscalco, Manfredi Picciotto, et al. "Critical Review of Life Cycle Assessment of Hydrogen Production Pathways." *Environments*, vol. 11, 2024, 108; Davids, Daniel, et al. "Impact of Methane Leakage Rate and Carbon Capture Rate on Blue Hydrogen Sustainability Using Combined Warming Index." *Applied Energy*, vol. 394, 2025, 125888.
[147] Maniscalco et al. (n 146) *supra*.
[148] Zamberi, Faziana Zarith Binti, et al. "High-Level Hazard Analysis for Pink Hydrogen Production." *International Journal of Green Energy*, vol. 1, 2025.
[149] ICJ Advisory Opinion (n 138) *supra* [282].

viable lower carbon option is available, and put in place reliable monitoring, reporting, and verification systems.

Another very important aspect of the Opinion is that treaty withdrawal does not allow States to avoid climate obligations. These duties are upheld by human rights frameworks and customary law, and they may be strengthened by additional legal frameworks such as trade law and domestic judicial interpretation of international standards. Thus, for example, a withdrawal from the Paris Agreement, as the US underwent, does not negate its climate obligations. Further, the US remains a party to the UNFCCC.[150]

The ICJ's Opinion may also strengthen the case for carbon border adjustments and certification requirements for hydrogen trade, as countries seek to ensure that imports meet the same stringent lifecycle standards required domestically under international law.

VII. **Conclusion**

The comparative analysis undertaken in this article suggests that binding or at least credibly anchored climate goals are an important catalyst for the renewable and low-carbon hydrogen market creation. A renewable-only hydrogen sector is unlikely to scale in the near term without those goals and low-carbon frameworks can contribute to climate objectives where they are paired with stringent lifecycle rules and guardrails. Absent these, such frameworks risk entrenching fossil-dependence.

Overall, this article reveals that hydrogen policy cannot be decoupled from climate policy, climate goals fundamentally define its trajectory, stringency, and purpose, although to differing extents in the EU and US. However, hydrogen development is heavily shaped by multiple overlapping forces such as geopolitics, internal politics, industrial competitiveness, and fiscal capacity.

EU-HB	Years of the Auction Results	Available Funding	Ceiling Price (Fixed Premium)	Eligible Hydrogen
The first auction – IF23 Hydrogen Auction	2024	EUR 800 million	4.5 EUR/kg	RFNBO
The second auction – IF24 Hydrogen Auction	2025	EUR 1.2 billion	4 EUR/kg	RFNBO
The third auction – IF25 Hydrogen Auction	2026	EUR 1.3 billion	4 EUR/kg	RFNBO and electrolytic low-carbon hydrogen

Table 1: The Auctions of the European Hydrogen Bank.

GHG emission requirements	PTC per kilogram of hydrogen in USD
2.5 to 4 $kgCO_2e/kgH_2$	0.60
1.5 to less than 2.5 $kgCO_2e/kgH_2$	0.75
0.45 to less than 1.5 $kgCO_2e/kgH_2$	1.00
Less than 0.45 $kgCO_2e/kgH_2$	3.00

Table 2: Credit Values under Section 45V of the IRA.

[150] "Parties to the United Nations Framework Convention on Climate Change." *UNFCCC Webpage*.

	Hydrogen Bank	***IRA-45V***
Form of Support	*Fixed premium*	*Tax credit*
Grounds for Providing Support	*Winners to the auction*	*All hydrogen producers complying with defined requirements*
Period of Support	*10 years*	*10 years*
Supported Hydrogen Types	*Renewable hydrogen and electrolytic low-carbon hydrogen*	*Clean hydrogen*
Emission Threshold	*3,4 kgCO_2e/kgH_2*	*4 kgCO_2e/kgH_2*
Boundaries for Emission Threshold	*Well-to-Wheel*	*Well-to Gate*
Fixed Premium	*4-4.5 EUR/kg*	*0.60-3 USD/kg*
Additionality / Incrementality	*Renewable energy capacity installed 3 years before the electrolyser.* *No public support for renewable installations.*	*Commissioning of generation capacity three years before the electrolyser.* *Eligibility of all power generation technologies emission measuring.*
Temporal Correlation	*Before 2030: monthly* *From 2030: hourly*	*Until 2028: annually* *From 2028: hourly*
Geographic Correlation	*Renewable electricity produced in the same bidding zone as electrolyser's location.*	*Electricity generated in the grouping of Balancing Authorities as electrolyser's location.*

Table 3: Comparison of Support Schemes for Hydrogen Production in the EU and the US.

EU–US COMPARATIVE HYDROGEN REGULATION AND CLIMATE GOALS AT A GLANCE (2019–2025)			
Date	**European Union**	**United States**	**Headline Analysis**
2019	**Climate:** 2019 UN Climate Summit, to meet net-zero carbon emissions targets by 2050. European Green Deal announced. European Council endorses the concept of being climate-neutral by 2050. **Hydrogen:** Mentions clean hydrogen as priority area in the European Green Deal.	**Climate:** The US did not confirm commitments under the 2019 UN Climate Summit. The US was in the process of withdrawing from the Paris Agreement. **Hydrogen**: No specific initiatives.	*The EU identifies climate goals to reach climate neutrality by 2050 and includes development of clean hydrogen sector for these purposes.* *The US was not a party to the Paris Agreement and did not have any notable specific initiatives for hydrogen sector at this period.*
2020	**Hydrogen:** EU Hydrogen and System Integration Strategy adopted.	No specific initiatives.	
2021	**Climate:** Climate Law sets legally binging climate neutrality target. 'Fit for 55' package. **Hydrogen**: 'Fit for 55' package.	**Climate:** The US rejoined the Paris Agreement. **Hydrogen:** IIJA becomes law. Creation of Regional Clean Hydrogen Hubs. Hydrogen Shot Initiative.	*EU sets the strategic frame for hydrogen and already signals a preference for renewable hydrogen, bolstered by the legally binding climate law target. US rejoints the Paris Agreement, and hydrogen hubs programme announced.*
2022	**Hydrogen**: Gas Supply Crisis. REPowerEU (10 Mt domestic + 10 Mt imports of renewable hydrogen by 2030).	**Hydrogen:** IRA with its S45V Credit announced. Clean Hydrogen Production Standard (CHPS).	*The EU pivots more prominently to energy security amidst the gas crisis and the US adds powerful fiscal signals with the IRA.*
2023	**Hydrogen**: RED III revision. Delegated Acts defining RFNBO rules. ReFuelEU Aviation. FuelEU Maritime.	**Hydrogen:** National Clean Hydrogen Strategy & Roadmap. Treasury proposes Section 45V three-pillar guidance. IIJA programs advance (H2Hubs selections / negotiations).	*Convergence of similar three pillar strategies.*

2024	**Hydrogen:** Hydrogen & Decarbonised Gas Market package adopted. Net-Zero Industry Act. EU-HB auction.	**Climate**: US NDC was made more stringent in 2024 by the Biden administration from 61% to a 66%.	
2025	**Climate**: The Competitive Compass published Clean Industrial Deal. CISAF (to 2030). Proposal of amendment Climate Law for 2040 90% net-zero GHG emissions target. **Hydrogen**: Low-Carbon Delegated Act. EU-HB third auction includes electrolytic low-carbon hydrogen.	**Climate**: Start of process to withdraw US from Paris Agreement. **Hydrogen**: Final S45V Credit rules. One Big Beautiful Bill Act (begin construction for 45V brought forward to 31 Dec 2027). Some clean-power credits narrowed; 45Q retained.	*Both jurisdictions seem to be converging on a more low-carbon friendly position; however, the EU remains renewable hydrogen focused.*

Table 4: Illustrative Comparative Table of EU and US Climate and Hydrogen Frameworks (Period 2019-2025

The Just Transition at the UNFCCC: Power and Discourse in COP Negotiations

Melissa Saoudy*

* MSt Candidate (Judge Business School), University of Cambridge, UK

KEYWORDS

climate governance, just transition, climate policy, climate narrative, sensemaking, narrative contestation, UNFCCC, Global South

ABSTRACT

The 'just transition' is a conceptually plural and politically contested term, yet UNFCCC decisions can stabilise which meanings travel as global policy precedent. This study examines how, under enduring power asymmetries, less-powerful actors contest dominant climate policy framings and secure institutional recognition for counter-narratives during COP negotiations and which interpretations become institutionalised in UNFCCC texts.

Drawing on organisational theory, the article integrates sensemaking with a critical discourse perspective to specify the mechanisms through which meaning shifts are produced in real time, through conflictual cycles of sensegiving and sensebreaking, the policing of what counts as 'within mandate', and the strategic mobilisation of discursive resources. Empirically, the analysis focuses on negotiations surrounding the Just Transition Work Programme (JTWP), using observation and critical discursive analysis of evolving negotiation texts.

The findings show how Global South coalitions advanced a justice-centred framing of just transition, linking it to equity, development priorities, and differentiated responsibilities, while more powerful actors sought to contain the concept within narrower, labour-centred and operationally limited formulations. The negotiated outcome institutionalised a more justice-oriented meaning in authoritative UNFCCC language while leaving implementation commitments constrained, illustrating how institutional traction can occur without integrated action.

The article contributes to climate governance scholarship by explaining how negotiated meanings are produced and stabilised under asymmetrical power, and to organisational theory by extending sensemaking and discursive strategy concepts to multilateral negotiation arenas where texts function as instruments of governance and power.

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I. **Introduction**

Climate governance scholarship has long shown that multilateral negotiations at UNFCCC COPs are structured by deep power asymmetries: developed countries command disproportionate financial resources, technical capacity, and institutional leverage, shaping agendas and acceptable outcomes.[1] Yet COPs are not only bargaining arenas. They are meaning-making institutions: their decisions, mandates, and work programmes stabilise categories that travel across ministries, development banks, civil society, and climate finance. This raises a basic puzzle: if structural constraints are so durable, how do less-powerful actors ever secure institutional traction for counter-framings inside formal UNFCCC negotiations?

This puzzle becomes particularly visible in the case of the 'just transition'. The term is widely invoked yet remains conceptually plural and politically loaded. As Wang and Lo show, 'just transition' circulates across multiple meanings, ranging from labour adjustment to broader frameworks of justice, making the term a site of persistent contestation rather than a settled policy concept.[2] At COP28, this contestation moved from diffuse debate into authoritative text: parties negotiated the Just Transition Work Programme (JTWP) and, in the process, shifted the UNFCCC's institutional recognition of the just transition (JT) away from a predominantly labour-centric framing anchored in ILO language toward a broader justice-oriented framing linked to equity, development, and poverty reduction.[3] Existing climate governance work recognises that narrative shifts occur but offers less clarity on the mechanisms through which less-powerful actors achieve such shifts under conditions of asymmetric power.[4]

This study approaches the UNFCCC as a site where discourse is not decorative but constitutive. The ability to define problems, authorise legitimate knowledge, and police what counts as 'realistic' or 'within mandate' is itself a form of power.[5] To make that power analytically tractable in live negotiations, the paper draws on organisational theory, specifically sensemaking and critical discourse perspectives, to examine how meaning is produced, contested, and stabilised under pressure. COP negotiations are settings of conflictual sensemaking: actors must move texts forward despite ambiguity, time compression, and incompatible interpretations. In such settings, sensegiving and sensebreaking become strategic practices through which actors attempt to stabilise preferred meanings and unsettle rival ones.[6]

Empirically, the paper analyses COP28 as a field-configuring event: a bounded, high-stakes institutional episode that concentrates actors, intensifies interaction, and produces authoritative texts with wider field effects.[7]

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[1] Ciplet, David, and J Timmons Roberts. "Climate Change and the Transition to Neoliberal Environmental Governance." *Global Environmental Change*, vol. 46, 2017, pp. 148-56; Bäckstrand, Karin, and Eva Lövbrand. "The Road to Paris: Contending Climate Governance Discourses in the Post-Copenhagen Era." *Journal of Environmental Policy & Planning*, vol. 21, no. 5, 2019, pp. 519-32.

[2] Wang, Xin, and Kevin Lo. "Just Transition: A Conceptual Review." *Energy Research & Social Science*, vol. 82, 2021, 102291.

[3] *Guidelines for a Just Transition Towards Environmentally Sustainable Economies and Societies for All*. International Labour Organization, 2015.

[4] Dryzek, John. *The Politics of the Earth: Environmental Discourses*. 3rd edn, Oxford University Press, 2013.

[5] Foucault, Michel. *Discipline and Punish: The Birth of the Prison*. Random House, 1975; Fairclough, Norman. *Critical Discourse Analysis: The Critical Study of Language*. 2nd edn, Routledge, 2010; Hajer, Maarten. *Authoritative Governance: Policy-Making in the Age of Mediatization*. Oxford University Press, 2012.

[6] Weick, Karl. *Sensemaking in Organizations*. Sage, 1995; Gioia, Dennis, and Kumar Chittipeddi. "Sensemaking and Sensegiving in Strategic Change Initiation." *Strategic Management Journal*, vol. 12, no. 6, 1991, pp. 433-48; Pratt, Michael. "The Good, the Bad, and the Ambivalent: Managing Identification Among Amway Distributors." *Administrative Science Quarterly*, vol. 45, no. 3, 2000, pp. 456-93; Schildt, Henri, et al. "Power in Sensemaking Processes." *Organization Studies*, vol. 41, no. 2, 2020, pp. 241-65; Vaara, Eero, and Andrea Whittle. "Common Sense, New Sense or Non-Sense? A Critical Discursive Perspective on Power in Collective Sensemaking." *Journal of Management Studies*, vol. 59, no. 3, 2022, pp. 755-81.

[7] Lampel, Joseph, and Alan Meyer. "Field-Configuring Events as Structuring Mechanisms: How Conferences, Ceremonies, and Trade Shows Constitute New

The study draws on observations of COP28 negotiations, interviews with negotiators and civil society actors across the Global North and South, and critical discursive analysis of negotiation texts and related materials across three interlinked discursive spaces: formal negotiation settings, civil society and advocacy arenas, and external communications. This approach reveals not only what was ultimately written into the JTWP, but how actors contested proposals in real time, how procedural openings became discursive resources, and how the same text could be interpreted simultaneously as 'victory' by different coalitions.

The analysis traces how the JT evolved through three negotiation phases. First, a labour-centric 'common-sense' framing, anchored in established institutional authorities, was treated as the default. Second, a justice-oriented 'new-sense' framing gained traction as developing countries and allies amplified alternative linkages (notably to sustainable development, differentiation, and poverty) and converted procedural opportunities into textual leverage. Third, the final JTWP outcome produced a 'split' settlement: justice-oriented meaning gained institutional recognition in authoritative language while implementation provisions remained constrained and largely non-binding. The compressed timeline matters: a framing that had held for years shifted in roughly one negotiation cycle, illustrating how COPs can function as unusually concentrated sites of rapid institutional meaning change.

This article addresses the foundational question: *how do less-powerful actors secure institutional traction for counter-framings in UNFCCC negotiations despite enduring power asymmetries?* By examining the mechanisms through which narrative contestation operates—through sensemaking processes, discursive strategies, and procedural leverage—this study illuminates how actors exercise consequential agency within asymmetrical structures. Using the Just Transition Work Programme as a revealing empirical case, it also shows which interpretation of 'just transition' gained institutional recognition at the UNFCCC and what that institutionalisation enables, even when implementation remains constrained. The findings have implications for climate governance scholarship on narrative and framing by explaining how meanings shift inside formal negotiations, not only that they do. It also contributes to organisational scholarship by extending critical sensemaking to multilateral governance, where text, procedure, and legitimacy are central resources in political struggle.

II. **Literature Review**

A. *Power Asymmetries and the Problem of Meaning in Climate Negotiations*

Climate governance research shows that multilateral negotiations are structured by power asymmetries: developed countries hold disproportionate influence through finance, technical capacity, agenda control, and institutional familiarity, while developing countries possess fewer material resources and less institutional leverage.[8] These asymmetries shape both priorities and problem definitions. Developed nations tend to emphasise emissions-reduction pathways compatible with market economies, whereas developing nations emphasise climate finance, adaptation, and differentiated responsibilities.[9] Unlike technical governance domains where actors might share a diagnosis and debate solutions, climate governance involves deeper disagreement over meaning: actors contest not only how to respond to climate change but which impacts count, what should be prioritised, and whose knowledge is treated as legitimate.[10] Yet while scholars

Technologies, Industries, and Markets." *Journal of Management Studies*, vol. 45, 2008, pp. 1025-35; Hardy, Cynthia, and Steve Maguire. "Discourse, Field-Configuring Events, and Change in Organizations and Institutional Fields: Narratives of DDT and the Stockholm Convention." *Academy of Management Journal*, vol. 53, no. 6, 2010, pp. 1365-92.

[8] Ciplet & Roberts (n 1) *supra*; Bäckstrand & Lövbrand (n 1) *supra* at 290-306.

[9] Ciplet & Roberts (n 1) *supra*.

[10] Dryzek (n 4) *supra*.

document power imbalances extensively, and increasingly examine discursive contestation,[11] they specify less clearly how specific discursive processes operate as mechanisms of power, particularly in enabling less-powerful actors to gain institutional traction despite structural constraints.

Climate governance outcomes depend partly on which narratives and frames secure institutional legitimacy, not merely on material interests. Hajer shows how "storylines", condensed narratives that render complex phenomena intelligible, structure climate policy debates.[12] Fisher demonstrates that framing shapes which solutions become institutionally legitimate; once a framing gains traction, it acquires path-dependent force as subsequent decisions reference it as precedent and further institutionalise it.[13] Vanhala and Hestbaek analyse frame contestation over Loss and Damage, showing how framing strategies shaped institutional outcomes.[14] Wang and Huan document indigenous peoples' discursive strategies in UNFCCC negotiations.[15] Yet much of this work, while demonstrating that narrative and framing struggles occur, does not fully explain why and how some narratives gain institutional traction while others fade. Given the distinctive power asymmetries of multilateral negotiations, the puzzle is not whether power matters or narratives matter; both demonstrably do. Rather, it is how less-powerful actors exercise limited leverage to reshape what becomes institutionally negotiable and legitimate, despite structural constraints, and what it means when alternative narratives are institutionalised in formal language while implementation remains constrained.

B. *Just Transition(s) and Power*

The JT is a particularly revealing concept through which to examine these dynamics because it is both widely invoked and persistently unsettled. Wang and Lo's review shows that the term proliferates across at least five distinct meanings, including labour-oriented protection, broader justice frameworks, governance strategy, and more.[16] They argue that the term has become so plural and ambiguous that "communication and debate have become difficult" and call for empirical, power-sensitive studies of how the terminology is used in practice and how different interpretations relate to underlying power structures.[17] Emerging work on just transition advocacy in the United States and Ireland shows that actors explicitly mobilise different definitions with an acute awareness of economic and political power, and that these framings are fluid and contested.[18]

The JT explicitly names equity and redistribution as core principles, making power contestation visible and unavoidable in negotiations. Consistent with Healy and Barry's characterisation of JT advocacy as a deeply political struggle, this paper does not adopt a single definition of the term.[19] Instead, it examines how meanings of 'JT' are negotiated, contested, and stabilised in UNFCCC discourse and texts, and how power

11 Calliari, Elisa, et al. "Making Sense of the Politics in the Climate Change Loss and Damage Debate." *Global Environmental Change*, vol. 64, 2020, 102133; Pascoe, Sophie, et al. "The Discourses of Climate Change Science: Scientific Reporting, Climate Negotiations and the Case of Papua New Guinea." *Global Environmental Change*, vol. 54, 2019, pp. 78-87.

12 Hajer (n 5) *supra*.

13 Fisher, Dana. "Understanding the Relationship between Subnational and National Climate Change Politics in the United States: Toward a Theory of Boomerang Federalism." *Environment and Planning C: Politics and Space*, vol. 35, no. 5, 2017, pp. 769-84.

14 Vanhala, Lisa, and Carsten Hestbaek. "Framing Climate Change Loss and Damage in UNFCCC Negotiations." *Global Environmental Politics*, vol. 16, 2016, pp. 111-129.

15 Wang, G, and C Huan. "Negotiating Climate Change in Public Discourse: Insights from Critical Discourse Studies." *Critical Discourse Studies*, vol. 21, no. 2, 2024, pp. 133-145.

16 Wang & Lo (n 2) *supra*.

17 ibid.

18 Cha, J, and Manuel Pastor. "Just Transition: Framing, Organizing, and Power-Building for Decarbonization." *Energy Research & Social Science*, vol. 90, 2022, 102588; Murphy, Susan et al. "Just Transition Frames: Recognition, Representation, and Distribution in Irish Beef Farming." *Journal of Rural Studies*, vol. 94, 2022, pp. 150-160.

19 Healy, N, and J Barry. "Politicizing Energy Justice and Energy System Transitions: Fossil Fuel Divestment and a 'Just Transition.'" *Energy Policy*, vol. 108, 2017, pp. 451-459.

asymmetries shape which interpretations gain institutional recognition. To specify these mechanisms, this article draws on organisational theory concepts that link discursive practice to institutional outcomes under conditions of asymmetrical power.

C. *Integrating Organisational Theory: A Critical Discursive Lens on Sensemaking to (Re)Produce Power*

A Critical Discourse Studies (CDS) perspective is a useful lens for analysing how language operates as a site of power in institutional contexts such as the UNFCCC. CDS treats language not as neutral, but as constitutive: shaping what is sayable, credible and institutionally possible, including what forms of knowledge are authorised and marginalised.[20] A key objective of CDS is to understand how actors construct both overt and covert power struggles and how they encode power in discourse. As the word "critical" implies, CDS examines the exercise of power, including power structures, exploitation, and other issues. This is particularly relevant in climate negotiations, where power is unequal, and legitimacy often hinges on which framings are treated as within mandate, and which are dismissed as political, expansive, or unrealistic.[21]

Consistent with CDS, this article adopts a dynamic understanding of 'power' as both systemic and episodic. Episodic power is actors' strategic interventions to steer, influence, or disrupt others in ways that stabilise or destabilise shared meanings. This is the most observable form of power in negotiation settings. Systemic power refers to the durable structural conditions that pre-structure what becomes sayable, hearable, and conceptually plausible.[22] Systemic power can have an ill-recognised or even invisible impact, producing taken-for-granted knowledge structures and collective identities that shape how actors interpret problems and solutions. It operates through discourse: the ability to define problems, authorise legitimate speakers, and naturalise certain categories while marginalising others.[23]

Systemic power operates at scale, sedimented in institutions and taken-for-granted categories, while episodic power is exercised through bounded interventions. Yet episodic discursive strategies can, under specific conditions, destabilise systemic power by rendering its assumptions visible and contestable. The question is not whether less-powerful actors can "overcome" systemic power, which would require material resources and institutional authority they demonstrably lack. Rather, it is how they operate within systemic constraints and whether they deploy episodic discursive power to shift institutional meaning in ways that expand what is treated as negotiable and what subsequently claims legitimacy.

To make these processes observable in negotiation practice, the article integrates sensemaking scholarship. Sensemaking refers to the social process through which actors create coherence in ambiguous or contested situations, enabling coordinated action despite uncertainty.[24] Conflict and contradiction often trigger sensemaking because actors must reconcile competing interpretations to move forward.[25] These concepts are useful for climate negotiations because they make the mechanisms of meaning-making observable rather than assumed. In multilateral negotiations, conflict is not incidental: it is produced by competing mandates, time pressure, and contested responsibilities. Under these conditions, actors do not simply state preferences; they work to make particular interpretations appear reasonable, urgent, and legitimate.

[20] Fairclough (n 5) *supra*; Wodak, Ruth, and Michael Meyer. *Methods of Critical Discourse Analysis*. 2nd edn, Sage, 2009.
[21] Fisher (n 13) *supra*.
[22] Foucault (n 5) *supra*; Schildt et al. (n 6) *supra*.
[23] Fairclough (n 5) *supra*.
[24] Weick (n 6) *supra*; Maitlis, Sally. "The Social Processes of Organizational Sensemaking." *Academy of Management Journal,* vol. 48, no. 1, 2005, pp. 21-49.
[25] Weick (n 6) *supra*.

Sensemaking scholarship also distinguishes between interpretation and strategic efforts to shape interpretation. *Sensegiving* refers to deliberate attempts to influence how others understand an issue by framing problems, proposing interpretations, and legitimising certain courses of action.[26] *Sensebreaking* refers to efforts to unsettle, delegitimise, or disrupt established understandings, often to create space for an alternative interpretation to take hold.[27] In negotiation settings, these processes are central because actors contest not only outcomes but the meaning of key policy concepts. These two concepts specify how actors can exercise episodic power through discursive moves that shape what becomes reasonable, urgent, and legitimate.

Vaara and Whittle extend this line of thinking and adopt a CDS perspective to theorise that discursive conflict may result in three distinct outcomes: common-sense, where an interpretation becomes taken for granted and reproduces existing power relations; non-sense, where alternative interpretations are dismissed as illegitimate or implausible; and new-sense, where a previously taken-for-granted framing is challenged and a counter-interpretation gains sufficient legitimacy to reshape what is considered reasonable and negotiable.[28] Crucially, the authors specify discursive strategies, or the observable choices of framing, wording, narrative devices, and genre, as the means through which actors attempt to legitimise preferred interpretations and delegitimise challengers. In the UNFCCC context, which relies heavily on negotiation texts and practices, this perspective makes narrative power analytically tractable: it links institutional shifts in negotiated meaning to the strategic, observable discursive moves through which actors, including those with less power, contest and stabilise interpretations.

D. *Field-Configuring Events: The UNFCCC COP as a Site of Concentrated Meaning-Making*

This article examines the UNFCCC's COP, which convenes a wide array of stakeholders in an arena of struggle over the field of climate change and how to address it, as a 'field-configuring event'.[29] Field-configuring events or FCEs create unique conditions for rapid field reconfiguration through the proliferation of competing discourses in which texts are used as 'weapons'.[30] These conditions include temporal-boundedness, spatial density, and the ability to convey procedural authority.[31] Through their unique qualities, field-configuring events compress sensemaking processes into a bounded timeframe with high stakes and visibility, making discursive strategies observable and traceable.

Hardy and Maguire demonstrate that field-configuring events enable narrative contestation to drive institutional change.[32] Through their analysis of another UN conference, the Stockholm Convention on DDT, they show how narratives evolved from "evil pesticide" to "necessary tool" to "necessary evil" as different coalitions mobilised competing interpretations. Critically, they show that less-powerful actors can influence field reconfiguration through narrative contestation rather than material power. Building on this insight, the contribution here is to specify how narrative traction is achieved under asymmetric power inside the COP, by linking discursive strategies to conflictual sensemaking in live negotiations.

III. **Research Questions**

Multilateral climate negotiations are structured by material and institutional power asymmetries, but they are also sites where institutional meanings are made. COP decisions, mandates, and work programmes do more than record compromise: they

[26] Gioia & Chittipeddi (n 6) *supra*.
[27] Pratt (n 6) *supra*; Schildt et al. (n 6) *supra*.
[28] Vaara & Whittle (n 6) *supra*.
[29] Lampel & Meyer (n 7) *supra*.
[30] Chalaby, Jean. "Twenty Years of Contrast: The French and British Press During the Inter-war Period." *European Journal of Sociology*, vol. 37, no. 1, 1996, pp. 143-159; Hardy & Maguire (n 7) *supra*.
[31] Lampel & Meyer (n 7) *supra*; Chalaby (n 30) *supra*; Hardy & Maguire (n 7) *supra*.
[32] Hardy & Maguire (n 7) *supra*.

stabilise categories and interpretations that become globally referenced in policy and finance. Many climate policy concepts are contested at the level of meaning, and power shapes which interpretations are treated as plausible, 'within mandate', and fit for institutionalisation.

A. *How Do Less Powerful Actors Secure Institutional Traction for Counter-Framings in UNFCCC Negotiations Despite Enduring Power Asymmetries?*
A purely material account of power explains unequal leverage, but it does not fully explain how contested meanings shift inside negotiation practice, or how less powerful actors sometimes secure institutional recognition for counter-framings despite structural constraints. To specify that 'how', this paper draws on organisational theory, specifically sensemaking, because it provides a mechanism-level account of meaning-making under ambiguity and conflict.

In negotiation rooms, actors must create enough shared coherence to move text forward under time pressure, while simultaneously contesting what key terms should mean. In this process, less-powerful actors can exercise episodic discursive power through observable practices such as sensegiving (advancing an interpretation), sensebreaking (disrupting or delegitimising a rival interpretation), and other discursive strategies (framing choices, wording, legitimacy claims) that affect what becomes negotiable and what enters authoritative text.

Integrating this sensemaking lens with a critical discourse perspective also keeps power in view: systemic power pre-structures what is sayable and credible, while episodic interventions contest and sometimes reshape those boundaries in real time. In FCE settings such as the COP, these processes are accelerated, intensified, and uniquely observable.

B. *In the Just Transition Work Programme Negotiations, How Did Actors Mobilise Competing Meanings of 'Just Transition' and What Meaning Became Institutionalised in UNFCCC Texts?*
The inaugural JTWP negotiations at COP28 provide a revealing site for examining institutional traction because it was the first time 'just transition' was negotiated as the basis for a dedicated UNFCCC work programme. It concentrates plural interpretations within a bounded decision-making process in which language is contested line by line, and outcomes can stabilise "what counts" as a legitimate meaning going forward. Analysing the JTWP, therefore, allows the study to specify not only *whether* narrative shifts occur, but *how* they are produced in real time through procedural leverage, sensegiving / sensebreaking, and mandate policing, and how those dynamics shape what becomes institutionalised.

The findings Section returns to these questions by tracing how meaning moved across sensemaking phases and reveals how these phases map to the institutionalisation of specific meanings in the final decision text.

IV. **Methods**

This study concerns the UNFCCC with a particular focus on COP28 held in 2023. The COP is the UNFCCC's supreme decision-making body and meets every year, making it a significant FCE where diverse stakeholders holding different levels of power, including nations, non-governmental organisations, and private sector representatives, gather to debate, shape, and decide on global policy. It is not just a negotiation platform but also hosts vibrant side-events where discourses are contested and redefined, making it an ideal site for examining the dynamics of climate narratives, power and discourse.

Although the concept of the just transition had appeared in previous UNFCCC documents, COP28 marked the first formal negotiation of the Just Transition *Work Program* (JTWP). The Program was announced the year before at COP27 by the Egyptian Presidency, with the stated focus to address the justice and socio-economic considerations of transitions to low-carbon economies. Being that it was a new

dedicated program, the JTWP provided a unique opportunity to study the conduct of actors to advocate for their perspectives and a unique opportunity to pay special focus to the discursive strategies deployed by less-powerful actors in shaping it in real time. By the end of COP28, the first JTWP decision was issued, codifying into text.

COP28 and the JTWP were selected for their representativeness and for the availability of primary texts and public records. This single, exploratory case study enables a detailed, holistic understanding of how climate governance narratives and negotiation dynamics are constructed and contested in multilateral policy settings.[33]

A. *Case Study*

The term 'just transition' initially emerged from the United States labour movement in the late 1980s, challenging the divisive rhetoric of 'jobs vs environment' and advocating for an approach that safeguards both environmental integrity and workers' rights.[34] Since then, the concept has evolved significantly, capturing the attention of scholars and inter-governmental organisations. There is no widely accepted just transition definition, with interpretations ranging from labour-oriented frameworks to broader, radical socio-technical transitions.[35] The United Nations Development Programme (UNDP), for example, relays an International Labour Organization (ILO) definition of just transition in largely workforce-centric terms as "greening the economy in a way that is as fair and inclusive as possible to everyone concerned, creating decent work opportunities and leaving no one behind".[36] In contrast, the Intergovernmental Panel on Climate Change (IPCC) adopts a broader framing, defining it as "a set of principles, processes and practices that aim to ensure that no people, workers, places, sectors, countries or regions are left behind in the transition from a high-carbon to a low-carbon economy".[37] A just transition ultimately aims to address the adverse effects of transitioning away from an emissions-dependent economy; however, which adverse effects are given priority depends on which definition of just transition is adopted.

The concept of just transition first received formal recognition in the international climate agenda at COP16 in Cancún (2010), where it was explicitly framed around workforce protection, decent work, and quality jobs. **Table 1**, below, outlines the development of just transition within the UNFCCC framework from 2010 to 2023, illustrating how the term evolved from a labour-centric focus to a broader mandate encompassing energy, socioeconomic dimensions, sustainable development, and poverty eradication.

In 2022, Egypt, as COP27 President, introduced the establishment of the Just Transition Work Programme (JTWP) in its cover decision, a Presidency-led initiative that signalled the prioritisation of just transition within the UNFCCC agenda. Notably, previous UNFCCC decisions had not addressed the potential for a dedicated work programme on just transition.

The COP27 Presidency, however, hailed the JTWP as a major highlight.[38] Parties subsequently engaged in formal negotiations at COP28 in 2023 to develop the operational scope and framework for the JTWP. An initial draft text circulated by the UNFCCC Secretariat was met with reservations, particularly from the G77 and China negotiating group of 134 Parties, who advocated for a comprehensive reflection of developing country perspectives. Subsequent draft texts evolved throughout the negotiating sessions, each iteration seeking to reconcile

[33] Yin, Robert. *Case Study Research: Design and Methods*. 3rd edn, Sage Publications, 2003.
[34] Wooding, Bill, et al. *Just Transition: A Fair Path to a Green Economy.* Labor Network for Sustainability, 1997.
[35] Wang & Lo (n 2) *supra*.
[36] "What Is Just Transition? And Why Is It Important?" *United Nations Development Programme,* 2022.
[37] IPCC. *Climate Change 2022: Impacts, Adaptation and Vulnerability (AR6 WGII)*. Cambridge University Press, 2022.
[38] "COP27 Debrief: Milestones for Climate-Resilient Development in Sharm El Sheikh." *United Nations Conference on Trade and Development*, 2023.

developed and developing country priorities and concerns. Key areas of contention included the needs of developing countries and mechanisms for international cooperation. The negotiation process culminated with Parties adopting a final decision text at COP28 that established the consensus framework to guide JTWP implementation.

B. *Data Collection*

Data collection encompassed multiple qualitative data sources across two phases. The first phase occurred at COP28, held from November 30 to December 12, 2023, and comprised of 168 hours of participant observation conducted by the author. This observation involved attending negotiation sessions, side-events, and informal gatherings, documenting these interactions yielded 192 photographs and videos. Field notes totalling 84 pages were compiled using thick description, capturing detailed observations of daily activities, conversations, and formal and informal interactions.[39] Some documentary evidence included field notes and reports from other researchers observing JTWP negotiations as published on the RINGO website; these external sources were treated as supplementary documents and analysed separately from the author's primary ethnographic fieldnotes and interviews.

Participant observation was particularly valuable for accessing an informal cross-constituency just transition working group, labelled by participating observers as the 'people's platform'. This group included representatives from five of the nine observer constituencies: Environmental NGOs (ENGOs), Women and Gender (WGC), Research (RINGO), Youth (YOUNGO), and Trade Unions (TUNGO). Engagement with this working group provided access to diverse perspectives on just transition and insights into how less powerful actors organised and mobilised within the multilateral negotiation space.

In the second phase, 24 semi-structured interviews were conducted with participants representing eight UNFCCC constituencies, international governmental organisations, and representatives from countries in the Global South and North. The 24 interviews, purposively sampled to ensure representation across eight UNFCCC constituencies and Global North / South positioning (see **Table 3**), provided saturation on key discursive strategies and narrative contestations. This sample, when triangulated with 168 hours of ethnographic observation and 20+ documents, ensured robust data for understanding diverse perspectives of narrative evolution and contestation. Interviews lasted 45-90 minutes, were recorded and transcribed for accuracy, and employed a guide revised post-COP28 to reflect emergent themes from the conference. Participants were sampled through initial convenience sampling facilitated by the working group, followed by snowball sampling as participants referred others, and subsequently more purposively to ensure representation of diverse viewpoints on just transition. [40] All interviews were conducted virtually with conditions ensuring confidentiality and informed consent

Document collection included 22 UNFCCC documents, plus 9 supplementary documents focused on tracing the discursive evolution of just transition within the UNFCCC. Sources included historical UNFCCC decisions referencing just transition from 2010 to 2022, submissions from Parties and observers on the UNFCCC's JTWP portal from May to June 2023, all evolving JTWP decision documents issued between December 2 and December 13, 2023, and the final JTWP decision document adopted at COP28. Additionally, RINGO COP28 notes and official COP28 program materials mentioning 'justice' or 'just transition' were

[39] Geertz, Clifford. "Thick Description: Toward an Interpretive Theory of Culture." *The Interpretation of Cultures: Selected Essays*. Basic Books, 1973, pp. 3-30.

[40] Emerson, Robert. "Convenience Sampling, Random Sampling, and Snowball Sampling: How Does Sampling Affect the Validity of Research?" *Journal of Visual Impairment & Blindness*, vol. 109, no. 2, 2015, pp. 164-168; Parker, Charlie, et al. "Snowball Sampling." *Handbook of Qualitative Research Methods*, edited by Norman Denzin and Yvonna Lincoln, Sage, 2017.

included to contextualise how observers engaged with discourse from the sidelines. Supplementary documents such as the ILO Guidelines on just transition and the IPCC Report, 2022, provided institutional context for understanding competing framings of just transition in the negotiation space.

C. *Data Analysis*

An abductive analytical approach was employed to iteratively align emerging findings with established theories, thereby enhancing the study's capacity to offer theoretical insight into how power, discourse, and sensemaking operate within multilateral climate negotiations.[41] The analysis adopted a discursive analytical perspective informed by Hardy and Maguire, who observe emerging fields across multiple field-configuring events to highlight how discourse evolves temporally.[42] This perspective was enriched by CDS, which emphasises how power relations are embedded in discourse. This framework enabled analysis to focus on concrete acts of talking and writing as sites of power struggle,[43] particularly illuminating how actors with varying structural power mobilised language and narrative to contest meanings around just transition at COP28.

In the first phase of analysis, field notes and interviews were classified according to several salient criteria: participant experience level with COPs, constituency affiliation, and geographic positioning (Global North / South). Open coding generated preliminary codes that were iteratively refined through ongoing engagement with field data. Codes such as "no justice without finance", "the JTWP is the home for justice", and "an arms race for narratives" were validated through iterative comparison with field observations and interview transcripts, ensuring alignment between actor statements and documented actions. The three epistemic phases (common-sense, new-sense, split-sense) emerged inductively from the chronological organisation of discourse evolution, reflecting the temporal arc of how narratives shifted across the case.

In the second phase, a discursive event history database was constructed from collated documents,[44] cataloguing events, submissions, and strategic actions associated with the JTWP and just transition more broadly. This chronological narrative of discourse evolution enabled temporal analysis of how framing shifted across the negotiation process.

In the third phase, three primary discursive spaces were identified as sites of distinct text production and consumption. The *Negotiation Space* is the most formal and decisive space, primarily shaped by the Parties' actions. It involves written and spoken texts, where draft and binding decisions emerge. Parties are the main decision-makers, and Observers have limited opportunities to speak. The *Advocacy Space* is characterised by diverse and opinionated contributions from Observers who aim to influence negotiations through various channels. This space includes formal side-events, protests, press conferences, and informal policy discussions that aim to shape negotiation outcomes. The *External Communications Space* encompasses discussions about the JT outside the UNFCCC framework. This covers a wide range of scientific papers, media accounts and much more. Texts produced and consumed here can influence internal UNFCCC discourse. This spatial framework enabled analysis of how different actors mobilised distinct discursive strategies across venues.

In the fourth phase, narrative analysis was conducted on texts within the discursive event history database using grounded theory principles. Texts were coded using Atlas.TI and thematically clustered via Miro to map relationships visually. The dual episodic

[41] Gustafsson, Karl Erik, and Linus Hagström. "What Is the Point? Teaching Graduate Students How to Construct Political Science Research Puzzles." *European Political Science*, vol. 17, no. 4, 2018, pp. 634-648.
[42] Hardy & Maguire (n 7) *supra*.
[43] Fairclough (n 5) *supra*; Wodak & Meyer (n 20) *supra*.
[44] Maguire, Steve. "The Co-evolution of Technology and Discourse: A Study of Substitution Processes for the Insecticide DDT." *Organization Studies*, vol. 25, no. 1, 2004, pp. 113-134.

power processes of sensegiving and sensebreaking were employed to identify how narratives functioned as key discursive strategies.[45] Drawing on Vaara and Whittle, narrative evolution was framed within the concepts of 'common-sense' (established framings) and 'new-sense' (alternative framings), revealing a critical finding termed 'split-sense', indicating simultaneous contestation and co-existence of competing sensemaking regimes.[46] *Discursive practices*, the concrete acts of speaking, writing, and framing through which actors construct meaning, were identified as the foundational level from which specific *discursive strategies* emerged.

In the fifth phase, distinct discursive strategies employed by differently positioned actors were identified through examination of evolving and final COP28 decision texts and detailed field notes from actual negotiations. Discursive strategies associated with protecting dominant narratives were contrasted with strategies employed by less-powerful actors advocating for alternative framings. For example, "present the alternative as impossible" was evident in actors protecting the dominant narrative, while "evoke symbolic and emotional rhetoric" was evident in less powerful actors. Considering the article's analytical focus, more attention was paid to the discursive activities of less powerful actors advocating for 'new-sense', depicting those in greater detail. The resulting analytical framework, illustrated in **Figure 1** below, maps the relationship between discursive practices (foundational level), sensemaking processes (sensegiving or sensebreaking), discursive strategies (how actors deploy practices), and sensemaking outcomes across three epistemic phases.

This multi-phase analytical approach yielded insights into how differently positioned actors engage in discursive contestation at field-configuring events and the resulting implications for field-level outcomes. The findings elucidate the critical interplay of sensemaking, power, and discourse in shaping emergent climate governance narratives.

V. **Findings**

This Section presents findings organised chronologically across three epistemic phases: common-sense, new-sense, and split-sense. For each phase, the analysis first describes the foundational sensegiving or sensebreaking narrative—its core goals, underlying beliefs, and associated action plans—before examining the discursive practices and strategies through which actors reinforced or contested these narratives. This structure mirrors the analytical framework outlined in the methods Section, moving from narratives to the specific discursive strategies actors deployed to institutionalise competing meanings. Specific discursive practices from **Figure 1** are capitalised and italicised for traceability.

A. *Common-Sense: Pragmatic Workforce Transitions (2015 to 2022)*

1. Sensegiving Narrative of Common-Sense

During this phase, developed countries, the International Labour Organization (ILO), and key UNFCCC Observer groups (Trade Unions and Businesses) advanced a JT narrative focused on economic stability and labour rights. The central goal was to support displaced workers and maintain economic stability as economies decarbonised, drawing authority from the ILO's 2013–2015 Guidelines. This labour-focused narrative was legitimised through the External Communication space, positioning JT as an applied framework to balance environmental and economic imperatives. One participant reflected the entrenchment of this view, humorously noting:

> *"Until COP28, I wasn't even aware that the JT could be anything else but a response to the jobs versus environment problem."* (IGO1)

At this stage, the JTWP did not yet exist, and the narrative did not propose a clear action

[45] Pratt (n 6) supra

[46] Vaara and Whittle (n 6) supra.

path beyond applying existing frameworks to the UNFCCC.

By aligning closely with established labour frameworks and avoiding broader socio-economic disruptions, the narrative presented the JT as a conservative yet essential response to the immediate challenges posed by climate policies. Notably, study participants had varying power levels; however, even those with limited power contributed to (re)producing the dominant discourse. Having described the narrative, the study will now demonstrate how actors deployed discursive strategies to sensegive.

(α) Institutionalising Common-Sense

During this phase, proponents of the common-sense frequently *invoked historical legacy to assert dominance*, anchoring their discourse in historical legitimacy. They emphasised JT's deep roots in United States labour movements (TUNGO1). Consistent deference to the ILO further emphasised this historical grounding, with participants urging deep engagement with its guidelines (IGO2).

Participants frequently highlighted their historical ownership: "the JT had always been a niche for the Trade Unions" (TUNGO1), and "the ILO's role at the UNFCCC has always been to advise on labour issues." This invocation of legacy positioned the JT as a continuation of an established tradition.

Strategic advocacy and formal declarations marked efforts to *enforce and institutionalise norms*. Trade Union representatives highlighted their role in integrating JT into the Paris Agreement, marking it a milestone for labour advocacy (TUNGO1). They further contributed to the 2021 JT Declaration at COP26 in Glasgow, where developed countries, the ILO, and Trade Unions collaboratively drafted a voluntary declaration enshrining the labour-oriented definitions of JT under the ILO guidelines. Thirty developed countries signed the Declaration, which Trade Unions celebrated as a significant victory for the labour-oriented narrative in climate discourse (TUNGO1).

This narrative was reinforced by efforts to control and sideline alternative interpretations by emphasising the ILO's authority as the legitimate source on JT. One participant highlighted a deliberate attempt to "make sure that the discussions that are happening in UNFCCC are grounded in the ILO guidelines and don't stray too far from that" (IGO2).

These discursive strategies not only established a historical and institutional legacy for the JT as defined by labour interests but also positioned developed nations and traditional labour organisations as its primary custodians and beneficiaries. The major milestones of the JT at COP24 (Paris Agreement) and COP26 (JT Declaration) occurred in developed countries, further institutionalising this leading role. These strategies' coherence and repeated reinforcement demonstrated a powerful alignment of historical legacy with institutional authority, centring the JT on labour issues often faced by developed countries while marginalising broader interpretations that could challenge its boundaries.

The sensebreaking narrative that followed contested these boundaries, as described in the next subsection.

2. Sensebreaking of Common-Sense

During the same period, less-powerful actors, including developing countries and various UNFCCC Observer constituencies like environmental NGOs (ENGO), women and gender (WGC), and youth (YOUNGO), challenged the prevailing labour-centric narrative of the JT. They criticised this narrative as overly prescriptive, arguing it perpetuated development gaps and exacerbated vulnerabilities.

The sensebreaking narrative's central goal was to challenge and redefine the JT at the UNFCCC, proposing a broader interpretation that integrated broader social impacts and international dimensions often overlooked by the dominant discourse. As one developing

country diplomat noted, "the JT at the UNFCCC … it's become hostage [sic]. We wanted to change the *narrative*" (PARTY2).

The narrative's specific observations and beliefs underscored the SDGs as a framework that could guide a more inclusive and equitable approach. Less powerful actors argued that the existing narrative marginalised factors critical to achieving genuine sustainability and equity in the developing world. Supporting this, another participant remarked that "the original just transition … didn't capture the colonial logic of that system and isn't applicable to developing countries" (ENGO2). The launch of the JTWP at COP27 marked a concrete action, opening the scope for all countries to negotiate implementation.

The sensegiving narrative aimed to denaturalise common-sense discourse towards a more inclusive and comprehensive framework that did not merely react to environmental imperatives but proactively considered the diverse needs of global stakeholders. This push for redefinition set the stage for a dynamic interplay of competing narratives within the UNFCCC.

(α) Challenge, Expose and Reframe

During this phase, less powerful actors *advocated for broadening the discourse*. They described the prevailing JT narrative at the UNFCCC as outdated and exclusionary, pointing to more inclusive interpretations of the concept by international bodies, academics, and civil society that had gained traction over recent years (ENGO13, IGO3, YOUNGO1). As one participant said, "the JT is stuck in a time warp" (PARTY2). Participants often spoke of JT(s) plural, noting that the 's' indicated its breadth and diversity (ENGO2, WGC2). Most participants were well aware of the JT's labour origins; however, they noted that the JT had evolved considerably to highlight broader concerns (ENGO3). These actors would often speak of the JT through their own lens, for example, "gender-just transition" (WGC1), and advocate for it through different discursive external to the UNFCCC by issuing papers and in the COP Advocacy Space through side-events and sometimes protests.

Activist participants shared novel ways of *communicating broader systemic injustices* using short phrases such as climate colonialism and extractive capitalism (ENGO5, IGO3, WGC2). The lack of financial support for climate action in developing countries was also frequently highlighted, with one advocate stating "there is no justice without finance" (ENGO3). Several participants referred to the negative impact of green transition costs on vulnerable groups: "the JT … it's the triple injustice, you know" (WGC1).

For some participants, the dominant JT discourse was an example of how institutionalised systemic injustices had become. A Global South negotiator highlighted this broader context and its impact on the JT, stating:

> *"This [climate change] is a field dominated by a few countries telling you what is sustainable, what JTs are, how to do it, where you must get your money … it's all being prescribed."* (PARTY2)

Participants from developing nations, in particular, highlighted the local disconnect between the dominant JT narrative and local realities. Many faced domestic resistance when aligning with global climate strategies deeply rooted in economic and social challenges. An environmental activist from the Global South expressed her struggle vividly: "how can I tell the miners, no, don't mine, don't feed your families? They see me as unjust!" (P1).

Further, as one participant clarified, the pushback was even more significant at the national policy level for developing countries, who struggled to get 'buy-in' without 'justice': "It's very fragile, you know? Development is a human right, the right of every country" (PARTY2).

With climate targets becoming more ambitious and the labour-oriented JT signed into Declaration in 2021, sensebreaking discourse was getting louder. This growing discontent highlighted that common-sense was increasingly seen as inadequate, creating a vacuum and intensifying the need for sensebreaking within the UNFCCC and the broader climate discourse.

(β) Establish New Discursive Opportunities

Egypt, a developing country, assumed the COP27 Presidency, a role that positioned it uniquely to leverage procedural authority while representing less powerful actors' interests. From this position, their goal was to open up a new discursive space that had not been there before. They wanted to, in one participant's words, "change the narrative" (PARTY2). In a move unexpected to other participants, Egypt strategically introduced UNFCCC language in a way that forced more-powerful actors to negotiate on the issues. By the end, they had created a new negotiation: the JTWP.

Egypt focused this effort on the COP27 cover page. Presidencies can introduce new language on their cover page without the usual negotiation, in which they *leveraged a discursive opening*. As one participant highlighted:

> *"It's very rare to create a new negotiation at the UNFCCC … But Egypt had the pen there … The only way you can do it is the way that Egypt did it. It is just an opening thing."* (PARTY2)

Egypt specifically included language on just transition, noting that the low-carbon transition creates "opportunities and challenges for sustainable economic development and poverty eradication" in developing countries.[47] By putting this into text, Egypt *institutionalised the discourse shift*, reframing just transition from ILO labour standards to Sustainable Development Goal (SDG) equity language.[48]

Egypt initiated the establishment of the JTWP to commence the following year at COP28, creating new opportunities for less powerful actors to bring justice discourse into the negotiation room, laying the groundwork for less-powerful actors to sensegive for new-sense.

The negotiation room is the most formal and decisive discursive space in the UNFCCC, where countries are the primary sensegivers. Therefore, this new-sense subsection will outline the discursive strategies of developing and developed Parties, which comprise less powerful and more powerful actors respectively.

B. *New-Sense: An Integrated Framework for Justice (2022 to 2023)*

1. Sensegiving of New-Sense

This phase marks a significant shift towards a broader, more justice-focused narrative within the JT discourse at the UNFCCC. A coalition of less-powerful actors, led by the G77, representing developing countries and 80% of the global population,[49] advanced this narrative. The central goal of this narrative was to redefine the JT as a framework that corrects historical injustices and fosters a more equitable approach to climate action. The narrative was notably broad; as one participant highlighted, "it has to be broad. JTs are for everyone" (PARTY1).

The sensegiving narrative was underpinned by specific observations and beliefs, such as widening development gaps and the need to address issues such as poverty and inequality. It focused on addressing these development issues, anchored in the SDGs for "social, economic, and environmental" impacts and principles like equity and CBDR (D4).

[47] United Nations Framework Convention on Climate Change. *Sharm el-Sheikh Implementation Plan*. Decision 1/CP.27, 2022, [28].

[48] "The 17 Goals." *United Nations Department of Economic and Social Affairs*, 2023.

[49] "About the Group of 77." *Group of 77 at the United Nations*, 2024.

Less powerful actors advocated for a clear action path centred on the JTWP, envisioned as a comprehensive platform to operationalise just decarbonisation efforts across all sectors of the global economy, with an indefinite timeline and substantial financial and technical support.

This broader interpretation departed from dominant discourse and introduced a new-sense to redefine the global approach to JT, celebrated by vocal expressions of "excitement" by G77 countries in the negotiation room and for its strategic value: "this (the JTWP) is quite a good place to land the system change narrative" (ENGO5).

(α) Mobilising for New-Sense

Before COP28, the G77 convened to *propose an inclusive new narrative*, submitting an official document to the UNFCCC. The submission reframed the problem, highlighting a "multidimensional crisis" of poverty, hunger, malnutrition, and energy security. They stressed that "the fight against climate change is inseparable from the fight against inequality," pointing out issues with the international economic system and calling for collaborative efforts to address these challenges within the SDG framework of "leaving no one behind".

They proposed the JTWP as the solution:

> *"The objective of establishing JTWP is an opportunity to promote JTs that are sustainable, affordable, and inclusive … enhancing international cooperation towards securing transitions to low-emissions and inclusive climate-resilient future that contribute to reducing inequalities, both within and among countries."* (D4)

The JTWP negotiations at COP28 were dynamic and contentious, with the UNFCCC's draft texts being revised daily.

In the negotiation room, the G77 *amplified their collective voice and action*, stating: "when you have 132 parties giving a united position… you have to listen". They stressed internal consultation and coordination, sometimes delaying their feedback to ensure unity, as Liberia expressed: "we may need one more day to consult now so that we save years into the future". The G77 countries also employed strategic silence and refused to provide their views on draft texts that did not reflect their perspectives; their representative said:

> *"We don't see our views reflected in the draft text; it doesn't reflect the massive excitement in the room … we cannot engage with this text."*

These tactics aimed to use their size as influence to force a revaluation of the drafts.

(β) Emotional and Symbolic Discourse

Some countries attempted to *reframe the JTWP as a new symbolic discursive space* where they could voice complex justice issues. Brazil stated:

> "This [the JTWP] should be the locus for talking about inequality and injustice … We are throwing in the dustbin a once-in-a-lifetime opportunity of creating a place where we can openly discuss *everything* that impacts justice."

Liberia echoed this, stating that "justice is what makes the JTWP different", indicating that the JTWP was unlike other negotiation spaces at the UNFCCC and had unique symbolic qualities.

The G77 nations *made emotional appeals* in the negotiation to humanise the debates and stress the moral and ethical implications of justice. For example, Brazil stated:

> *"I remind you all that the feeling of injustice is one of the most primitive feelings we*

> *learn as young toddlers. We learn that we cannot go ahead with injustice."*

Developing countries frequently used terms like "injustice" and "justice for all", labelling JTWP draft text favouring developed countries as "unjust". Some argued that engaging with the draft text, which did not reflect their views, would also be unjust.

G77 countries *imported external discourses* from global social movements, using terms like 'climate justice'. Brazil invoked the Occupy Wall Street movement's 1% terminology, defined in the External Communication Space, linking climate justice to broader economic inequalities.

The efforts of the G77 countries culminated in a significant revision of the draft negotiation text. After two days of negotiations, the UNFCCC introduced a new document reflecting the positions and demands of the developing countries, which the G77 countries celebrated as a "massive improvement". The new draft incorporated a broad definition of the JTWP, an indefinite timeline, financial mechanisms, and the need for international cooperation.

Sensegiving was met with sensebreaking from developed countries.

2. Sensebreaking of New-Sense

In this phase, new-sense faced significant challenges from actors who contested its broad and integrative approach. Developed countries, wielding considerable influence in the negotiation room, led this sensebreaking effort. The central goal of the sensebreaking narrative was to refocus the JT on immediate labour and economic issues, avoiding the expansive redefinition proposed by less-powerful actors.

Developed countries upheld the belief that the ILO already definitively defined the JT. Additionally, their narrative emphasised the Paris Agreement goals, requiring ambitious decarbonisation efforts from all countries, including developing ones. Sensebreaking argued that the new-sense narrative aimed to "water down climate action" (UK, Norway, Canada).

The action plan was clear: the JTWP should focus domestically without international support or financial mechanisms, functioning as a platform for dialogue and exchanging best practices over a two-to-three-year timeline. Advocates argued that a limited JTWP scope would ensure it remained practical and outcome-oriented. This sensebreaking narrative rooted the JT in the dominant discourse where it had originated. While the disagreements centred on the JTWP's purpose and scope, they reflected a more profound ideological divide within the UNFCCC discussions.

(α) Defending Dominant Discourse

Developed countries engaged in *undermining and delegitimising* the new draft, which reflected developing countries' new-sense proposals. They took a cooperative yet dismissive stance towards the new draft. The US, for instance, stated that the new draft contained "multiple deficiencies", and although it did not align with their views, they were "happy to engage with the text". Similarly, the EU expressed willingness to move forward "in the spirit of negotiation" but noted that any paragraphs not explicitly commented on did not "add anything to the work program or being within the mandate". This approach subtly dismissed elements of new-sense proposals without outright rejection, undermining their legitimacy.

A recurring theme was the portrayal of confusion, suggesting that developing countries' perspectives were poorly constructed or unclear. The US negotiator said:

> *"I am very confused by the comments made about it being* unjust *for parties to engage on the text while other parties are not engaging on the text … It's not helpful to say that by*

> *engaging in text, some parties are being* unjust.*"*

Similarly, Canada mentioned being "confused about duplicative elements" in new proposals. Developed nations also questioned the authenticity of the G77 countries' positions, framing them as potentially insincere or strategically deployed to delay action on decarbonisation. For example, the UK suggested that the G77's stance provided "an excuse to delay action", undermining their credibility and moral standing in the negotiations. This tactic shifted the focus from the content of the proposals to the intentions behind them, casting doubt on the legitimacy of the developing nations' claims.

Developed nations portrayed the broad JT understanding of developing countries *as impractical, unfeasible and even impossible*. Norway argued that "there are issues so key to the transition that we cannot lose focus on. The JTWP cannot be about absolutely everything".

The UK questioned whether the text would "result in a functional work program", framing the broader understanding as too unwieldy to be effective. The EU reinforced this view, stating: "JT is not a mere catchphrase; it directly addresses the livelihood of the workforce".

In response to the draft text that favoured developing countries, developed countries reaffirmed the original scope of the JTWP to *constrain discursive expansion*. The US stated, "The US does not support expanding scope" and read out their original submission on the JTWP's scope, focused on labour issues. Norway added: "Anything that waters out or undermines in any shape or form the definition of just transition in the ILO guidelines is unacceptable".

Developed countries further reinforced that the JT should address domestic issues without new finance. Several suggested deleting the section of the document that expanded the scope entirely, calling it "distracting" (Canada, US), representing an unwillingness to legitimise other viewpoints.

Developed nations tried to strip out the symbolic affordances that developing countries attempted to bestow upon the JTWP. By framing the JTWP as a space primarily for technical discussions and best practices, they aimed to limit its scope and reduce its potential as a platform for broader justice-related issues. The US emphasised that "The JTWP should be *a place* where parties talk about how they protect their workers and transition". The EU reinforced this view, stating that the "JTWP *is the place* to exchange best practices and practical implementation to achieve JT pathways goals of the Paris Agreement".

This tactic aimed to remove the metaphorical affordances of JTWP, aligning it with the original common-sense narrative and undermining the developing countries' efforts to elevate it as a justice-centred platform. By doing so, developed nations sought to retain control over the narrative and ensure that the JTWP remained within the bounds of practical implementation that emphasised past efforts done by countries to address workforce issues, devoid of the broader symbolic affordances that could challenge existing power structures.

By the end of this phase of the negotiations, disagreements had intensified, leading to the sealing of the negotiations to observers. The discussions carried on behind closed doors, resulting in the final decision text.

C. *Split-Sense: A Dis-Integrated Framework for Justice (December 2023)*

This subsection presents the JTWP outcome negotiated in COP28's final week and reveals a critical finding: rather than resolving narrative conflict, the decision text enabled a split-sense, or the simultaneous coexistence of competing interpretations that serve different strategic purposes for different actors.

The decision text's preamble highlighted goals and observations that strongly favoured

developing countries. It positioned JT as an inclusive framework aimed at eradicating poverty within climate action, referencing the SDGs, CBDR, and developing nations' specific needs, while broadening the JT's scope beyond energy and emphasising "international cooperation" as crucial for "just and equitable transitions".

However, the action plan reflected developed countries' preferences: a non-binding, dialogue-focused approach without financial commitments, establishing a two-year timeline of biannual dialogues rather than immediate outcomes.

The text thus reflects a strategic decoupling: developing countries secured a broad, justice-centred scope for the JTWP, while developed countries ensured that implementation remained limited to dialogue without binding commitments. Both sides claimed narrative victory while pursuing fundamentally different climate policy outcomes.

Table 2, below, synthesises how the three narratives were articulated through their central goals, specific beliefs and observations, and clear action plans across the three epistemic phases. Each column presents a distinct narrative: common-sense (labour-focused, 2015–2022), new-sense (justice-focused, 2022–2023), and split-sense (as codified in the final JTWP decision text adopted at COP28 in December 2023). The final column reveals the critical finding: while the JTWP decision text adopted new-sense framing in its stated goals and observations (equity, SDGs, international cooperation), the action plan retained common-sense constraints (non-binding, dialogue-focused, limited timeline). This decoupling, where narrative framing diverges from implementation mechanisms, allowed both coalitions to claim victory despite pursuing fundamentally different climate governance aims.

1. Making Sense of the Concluding Narrative

The outcome enabled divergent sensemaking: each coalition interpreted the JTWP decision through their own narrative lens, securing what they deemed most important while framing losses as strategic gains for future action.

(α) Original Proponents of the Common-Sense Narrative

Although initially enthusiastic, proponents of the common-sense narrative felt the JTWP discussions became overly politicised, straying from core labour issues and triggering a "definitional crisis" (TUNGO1). One called it an "arms race of narratives" (IGO1); another lamented that JT's expansion diluted its intent: "we already have SDGs for that" (BINGO1). The dialogue-focused approach yielded few actionable outcomes, relegating the JTWP to a "talk shop" (TUNGO1).

Yet significance was not lost. As one participant reflected: "Ten years ago, we would never have imagined having a dedicated discussion for JT at the UNFCCC, and now we are here, so in that way, it is a success" (BINGO1). The ongoing JTWP offered these actors the opportunity to steer future discussions toward core labour issues.

(β) Original Proponents of the New-Sense Narrative

The JTWP decision elicited varied responses from proponents of the new-sense narrative, marked by cautious optimism. Participants celebrated the significant expansion of the JT's scope at the UNFCCC as a crucial advancement for broader justice concerns (ENGO2, WGC1), seen as a "win for the people's platform" (WGC1). The omission of crucial financial support mechanisms was a point of disappointment for most (WGC1, WGC2, YOUNGO2, ENGO4). However, a Global South negotiator reframed the outcome strategically: "I think realistically in multilateralism these days, it is all about playing with narratives and protecting yourself through that" (PARTY2).

As another participant put it, narratives at the UNFCCC were seen to give "legitimacy to new ideas" (ENGO4) that impact the broader

climate regime. In her eyes, the JT's new broad understanding could "re-anchor" JT definitions by international development banks, resulting in more just and equitable transition financing (ENGO5). A G77 diplomat shared this view; the broader narrative was seen as a tool to influence financial institutions to adopt a wider range of justice-related parameters in climate finance:

> *"The JT has to be broad; the reason they [the developed nations] must define it is so that they can set the finance landscape around that … We needed to change that narrative."* (PARTY2)

This quote reflects a broader understanding of the strategic use of narratives in sending messages to the 'real world'. The G77 diplomat continued:

> *"It's all about narratives or signals to the real world … how to invest, when to invest … It's more of an outcome into the thinking. It's about sustainable development. Justice matters … I think we're at a crossroads now that this new economy has to be different and better than the ones before. We need to evolve."* (PARTY2)

The narrative shift was understood not as symbolic victory but as an instrumental reframing and a lever for influencing climate finance institutions toward justice-oriented parameters.

The evolution of JT discourse reveals a journey of contestation. While the JTWP decision text shifted the institutional narrative toward justice and equity, it simultaneously enabled decoupling: the narrative changed (broader scope, SDG-aligned framing), yet fundamental contestation persisted through implementation mechanisms (non-binding, dialogue-only approach). This decoupling allowed both coalitions to claim narrative victory while pursuing materially divergent climate policy outcomes. The dynamic interplay between competing narratives underscores how discourse shapes climate governance and how institutional compromise can generate semantic change while sustaining underlying power asymmetries and strategic contestation.

VI. **Discussion**

The discussion Section proceeds to address the study's research questions in reverse order, because the most immediate empirical contribution of the case is the JTWP decision's stabilisation of a particular framing with precedential effects. First, the discussion addresses Research Question B: the meaning of 'just transition' that has become institutionalised. Then it addresses Research Question A, how less powerful actors secured that traction, by explaining observed procedural and discursive mechanisms through which contested meanings were advanced, resisted, and partially closed in negotiation text.

A. *Research Question B—Institutionalising Just Transition at the UNFCCC: Meaning, Power and Precedent*

COP decisions do more than record bargaining outcomes; they stabilise categories that travel across policy, finance, and implementation systems.[50] This is especially consequential for the plural, contested term of the 'just transition'. Wang and Lo identify five dominant ways the concept is framed in the literature: (1) labour-oriented origins, (2) an integrated framework for justice, (3) socio-technical transition theory, (4) governance strategy, and (5) public perception.[51] This study's findings align strongly with just transition as a "governance strategy": actors contest, translate, and repurpose the term to secure institutional traction, and the JTWP decision then fixes a usable meaning in formal text. Additionally, the codified meaning draws on elements associated with an "an integrated

[50] Ciplet & Roberts (n 1) *supra*; Bäckstrand & Lövbrand (n 1) *supra* at 290-306.

[51] Wang & Lo (n 2) *supra*.

framework for justice", thereby broadening the discourse.

In the JTWP decision, "just and equitable transition" is articulated across energy, socioeconomic, and workforce dimensions; linked to nationally defined development priorities and social protection; and framed through the lens of "opportunities, challenges and barriers" relating to sustainable development and poverty eradication. This codification marks a shift from earlier UNFCCC milestones, where just transition appeared primarily through an ILO-inflected, labour-centred framing. As summarised in Figure 3, the framing expands from a domestic adjustment issue to an agenda warranting international cooperation, from energy to a whole-of-economy lens, and from "the workforce" to broader constituencies (including youth, women, Indigenous peoples, and others requiring social protection).

Empirically, the findings show how competing coalitions attempted to steer what "just transition" could legitimately mean within the UNFCCC, and how the negotiated outcome produced partial closure. It did not settle the concept into a single definition. Instead, it elevated some meanings as institutionally legitimate and harder to exclude in future negotiations, while containing others through constrained, largely non-binding implementation provisions. Once text is embedded in COP language, it gains precedential weight**.** It becomes harder to dismiss in subsequent negotiations, easier to invoke in other forums, and more likely to travel into the interpretive repertoires of ministries, development banks, and civil society. The significance of the contribution, therefore, is institutional rather than definitional: it explains how a contested concept becomes stabilised in authoritative negotiation text under asymmetric power, and why that stabilisation matters even when operational commitments remain limited.

Having established what meaning became institutionalised in the JTWP decision, this article now explains how less-powerful actors secured that institutional traction during COP negotiations.

B. *Research Question A—How Less Powerful Actors Secure Institutional Traction Under Asymmetric Power*

Research Question A asks how less powerful actors secure institutional traction for counter-framings in UNFCCC negotiations despite enduring power asymmetries. The findings suggest a two-part answer: (1) COPs create procedural opportunity structures that open space for reframing; and (2) less powerful actors convert those openings into traction through discursive strategies in conflictual sensemaking.

1. <u>COPs as Field-Configuring Events Create Discursive Opportunity Structures</u>

The COP process, when understood as a field-configuring event,[52] creates unique structural conditions for rapid narrative reframing through three amplifying features: temporal boundedness (fixed negotiation timelines concentrate actor attention), spatial density (thousands of negotiators, observers, and media co-present), and procedural authority (formal decision-making confers institutional legitimacy on outcomes). These conditions enable discursive shifts that would be difficult to achieve in dispersed, ongoing governance forums.

The JTWP case exemplifies this dynamic and directly addresses the research question by showing how less powerful actors leveraged these structural conditions. Rather than emerging gradually through consensus-building, the JT narrative underwent dramatic reframing within a compressed timeframe. While the common-sense labour-framing of the JT is evident in UNFCCC texts from at least 2010, the shift from new-sense (2022–2023) to split-sense occurred within approximately one year (December 2023). This compressed timeline suggests that COPs function as concentrated discursive pressure chambers in which rapid reframing can occur, whereas in

[52] Lampel & Meyer (n 7) *supra*.

other institutional contexts, such reframing would take years or decades.

Crucially, procedural authority created leverage for less-powerful actors, directly answering how they contest dominant framings. Egypt's COP27 presidency, a formal institutional role, enabled the introduction of language on the COP27 cover page that redirected subsequent negotiations toward the JTWP's establishment. This procedural intervention was discursive leverage: a formal position became a vehicle for narrative reframing. This finding challenges assumptions that multilateral climate governance operates primarily through consensus and hierarchical power. Instead, procedural openings become discursive resources that less powerful actors can leverage strategically. The G77's collective mobilisation amplified this: they recognised the opportunity and pressed Egypt to use procedural authority in the service of reframing. This highlights that less-powerful actors can reshape governance outcomes not through material resources but through strategic deployment of institutional procedure itself.[53] These procedural openings create the conditions for reframing; discursive strategies determine whether reframing actually enters and survives in text.

2. Discursive Strategies as Episodic Power in Conflictual Sensemaking

Building on this opportunity-structure account, the paper specifies the mechanism-level practices through which traction is produced in the room: strategic cycles of sensegiving and sensebreaking, mandate policing, and legitimacy work that shape what becomes negotiable and what enters authoritative text.

Climate governance literature is clear that narratives and frames matter; this is well established.[54] The unresolved question is how, under asymmetrical conditions, specific framings gain traction inside formal negotiations rather than remaining marginal. Studies of framing contests in the UNFCCC mobilise discursive strategies.[55] Yet these literatures often stop short of specifying the mechanisms through which meaning shifts are produced in real time, in rooms where procedural constraints, 'within mandate' policing, and technocratic gatekeeping can suppress redistributive claims.

This study aims to specify those mechanisms more clearly by combining sensemaking theory with a critical discourse perspective. COP negotiations are settings of conflictual sensemaking: actors must create sufficient coherence to move texts forward under time pressure, competing mandates, and contested responsibilities.[56] Crucially, sensemaking in such settings is not merely interpretive; it is strategic. Actors engage in sensegiving to advance preferred interpretations and sensebreaking to destabilise rival interpretations.[57] From a critical discourse view, these struggles are not about words as decoration but about discourse as power: what counts as realistic, technical, pragmatic, or 'within mandate' is itself an effect of hegemonic discourses.[58]

Empirically, the JTWP case shows that less powerful actors did not 'win' by outspending or out-leveraging counterparts materially. They gained traction by mobilising discursive strategies that exposed the taken-for-granted assumptions embedded in dominant framings, linked counter-claims to authoritative normative resources (for example, equity principles and broader development

[53] Ciplet & Roberts (n 1) *supra*; Bäckstrand, Karin. "Multi-Stakeholder Partnerships for Sustainable Development: Rethinking Legitimacy, Accountability and Effectiveness." *European Environment*, vol. 16, no. 5, 2006, pp. 290-306.
[54] Hajer, Maarten. "Policy without Polity? Policy Analysis and the Institutional Void." *Policy Sciences*, vol. 36, no. 2, 2003, pp. 175-195; Fisher (n 13) *supra*.
[55] Wang & Huan (n 15) *supra*.
[56] Weick (n 6) *supra*; Weick, Karl. "Leadership as the Legitimation of Doubt." *The Future of Leadership: Today's Top Leadership Thinkers Speak to Tomorrow's Leaders*, edited by Warren Bennis et al., Jossey-Bass, 2001, pp. 91-102; Maitlis (n 24) *supra*.
[57] Gioia & Chittipeddi (n 6) *supra*; Pratt (n 13) *supra*; Schildt (n 13) *supra*.
[58] Fairclough (n 5) *supra*; Wodak & Meyer (n 20) *supra*.

language), and exploited procedural opportunities that made certain formulations harder to exclude from the text once introduced under time constraints. These moves were often combined with collective amplification: coordinated repetition, strategic coalition alignment, and deliberate insistence on particular terms and linkages until they became part of the textual terrain.

3. Institutionalising Meaning Under Constrained Implementation

A central empirical finding is that institutional traction does not necessarily yield integrated outcomes. In the JTWP negotiations, counter-meanings achieved partial legitimation in authoritative language, while practical mechanisms remained limited, non-binding, or otherwise constrained. This pattern is poorly captured if we assume that successful sensemaking necessarily integrates meaning and action into a coherent whole, or if we treat outcomes merely as 'compromise'.[59]

To theorise this, the article reflects a sensemaking stage called split-sense: a sensemaking outcome in which discursive struggle results in partial legitimation of counter-discourse (as new-sense) alongside containment or dismissal of associated action pathways (as non-sense or as bounded, proceduralised dialogue). Split-sense is analytically useful because it explains why actors can experience the same outcome as victory for different reasons: one side can claim success for preserving implementation constraints; the other can claim success for securing institutional recognition of a justice-oriented meaning that was previously marginal or contestable.

Split-sense also reframes what constitutes 'success' for less-powerful actors. Under systemic asymmetries, immediate material commitments may be unattainable. Yet institutionalising a counter-meaning at the COP can still be emancipatory insofar as it *denaturalises* dominant common-sense and expands the space of legitimate future claims.[60] Once a justice-oriented framing is encoded in UNFCCC language, it becomes harder to treat redistribution-relevant concerns as simply 'political' or 'out of scope' in subsequent rounds. It provides discursive resources for future negotiations and for actors outside the COP who rely on UNFCCC texts as anchors for policy coherence, legitimacy claims, and funding rationales.

That said, split-sense names a tension: institutional recognition can coexist with continued constraints on implementation capacity. The contribution is therefore twofold. First, it explains why a shift in meaning can be consequential even when action lags. Second, it clarifies the risk: split-sense can stabilise a settlement in which justice-oriented language persists without enforceable pathways, potentially enabling symbolic accommodation rather than structural change. Whether split-sense becomes a stepping-stone or fades into non-sense is an empirical question that requires longitudinal study beyond the scope of this article.

VII. **Implications and Limits**

For climate governance scholars, the article argues for treating COP outcomes not only as distributions of commitments but as *institutionalised meaning settlements* produced through contestable discursive practice. This shifts analytical attention toward the micro-politics of negotiation language, how 'mandate', 'technicality', 'pragmatism', and 'realism' are invoked as power-laden categories, and how coalitions strategically work within and against those categories.

For research on just transition, the contribution is concrete: rather than selecting a preferred definition, the paper demonstrates how a highly plural concept becomes *authoritatively negotiated* at the UNFCCC, and how power shapes which interpretations

[59] Weick (n 56) *supra*.

[60] Fairclough, Norman. "Critical and Descriptive Goals in Discourse Analysis." *Journal of Pragmatics*, vol. 9, no. 6, 1985, pp. 739-763; Vaara and Whittle (n 6) *supra*.

become institutionally legible. This responds directly to the empirical and power-sensitive agenda called for in definitional work[61] while showing why the COP is a uniquely consequential site for that empirical inquiry.

A key limitation is temporal: the analysis captures a moment of institutionalisation and its immediate meaning-making dynamics. It cannot adjudicate whether institutional recognition will translate into binding implementation or broader field reconfiguration. Future work should follow the JTWP across multiple COP cycles and trace how UNFCCC meanings travel into finance institutions, national policy templates, and implementation architectures, testing whether split-sense is transient or durable, and under what conditions recoupling becomes possible.

In sum, the study shows that less-powerful actors can shape climate governance not only by contesting outcomes but by contesting the terms on which outcomes are understood. At COPs, those contests can produce durable institutional meanings. Sometimes, however, the result is split-sense: meaning moves first, action later, or not at all.

VIII. **Conclusion**

This study shows that less powerful actors can shape multilateral climate governance not only by negotiating outcomes, but by contesting the meanings that determine what outcomes are legitimate and 'within mandate'. Using the JTWP as a revealing case, the article demonstrates how a conceptually plural term, 'just transition(s)', was narrowed through conflictual negotiation into an institutionalised framing that now carries precedential weight within and beyond the UNFCCC. At COP28, less powerful actors, including Global South countries and civil society actors, formed coalitions and advanced a justice-centred understanding linked to equity, development priorities, and poverty eradication, while more powerful actors worked to contain operational implications. The resulting settlement institutionalised a broader meaning in authoritative text while leaving implementation mechanisms constrained.

The article contributes to climate governance scholarship by showing both a broadened, justice-linked institutional meaning of just transition in UNFCCC text and the procedural and discursive mechanisms through which less-powerful actors achieved that traction despite enduring asymmetries. The study specifies how negotiated meanings are produced under asymmetric power, through cycles of sensegiving and sensebreaking, the policing of mandate and practicality, and strategic use of procedure and legitimacy claims. It also extends organisational theory by showing how sensemaking and discursive strategy operate in multilateral arenas where texts are not just records of agreement but instruments of governance.

A key limitation is temporal and scope-bound: the analysis captures a moment of institutionalisation at COP28 and cannot determine whether this reframing will translate into material change. Future research should follow the JTWP across subsequent COP cycles and trace how UNFCCC language travels into climate finance institutions, national policy templates, and implementation architectures, testing when institutional recognition becomes leverage for action, and when it remains symbolic accommodation.

[61] Wang and Lo (n 2) supra.

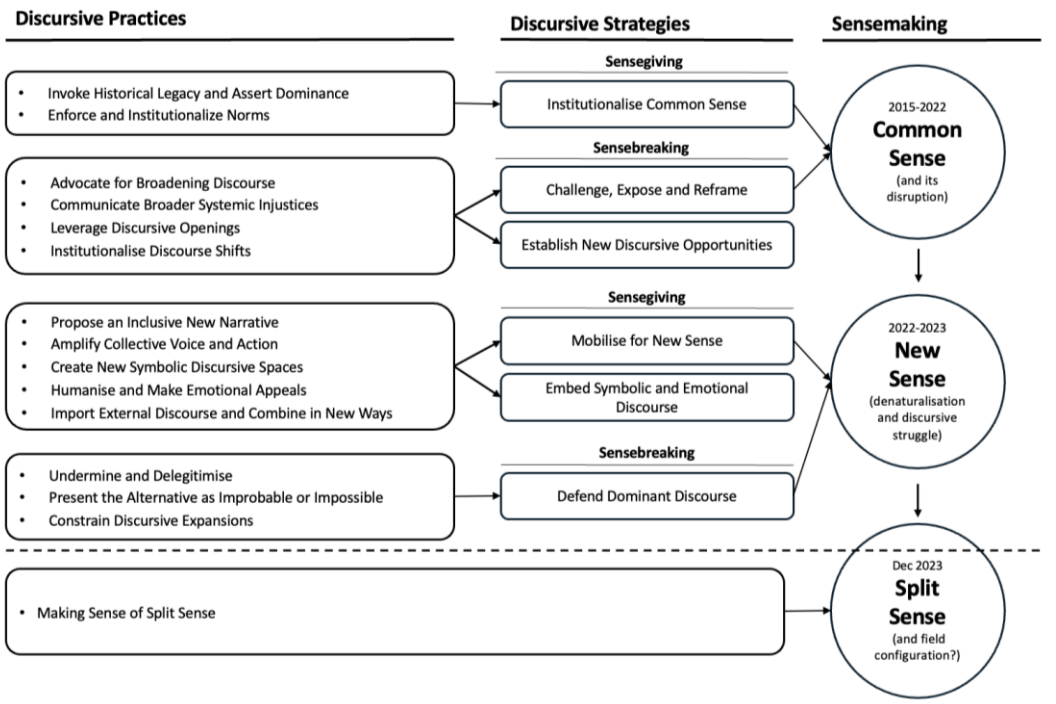


Figure 1: Data Structure.

Date	***Event***	***Focus and Framing***	***UNFCCC Decision Text***
2010	*COP16 Cancún*	*First mention: Workforce-centric focus; just transition explicitly tied to decent work and quality jobs for workers.*	*"While ensuring a just transition of the workforce that creates decent work and quality jobs." (Decision 1/CP.16)*
2015	*COP21 Paris*	*Paris Agreement: Workforce focus maintained, explicit reference to just transition of the workforce and decent work in preamble.*	*"Acknowledging the imperatives of a just transition of the workforce and the creation of decent work and quality jobs." (Paris Agreement, Preamble)*
2018	*COP24 Poland*	*Institutional mechanism: Katowice Committee of Experts (KCI) established to support response measures including workforce transition, decent work, and economic diversification.*	*"Just transition of the workforce and creation of decent work and quality jobs" sits as a defined work area alongside economic diversification. (Decision 4/CMA.2, annex II)*
2022	*COP27 Egypt*	*Broadened mandate: Just transition expands beyond workforce to encompass energy, socioeconomic, workforce and other dimensions, with emphasis on nationally defined priorities and social protection.*	*"Emphasizes that just and equitable transition encompasses pathways that include energy, socioeconomic, workforce and other dimensions." (COP27, Decision 1/CMA.4, para. 51)*
2023	*COP28 UAE*	*Comprehensive framework: Just transition integrated across climate action, sustainable development, poverty eradication, and diverse stakeholder needs.*	*"Decides that the work programme shall include the following elements: just transition pathways…energy, socioeconomic, workforce and other dimensions…sustainable development and poverty eradication…just transition of the workforce and the creation of decent work…inclusive and participatory approaches…international cooperation." (COP28, Decision 3/CMA.5)*

Table 1: Summary Chronology of Just Transition Development at the UNFCCC (2010-2023).

Common-Sense Discourse: Pragmatic Workforce Transitions (2010 to 2022)		**New-Sense Discourse:** A Broad, Integrated Framework for Justice (2022 to 2023)		**Split-Sense Discourse:** A Broad, Dis-integrated Framework for Justice (Dec, 2023)
Sensegiving	**Sensebreaking** Less powerful actors	**Sensegiving** Less powerful actors	**Sensebreaking**	**Concluding Sense**
		Central Goals		
Supporting displaced workers and communities caused by the sustainability transition.	Mitigating developed countries prescribing climate action despite widening development gaps.	Addressing a multidimensional crisis of poverty, inequality and energy security for developing countries AND issues faced by vulnerable groups.	Social and economic stability for rapidly decarbonizing developed countries.	Addressing the multidimensional crisis for developing countries, social and economic stability.
Stable decarbonized economies.	Redefinition of the Just Transition at the UNFCCC.	Correction of historical injustices in the developing world and for vulnerable groups.	Ambitious climate action for all countries, including developing countries.	Ambitious climate action and correction of historical injustices in the developing world.
		Observations and Beliefs: Sources of Truth		
ILO	SDGs	SDGs & CBDR	ILO, Paris Agreement	SDGs & CBDR
		Specific Observations and Beliefs		
The Just Transition is a labour-oriented response to decarbonisation, focusing on energy sector impacts.	Destabilise a perceived overly narrow understanding, integrating broader social impacts and international dimensions.	The Just Transition is an inclusive framework for broader justice, integrating social, economic, and environmental dimensions.	Must challenge a perceived over-expansion and dilution of focus on core, domestic labour issues.	The Just Transition is an integrated framework for justice, challenged by implementation
		Clear Action Path: How Should the Just Transition Work Program be Implemented		
Non existent	Silent	All sectors	Energy sector only	All sectors
		International support	Domestic focus	International cooperation, domestic focus
		Financial support	No financial support	No financial support
		Indefinite timeline	2-3 year timeline	2-3 year timeline
		Integrated framework	Twice yearly dialogues	Twice yearly dialogues

Table 2: Summary of Discursive Conflict.

Participant Interview ID	Participation at COP28	Type of Observer or Party	Global North or South
ENGO1	Observer	Environmental NGO	South
PARTY1	Party	G77 Country Environmental Secretariat	South
YOUNGO1	Observer	Youth NGO	South
ENGO2	Observer	Environmental NGO	South
WGC1	Observer	Women and Gender	South
ENGO3	Observer	Environmental NGO	South
WGC2	Observer	Women and Gender Constituency	North
YOUNGO2	Observer	Youth NGO	South

YOUNGO3	Observer	Youth NGO	North
RINGO1	Observer	Research and Independent NGOs	North
FARMERS1	Observer	Farmers Constituency	South
IGO1	Observer	United Nations (UN) organizations and Specialised Agencies	North
TUNGO1	Observer	Trade Union NGO	North
YOUNGO4	Observer	Youth NGO	North
IGO2	Observer	United Nations (UN) organizations and Specialised Agencies	South
ENGO4	Observer	Environmental NGO	South
BINGO1	Observer	Business and Industry Organizations	North
IGO3	Observer	United Nations (UN) organizations and Specialised Agencies	North
ENGO5	Observer	Environmental NGO	North
RINGO2	Observer	Research and Independent NGOs	North
PARTY2	Party	G77 Country Representative	South
IPO1	Observer	Indigenous Peoples Organization	South
RINGO3	Observer	Research and Independent NGOs	North
RINGO4	Observer	Research and Independent NGOs	North

Table 3: Interview Participant List.

Document	Date	Type of Document
Paris Agreement	2016	International Treaty
Katowice Committee of Experts (KCI) Outcomes	2018	Report
Sharm El Sheikh Implementation Plan	2022	Presidency Cover Page
G77 pre-COP28 Submission	2023	Online Submission
United States pre-COP28 Decision	2023	Online Submission
International Labour Organisation pre-COP28 Submission	2023	Online Submission
Climate Action Network Submission	2023	Online Submission
Work Program on just transition Pathways: Draft 1	2023	Draft Text
Work Program on just transition Pathways: Draft 2	2023	Draft Text
Work Program on just transition Pathways: Draft 3	2023	Draft Text
Work Program on just transition Pathways: Draft 4	2023	Draft Text
Work Program on just transition Pathways: Draft 5	2023	Draft Text
Work Program on just transition Pathways: Draft 6	2023	Draft Text
Work Program on just transition Pathways: Week 1 Draft Conclusions	2023	Report
Work Program on just transition Pathways: Presidency Proposal	2023	Draft Text
Work Program on just transition Pathways: Advance Unedited Version	2023	Decision Text

Research and Independent Non-governmental Organization: Final Memo 1	2023	Report
Research and Independent Non-governmental Organization: Final Memo 2	2023	Report
Research and Independent Non-governmental Organization: JTWP Field Notes Day 1	2023	Field Notes
Research and Independent Non-governmental Organization: JTWP Field Notes Day 2	2023	Field Notes
Research and Independent Non-governmental Organization: JTWP Field Notes Day 3	2023	Field Notes
Research and Independent Non-governmental Organization: JTWP Field Notes Day 4	2023	Field Notes

Table 4: Document Analysis List.

The Political Economy of Energy Transitions and the Role of Fusion in the Climate Change Debate

Eugenia Obeng-Akrofi*

* PhD Candidate & Graduate Teaching Assistant (Department of Environment and Geography; Department of Politics), University of York, UK

KEYWORDS

fusion energy, political economy, energy transitions, climate policy, stakeholder analysis, public-private partnerships

ABSTRACT

This article examines the political economy of energy transitions with a particular focus on the role of nuclear fusion in the climate change debate. Drawing on an ideas–interests–institutions framework, the analysis investigates how fusion is integrated into national decarbonisation pathways in the United Kingdom and the United States. The study combines a documentary analysis of 28 policy documents with 22 semi-structured interviews, which were coded manually using thematic content analysis. Findings show that although both countries demonstrate strong commitments to decarbonisation, their institutional architectures differ markedly: the United Kingdom relies on State-led coordination whereas the United States emphasises private-sector innovation. These structural variations shape stakeholder power, investment patterns, regulatory clarity, and social acceptance. Fusion's growing presence within policy discourse, especially after COP26, illustrates its symbolic and strategic significance for long-term climate governance. The study concludes that fusion's political prospects depend not only on technological progress but on the alignment of institutional incentives and stakeholder interests, demonstrating the need for a multidisciplinary governance approach to support its potential as a low-carbon energy source.

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I. **Introduction**

The accelerating climate crisis has transformed global energy debates from questions primarily about technological innovation to questions about political will, institutional capacity, and economic justice. Over the last two centuries, industrialisation driven by fossil fuels has emitted more than 2.4 trillion tonnes of carbon emissions which has reshaped the biosphere and the political order that governs it.[1] The accumulation of greenhouse gases such as carbon dioxide, methane, and nitrous oxide have intensified global warming and influenced States to adopt sustainable energy alternatives.[2] Within this context, nuclear fusion has re-emerged as a compelling but complex energy solution. As a process that fuses light atomic nuclei to release vast quantities of clean power, nuclear

[1] Zhong, Qirui, et al. "Global Estimates of Carbon Monoxide Emissions from 1960 to 2013." *Environmental Science & Pollution Research*, vol. 24, 2017, pp. 864-873.

[2] Fouquet, Roger. "Historical Energy Transitions: Speed, Prices and System Transformation." *Energy Research & Social Science*, vol. 22, 2016, pp. 7–12.

fusion promises a virtually limitless, non-polluting energy source.[3] Yet the path from scientific demonstration to commercial deployment is deeply political. National governments, private investors, regulators, and civil society actors all compete to define how fusion will be governed, financed, and integrated into the energy mix. The technology's promise of near-infinite clean energy sits beside questions of ownership, control, and legitimacy, which are issues that have historically shaped energy transitions since the Industrial Revolution.

In this article, the "role of fusion" refers specifically to the political, institutional, and socio-economic mechanisms through which fusion energy is framed, governed, and incorporated into national energy-transition strategies. Rather than treating fusion solely as a technological case study, the study examines how political incentives, institutional path dependencies, and stakeholder coalitions shape its development. In doing so, it extends existing work in the political economy of energy transitions by conceptualising fusion as a political artefact embedded in climate governance, industrial policy, and long-term decarbonisation planning. The analysis is based on an ideas–interests–institutions framework, which provides a structured lens for examining how actors construct meaning around fusion, how competing interests are translated into policy preferences, and how institutional arrangements stabilise or constrain change. Ideas capture normative visions such as sustainability, energy security, or technological leadership; interests refer to the strategic aims of State and non-State stakeholders; and institutions encompass the formal and informal rules that govern decision-making. This framework allows fusion to be situated within broader debates in comparative political economy concerning State capacity, market liberalisation, and the politics of technological transitions.

This article adopts a comparative approach between the United Kingdom and the United States which are two industrial democracies with advanced fusion programmes to understand how divergent policy architectures are working towards fusion commercialisation. The United Kingdom's State-centric model relies on public research infrastructure such as the Spherical Tokamak for Energy Production project, while the United States emphasises private-sector leadership under milestone-based funding schemes.[4] By analysing these contrasting pathways, this study identifies how institutional quality, stakeholder power, and policy design shape the political economy of energy transitions. The significance of this analysis lies in connecting technological prospects to the realities of governance. Energy transitions are never purely technical transformations; they redistribute resources, influence social hierarchies, and redefine State–market relations. Understanding these political and economic dimensions is therefore essential for formulating policies that ensure fusion's potential contributes effectively to global decarbonisation targets. The urgency of this debate has grown since COP26, where renewed commitments to net-zero targets underscored the need for novel clean-energy technologies. Fusion now occupies a symbolic position within climate politics; a technological frontier representing human ingenuity and the obstacles of institutional inertia. Accordingly, this article is guided by three questions:

- How do national institutional frameworks shape the direction of fusion development?
- To what extent do stakeholder interests and governance models influence fusion's integration into broader decarbonisation strategies?

[3] El Bassam, N, "Energy Basics." *Distributed Renewable Energies for Off-Grid Communities: Empowering a Sustainable, Competitive, and Secure Twenty-First Century*, edited by Marcia Schlichting and Daniele Pagani, 2nd edn, Elsevier, 2021.

[4] *Towards Fusion Energy 2023: The Next Stage of the UK's Fusion Energy Strategy.* UK Department for Energy Security and Net Zero, Oct. 2023; *Fusion Energy Strategy 2024.* US Department of Energy, 2024.

- What lessons can comparative political economy offer for aligning innovation with equitable climate governance?

The article is structured as follows. Section II reviews the literature on the political economy of energy transitions and outlines the ideas–interests–institutions framework. Section III presents the research design, including the documentary analysis and semi-structured interviews. Section IV discusses the empirical findings from both data sources, structured around the research questions. Section V concludes by summarising the key contributions, reflecting on the study's limitations, and outlining policy implications for the governance of fusion energy.

II. **Literature Review**

A. *The Political Economy of Energy Transitions*

Notwithstanding that the energy transition is not a singular technological shift but a contest over political priorities, institutional frameworks, and market incentives, recent scholarship argues that policy reforms must balance technical feasibility with political legitimacy and institutional quality. In the low-carbon sector, nuclear fusion represents a distinctive case: an emerging technology with transformative potential but constrained by high capital, regulatory uncertainty, and public unfamiliarity. Using a political-economy approach which traditionally focuses on State–market interactions,[5] the negotiation between State and non-State actors in its adoption is analysed and, as Collinson observes, these negotiations are embedded in power structures that shape economic outcomes over time.[6]

Building on Newell and Paterson's[7] argument that climate governance is embedded within capitalist political structures, fusion development can be understood as part of a broader contest over technological change, power, and institutional adaptation. Energy transitions often replicate existing power hierarchies unless deliberate policy interventions redistribute influence and investment. Studies of electricity-market evolution identify three phases: regional integration, liberalisation, and low-carbon inclusion, all of which reflect different constellations of political and economic interests.[8] Where liberalisation privileges private investment, integration and inclusion rely more on State direction. Fusion's development depends on this balance, and its progress will show how national regimes align or diverge from their governance philosophies.

The literature further emphasises that energy transitions are path-dependent processes which are constructed through institutional legacies and political culture. Countries with coordinated market economies tend to pursue State-led industrial policy, while liberal economies favour competition and decentralisation.[9] The UK and US exemplify this distinction: Britain's emphasis on regulatory stability contrasts with America's entrepreneurial dynamism which provides an ideal case study for assessing how institutional differences affect technological deployment. Despite extensive research on renewable energy deployment and nuclear fission politics, the political economy of fusion remains relatively underexplored. Existing studies tend to prioritise technical feasibility, cost projections, or long-term scenario modelling, with limited studies focusing on how governance structures and stakeholder influence shape fusion's political landscape.

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[5] Butler, Catherine, et al. "Nuclear Power After Japan: The Social Dimensions." *Environment: Science and Policy for Sustainable Development*, vol. 53, no. 6, 2011, pp. 3-14.

[6] Collins, Stephen. *People, Politics and Power: From O'Connell to Ahern*. O'Brien Press, 2007.

[7] Newell, Peter, and Matthew Paterson. *Climate Capitalism: Global Warming and the Transformation of the Global Economy*. Cambridge University Press, 2010.

[8] Grubb, Michael, and David Newbery. "UK Electricity Market Reform and the Energy Transition: Emerging Lessons." MIT Center for Energy and Environmental Policy Research Working Paper No. 2018-004, Feb. 2018.

[9] Bridge, Gavin, and Ludger Gailing. "New Energy Spaces: Towards a Geographical Political Economy of Energy Transition." *Environment and Planning A: Economy and Space*, vol. 52, no. 6, 2020, pp. 1037-1050.

Within the climate change debate, fusion occupies an ambiguous position. On the one hand, it is framed as a potential long-term contributor to decarbonisation and energy security; on the other, its lengthy timelines and capital costs raises questions about its practicality for near-term transition strategies. Fusion is therefore used as a symbol of technological ambition and national leadership, not merely as a prospective technology. Thus, this article addresses a research gap by offering a comparative political-economy analysis of the UK and US fusion sectors, focusing on how ideas, interests, and institutions mediate fusion's role on the climate change debate.

B. *Ideas, Interests, and Institutions*

Following the 'three Is' framework,[10] ideas comprise of normative visions such as sustainability, energy security, or national competitiveness which justify State intervention. These ideas influence energy discourse by shaping the cognitive frames of stakeholders through the interpretation of risk and opportunity. Interests translate these ideas into action, producing coalitions that influence technological change through the strategic aims of stakeholders, and institutions stabilise these relationships through laws, regulations, and organisational routines.[11]

Fusion deployment requires an analysis of how formal structures interact with informal norms and institutional quality mediates between ideas and interests to determine transparency, rule enforcement, and access to decision-making.[12] When institutional coherence is high, fusion policy tends to evolve through structured public–private partnerships. When this coherence is fragmented, progress depends more on entrepreneurial initiative and venture capital.[13] Critical institutionalism however, challenges earlier functionalist views by emphasising historical contingency, social inequality, and the politics of knowledge.[14] Leach and Cleaver support this school, stating that communities and institutions are not neutral collectives but arenas of contestation. These insights underscore that institutions are not static containers but dynamic arenas where ideas and interests continually reconfigure. While institutions often stabilise existing coalitions of interest, they can also exert a transformative force by reshaping incentives, altering access to authority, and reframing what actors perceive as politically or economically viable. In this sense, institutions do not merely reproduce established power relations but can actively redirect them, precipitating change in energy governance trajectories.

C. *Social Acceptability and Public Engagement*

Social acceptability also intersects with political economy through the reinforcement of existing hierarchies of energy access, technological control and the need for an equitable policy design.[15] The history of fission has left ambivalent public attitudes toward nuclear technologies, from which fusion must consciously differentiate itself. Though technological feasibility is important, the societal acceptance of fusion determines its traction within national energy systems. Empirical studies show that continuous stakeholder participation, policy commitment and credible commercialisation are factors that influence social acceptability.[16] Recent research also links public trust to perceptions

[10] Butler et al. (n 5) *supra*.
[11] Sayer, Andrew. *Radical Political Economy: A Critique*. Oxford Blackwell, 1995.
[12] Umut, Uzar. "Political Economy of Renewable Energy: Does Institutional Quality Make a Difference in Renewable Energy Consumption?" *Renewable Energy*, vol. 155, 2020, pp. 591-603.
[13] Anadón, Laura Díaz. "Missions-Oriented RD&D Institutions in Energy Between 2000 and 2010: A Comparative Analysis of China, the United Kingdom, and the United States." *Research Policy*, vol. 41, no. 10, 2012, pp. 1742-1756.
[14] Cleaver, Frances, and Jessica de Koning. "Furthering Critical Institutionalism." *International Journal of the Commons*, vol. 9, no. 1, 2015, pp. 1-18.
[15] Setyowati, A, and J Quist. "Contested Transition? Exploring the Politics and Process of Regional Energy Planning in Indonesia." *Energy Policy*, vol. 165, 2022, 112997.
[16] Grundel, Ida, et al. "Identifying Interests and Values in Forest Areas through Collaborative Processes and Landscape Resource Analysis." *Forest Policy and Economics*, vol. 142, 2022, 102801.

of procedural justice. In situations where the public is excluded from the decision-making process, resistance intensifies.[17] Conversely, transparent communication and visible community benefits can generate legitimacy even for high-technology projects. However, the case studies illustrate divergent engagement strategies. While the United Kingdom embeds engagement through consultations within its government-led initiatives, the United States is inclined towards outreach events such as lobbying. Both the UK's STEP consultations and the US Department of Energy's outreach programmes demonstrate the growing role of dialogue in technology governance.[18] However as Stirling warns, community participation should transition from deficit models of education to genuine co-production of knowledge.[19]

III. **Methodology**

A. *Research Design*

This study adopts a qualitative comparative research design to examine how political and institutional dynamics shape fusion deployment within two national contexts: the United Kingdom and the United States. The article combines policy documentation analyses and semi-structured interviews to generate a multi-layered understanding of the political economy of energy transitions, while the comparative approach allows for the identification of both convergence and divergence models across governance systems.[20] The United Kingdom represents a centralised, State-led model in which government agencies such as the Department for Energy Security and Net Zero and the UK Atomic Energy Authority retain strategic control. In contrast, The United States embodies a decentralised, market-oriented framework which is dominated by the private-sector and supported through government funding.[21] This dual-case design aligns with the logic of comparative political economy, where differences in institutional quality, regulatory culture, and stakeholder participation produce distinct policy outcomes.[22]

A qualitative research design was selected due to the exploratory nature of the study, allowing for detailed analysis of stakeholder interpretations, institutional processes, and policy evolution that cannot be captured through quantitative indicators alone.[23] The use of thematic analysis in analysing the policy documents and semi-structured interviews was also chosen for its flexibility in identifying latent meanings across textual and verbal data.[24] A comparative angle further strengthens the explanatory depth of this article by investigating how national institutional variations benefit from divergent approaches. This approach mirrors the most-similar systems logic, as both the UK and US have strong economic capabilities, democratic governance, and scientific leadership in fusion.

B. *Data Collection*

For this study, I conducted a policy review of 28 fusion policy documents, which is based on substantial and ongoing commitment within the fusion sector and 22 semi-structured interviews which provided a basis for stakeholder ideas and interests in fusion deployment (**Table 1**, below).

1. Policy Documentation Analysis

Documentary analysis was used to examine how fusion is formally positioned within

[17] Bridge & Gailing (n 9) *supra*.
[18] *Technology Report: Safety and Waste Aspects for Fusion Power Plants.* UK Atomic Energy, UKAEA-RE(21)01, no. 1, Sept. 2021; *The Global Fusion Industry in 2022: Fusion Companies Survey.* Fusion Industry Association, 2022.
[19] Stirling, Andrew. "Risk, Precaution and Science: Towards a More Constructive Policy Debate." *EMBO Reports*, vol. 8, no. 4, 2007, pp. 309-315.
[20] Onwuegbuzie, Anthony, and R Burke Johnson. "The Validity Issue in Mixed Research." *Research in the Schools*, vol. 13, no. 1, 2006, pp. 48-63.
[21] US Department of Energy (n 4) *supra*.
[22] Persson, Torsten, and Guido Tabellini. "Political Institutions and Policy Outcomes: What Are the Stylized Facts?" Institute for International Economic Studies Working Paper, Feb. 2001.
[23] Flick, Uwe. *An Introduction to Qualitative Research*. 4th edn, Sage, 2009.
[24] Braun, Virginia, and Victoria Clarke. "Using Thematic Analysis in Psychology." *Qualitative Research in Psychology*, vol. 3, no. 2, 2006, pp. 77-101.

national strategies, legislation, and regulatory frameworks, which directly addresses the first research objective on how institutional frameworks shape fusion development. A systematic review of 28 policy documents published between 1965 and 2024 was conducted, and these documents comprised legislations, national strategies, and bilateral agreements. These texts were obtained from official UK and US government databases to analyse the evolution of fusion governance frameworks. Thematic coding identified recurrent patterns relating to stakeholder roles, funding mechanisms, and regulatory principles. Policy documents included the UK Energy Act 1965, Energy White Papers (2003, 2017, 2020), Fusion Strategy 2023, and the US Fusion Energy Act 1974 and Fusion Energy Act 2023.

2. Semi-Structured Interviews

Semi-structured interviews were conducted to capture stakeholder interpretations of political willingness, interests, and institutional constraints, which directly addressed the second and third research objectives which focus on stakeholder power and strategies of influence. 22 in-depth interviews were conducted with policy officials, research directors, private-sector executives, and civil-society representatives. The interviews explored perceptions of fusion's commercial viability, political support, and barriers to integration. Participants were selected through a purposive snowball sampling to ensure representation from both public and private stakeholders. Interview questions were open-ended to allow participants to define salient issues in their own terms, which is consistent with interpretivist research principles.[25] Transcripts were coded manually to identify thematic clusters such as viability and stakeholder significance.

C. *Analytical Framework*

The analytical framework draws on the concept of ideas–interests–institutions which was outlined in the literature review. This framework conceptualises political economy as a relational system where stakeholders pursue interests within institutional constraints and discursive contexts.[26] Coding categories were derived inductively from the data but aligned deductively with this theoretical model. Stakeholders were categorised by power and influence. Power is defined as control over resources and decision-making processes, while influence reflects the ability to shape outcomes indirectly through persuasion or alliance-building.[27] To assess these dimensions, the study modified Clucas's index of legislative influence to examine formal powers (policy authorship, site selection) and informal powers (advisory roles, agenda-setting).[28] Cross-case synthesis was then applied to compare institutional configurations between the United Kingdom and the United States. This method, following Drass and Ragin,[29] is appropriate for multi-country qualitative research where causal mechanisms are configurational rather than linear. The choice of an interpretivist rather than a positivist framework reflects the study's agenda with meaning and agency in policy processes. As Yanow argues, political analysis must capture how actors interpret rules and norms, alongside their reason for compliance, and this perspective was essential for unpacking differences in how UK and US stakeholders frame fusion, and how these framings shape commercialisation.[30]

IV. **Results and Discussion**

These findings are presented in alignment with the three research questions, which focuses on the role of national institutional frameworks, influence of stakeholder

[25] Kvale, Steinar. *Doing Interviews*. 2nd edn, Sage, 2018.
[26] Butler et al. (n 5) *supra*.
[27] Willer, Robb, et al. "Influence over Observers of Structural Power: An Experimental Investigation." *The Sociological Quarterly*, vol. 46, no. 2, 2005, pp. 263-277.
[28] Clucas, Richard. "Legislative Professionalism and the Power of State House Leaders." *State Politics & Policy Quarterly*, vol. 7, no. 1, 2007, pp. 1-19.
[29] Drass, Kriss, and Charles Ragin. "QCA: Qualitative Comparative Analysis." Northwestern University Institute for Policy Research Working Paper, 1992.
[30] Yanow, Dvora. *Conducting Interpretive Policy Analysis*. Sage, 2000.

interests and governance models and the comparative political economy for aligning innovation with equitable climate governance.

A. *Stakeholder Constellations and Power Relations*

The policy documents and interview data identified a diverse ecosystem of stakeholders which shape fusion policy within the United Kingdom and the United States. In both countries, State actors form the core of influence and are supported by non-State actors. The mapping of power relations revealed four recurring coalitions (**Figure 1**, below).

Though non-State actors increasingly shape the agenda through think tanks and industry associations that frame fusion as both climate imperative and economic opportunity, influence flows differ. In the United Kingdom, the Department for Energy Security and Net Zero (DESNZ) and the UK Atomic Energy Authority (UKAEA) are centrally responsible for policy execution. Their collaboration under the Spherical Tokamak for Energy Production (STEP) programme consolidates public oversight and directs funding streams toward research hubs such as Culham Science Centre and private partners such as Tokamak Energy.[31] This arrangement produces a vertically integrated governance model where State agencies are involved in partnerships through contractual frameworks and strategic memoranda. In contrast, the United States exhibits a decentralised, market-driven model. The Department of Energy's Office of Fusion Energy Sciences sets energy priorities, but execution is designated to private firms such as Commonwealth Fusion Systems and Xcimer Energy.[32] For instance, the Department of Energy's Milestone-Based Development Program is based on competitive funding, where grants are disbursed based on demonstrable technical progress. As US6 noted, "government acts less as a regulator and more as a catalyst—our role is to prove commercial pathways rather than design them".

While influence flows in the UK move hierarchically from government departments to delivery agencies, influence flows in the US circulate horizontally through a network of investors, start-up companies, and laboratories. These differing institutional logics shape stakeholder power as UK stakeholders perceive legitimacy through State endorsement while US stakeholders derive influence from market credibility and technological performance. In both contexts, academic institutions serve as epistemic brokers which translate scientific advances into policy discourse.

However, the degree of stakeholder integration also reflects deeper historical legacies in national innovation systems. In the UK, fusion policy evolved within a long tradition of corporatist governance in energy and defence industries.[33] The central government historically retained ownership over major scientific assets such as the Atomic Energy Authority, ensuring close alignment between research priorities and State industrial policy. Even after market liberalisation in the 1980s, this centralised pattern persisted through quasi-autonomous agencies such as the UK Atomic Energy Authority. The UK's model of coordination thus remains hierarchical and strategic, reflecting what Hall and Soskice describe as a coordinated market economy.[34] While the UK approach provides institutional coherence and continuity, it can also produce bureaucratic inertia. Interviewees in the UK highlighted the challenge of reconciling long-term public missions with short-term fiscal constraints. In contrast, the US exhibits traits of a liberal market economy where private

[31] *Our Strategy 2022–2026: Leading the Delivery of Sustainable Fusion Energy and Maximising Scientific and Economic Benefit.* UK Atomic Energy Authority, 2023.
[32] *Department of Energy Announces $46 Million in Awards for Commercial Fusion Development.* US Department of Energy Funding Opportunity Announcement DE-FOA-0002809, 31 May 2023.
[33] Helm, Dieter. *Energy, the State, and the Market: British Energy Policy Since 1979*. Oxford University Press, 2004.
[34] Hall, Peter, and David Soskice, *Varieties of Capitalism: The Institutional Foundations of Comparative Advantage*. Oxford University Press, 2001.

entrepreneurship and venture capital act as primary drivers of innovation. This explains the rapid emergence of fusion start-ups that dominate the American fusion landscape.[35] The US system rewards rapid innovation, but the absence of a unified national roadmap can result in duplication and inconsistent licensing practices. US7 stated, "our advantage is speed, but our weakness is alignment". Though public–private coordination exists, it is grounded on transactional characteristics as the government provides funding with minimal involvement in technological development.

From a political-economy perspective, stakeholder influence in the UK and the US reflect the interplay of formal power and informal influence. The UK's institutionalised partnerships foster predictability but limit diversity of perspectives while the US encourages competition but can amplify inequities in access to decision-making. The overall pattern supports the argument that governance design mediates technological outcomes, and institutions determine not only what policies are possible but who gets to define them.[36]

B. *Themes from the Qualitative Analysis*

1. International Cooperation and Governance

Cross-national collaboration emerged as a recurrent theme. Both countries participate in ITER and maintain bilateral agreements such as the 2023 UK–US Joint Statement on Fusion Energy.[37] Interviewees viewed these alliances as crucial for standardising regulatory frameworks and sharing risk. However, institutional asymmetry complicates cooperation: UK interviewees emphasised compliance with European safety norms, while US counterparts focused on export-control flexibility and intellectual property protection. This divergence reflects broader geopolitical strategies, with Britain positioning itself as a regulatory leader within global climate diplomacy, and the US as a commercial innovator seeking first-mover advantage. Thus, effective international governance will depend on reconciling these regulatory cultures. Scholars such as Stirling & Johnstone argue that energy geopolitics increasingly hinges on technological sovereignty, which is the ability of States to shape global standards through early adoption and rulemaking.[38] In this context, the UK's commitment to transparency and public-sector leadership represents a soft-power strategy for influencing international norms while American private-sector dominance represents a market diffusion strategy.[39] Interviewees from both contexts acknowledged that collaboration is essential but fraught with political tension. UK stakeholders highlighted the importance of continued involvement in multilateral initiatives like EUROfusion despite post-Brexit uncertainty. US stakeholders also expressed concerns that international cooperation could affect domestic innovation, if overly constrained by bureaucratic harmonisation. US8 supported this notion, stating that "global alignment is vital, but we can't wait for consensus to make progress". This evidence suggests that while the UK and the US both value collaboration, they differ in the logic underpinning it, and these variations reflect each country's historical experience with nuclear technology governance and broader climate diplomacy strategies.[40]

2. Regulatory Frameworks and Institutional Capacity

Interviewees consistently described regulation as both enabling and constraining.

[35] *Global Investment in the Private Fusion Sector*. F4E Fusion Observatory, 2nd edn, 2025.

[36] Pierson, Paul. "Increasing Returns, Path Dependence, and the Study of Politics." *American Political Science Review*, vol. 94, no. 2, 2000, pp. 251-267.

[37] *Joint Statement Between the United Kingdom and the United States on a Strategic Partnership to Accelerate Fusion Energy Demonstration and Commercialisation.* UK Department for Energy Security and Net Zero / US Department of Energy, 8 Nov. 2023.

[38] Stirling, Andrew, and Philip Johnstone. "Hidden Military Implications of 'Building Back' with New Nuclear in the UK." *Responsible Science*, no. 3, 2021, pp. 11-14.

[39] Mazzucato, Mariana. *The Entrepreneurial State*. Anthem Press, 2013.

[40] Goldthau, Andreas, and Benjamin Sovacool. "The Uniqueness of the Energy Security, Justice, and Governance Problem." *Energy Policy*, vol. 41, 2012, pp. 232-240.

The UK's Towards Fusion Energy (2021) introduced proportional licensing distinct from fission law,[41] which stakeholders praised for legal clarity. Although not statutory, it functions as formal policy guidance that shapes regulatory expectations for both the Office for Nuclear Regulation and the Environment Agency. As government-issued guidance, it carries persuasive authority and frames how regulators interpret compliance obligations for emerging fusion facilities. This document was developed through extensive consultation between the UK Atomic Energy Authority, the Office for Nuclear Regulation and the Environment Agency to reflect a participatory approach in decision-making. UK5 also noted that "the challenge is to remain flexible enough to support innovation but strict enough to maintain credibility". Comparatively, the US Fusion Energy Act (introduced in 2023 and not yet made law) establishes a dedicated regulatory pathway under the Nuclear Regulatory Commission by clarifying safety requirements, distinguishing fusion from fission in licensing burden, and mandating the development of risk-proportionate standards. It also directs agencies to develop technical guidance notes and consult with industry to ensure regulatory predictability for pilot plants.[42] Nevertheless, interviewees cited residual uncertainty about liability regimes and waste classification. US4 supported this claim, stating that "regulatory clarity is improving, but we're still navigating uncharted territory". In both cases, institutional capacity proved decisive: where bureaucratic expertise was thin, policy innovation lagged. These findings align with Uzar's argument that institutional quality correlates directly with low-carbon investment inflows.[43] From the analysis, the UK's approach exemplifies anticipatory regulation, where rules evolve proactively alongside technology while the American approach exhibits adaptive regulation where rules are adjusted incrementally in response to market developments. Both approaches have merits; anticipatory frameworks build public trust and reduce future uncertainty, while adaptive ones preserve flexibility and innovation. Yet, as Stirling notes, governance must also confront the political dimension of uncertainty. The evolving regulatory landscapes in both nations thus reflect broader struggles to balance technological optimism with accountability.[44]

3. Public–Private Partnerships and Financing Models

Both the UK and the US utilise public–private partnerships which differ in architecture. In the UK, partnerships are formalised through strategic funding calls administered by the Department for Energy Security and Net Zero and the UK Atomic Energy Authority. The British model is known for emphasising risk sharing, where government funds early-stage research while private partners contribute to innovation and project-specific capital. The STEP Programme epitomises this approach as an integrated framework which links national laboratories, industrial suppliers, and universities under a single strategic mission.[45] Interviewees also noted that this structure encourages continuity but sometimes slows decision-making. In the US, venture capital and philanthropic investment dominate early-stage funding, which is complemented by the Department of Energy's matching grants.[46] This model reflects a venture governance, where competition and milestone validation are substituted for State coordination, but increases volatility and dependence on private risk tolerance.

Comparative synthesis indicates that hybrid financing which combines UK-style stability with US-type entrepreneurialism is an effective model for fusion commercialisation and the safeguarding of public accountability.

[41] *Towards Fusion Energy: The UK Government's Fusion Strategy*. UK Department for Business, Energy & Industrial Strategy, Oct. 2021.

[42] Fusion Energy Act, HR 5244. Introduced in the House of Representatives to amend the Atomic Energy Act of 1954 to include fusion energy machines and referred to the House Committee on Energy and Commerce.

[43] Uzar (n 12) *supra*.

[44] Stirling (n 19) *supra*.

[45] UK Atomic Energy Authority (n 31) *supra*.

[46] Casady, Carter, et al. "Public–Private Partnerships for Low-Carbon, Climate-Resilient Infrastructure: Insights from the Literature." *Journal of Cleaner Production*, vol. 470, 2024, 143338.

For instance, UK7 stated that "the challenge is to de-risk private investment without re-nationalising science", while US7 remarked that "federal milestones give us legitimacy; private equity gives us speed". It is evident that both perspectives highlight tensions between public and private interests, and the literature also supports these findings. Mazzucato argues that the State's role as market shaper is critical for de-risking low-carbon technologies while retaining social value.[47] In fusion where high capital and long timelines are associated with its development, private finance remains insufficient and public finance struggles to scale. Successful transitions require polycentric innovation ecosystems, where multiple actors share authority and responsibility and policy frameworks that embody these hybrid arrangements through co-funding, intellectual property agreements, and transparent oversight are more resilient to political change.[48]

4. Energy Security and Social Acceptance

Energy security discourse is grounded in the UK and US policy environments. UK interviewees framed fusion as a sovereign capability which ensures net-zero resilience, whereas US interviewees highlighted global competitiveness and technological leadership. In both countries, the political narratives of autonomy and modernisation are reinforced due to fusion's potential as a sustainable energy source. However, these narratives are filtered through the UK's climate responsibility and American innovation exceptionalism.[49]

Public understanding of fusion remains limited and often conflicted with nuclear fission.[50] Several interviewees in both contexts acknowledged that public perception "lags decades behind the science". The UK has taken deliberate steps to address this gap through outreach programmes by the UK Atomic Energy Authority and consultations at the designated STEP host community, West Burton. These processes include community benefits packages and local skills development initiatives to generate socioeconomic value. Similarly, American communication efforts are industry-led, with private firms investing in branding fusion as clean nuclear through media campaigns and university partnerships.[51] Societal legitimacy thus depends on perceived fairness, transparency, and inclusion. Interdisciplinary scholars of science and technology emphasise that acceptance emerges from the co-production of knowledge.[52] Empirical studies of wind and geothermal projects show that procedural justice, where communities can design and shape governance is strongly linked to acceptance and is applicable to nuclear fusion.[53]

In both countries, interviewees highlighted equity concerns: who benefits from fusion development, and who bears its risks? Civil-society actors cautioned that inconsistent engagement within the fusion sector could result in regional inequalities. Though the UK fosters a higher baseline trust through government stewardship, consultation fatigue can emerge if communities perceive decisions as predetermined. The American approach, which encourages diverse experimentation, has the limitation of uneven participation because of its market-driven engagement. Bridging these gaps requires mechanisms such as citizen panels, deliberative assemblies, or

[47] Mazzucato (n 39) *supra*.
[48] Sovacool, Benjamin, et al. "Energy Transitions from the Cradle to the Grave: A Meta-Theoretical Framework Integrating Responsible Innovation, Social Practices, and Energy Justice." *Energy Research & Social Science*, vol. 75, May 2021, 102027.
[49] Labussière, Olivier, and Alain Nadaï. *Energy Transitions: A Socio-Technical Inquiry*. Palgrave Macmillan, 2018.
[50] Jones, Christopher, et al. "Predicting Attitudes Towards Fusion Energy in Europe: Results of a Cross-National Public Survey in Austria, Finland, Spain and the UK." *Energy Research & Social Science*, vol. 75, 2021, article 102028.
[51] *The Global Fusion Industry in 2023: Fusion Companies Survey*. Fusion Industry Association, 2023.
[52] Jasanoff, Sheila. *Designs on Nature: Science and Democracy in Europe and the United States*. Princeton University Press, 2005.
[53] Wolsink, Maarten. "Wind Power Implementation: The Nature of Public Attitudes—Equity and Fairness Instead of 'Backyard Motives'." *Renewable and Sustainable Energy Reviews*, vol. 11, no. 6, 2007, pp. 1188-1207.

statutory advisory boards that embed citizen voice in planning. These mechanisms align fusion governance with the required democratic accountability of low-carbon technologies. As Mercer et al. note, distributive justice is integral to sustainable technology governance.[54] Therefore, governments face a dual mandate: the delivery of clean energy and its contribution to social inclusion.

C. *Cross-Case Comparison*

This subsection presents a comparative synthesis which underscores how institutional variations shape fusion deployment. The findings reinforce the broader theoretical claim that energy transitions are political projects embedded in institutional contexts. They also show that while fusion is technologically universal, its governance is nationally specific. Thus, its political economy exemplifies how climate goals are negotiated through institutional systems. These contrasts further illuminate nuclear fusion's dual identity: as a technological frontier and as an arena of political negotiation.

Across the UK and the US, three patterns emerged to illustrate stakeholder interpretations (**Figure 2**, below). These patterns were generated through a thematic analysis of both policy documents and interview transcripts, which involved an iterative process of manual coding and a cross-case comparison between the UK and US data. The first pattern shows that institutional coherence provides predictable pathways for fusion development, but it also constrains adaptive decision-making when political priorities shift. In contrast, institutionally flexible environments such as the US accelerate experimentation but generate coordination challenges, highlighting a trade-off between stability and innovation. The second pattern illustrates that public–private partnerships operate differently across governance regimes: the UK model embeds partnership within State-led strategy, while the US model relies on competitive market dynamics. These differences shape how risk is distributed, which actors hold agenda-setting power, and how accountability mechanisms are constructed. The final pattern underscores the fragility of societal legitimacy, showing that technical optimism alone is insufficient for public acceptance. Community involvement, procedural fairness, and distributive equity emerged across interviews as core determinants of social license to operate.

V. **Conclusion and Policy Implications**

This comparative investigation of the United Kingdom and the United States demonstrates that the political economy of energy transitions is about governance, ideology and technology. Though it is scientifically promising, fusion energy advances within complex systems of interests, institutions, and discourses that determine its commercialisation. The study shows that fusion is neither a purely technical innovation nor a politically neutral enterprise: but its development reflects underlying social contracts between the State and the market.[55] The UK's model of fusion governance shows the strength of State coordination and long-term strategic planning. Its reliance on government-led frameworks such as STEP programme and the Fusion Strategy 2023 has created institutional coherence and public trust, at the cost of bureaucracy. By embedding fusion within its national decarbonisation and industrial strategy, the UK demonstrates how government-led planning can foster stability and legitimacy. However, the system's highly centralised character also constrains responsiveness to changing scientific or fiscal conditions. Conversely, the US model exemplifies innovation through decentralisation. Competitive funding, venture capital participation, and milestone-based incentives have accelerated technological breakthroughs

[54] Mercer, Jessica, et al. "Ecosystem-Based Adaptation to Climate Change in Caribbean Small Island Developing States: Integrating Local and External Knowledge." *Sustainability*, vol. 4, no. 8, 2012, pp. 1908-1932.

[55] Meadowcroft, James. "What About the Politics? Sustainable Development, Transition Management, and Long-Term Energy Transitions." *Policy Sciences*, vol. 42, no. 4, 2009, pp. 323-340.

but produced uneven regulation and limited civic engagement. While this pluralism encourages experimentation, it affects policy coherence and long-term accountability. These findings affirm the dual nature of liberal regimes: adaptive and entrepreneurial, but fragmented and vulnerable to short political cycles. Both countries reveal that institutional quality and political will are decisive in transforming fusion from experimental research into commercial reality. The analysis yields three core insights. First, fusion development in the UK and US is shaped by distinct national governance logics, with the United Kingdom relying more heavily on State-led frameworks and the United States on private-sector innovation. Secondly, stakeholder interests and the distribution of power across public, private, and civil-society actors significantly influence the degree of political willingness to prioritise fusion within broader decarbonisation strategies. Third, fusion's integration into climate policy remains contingent on regulatory clarity, credible timelines, and the alignment of fusion narratives with existing low-carbon regimes. The study is not without limitations: it focuses on two advanced industrial democracies and captures stakeholder perspectives at a specific moment in time, when fusion policy and technology are rapidly evolving. Future research could extend this analysis to additional countries and explore longitudinal changes in fusion governance. Where political consensus aligns with transparent governance and inclusive stakeholder participation, fusion can emerge as a suitable low-carbon technology.

A. *Policy Implications*

This subsection discusses the three central policy implications that emerged from this study.

1. Institutional Integration

Fusion policy should be integrated into comprehensive national climate and industrial strategies rather than a stand-alone innovation agenda to ensure coherence between research, regulation, and market deployment.

For the UK, this means sustaining cross-ministerial collaboration between the Department for Energy Security and Net Zero, the Treasury, and the Department for Business and Trade to ensure that fusion's industrial potential aligns with regional development. For the US, this implies that a more coordinated national framework that aligns the Department of Energy's programmes with State-level initiatives and private-sector investments. The renewable sector suggests that this policy design enhances investor confidence and accelerates deployment.[56]

This recommendation follows from the finding that institutional coherence significantly shapes fusion's political trajectory in the UK, while institutional fragmentation in the US has hindered regulatory predictability (Sections IV.A and IV.B).

2. Public Trust and Social Legitimacy

The governance of fusion must prioritise social legitimacy as a condition of its development. Public understanding of fusion remains limited and susceptible to association with fission. Transparent communication, inclusive consultation, and equitable benefit-sharing are essential.

In the UK, this could take the form of permanent citizen advisory panels linked to STEP host communities. In the US, this requires stronger environmental-justice protocols and clear community engagement standards in Department of Energy milestone funding initiatives. Social acceptance is not peripheral but central, and political coalitions within the fusion sector remain fragile in its absence.

This emphasis on public trust derives from the observed fragility of societal legitimacy across both cases, where interviewees warned that fusion's public acceptance is contingent upon

[56] Panos, Evangelos, et al. "Deep Decarbonisation Pathways of the Energy System in Times of Unprecedented Uncertainty in the Energy Sector." *Energy Policy*, vol. 180, 2023, 113642.

transparency and meaningful participation (Sections IV.B.4 and IV.C).

3. International Coordination and Standardisation

Global progress in fusion requires harmonised regulation and shared R&D infrastructures. The 2023 UK–US bilateral framework is a significant achievement, but broader multilateral collaboration through the OECD and IAEA platforms is necessary to establish common safety, waste, and licensing standards. As technological maturity increases, coordinated global standards will reduce duplication and improve public confidence. International cooperation also mitigates technological nationalism, ensuring that fusion contributes to collective decarbonisation rather than competitive advantage.

These policy implications highlight a common principle: fusion must be governed as a public good. While market incentives can accelerate innovation, strong public institutions can guarantee that its benefits are distributed equitably and sustainably. The political economy of energy transitions underscores a broader truth of climate governance; the success of technological revolutions is embedded in credible, legitimate, and accountable political orders.

This recommendation reflects findings on cross-national interdependence and interviewee concerns that regulatory divergence may slow commercialisation unless harmonised global standards evolve in parallel (Section IV.B.1).

VI. **Future Research Directions**

This study offers a comparative framework but also recognises its limits. Further research could extend this analysis to include emerging economies such as China, South Korea, and India, where fusion policy operates within different developmental and institutional contexts.[57] Comparative multi-level analyses could also examine how local authorities address national policy goals. Moreover, as fusion powerplants are starting to reach viability, longitudinal research which tracking socio-economic outcomes such as employment, community benefits, and environmental performance is crucial. From a methodological presentative, integrating quantitative indicators such as investment flows and patent data could complement qualitative insights and future interdisciplinary studies could explore how fusion interacts with other low-carbon technologies in energy-system modelling. These extensions would not only refine academic understanding but also support evidence-based policymaking in an era where climate, technology, and geopolitics are increasingly intertwined.

[57] Zheng, Jinxing, et al. "Recent Progress in Chinese Fusion Research Based on Superconducting Tokamak Configuration." *The Innovation*, vol. 3, no. 4, 2022, 100269.

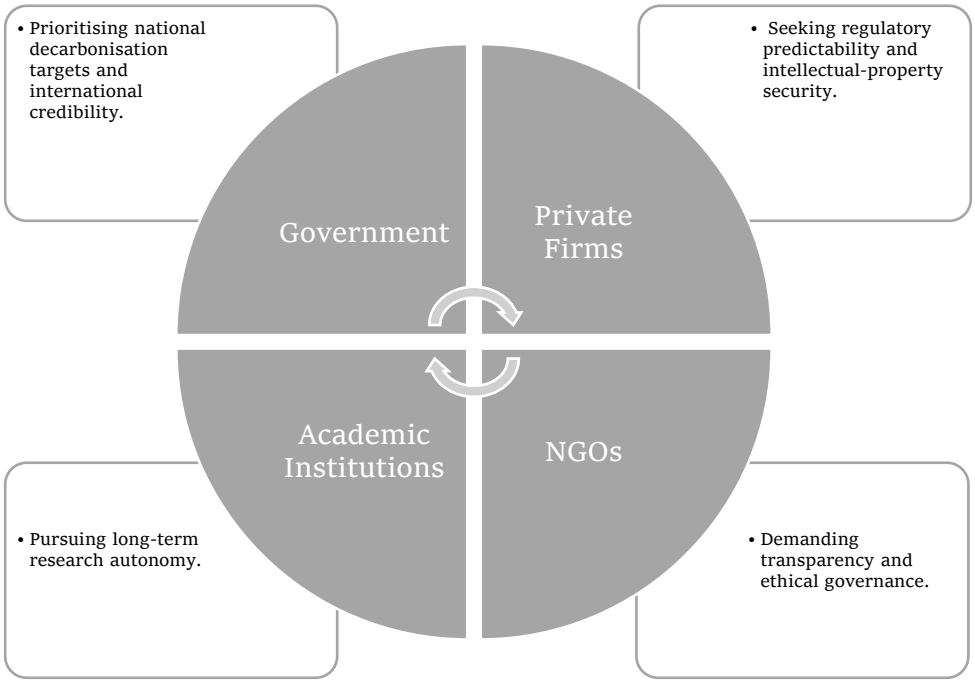


Figure 1: Stakeholder Coalitions.

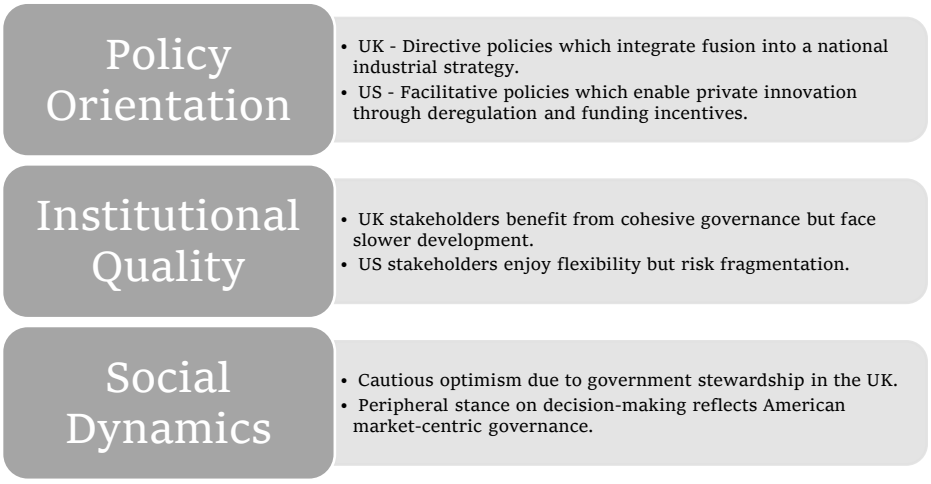


Figure 2: Comparative Stakeholder Synthesis.

Stakeholder	***Organisation***	***Code***
State Actors	*Department for Energy Security and Net Zero*	*UK1*
	Fusion Energy Advisory Committee	*US1*
	Gloucestershire County Council	*UK2*
	North Dakota Energy Office	*US2*
	Office of Fusion Energy Sciences	*US3*
	Stroud District Council	*UK3*
	UK Atomic Energy Authority	*UK4*
	UK Parliament	*UK5*
	US Fusion Outreach Team	*US4*
	US Congress	*US5*
Private Firms	*Commonwealth Fusion Systems*	*US6*
	First Light Fusion	*UK6*
	Tokamak Energy	*UK7*
	Xcimer Energy	*US7*
Academic Institutions	*Dalton Nuclear Institute*	*UK8*
	Fusion Centre for Doctoral Training	*UK9*
	Institute for Fusion Studies	*US8*
	Princeton Plasma Physics Laboratory	*US9*
Non-Governmental Organisations	*British-American Security Information Council*	*UK10*
	Campaign for Nuclear Disarmament	*UK11*
	Clean Air Task Force	*US10*
	Energy for the Common Good	*US11*

Table 1: Interview Participants and Coding Schemes.

Knowledge Asymmetries and Climate Finance: An Inquiry into Environmental Market Failures and Political Legitimacy

James Rice*

* PhD Candidate (Department of Government), University of Essex, UK

KEYWORDS

asymmetric information, environmental market failures, climate risk, capital misallocation, democratic legitimacy,

ABSTRACT

This paper examines how asymmetric information distorts climate-related financial markets and undermines democratic legitimacy in political institutions, contributing to epistemic climate injustice. Building upon canonical theories of information economics, I refine the classical concepts of adverse selection and moral hazard to accommodate the distinctive features of climate risk: deep uncertainty, cascading fluctuations over time in trend and cyclicality, systemic feedback loops, and intergenerational trade-offs. I show how informational gaps generate market failures in the pricing and allocation of green assets and climate-linked securities, demonstrating that, for some agents, climate modelling and verification mechanisms produce systematic mispricing of green assets, leading to inefficient capital misallocation that cannot be remediated without recourse to new forms of global governance. I propose a multi-pronged normative framework for democratising climate knowledge production through democratic changes that amplify deliberative processes using intergenerational mechanisms based on the institutionalisation of access to information. This article offers a roadmap for mitigating informational asymmetries while advancing a substantive global response to climate change.

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I. Introduction

Climate change represents what Gardiner characterises as a "perfect moral storm"—a convergence of global, intergenerational, and theoretical challenges that strain conventional frameworks of ethics, politics, and economics.[1] The gradual but inexorable transformation of Earth's climate system creates profound risks for current and future societies, demanding not merely technological innovation and political will, but fundamentally new approaches to organising markets and institutions under conditions of deep uncertainty.[2] Yet as this article argues, the informational foundations necessary for effective climate governance are

[1] Gardiner, S. *A Perfect Moral Storm: The Ethical Tragedy of Climate Change*. Oxford University Press, 2013.

[2] Knight, F. *Risk, Uncertainty, And Profit*. Houghton Mifflin, 1921; Keynes, J. "The General Theory of Employment." *The Quarterly Journal of Economics*, vol. 51, no. 2, 1937, pp. 209-223.

systematically corrupted by asymmetries in knowledge, access to information, and illiberal epistemic authority that generate both market failures and threats to democracy. The theory of asymmetric information, pioneered in the seminal contributions of Akerlof,[3] Mirrlees,[4] and subsequently formalised by Rothschild and Stiglitz,[5] illuminates how disparities in knowledge among economic agents give rise to adverse selection, moral hazard, and market structures that are adversarial and opaque. Throughout this article, I draw on both Rawlsian traditions of justice as well as those from Amartya Sen, but with distinct emphases. From Rawls, I take the concern for fairness in institutional design and the intergenerational obligations that follow from it. From Sen, I adopt the view that justice must be judged by the expansion of people's real freedoms and capabilities to act within and upon climate-affected environments.

In archetypal credit and capital markets, informational gaps can lead to the withdrawal of high-impact participants and incentivise excessive risk-taking by parties unaware of the risks they face. Within climate-related markets there is a similar trend: investors systematically underestimate tail risks associated with carbon-intensive assets—including risks from climate-caused natural events, which threaten those assets—while firms strategically under-disclose their exposure to these physical and transition risks.[6] However, unlike conventional markets operating under risk (where probability distributions are known), climate change is one of the phenomena of our modern era that involves a deeper level of uncertainty—situations where the probability distributions themselves are unknown or contested.[7] This distinction proves philosophically crucial. Standard models of asymmetric information presuppose well-defined probability spaces and short temporal horizons over which rational agents optimise. Climate risk, by contrast, involves black swan events: low-probability, high-impact occurrences that resist probabilistic quantification.[8] More fundamentally, climate change involves fat-tailed distributions where extreme outcomes become disproportionately likely, rendering expected utility maximisation inadequate or meaningless.[9] The temporal scales over which climate impacts unfold—spanning decades to centuries—further complicate standard decision-theoretic approaches by introducing the non-identity problem, whereby the actions we take today will determine not merely the welfare of future persons, but their very identities.[10]

These epistemic challenges generate informational climate injustice—social structures within which systematic patterns of knowledge asymmetry concentrate climate-relevant information among powerful actors while marginalising the epistemic contributions of those most vulnerable when searching for solutions to global climate impacts. Drawing on Fricker's groundbreaking analysis,[11] I argue that modern, present day climate governance exhibits both discriminatory injustice (whereby marginalised groups are deemed less credible sources of climate knowledge) and hermeneutical injustice (whereby dominant

[3] Akerlof G. "The Market For "Lemons": Quality Uncertainty and The Market Mechanism." *The Quarterly Journal of Economics*, vol. 84, no. 3, 1970, pp. 488-500.
[4] Mirrlees, J. "An Exploration in the Theory of Optimum Income Taxation." *Proceedings of the Royal Society of London: Series A, Mathematical and Physical Sciences*, vol. 330, no. 1584, 1971, pp. 3-98.
[5] Rothschild, M, and J Stiglitz. "Equilibrium in Competitive Insurance Markets: An Essay on The Economics of Imperfect Information." *The Quarterly Journal of Economics*, vol. 90, no. 4, 1976, pp. 629-649.
[6] Bolton, P, et al. "The Green Swan: Central Banking and Financial Stability in The Age of Climate Change." BIS Working Paper, 2021.
[7] Knight (n 2) *supra.*
[8] Taleb, N. *The Black Swan: The Impact of the Highly Improbable.* Random House, 2007.
[9] Weitzman, M. "On Modeling and Interpreting the Economics of Catastrophic Climate Change: The Limits of Integrated Assessment Models." *The Review of Economics and Statistics*, vol. 91, no. 1, 2009, pp. 1-19. Liesen, A. "Climate Change and Financial Market Efficiency." *Business & Society*, vol. 54, no. 4, 2015, pp. 511-539.
[10] Parfit, D. *Reasons and Persons.* Oxford University Press, 1984.
[11] Fricker, M. *Epistemic Injustice: Power and the Ethics of Knowing*. Oxford University Press, 2007.

interpretive frameworks obscure or delegitimise alternative ways of understanding climate risk). In financial markets, asymmetric information regarding climate risk manifests across multiple dimensions that compound these epistemic injustices. First, the valuation of green financial instruments—including green bonds, sustainability-linked loans, and ESG-rated securities—depends critically on credible disclosures by issuers. Yet corporate reporting standards for greenhouse gas emissions and climate-related risks remain voluntary in many jurisdictions and exhibit wide variation in scope, methodology, and verification.[12] Climate policy, worldwide, still suffers from weak enforcement mechanisms and allows substantial discretion in the risk modelling approaches used by a variety of stakeholder parties including states, NGOs, multinational corporations, and firms.[13]

Second, conventional asset pricing models systematically understate transition risks—the financial risks arising from the shift toward a low-carbon economy. As Carney warns,[14] current carbon-intensive investments may become stranded assets if future regulation or technological shifts abruptly re-price fossil fuel holdings, potentially triggering a Minsky moment in carbon markets.[15] Third, tail risks associated with extreme climate scenarios are often omitted from risk management systems or assigned negligible probabilities, leading to inadequate capital buffers and systemic financial fragility.[16] These market failures cannot be understood merely as technical inefficiencies; they constitute forms of structural injustice that systematically disadvantage market participants without necessarily involving intentional wrongdoing by any individual actor.[17] The concentration of climate-relevant information among financial elites and fossil fuel incumbents perpetuates the status-quo of sophisticated investors with access to proprietary climate models systematically outperforming retail investors in climate-sensitive markets, extracting rents from informational advantages while externalising climate risks onto less informed market participants.[18]

These challenges are compounded by the value-ladenness of climate science.[19] Despite efforts and theories that emphasise neutrality, scientific assessments of climate risk necessarily involve value judgments about acceptable levels of risk, appropriate discount rates for future benefits and costs, and the relative importance of different types (or magnitudes) of climate impacts. When these value judgments remain implicit or are delegated to a unique and isolated cadre of technical experts, they can systematically exclude certain critical players in international diplomacy who have financial power, generating forms of epistemic injustice, which can lead to malign incentive structures disincentivising participation in what should be a democratic market.[20] The politics of climate expertise thus become entangled with broader questions of epistemic authority and democratic inclusion within the

[12] Li, Q, et al. "Corporate Climate Risk: Measurements and Responses." *The Review of Financial Studies*, vol. 37, no. 6, 2024, pp. 1778-1830.
[13] *Recommendations Of the Task Force on Climate-related Financial Disclosures*. Financial Stability Board, 2017; *see* also Krueger, P, et al. "The Effects of Mandatory ESG Disclosure Around the World." ECGI Finance Working Paper No. 754/2021, 2023; thanks to a reviewer for pointing to this paper which discusses international ESG disclosure and compliance using a data-driven approach.
[14] Carney, M. "Breaking the Tragedy of The Horizon—Climate Change and Financial Stability." Bank of England. Speech at Lloyd's of London, 2015.
[15] A Minsky moment is a tipping point in a credit cycle when excessive speculation and leverage suddenly reverse into panic-selling and widespread deleveraging: *see* Minsky, H. *Stabilizing an Unstable Economy.* Yale University Press, 1986.
[16] Battiston, S, et al. "A Climate Stress-Test of the Financial System." *Nature Climate Change*, vol. 7, no. 4, 2017, pp. 283-288.
[17] Young, I. *Responsibility for Justice*. Oxford University Press, 2011.
[18] Eren, E, et al. "Pricing of Climate Risks in Financial Markets: A Summary of The Literature." *BIS Papers*, vol. 130, 2022, pp. 1-11.
[19] Douglas, H. *Science, Policy, And the Value-Free Ideal*. University of Pittsburgh Press, 2009.
[20] Anderson, E. "Epistemic Justice as A Virtue of Social Institutions." *Social Epistemology*, vol. 26, no. 2, 2012, pp. 163-173.

scientific project.[21] The sciences are, alas, distinct from financial markets and the international political forum where decisions are often made. Yet climate science operates under conditions of urgency and technical complexity that seem to preclude extensive democratic deliberation and careful prudence with respect to investment. This tension between epistemic and democratic values generates a climate knowledge dilemma such that the urgent need for authoritative climate knowledge conflicts with democratic requirements for inclusive deliberation about the values that should guide climate research and policy.

This article develops a systematic philosophical treatment of these issues by examining how informational asymmetries corrupt both market mechanisms and democratic institutions in the climate domain. I begin in Section II by describing a theoretical framework that extends canonical models of asymmetric information to accommodate the distinctive epistemic features of climate change. These include deep uncertainty about physical processes, overlapping awareness about knowledge pertaining to the interactions between the climate and the economy, systemic risks arising from tipping points and feedback loops, and the intergenerational transmission of both benefits and burdens from pollution and abatement. Section III analyses how these informational asymmetries generate specific forms of market failure in climate finance, including systematic under-pricing of tail risks, misallocation of capital toward high-carbon investments, and the emergence of green bubbles—greenwashing—even in supposedly sustainable subsets of financial markets. I also demonstrate how opacity in climate risk modelling creates opportunities for sophisticated actors to extract rents from information asymmetries while normalising (extreme) climate risks.

Section IV explores the political implications of the financial aspects of this theory, focusing on how informational asymmetries undermine the epistemic conditions necessary for legitimate democratic governance of international climate policy. Drawing on theories of deliberative democracy, global justice, and intergenerational ethics, I argue that current patterns of climate knowledge production and dissemination violate principles of epistemic justice and democratic inclusion. This section also proposes normative and institutional solutions designed to mitigate informational failures while advancing egalitarian epistemic climate justice. I do not advocate for any singular ideological position but instead suggest the need for the institutionalisation of structured information environments (both public and private) where climate-aware groups can exchange ideas, knowledge, goods, services, and solutions.

Finally, Section V offers concluding reflections on the broader implications of financial and informational climate injustice for theories of market failure, democratic legitimacy, and global justice. I identify promising avenues for future research at the intersection of philosophy, climate economics, and political theory, while acknowledging that there exist tensions between urgent climate action and the deliberative processes required for legitimate democratic governance. This article aims to contribute a novel framework for understanding how informational asymmetries both generate and perpetuate injustices in climate governance. My analysis reveals that addressing climate change effectively requires not merely better information, but more just distributions of epistemic power and more inclusive processes of knowledge production that honour both scientific rigor and democratic values.

II. **Concepts of Asymmetric Information**

At its core, asymmetric information arises when economic actors differ in either the data they hold or their ability to interpret it. Traditional treatments emphasise the distribution of explicit facts, but in climate

[21] Kitcher, P. *Science in a Democratic Society*. Prometheus Books, 2011.

settings we must also attend to Polanyi's notion of tacit knowledge—those embodied, context-sensitive understandings that defy complete formalisation.[22] In the standard formalism, two (or more) parties trade with different, basic, sets of available information, each comprising propositions and facts about the world with clearly defined truth values. In contrast, many climate-related insights fall into Rescher's category of aporetic knowledge: aporetic in the sense that there exist, within climate science, inherently indeterminate propositions—such as future weather patterns or the reactions of politics—for which stronger data alone cannot eliminate uncertainty.[23]

We can therefore refine asymmetric information into three interconnected forms. Distributional asymmetry denotes unequal access to the same information, reflecting not only market power but also the social processes that shape knowledge production—a dynamic Harding highlights when she describes how research always embodies the perspectives of its producers.[24] In climate finance, this plays out when sophisticated institutional investors commission proprietary, high-resolution financial models, while smaller actors depend on public reports that often lag behind current market movements or omit localised (systemic or tail) risks. Asymmetry we might term interpretative arises when agents share identical datasets but apply divergent hermeneutical or cognitive frameworks. As Gadamer observes, our readings always occur within particular "horizons of understanding" shaped by history, culture, and institutional norms.[25] Thus, a petroleum engineer and a climate scientist examining the same geological survey might reach sharply different conclusions about stranded-asset risk, not because the raw data differ but because their disciplinary paradigms guide which variables they consider salient. Finally, epistemic—or, more fundamentally, knowledge—asymmetry concerns disparities in the capacity to generate, validate, and deploy specialised knowledge. In climate governance, engaging with technical or political discourse creates asymmetries based on skill and individual awareness of technological frontiers that determine which voices are heard at decision-making tables and whose knowledge is deemed credible.[26]

In neoclassical economics, Akerlof's seminal analysis of markets treats quality disparities as hidden yet objectively determinable, leading informed sellers to drive uninformed buyers from the market due to losses founded on their lack of awareness of market conditions.[27] Climate risk challenges the assumption that we understand objective reality as pure, untarnished information; indeed, we may be corrupting or causal players in the information we seek to understand.[28] As Dupuy argues, our understanding of future environmental and regulatory outcomes is "projective", co-constituted by present beliefs and decisions.[29] Investors' current judgments about a green bond's quality, or the creditworthiness of a particular entrepreneurial endeavour feed back into policy debates and technological development pathways, thereby altering the very future states they seek to forecast. Akerlof's model assumes stable preferences and technologies, whereas climate dynamics often unfold as increasing-returns processes, in Arthur's sense, where small early advantages become self-reinforcing through feedback loops.[30] Early movers in emerging clean-tech markets have the ability to build

[22] Polanyi, M. *Personal Knowledge: Towards A Post-Critical Philosophy*. University of Chicago Press, 1958.
[23] Rescher, N. *Luck: The Brilliant Randomness of Everyday Life*. University of Pittsburgh Press, 2001.
[24] Harding, S. *Whose Science? Whose knowledge? Thinking From Women's Lives*. Cornell University Press, 1991.
[25] Gadamer, H. *Truth and Method.* Continuum International Publishing Group, 1960.
[26] Collins, H, and R Evans. "The Third Wave of Science Studies: Studies of Expertise and Experience." *Social Studies of Science*, vol. 32, no. 2, 2002, pp. 235-296.
[27] Akerlof (n 3) *supra*.
[28] Putnam, H. *Reason, Truth and History*. Cambridge University Press, 1981.
[29] Dupuy, J. *The Mark of The Sacred*. Stanford University Press, 2009.
[30] Arthur, W. *Increasing Returns and Path Dependence in The Economy*. University of Michigan Press, 1994.

critical expertise and network connections that allow them to capture information rents over extended periods, undercutting the equilibrium parity that standard neoclassical models often assume.

Mirrlees's mechanism design framework holds that a principal (an investor, politician, or economic agent), armed with knowledge of the incentive constraints faced by their interlocutors or trading partners, can engineer contracts to elicit truthful information from those partners.[31] Such an approach relies on a condition of internal consistency in choice—the idea that agents hold complete, transitive preferences that remain stable across contexts.[32] Yet climate decision-making often involves incommensurable values due to fundamental differences in moral standing among agents party to environmental decisions—one agent could be a major emitter of CO_2 and the other could be a denizen of a small island nation, for example.[33] For example, a pension fund must weigh fiduciary duties to current retirees against stewardship responsibilities to future beneficiaries who will face climate-driven dislocations—a dilemma that resists reduction to a single utility function. Furthermore, Mirrlees's model depends on the designer's near-omniscience to identify and enforce incentive-compatible allocations, running headlong into Hayek's critique of the knowledge problem. In Hayek's terms, no central planner can aggregate and process the dispersed, tacit, and context-specific information embedded in complex socio-ecological systems.[34] Instead, governance must incorporate Metis—practical, localised wisdom and Indigenous ecological knowledge that frequently, if not always, fall outside formal modelling frameworks.[35]

Stiglitz and Weiss's analysis of credit allocation and rationing assumes that lenders can observe loan performance over time and update their beliefs accordingly, such that the value of information is aligned through economic and financial mechanisms with outcomes that matter at the individual level.[36] Climate finance often operates similarly, on a kind of normative trust which can be defined as faith in counterparties' (or the planners') commitment to shared environmental and policy goals despite persistent technical uncertainties. Financing a large-scale solar or carbon capture project not only requires projections of future cash flows but also a belief in the durability and continued engagement of supportive, democratic, policy regimes. These complexities emphasise the necessity to study how evolving rules, norms, and collective strategies can govern common-pool resources—in this case, shared climate knowledge with the ability to move and motivate financial and political actors—under deep uncertainty.[37]

Prevailing information economics embeds certain philosophical commitments about the nature of knowledge, rationality, and agency that falter when applied to climate systems. Knight's foundational distinction between risk and uncertainty, later formalised by Savage, treats uncertainty as a temporary state of ignorance resolvable through additional data collection.[38] Climate science also exemplifies Funtowicz and Ravetz's notion of post-normal science, where facts are uncertain, values in dispute, stakes high, and decisions urgent.[39] In this context, Nowotny et al. argue for a

[31] Mirrlees (n 4) *supra*.
[32] Sen, A. "Rational Fools: A Critique of The Behavioural Foundations of Economic Theory." *Philosophy & Public Affairs*, vol. 6, no. 4, 1977, pp. 317-344.
[33] *see* Raz, J. *The Morality of Freedom*. Oxford University Press, 1986, on incommensurable values.
[34] Hayek, F. "The Use of Knowledge in Society." *The American Economic Review*, vol. 35, no. 4, 1945, pp. 519-530.
[35] Scott, J. *Seeing Like a State: How Certain Schemes to Improve the Human Condition Have Failed*. Yale University Press, 1998.
[36] Stiglitz, J, and A Weiss. "Credit Rationing in Markets with Imperfect Information." *American Economic Review*, vol. 71, no. 3, 1981, pp. 393–410.
[37] Ostrom, E. *Understanding Institutional Diversity*. Princeton University Press, 2006.
[38] Knight (n 2) *supra*; Savage, L. *The Foundations of Statistics*. 1st edn, John Wiley & Sons, 1954.
[39] Funtowicz, S, and J Ravetz. "Science for the Post-Normal Age." *Futures*, vol. 25, no. 7, 1993, pp. 739-755.

socially robust knowledge that calls for a validation of social and political information by insisting that broader communities of practice have a role in certifying the credibility of scientific findings.[40] Thus, information asymmetries in climate governance become not merely technical issues but questions of democratic legitimacy, equity, and procedural justice. Individuals' lives depend on the findings of scientists and the actions that financiers and pundits take every day.

Decision theory under uncertainty further illuminates these tensions. Savage's expected utility framework presumes that rational agents can assign precise probabilities to all conceivable states of the world, a subjective requirement Jeffrey has developed some time ago.[41] Yet many climate phenomena involve ambiguity—situations in which meaningful probability assignments are impossible.[42] Gilboa and Schmeidler's maxmin expected utility model captures agents' aversion to ambiguity by privileging worst-case evaluations over uncertain prospects.[43] In the climate domain, choices made today will shape the well-being of future people whose identities and life circumstances cannot be fully anticipated. Parfit's non-identity problem expresses this and further complicates welfare analyses by demonstrating that policies determining which future individuals come into existence cannot be judged solely by whether those individuals fare better or worse than counterfactual selves.[44] Closely following this, O'Neill argues that intergenerational justice requires safeguarding substantial freedoms—including accepting variations in deciding, politically, what are the core requirements necessary for human flourishing irrespective of historical (or environmental) context.[45] When information asymmetries concentrate decision power among present-day elites, they risk undermining freedoms for those yet unborn, reflecting democratic failures as much as market failures.[46]

Integrating these perspectives, I reconceive the climate information environment as an epistemic commons: a shared knowledge resource demanding collective stewardship to remain vibrant, equitable, and adaptive. Building on Ostrom's analysis of common-pool resources,[47] I recognise that epistemic goods face central challenges familiar from material commons, particularly exclusion—when communities or stakeholders are barred from accessing or contributing to data when proprietary models or closed platforms create competitive advantages that discourage sharing. In addition to this, as Hess in collaboration with Ostrom emphasises, information is fundamentally non-rivalrous in consumption,[48] even though intellectual property regimes and technical barriers can impose artificial scarcity. Moreover, Fuller's account of knowledge through network effects can be used to show that the value of climate knowledge increases with the size and diversity of the community engaged in its production and use.[49] Addressing climate information asymmetries thus becomes a collective-action problem requiring institutional innovation and careful analysis by agents who enter the environmental and financial space.

Drawing on Ostrom's design principles for robust governance of common-pool resources,[50] I argue that six interlinked

[40] Nowotny, H, et al. *Re-Thinking Science: Knowledge and The Public in An Age of Uncertainty.* Polity Press, 2001.
[41] Jeffrey, R. *The Logic of Decision.* University of Chicago Press, 1965.
[42] Schmeidler, D. "Subjective Probability and Expected Utility Without Additivity." *Econometrica*, vol. 57, no. 3, 1989, pp. 571-587.
[43] Gilboa, I, and D Schmeidler. "Maxmin Expected Utility with Non-Unique Prior." *Journal of Mathematical Economics*, vol. 18, no. 2, 1989, pp. 141-153.
[44] Parfit (n 10) *supra*.
[45] O'Neill, O. *Justice Across Boundaries: Whose Obligations?* Cambridge University Press, 2001.
[46] Anderson, E. "What Is the Point of Equality?" *Ethics,* vol. 109, no. 2, 1999, pp. 287-337.
[47] Ostrom, E. *Governing the Commons: The Evolution of Institutions for Collective Action.* Cambridge University Press, 1990.
[48] Hess, C, and E Ostrom. *Understanding Knowledge as a Commons: From Theory to Practice*. MIT Press, 2006.
[49] Fuller, S. *Social Epistemology.* 2nd edn, Indiana University Press, 2002.
[50] Ostrom (n 37) *supra*.

requirements emerge for an epistemic commons based on climate action and a just green transition. First, clearly defined boundaries that determine who may access, interpret, and enrich the shared knowledge base, must be balanced with the need for more, and more powerful, expertise and the universal imperative of inclusivity. Second, collective-choice mechanisms should empower all stakeholders in global climatological affairs to shape and revise the rules governing data collection, curation, and dissemination, particularly on closed platforms. Third, robust monitoring protocols are essential to detect and deter misuse of information—such as selective disclosure, false reporting, or greenwashing—and to ensure transparency in both model assumptions and data provenance. Fourth, graduated efforts to rectify norm violations can be proportional to the severity and frequency of breaches of trust, ensuring accountability without discouraging participation. Fifth, accessible conflict-resolution processes must adjudicate disputes over contested knowledge claims, methodological approaches, or policy interpretations in a manner perceived as fair by all parties. Finally, by recognising the rights to self-organise can acknowledge grassroots communities' ability to develop localised and decentralised climate knowledge systems. This may help foster epistemic diversity and resilience in an era shaped by big data and institutional agglomeration of knowledge and resources. By operationalising these principles, existing institutions, as well as activist groups, can both mitigate informational asymmetry and strengthen democratic legitimacy. Subsequent Sections will illustrate how these design elements can be deployed in specific arenas of climate finance and policy, bridging rigorous market analysis with broader concerns of justice, democracy, and collective action.

III. **Asymmetric Information in Climate-Related Financial Markets**

As global financial markets increasingly seek to incorporate climate considerations into asset valuation and risk management, the pervasive influence of asymmetric information has become ever more salient. Financial instruments explicitly tied to environmental performance—green bonds, sustainability-linked loans, and carbon derivatives[51]—promise to mobilise capital toward emissions reduction and climate adaptation. Yet these markets suffer from profound information gaps that reflect deeper philosophical issues that plague the space including issues of knowledge, risk, and responsibility in the face of climate, economic, and political uncertainty.[52] The asymmetric distribution of information in climate finance is not a technical problem that can be solved through better disclosure regimes, but is, in fact, a manifestation of fundamental epistemological challenges that echo classical debates within economics and philosophy about the nature of practical knowledge and the limits of rational decision-making under uncertainty.[53] Insiders—leadership and elites within politics and firms—often possess private knowledge about the true macroeconomic exposure to both physical and transition risks, while investors and regulators—everyday market agents—must rely on imperfect disclosures and model-based projections. This misalignment of information can lead to mispricing, inadequate risk protection, and the misallocation of investment, undermining the very objectives that climate-oriented finance is meant to achieve—namely, protection of the environment and justice for different forms of life.[54]

The time-dependent dimension of climate risk—i.e., the necessity for immediate action—introduces additional philosophical

[51] Little, R, et al. "Funding Climate Adaptation Strategies with Climate Derivatives." *Climate Risk Management*, vol. 8, 2015, pp. 9-15.
[52] Boettke, P. "Economics in a World Amid Flux." *Behavioural Public Policy*, vol. 9, no. 3, 2025, pp. 630-645.
[53] Knight (n 2) *supra*; Polanyi (n 22) *supra*; Sunstein, C. "Knightian Uncertainty in The Regulatory Context." *Behavioural Public Policy*, vol. 9, no. 3, 2025, pp. 614-629.
[54] Grasso, M. "An Ethical Approach to Climate Adaptation Finance." *Global Environmental Change*, vol. 20, no. 1, 2010, pp. 74-81.

complexity that extends beyond conventional treatments of uncertainty in financial theory. Traditional economic models of asymmetric information assume that quality differences are ultimately discoverable through experience or reputation mechanisms.[55] They also suggest that some parties to praxeological coordination (i.e., market participants) benefit from access to private, closed information, through the process of exclusion and adverse selection.[56] Climate risks, I argue, operate on temporal scales that feed into these types of ethical quandaries. The long-term emergency of climate change, and the short horizon to implement a solution, means that the full consequences of today's market failures, exacerbated by incentive distorting information asymmetries, may not become apparent for decades, by which time the opportunity for corrective action may have passed.[57] This temporal mismatch between awareness of—or lack of awareness of—information and the policy response required creates the phenomenon of intergenerational moral hazard—a scenario where current actors can externalise the consequences of their private information advantages onto future generations who cannot participate in today's markets.[58]

The epistemic challenges of climate finance are further complicated by the problem of risks that cannot be quantified or even anticipated within existing analytical frameworks.[59] These are fundamentally the types of problems that will face future generations—their world will be very different from ours.[60] Drawing on Rescher's analysis of luck and contingency in human affairs, climate finance must grapple with the possibility that the most consequential risks are precisely those that lie outside the domain of calculable probability[61]—these future oriented risks might be termed "unknown unknowns".[62] This radical uncertainty differs qualitatively from the parametric uncertainty that can be addressed through improved data collection or more sophisticated modelling. It points instead to the limits of rational choice theory as a foundation for climate finance and suggests the need for more robust decision-making practices that allow for and anticipate irreducible uncertainty about future states of the world.[63]

It is worth noting that such irreducible uncertainties also exist within the physical climate models themselves. Even the most sophisticated models face inherent limits due to natural variability in the climate system and imperfect parameterisation. As Alizadeh observes, these uncertainties propagate into downstream financial and economic models, meaning that climate-related financial risks embed not only environmental uncertainty but also the epistemic uncertainty of climate science itself.[64]

Green bonds have emerged as a flagship instrument for channelling capital into environmentally beneficial projects. Unlike conventional bonds, green bonds commit issuers to allocate proceeds exclusively to projects that deliver climate or ecological benefits, such as installing and manufacturing renewable energy generation assets,

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[55] Akerlof (n 3) *supra*.
[56] Bebczuk, R. *Asymmetric Information in Financial Markets: Introduction and Applications.* Cambridge University Press, 2003.
[57] Kunstler, J. *The Long Emergency: Surviving The End of Oil, Climate Change, And Other Converging Catastrophes of The Twenty-First Century*. Atlantic Monthly Press, 2006.
[58] Tremmel, J. *A Theory of Intergenerational Justice*. Routledge, 2009.
[59] Ripple, W, et al. "World Scientists' Warning of a Climate Emergency." *BioScience*, vol. 70, no. 1, 2019, pp. 8-12.
[60] Jaakkola, H, et al. "Artificial Intelligence Yesterday, Today and Tomorrow." Proceedings of the 42nd International Convention on Information and Communication Technology, Electronics and Microelectronics (MIPRO), 2019, pp. 860-867.
[61] Rescher (n 23) *supra*.
[62] *see* Ilmola, L, and E Rovenskaya. "Three Experiments: The Exploration of Unknown Unknowns in Foresight." *Technological Forecasting and Social Change*, vol. 106, 2016, pp. 85-100; Seitz, R. "Knowing the Unknowns." *Earth's Future*, vol. 1, no. 1, 2013, pp. 45-52.
[63] Savage (n 38) *supra*; Schmeidler (n 42) *supra*.
[64] Alizadeh, O. "Advances and Challenges in Climate Modelling." *Climatic Change*, vol. 170, no. 18, 2022, pp. 1-26. Thanks to an anonymous reviewer for suggesting this point.

upgrading the energy efficiency of existing infrastructure, or investing in R&D for sustainable, future-oriented infrastructure. In principle, in the present state of climate finance investors must be willing to accept a modest yield concession to support the transition to a low-carbon economy.[65] In practice, however, the credibility—and therefore financial viability—of green financial instruments depends crucially on robust disclosure and verification regimes that must navigate difficult questions of environmental epistemology and measurement.[66] Drawing parallels across these divides between epistemological knowledge creation within a laboratory or study, and within an innovative entrepreneurial start-up, vying for venture funding for green innovation projects, could represent a major step toward standardising a climate-related ontology of knowledge creation, encouraging economic agents to disclose internal governance structures, strategy, risk management practices, and climate metrics such that information is democratised.[67] The voluntary nature of these regulatory frameworks, even within modern financial markets, reflects deeper philosophical challenges regarding the relationship between market-based governance and regulatory authority, echoing debates about the limits of self-regulation in complex systems.[68]

In the context of the EU ETS,[69] regulators possess private information about future emissions cap trajectories, the number and dispersion of free allocations, and the pace of market interventions, while market participants must infer policy intentions from sparse public pronouncements. This fundamental information asymmetry between regulators and market participants creates a reverse process of regulatory capture where market actors must constantly anticipate and respond to policy signals that may themselves be responses to private information held by regulators about political feasibility and technological constraints.[70] Moreover, firms operating in the climate finance space often hold proprietary data on abatement costs or technological readiness that they do not fully disclose, creating opportunities for strategic behaviour and covert planning and decision-making that can distort price signals. These asymmetries can generate price volatility of financial instruments tied to specific firms, but which are unrelated to actual emissions performance or environmental fundamentals, as observed in the EU ETS's abrupt price collapses following policy uncertainty in 2007–2008.[71] The resulting volatility and uncertainty in both financial viability of returns to green investment and the friendliness of the political / regulatory agents to environmental initiatives raises the cost of engaging in climate finance for energy-intensive industries and may discourage long-term investments in low-carbon technologies.[72] I claim that this shows how information asymmetries can create path dependencies that lock in suboptimal technological trajectories.[73]

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[65] del Giudice, A, et al. "Climate Change Risk and Green Bond Pricing." *Journal of Empirical Finance*, vol. 82, 2025, 101616.

[66] Harding (n 24) *supra* argues that knowledge is embodied by practitioners who create and practice science. We might extend this philosophical definition to include financiers who are exposed to market mechanisms and pricing tools and are thus able to have a fuller view of the landscape of climate related asset valuations—science and (financial) economics rolled into one.

[67] FSB (n 13) *supra*.

[68] Ostrom (n 47) *supra*; Scott (n 35) *supra*.

[69] A cap-and-trade system—e.g., the European Union Emissions Trading System (EU ETS)—sets an aggregate emissions cap and allocate or auction allowances that firms can buy, sell, or bank for future compliance: *see Report on the Review of The European Union Emissions Trading System (EU ETS)*. European Commission, 2021.

[70] Stigler, G. "The Theory of Economic Regulation." *The Bell Journal of Economics and Management Science*, vol. 2, no. 1, 1971, pp. 3-21.

[71] Hepburn, C, et al. "The Economics of the EU ETS Market Stability Reserve." *Journal of Environmental Economics and Management*, vol. 80, 2016, pp. 1-5.

[72] Labatt, S, and R White. *Carbon Finance: The Financial Implications of Climate Change*. Wiley, 2007. Padvan, A, and X Vives. "Information, Coordination, And Market Frictions: An Introduction." *Journal of Economic Theory*, vol. 158, 2015, pp. 407-426, provide an excellent introduction to these issues with several citations to classical and contemporary texts.

[73] Arthur (n 30) *supra*.

Beyond details of specific instruments and assessments of various green financial vehicles, broader information gaps plague the modelling and quantification of climate risk itself,[74] raising basic questions about the nature of economic knowledge about the structure of environmental financial markets for products like derivatives and swaps and the application of these tools for the movement and growth of capital to policy problems. Standard financial risk models rely on historical data and established distributions of risk and payoffs, but climate change introduces future-oriented uncertainty that challenges the philosophical and mathematical foundations of quantitative risk assessment.[75] The assumption that statistical properties observed in the past will continue to hold in the future breaks down when dealing with climate risks that may trigger irreversible changes in Earth system dynamics.[76] This breakdown has profound implications for the philosophy of science underlying the study of climate change and climate finance,[77] suggesting the need for post-normal science, suggested by Funtowicz and Ravetz—modes of scientific practice appropriate for situations where "facts are uncertain, values in dispute, stakes high, and decisions urgent".[78]

Tail-risks associated with catastrophic outcomes—such as rapid ice-sheet collapse in Antarctica or Greenland, or cascading tipping points—are difficult to parameterise and often excluded from scenario analyses, reflecting deeper philosophical disagreements about how to reason about low-probability, high-impact events.[79] Modelling tail risks using financial models is not simply a technical challenge but a philosophical problem scientists and theorists face about the nature of different environmental and financial choices faced by rational decision-makers who must cope with an uncertain present and an even more uncertain future.[80] Traditional expected utility theory, as formalised by Savage and others, assumes that any outcome can be assigned a meaningful probability within a framework of possible states of the world.[81] Yet climate tipping points may represent situations where the likelihood of outcomes cannot be meaningfully quantified[82]—this includes high-risk low-probability events where bad luck (or poor decision making in the present) can prove catastrophic in the (near or distant) future. The lack of information and knowledge about future states of the world, given extrapolation of present variables, requires alternative decision-making frameworks that can accommodate irreducible ignorance about the incentives we currently face—i.e., subtle behavioural feedback loops that, for example, induce pollution, consumption, and extreme risk taking politically, economically, and financially. The maximin criterion proposed by Rawls or the precautionary principle developed in environmental law[83] may be solutions but their implementation is far from guaranteed.[84]

Advanced climate models, used by economists and financial institutions to assess

[74] Notably, this is an issue that has been taken up by statist institutions around the world, including but not limited to, international financial institutions like the BIS and national central banks: *see* Bolton (n 6) *supra*.
[75] *see* Knight (n 2) *supra*; Keynes (n 2) *supra*; *see also* Aldereai, O, et al. "Application of Mathematics in Finance, Natural and Social Sciences: A Perspective Study." *Applications of Mathematical Sciences*, vol. 1, no. 1, 2022, pp. 54-65.
[76] Peters, O. "The Ergodicity Problem in Economics." *Nature Physics*, vol. 15, no. 12, 2019, pp. 1216-1221.
[77] Winsberg, E. *Philosophy and Climate Science*. Cambridge University Press, 2018.
[78] Funtowicz & Ravetz (n 39) *supra*.
[79] Liesen (n 9) *supra*; Weitzman (n 9) *supra*.
[80] On tail risks, also known as black swan events due to their unexpected nature, extreme impacts, and our only post-hoc ability to explain their occurrence, *see* Taleb (n 8) *supra*.
[81] Savage (n 38) *supra*.
[82] Knight (n 2) *supra*.
[83] Rawls, J. *A Theory of Justice.* 1st edn, Harvard University Press, 1971; Sunstein, C. *Laws of Fear: Beyond the Precautionary Principle.* Cambridge University Press, 2009.
[84] It certainly has not been seen in the present, and it is doubtful if even the best publicly proposed and debated academic ideas regarding environmental protection and climate mitigation will be put into practice in the future; *see* Schutze, P, and P Haueis. "Philosophy and the Climate Crisis: An Agenda for Change." *Public Philosophy Journal*, vol. 5, no. 1, 2023, pp. 1-27.

environmental risk—whether from extreme weather events or the economic transition—and estimate consequent payoffs to sustainable investment, incorporate subjective judgments about climate sensitivity, damage functions, and socio-economic pathways that make accurate analysis of the future impacts of climate change more of an art than a science.[85] Within industry, models are frequently more sophisticated, powerful, and resource intensive than even the most complex systems created in academic social science due to researchers' inherent bias towards generalisability, comprehensiveness, and the necessity for valid and cross sectionally significant results. In this context, innovative private initiatives might be able to move faster in endeavours using artificial intelligence (AI) to model future emissions pathways and the corresponding economic costs and benefits. Indeed, the details of modern coupled environmental and economic models—driven by modern machine learning or more traditional techniques—are often confined to limited, expert audiences; the public needs to be informed about the nature and magnitude of damages we face now and will continue to face in the future through effective environmental communication. Without expert support and input, the interpretation of these models risks being obscured by the political and ethical interests embedded in the fossil fuel industry, and the models themselves risk becoming technical artifacts that mask nuanced social, political, and mathematical features that constitute robust claims of scientific validity.[86] Risks of scientific neglect, or a pushback against experts can arise when investors place undue confidence in a particular modelling framework, potentially underestimating the stochastic nature of possible environmental outcomes perhaps better explained by newer or more involved models.[87] Scientists themselves often rely on methodological assumptions and calibration methods that are taken as convention within the discipline but can neglect public interests. Key stakeholders must be aware of critical sensitivities and tipping points within interdependent variables used in models studied by researchers in both the economy and in the climate system.

These nuanced and calibrated features of climate science, and the ease of misinterpretation, create incentives for sophisticated investors to trade on proprietary risk assessments, taking advantage of pockets of insight inaccessible to less privileged market actors, at their expense. The consequences of informational asymmetries for climate asset pricing and the valuation of risk premia within environmental finance are steep and reflect deeper philosophical questions about the value of the natural world and the desirability of justice within financial markets. Investors often incorporate climate premia into the required returns on carbon-intensive assets. This premium reflects the unknowns inherent in the expected costs of future regulation and physical damages, as well as an uncertainty premium that often takes the form of insurance against the possibility that current risk models fundamentally mischaracterise the nature of climate risk.[88] The philosophical challenge lies in determining whether such premiums represent rational responses to uncertainty or are simply manifestations of bounded rationality that may systematically bias capital allocation away from socially optimal outcomes.[89]

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[85] Stern, N. *The Economics of Climate Change: The Stern Review*. Cambridge University Press, 2007; Nordhaus, W. "Climate Change: The Ultimate Challenge for Economics." *American Economic Review*, vol. 109, no. 6, 2019, pp. 1991–2014.

[86] Latour, B. *Science in Action: How to Follow Scientists and Engineers Through Society*. Harvard University Press, 1988.

[87] What I mean to argue here is that the space of outcomes is much larger than many practitioners believe. With the advent of the fourth industrial revolution and its transformation of society, possibilities arguably range from brink of worldwide humanitarian disaster fuelled by a rapidly warming climate to a new renaissance guided by AI and cultural vitality.

[88] Weitzman (n 9) *supra*.

[89] Simon, H. "A Behavioral Model of Rational Choice." *The Quarterly Journal of Economics*, vol. 69, no. 1, 1955, pp. 99-118; Kahneman, D. *Thinking, Fast and Slow*. Penguin, 2011.

Empirical work suggests that firms in high-emitting sectors trade at lower valuations relative to fundamentals, consistent with a risk premium that creates the potential for, and aims to nudge markets towards, carbon repricing.[90] Carbon discounts can be understood as market-based mechanisms for internalising environmental externalities, but they also raise questions about distributive justice and the fair allocation of transition costs. The discount may disproportionately affect firms and communities that are least able to adapt to a low-carbon economy, potentially exacerbating existing inequalities[91] and funnelling already high-yield liquidity into cheap but potentially high-growth green financial instruments. Conversely, credible green financiers can enjoy a greenium, trading at tighter spreads than comparable conventional bonds[92]—more return for the same level of risk.

This misallocation is exacerbated by regulatory frameworks that treat climate risks as part of operational or market risk, rather than recognising them as distinct categories requiring scenario-based stress tests.[93] The regulatory treatment of climate risks reflects deeper philosophical disagreements about the nature of systemic risk and the appropriate role of financial regulation in addressing collective action problems. Traditional approaches to financial regulation assume that systemic risks can be managed through the aggregation of individual firm-level risk assessments, but climate risks may require more holistic approaches that recognise the interconnectedness of financial, social, and ecological systems.[94] The introduction of climate stress scenarios by central banks and supervisors aims to correct this, but the design of stress tests is itself subject to asymmetric information: regulators must set scenario parameters which firms then anticipate and may systematically exploit.[95] The exploitation of regulatory stress tests illustrates a broader problem in the governance of climate finance: the tendency for regulatory responses to information asymmetries to create new forms of strategic behaviour that may undermine the original policy objectives. Different sectors of society learn and adapt to the behaviour of other groups—driving innovation, evolution, and a steep increase in organisational dependency and complexity. The result is an ongoing arms race between legal regulators seeking to elicit truthful disclosure and firms seeking to maintain their informational advantages, with potentially counterproductive consequences for both financial stability and climate policy.[96]

The disconnect between local risk assessment and global capital markets illustrates a dichotomy—a substantial division—in climate finance between the spatial specificity of environmental risks—based in specific locations with identifiable properties—and the spatial abstraction of financial markets whose foundations are often algorithmic, intangible, and based on decentralised technology.[97] Financial instruments that are designed to be tradable across different contexts may systematically obscure the place-based knowledge that is essential for accurate risk assessment, creating spatially demarcated moral hazard, where global investors externalise environmental risks onto local communities that cannot participate in risk-sharing arrangements.[98] An example of this is found in the placement of chemical plants in New Orleans ('cancer alley') among poor, black communities for instance. Corporate carbon reporting presents another case of disclosure failure that surfaces deeper theoretical issues to do with the

[90] Bolton (n 6) supra; Carney (n 14) supra.
[91] Anderson (n 46) supra.
[92] Pietsch, A, and D Salakhova. "Pricing of Green Bonds: Drivers and Dynamics of The Greenium." European Central Bank Working Paper, 2022; Zerbib, O. "The Effect of Pro-Environmental Preferences on Bond Prices: Evidence from Green Bonds." *Journal of Banking & Finance*, vol. 98, 2019, pp. 39-60.
[93] Bolton (n 6) supra.
[94] Ostrom (n 37) supra.
[95] Acharya, V, et al. "Measuring Systemic Risk." *The Review of Financial Studies*, vol. 30, no. 1, 2017, pp. 2-47.
[96] Admati, A, and M Hellwig. *The Bankers' New Clothes: What's Wrong with Banking and What to Do About It*. Princeton University Press, 2014.
[97] Harvey, D. *The Limits to Capital*. 2nd edn, Verso, 2006.
[98] Beck, U. *Risk Society: Towards A New Modernity*. Sage Publications, 1992.

commodification of environmental information and the possibility of quantifying ecological assets.[99] Reporting has become widespread—many large firms now publish annual sustainability reports containing accounting statistics for emissions and climate-risk assessments within their supply chains—however there are still issues: these reports often vary widely in methodological rigor and scope[100] and the variation in reporting quality reflects not only different levels of organisational capacity but also deep disagreements within corporate and political leadership about what counts as relevant environmental information and how such information should be measured and disclosed.[101]

Some companies misuse financial accounting techniques by omitting scope 3 or other indirect emissions in their value chains—even when those emissions far exceed direct (scope 1) emissions.[102] This exemplifies a particular conception of corporate responsibility that privileges shareholder interests (profit, revenues, dividends, and stock buybacks, etc.) over broader stakeholder concerns (social impact, employee welfare, etc.), but it may be inadequate for addressing the systemic risks posed by climate change.[103] The boundaries of corporate environmental responsibility are not given by nature but are socially constructed through ethical accounting practices, just regulatory frameworks, and benevolent and trust-based stakeholder negotiations that reflect particular power relations and ideological commitments founded on equality among market and discourse participants. Investors seeking *comprehensive* risk assessments—not biased by insider knowledge or omissions due to knowledge asymmetries—must often rely on third-party data providers, such as the Carbon Disclosure Project (CDP), which aggregates voluntary disclosures but cannot enforce completeness or accuracy.[104] This reliance on intermediaries creates new forms of information heterogeneity, that can serve to deepen the divide between corporate data providers and institutional or independent users, creating potential conflicts of interest that can bias the selection and presentation of environmental information. The emergence in the digital era of a commercial market for environmental data reflects the broader commodification of environmental information, and also raises questions about the democratic governance of environmental knowledge and the potential for market-based solutions to address collective action problems.[105] The patchwork of data leaves analysts to fill in gaps using guesswork, thereby introducing significant uncertainty into climate risk assessments intended for use in portfolio construction.[106] This reflects a particular epistemological approach that assumes gaps in the foundation of knowledge an agent acts upon can be pieces together from sometimes sparse available information, but this approach may be inappropriate for environmental risks that exhibit complex, non-linear relationships[107] and in a more general sense where more (financial) information is always better. Firms with superior internal data can exploit firms having lower engagement with relevant and topical

[99] Such as forests, rivers, marshes, oceans, and deserts—not to mention the (non-human) living beings that inhabit them.

[100] Christensen, H, et al. "Mandatory CSR And Sustainability Reporting: Economic Analysis and Literature Review." *Review of Accounting Studies*, vol. 26, no. 3, 2021, pp. 1176-1248.

[101] Power, M. *The Audit Society: Rituals Of Verification*. Oxford University Press, 1999.

[102] Some firms have strong institutional commitments to environmental protection—I do not intend to rule these out; indeed, they are crucial players in the climate finance landscape.

[103] Blowfield, M. *Business and Sustainability.* Oxford University Press, 2013; Freeman, R. *Strategic Management: A Stakeholder Approach*. Pitman, 1984.

[104] Gibson, R, et al. "ESG Rating Disagreement and Stock Returns." *Financial Analysts Journal*, vol. 77, no. 3, 2021, pp. 104-127; "CDP Global Climate Change Report 2020." *Carbon Disclosure Project*, 2020.

[105] I will address this issue of democratic governance of what may be called the "knowledge commons" below; *see* Castree, N. "Commodifying What Nature?" *Progress in Human Geography,* vol. 27, no. 3, 2003, pp. 273-297.

[106] Benedetti, D, et al. "Climate Change Investment Risk: Optimal Portfolio Construction Ahead of the Transition to a Lower-Carbon Economy." *Annals of Operations Research*, vol. 299, 2019, pp. 847-871.

[107] Bachelard, G. *The New Scientific Spirit*. Beacon Press, 1984.

information by engaging in strategic disclosure to signal lower risk while withholding adverse information[108]—a clear instance of moral hazard that undermines the integrity of individual judgment within and alongside environmental reporting systems.[109] The strategic manipulation of environmental information reflects broader questions about the relationship between knowledge and power in the governance of climate finance. Following Foucault's analysis of disciplinary power, environmental disclosure requirements can be understood as technologies of governance that shape corporate behaviour not only through direct regulation but also through the creation of new forms of visibility and accountability with respect to sustainability and an awareness of the impact of the cycle of production and consumption on the natural world.[110] However, the effectiveness of environmental governance depends on its ability to generate reliable frameworks for environmental action in a world shaped by profit motives and self-interest. The credibility of initiatives blending the duties of a financial institution with those of a regulator may be undermined by the strategic behaviour of the organisations such initiatives seek to moderate or control.[111]

In sum, climate-related financial markets show the systemic structural presence of asymmetric information, but they also reveal how informational problems are intertwined with deeper philosophical questions about knowledge, uncertainty, and responsibility in the face of environmental crisis. From green bonds and carbon markets to mortgage portfolios and corporate disclosures, information gaps distort prices, elevate risk premiums, and misdirect capital, but these distortions cannot be addressed through purely technical solutions. The challenge of governing climate finance requires attention not only to improved disclosure regimes and regulatory frameworks, but also to the normative, epistemic, and moral foundations of environmental decision-making. The philosophical dimensions of asymmetric information in climate finance point toward the need for more reflexive and participatory approaches to environmental governance that can accommodate irreducible uncertainty while maintaining democratic legitimacy and social justice. In the next section, we turn to the implications of these informational failures, examining how issues of agency, legitimacy, and justice shape the governance of climate finance within the disciplinary context of contemporary political theory.

IV. **Environmental Political Theory and Finance**

The intersection of asymmetric information and climate finance raises deep questions about agency and accountability within political institutions that extend far beyond conventional treatments of market failure. In addition to serving as aggregators and temperature gauges of private preferences and economic risk assessment, financial markets are also embedded within networks of diverse regulatory regimes, democratic (and non-democratic) governments and institutions, and are affected by power relations that, in turn, shape the incentives and constraints facing firms, investors, and citizens.[112] As we have seen, information about climate risks is unevenly distributed, and certain actors—typically large firms and incumbent energy producers—can leverage their private, acquired knowledge about specific economic metrics to skew policy outcomes in their favour, creating a form of hegemonic control that is exercised through technical expertise rather than overt coercion derived from the use of force (hard or soft).[113] This subversion of traditional accountability mechanisms through the acquisition of proprietary power undermines normative

[108] This is the classical definition of asymmetric information—*see* Bebczuk (n 56) *supra*.
[109] Tversky, A, and D Kahneman. "Judgment Under Uncertainty: Heuristics and Biases." *Science*, vol. 185, no. 4157, 1974, pp. 1124-1131.
[110] Foucault, M. *Discipline and Punish: The Birth of The Prison*. Vintage Books, 1977.
[111] Scott (n 35) *supra*.
[112] Block, F, and M Somers. *The Power of Market Fundamentalism: Karl Polanyi's Critique*. Harvard University Press, 2016.
[113] Gramsci, A. *Selections from the Prison Notebooks*. International Publishers, 1971.

ideals of corporate and political norms: regulators, elected or otherwise, may find their deliberations siphoned-off by well-resourced organisations that possess privileged access to scientific data, model projections, and to exclusive lobbying channels.[114] The result is a deficit of democratic integrity within climate governance, in which the institutions safeguarding the public interest become instruments for private gain as a result of hierarchies of access to information, showing that Schumpeter's concerns about the bureaucratisation of democratic life—demarcated by status and insider knowledge—remains prescient.[115]

When constitutive knowledge is excluded from decisions made on behalf of stakeholders, we run into the problem of lack of political legitimacy, which must be understood not merely as the absence of consent or compliance but a form of epistemic and illegitimate informational domination—the unwilling (or unwitting) surrender to authority because of a presumption of shared beliefs about the rightfulness of the trajectory in vogue.[116] Market-based instruments such as emissions trading schemes rest on the premise that price signals are accepted as fair and credible by all stakeholders, but this acceptance cannot be taken for granted when the informational foundations of climate asset pricing are opaque or contested. When asymmetric information breeds suspicion—whether through real incidents of greenwashing or more subtle forms of epistemic injustice—the moral authority of the political decision-making mechanisms erodes.[117] Citizens who perceive that policy on climate change is set behind closed doors, or that exceptions to the just exercise of environmental law—i.e., applying to everyone equally—are allocated to incumbent and culpable polluters, are less likely to view market instruments as legitimate expressions of collective will.

If information about potential harms from selective information exposure is fragmentary or contested, the epistemic conditions by which governments secure the consent of the public on issues of intergenerational justice and economic policy could be severely weakened, raising fundamental questions about the possibility of legitimate governance of these issues across time.[118] While we know that today's policies determine which future lives come into existence,[119] hypothetical consent is problematic as a foundation for intergenerational justice when considering investments in sustainable technologies because we fundamentally do not know the preferences of people living in the future. Instead, we might appeal to principles of just savings or stewardship of existing (natural) resources, having present generations act as custodians of the planet's habitability, but these principles require robust epistemic foundations of knowledge about the future state of the world that may be undermined by the very information asymmetries they seek to address.[120] Unless the epistemic foundations of stewardship are rooted in comprehensive, inclusive disclosure and consensus, trusteeship can decay into paternalism or hegemonic opportunism, perpetuating forms of domination that democratic theory seeks to overcome.

Epistemic injustice arising from information asymmetries that in turn advantage or disadvantage particular market actors emerges as a crucial analytical framework for understanding how the topology of information in climate finance reproduces and amplifies existing patterns of social domination. We can extend this to define testimonial and hermeneutical injustice to show how losers in the competition for

[114] Stiglitz, J, and J Rosengard. *Economics of the Public Sector*. 4th edn, WW Norton & Company, 2015.
[115] Schumpeter, J. *Capitalism, Socialism and Democracy*. Harper & Brothers, 1942.
[116] Weber, M. *Economy and Society: An Outline of Interpretive Sociology*. University of California Press, 1978.
[117] Fricker (n 11) *supra*.
[118] Rawls (n 83) *supra*.
[119] Parfit (n 10) *supra*.
[120] Gardiner (n 1) *supra*.

predominance and access can be systematically discredited or silenced in public discourse—in addition to being put at a financial disadvantage—and the temporal and ecological dimensions of climate injustice give rise to high hurdles for those left behind.[121] In climate finance, some voices that are often absent from corporate, technocratic, and academic governance negotiations over carbon budgets and transition pathways, reflect systematic patterns of closed-mindedness and epistemic arrogance by elite managers that prevent dominant groups from recognising alternative instantiations of knowledge and information.[122] These groups may hold valuable micro knowledge about environmental thresholds and adaptation practices, but without institutional mechanisms for incorporating these data resources, epistemic contributions remain invisible and are systematically devalued.[123] This exclusion perpetuates social injustice and also impoverishes the informational ecosystem upon which robust policy depends, creating structural poverty traps where marginalised market actors avoid making claims or interventions because they predict that their audience will respond with epistemic bias and domination.[124] The politics of an inclusive information landscape, therefore, must attend to both hierarchical material and asset-based distribution and to the equitable diversification of sources of (financial) data, recognising that epistemic justice is a prerequisite for effective climate governance.

Dominated financial and political actors may need to develop oppositional strategies to recognise and vocally articulate their experiences of subordination.[125] In the context of climate finance, this suggests that practices of questioning dominant frameworks and developing alternative ways of understanding climate risks and responses[126] can be of value in creating a cognitive supply chain of knowledge. As noted in the introduction, Amartya Sen's capability approach complements rather than replaces the Rawlsian vision of justice. While Rawls emphasises fairness in institutional design, Sen insists that justice also depends on the substantive freedoms people possess to realise valued forms of life. In this framework, addressing information asymmetries in climate finance becomes both a procedural and an empowerment challenge: ensuring fair institutional rules while expanding the real capacities of individuals and communities to act within them.[127] Financial economics, by placing value on asset allocations and through the quantitative hedging of systemic pricing and valuation risk, often overlooks whether individuals and communities have the substantive capacity to respond emotionally, as well as physically, to climate impacts—these issues are central to human welfare including long-life, bodily health, social and economic equity, and control over one's environment.[128] Asymmetric information exacerbates the decay of human capacity; without knowledge of shifting economic and financial conditions, households cannot make informed investment decisions in housing, investment, saving, or education, undermining their capacity for self-determination.

Bridging this gap within potential human vitality requires concerted efforts to democratise climate information, through participatory mapping exercises, and educational outreach programs that build critical consciousness: the ability to perceive social, political, and economic contradictions and to take action to advantage and exploit

[121] Fricker (n 11) *supra*.
[122] Medina, J. *The Epistemology of Resistance: Gender and Racial Oppression, Epistemic Injustice, And Resistant Imaginations*. Oxford University Press, 2012.
[123] Scott (n 35) *supra*.
[124] Dotson, K. "Tracking Epistemic Violence, Tracking Practices of Silencing." *Hypatia*, vol. 26, no. 2, 2011, pp. 236-257.
[125] Pateman, C. *The Sexual Contract*. Polity, 1988; MacKinnon, C. *Toward A Feminist Theory of The State*. Harvard University Press, 1989.
[126] Stern (n 85) *supra*.
[127] Sen, A. *The Idea of Justice*. Harvard University Press, 2009.
[128] Nussbaum, M. *Women and Human Development: The Capabilities Approach*. Cambridge University Press, 2000.

one's own position through self-determination.[129] The goal is to empower citizens to convert environmental information into economic capabilities while transforming the social relations that structure access to and use of such information. The capability approach thus points toward a more fundamental reconstruction of climate finance that would prioritise human development over capital accumulation, following a vision of governance based on ecological principles and the rights of all life forms.[130] This might involve alternative economic models such as participatory economics, ecological economics, or post-growth (or de-growth) economics that challenge the assumption that climate problems can be solved within existing capitalist frameworks.[131] Such alternatives would require not only different institutions but different ways of understanding the relationship between human societies and natural systems, following the recognition that capitalism and fossil fuel dependence are structurally linked.[132]

In sum, the theoretical political implications of asymmetric information in climate finance cut across questions of accountability, legitimacy, justice, and freedom, but they also reveal the limitations of conventional democratic theory when applied to problems that span multiple temporal and spatial scales. Addressing these implications demands innovative institutional architectures that promote transparency, inclusion, and deliberation, while safeguarding the agency of both current and future generations. However, such reforms may ultimately require more fundamental transformations in the political and economic systems that structure climate governance and point toward post-capitalist governance alternatives that address the causes of climate change itself as well as democratic failures and institutional blind spots. The next section will conclude by examining normative solutions, evaluating how robust access to decision-making frameworks, and democratic access can mitigate the informational asymmetries identified above while remaining optimistic that these reforms may be able to mitigate deeper structural challenges.

V. **Conclusions**

The analysis in this article has shown that asymmetric information permeates climate-related financial markets as well as political institutions. It gives rise to adverse selection, moral hazard, and epistemic injustice that threaten both economic efficiency and democratic legitimacy. In financial markets, these issues lead to the mispricing of climate risk, misallocation of capital, and insufficient incentives for mitigation and adaptation. In political spheres, privileged access to specialised knowledge enables elite actors to navigate regulatory barriers, which undermines accountability and leaves rural, non-technocratic communities and future generations without effective representation. To find solutions to these challenges, normative and policy solutions must address the core of information asymmetries. They can do this by combining transparency, regulatory and mechanism design, with inclusive governance mechanisms and a commitment to intergenerational justice.[133]

Complementing disclosure obligations, regulatory governance frameworks must incorporate robust decision-making under deep uncertainty. Traditional economic and information theoretic models inadequately capture tail climate risks.[134] Regulators should therefore adopt adaptive rulemaking processes that embed scenario-based stress tests and robust control criteria within managed economies.[135] These initiatives could guide capital stock requirements and enact

[129] Freire, P. *Pedagogy of the Oppressed.* Continuum International Publishing Group, 1970.
[130] Shiva, V. *Earth Democracy: Justice, Sustainability and Peace.* South End Press, 2005.
[131] *see* Albert, M. *Parecon: Life After Capitalism*. Verso, 2004; *see also* Daly, H. *Beyond Growth: The Economics of Sustainable Development.* Beacon Press, 1997.
[132] Malm, A. *Fossil Capital: The Rise of Steam Power and The Roots of Global Warming*. Verso, 2016.
[133] Tremmel (n 58) *supra*.
[134] Liesen (n 9) *supra*.
[135] *see* Gilboa & Schmeidler (n 43) *supra* and the book by Hansen, L, and T Sargent. *Robustness*. Princeton University Press, 2007.

prudential investment and debt allocation buffers for financial institutions and market actors. For example, central banks could require supervised institutions to hold additional capital proportional to losses in worst-case climate change scenarios, thereby accounting for tail-risks and minimising over-exposure to carbon intensive assets. These stress tests should have parameters co-designed by regulators, civil society, and industry experts ensuring collaborative procedural democratic legitimacy.

Finally, continued research at the intersection of philosophy, economics, and political science is essential for refining information markets and knowledge economies. Open questions include the optimal design of environmental disclosure under epistemic ambiguity, the trade-offs between robust regulatory oversight and market liquidity, and the conditions within which deliberative forums produce robust policy consensus. Empirical studies could evaluate the effects of mandatory climate disclosures on cost of capital, while normative scholarship must clarify the moral premises of intergenerational respect and foresight as well as epistemic inclusion.

In conclusion, mitigating the effects of asymmetric information in climate finance using democratic political values demands a strategy that unites legal scholarship, just regulatory frameworks, market-based incentives, democratic novelty, and ethical commitments, respecting both present and future citizens. Only through this integrated approach can modern societies align private incentives with the public good and enhance the credibility and effectiveness of climate-related financial instruments, fostering a political order worthy of the challenges posed by the transformation of the planet known as the Anthropocene.

Lending from the Shadows: Physical Climate Risk and Shadow Bank Mortgage Financing in US Flood Prone Areas

Thanos Bikakis*

* PhD Candidate (Department of Land Economy), University of Cambridge, UK

KEYWORDS

physical climate risk, flood risk, shadow banks, mortgage finance, residential real estate

ABSTRACT

This article aims to investigate the impact of physical climate risk, in particular flood-related property damage on shadow bank mortgage underwriting activity. While existing literature has explored the intersection of physical climate risk and financial markets, the specific impact of shadow banking on mortgage underwriting in flood-prone areas remains underexplored. Using data from the Home Mortgage Disclosure Act (HMDA) and the National Oceanic and Atmospheric Administration (NOAA) from 2010 to 2017, this article analyses shadow banks' lending behaviour in the three states most prone to flood-related property damage: Texas, New Jersey, and Louisiana. The research is particularly timely given that shadow banks currently originate more than 50% of US mortgages by value, and recent estimates indicate that more than $1 trillion worth of private coastal property is at risk from climate change in the US. I find that shadow bank lending, as a proportion of total lending, increases by 5.3%, on aggregate, following a high damage flood event. I believe this is driven by reduced credit supply from depository institutions due to their regulatory constraints and capital requirements, as a result of the Dodd-Frank Act, thus leaving a gap for non-depository institutions to fill. Whilst this paper focuses on Texas, New Jersey, and Louisiana, which in aggregate account for 79.5% of flood-related property damage during the study period, the findings can be applied to the rest of the US with differing orders of magnitude. Overall, this study seeks to contribute to the corpus of literature by examining how shadow bank lending activity changes following a physical climate risk, such as a flood event and how their unique regulatory framework and risk management practices may affect financial stability in flood-exposed areas. These findings have important implications for policymakers concerned with systemic risk, consumer protection, and the resilience of the mortgage market in flood and physical climate risk prone areas more broadly.

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I. **Introduction**

The intersection of finance and climate risk has garnered significant attention in recent years with studies indicating that properties in physical climate risk areas face increasing valuation risks. This emerging body of

research emphasises the need to evaluate how financial institutions, including non-depository financial institutions (also known as shadow banks or NDFIs), are adapting their credit underwriting practices to account for climate risk. The specific impact of shadow bank mortgage underwriting in flood-prone areas, however, remains underexplored and thus presents a critical gap in the literature.

The urgency of this research is underscored by recent developments in both climate science and financial markets. The acceleration of climate change impacts, particularly in coastal areas, has created an unprecedented challenge for the United States (US) housing market, with over $1 trillion in coastal real estate threatened by climate change impacts.[1] This significant exposure, combined with the increasing frequency and severity of climate-related physical events, offers an interesting opportunity to examine how depository and non-depository institutions respond to mortgage underwriting in the presence of physical climate risks.

The role of shadow banks in this context is particularly crucial as they now originate more than 50% of all mortgage issuances in the US,[2] marking a significant shift in the mortgage market landscape since the 2008 financial crisis. NDFIs are increasingly favoured over traditional banks as they are able to offer faster, more flexible mortgage underwriting with little to no regulatory constraints and lower capital requirements. These unique characteristics enable them to serve riskier or non-conforming borrowers that regulated banks often avoid. Therefore, the growing dominance of non-depository institutions in mortgage origination, combined with their unique regulatory framework and risk management practices, raises important questions about the stability of the housing system in the face of increasing climate-related damages and losses.

The interaction between shadow banking practices and physical climate risk presents potentially systemic implications that extend beyond individual property values. As traditional banks are increasingly mandated to incorporate climate risk measures into their lending decisions, the possibility of risk concentration within the unregulated shadow banking sector becomes more pronounced. Whilst climate risk disclosure requirements strengthen the capital adequacy ratio of tradition banks, they create the opportunity for shadow banks to offer more competitive mortgages. This dynamic is particularly concerning given the sector's interconnectedness with the broader financial system and its history of rapid risk transmission, through securitisation, during periods of market stress.

Recent developments, including proposed climate risk disclosure requirements and changes to climate insurance programmes, add another layer of complexity to this research area. The varying responses of shadow banks and traditional banks to these regulatory changes could create new patterns of risk distribution in the mortgage market as shadow banks become more competitive in mortgage underwriting, potentially affecting both financial stability and housing affordability in climate-vulnerable areas. The pertinence of this research is further emphasised by emerging trends in the insurance industry, where major carriers are withdrawing from high-risk areas or significantly increasing premiums.[3] This retreat of traditional insurers creates additional complications for mortgage lending in these regions and raises questions about how lending institutions might adjust their underwriting practices in response. Ultimately this may lead to a change in property values and climate gentrification. The latter is a climate-driven change in neighbourhood desirability which may result

[1] "Impacts, Risks, and Adaptation in the United States." *Fourth National Climate Assessment*, vol. 2, US Global Change Research Program, 2018.
[2] Kim, You Suk, et al. "Non-Banks and Mortgage Securitization." *Annual Review of Financial Economics*, vol. 14, no. 1, 2022, pp. 137-166.
[3] Flavelle, Christopher, and Mira Rojanasakul. "The Home Insurance Crunch: See What's Happening in Your State." *The New York Times*, 13 May 2024.

in the displacement of lower-income households as higher-income households seek to move to climate-resilient areas. This has already been observed in Liberty City, Florida.[4] The potential for shadow banks to fill lending gaps in areas from which traditional banks are retreating, possibly without fully pricing in climate risks, represents a critical area for investigation.

Numerous academics and organisations, such as the Bank of England, the United Nations Environment Programme Finance Initiative, and the Dutch National Bank[5] have attempted to measure the financial risks originating from climate change. In general, climate change poses two primary risks to the financial system: transitional and physical risks. This article will solely focus on the impact of physical risks and therefore not discuss transitional risks.

Physical risks are the threats caused by the increase in extreme weather events such as floods, droughts, wildfires, storms, hurricanes. Due to the complexity and unpredictability of natural events, identifying physical risks is challenging and relies on a great deal of human expertise. Whilst a plethora of physical climate risks affect the US real estate market, floods are the single largest contributor of climate-related property damage. The most recent flash floods in Texas resulted in more than 130 people dead and caused an estimated $18–20 billion in damage, emphasising the catastrophic nature of flood events.[6] For this reason, this study focuses on flood risk in the top three states by flood-related property damage from 2010 to 2017. For context, flood-related property damages account for 79.5% of all property damage during the study period.

For simplicity of argument in this article, it is assumed that climate change is the increase in frequency of natural disaster events.

II. **Literature Review**

This Section will provide an overview of the existing literature by dividing it into three subsections covering: (i) an overview shadow banks, (ii) climate risk in real estate, and (iii) regulation and socio-economic impacts.

A. *An Overview of Shadow Banks*

The term "shadow banking" was first coined by McCulley[7] to describe financial intermediaries operating outside the traditional banking regulations while performing bank-like functions. According to the Financial Stability Board,[8] shadow banking encompasses entities involved in credit intermediation and activities outside the regular banking system. This definition highlights the parallel financial system that has evolved alongside traditional banking, often with less regulatory oversight and transparency. In a similar manner, Claessens & Ratnovski[9] describe shadow banking as "all financial activities, except traditional banking, which require a private or public backstop to operate". This highlights shadow banks' implicit reliance on traditional banking institutions or government guarantees during periods of financial stress, creating a degree of interconnectedness that may amplify systemic risk. In turn, this interconnectedness creates complex risk transmission channels that are difficult for regulators to monitor and control, and for investors to comprehend and price appropriately.

Whilst the concept of shadow banking may appear new, its roots trace back to the 1970s

[4] Contreras, Joseph. "How a Black Miami Neighborhood Became 'Ground Zero for Climate Gentrification'." *The Guardian*, 29 Jan. 2024.

[5] Scott, Matthew, et al. "The Bank's Response to Climate Change." *BoE Quarterly Bulletin,* 2017; "Transition-Related Risks & Opportunities." *Extending Our Horizons,* UNEP FI, 2018; "Physical Risk & Opportunities." *Navigating a New Climate*, UNEP FI, 2018; Vermeulen, Robert, et al. "The Heat Is On: A Framework Measuring Financial Stress Under Disruptive Energy Transition Scenarios." DNB Working Paper No. 625, 2019.

[6] Kaufman, Leslie, and Isabela Fleischmann. "Why Texas Is So Vulnerable to Climate Disasters." *Bloomberg*, 14 Jul. 2025.

[7] McCulley, Paul. "The Shadow Banking System and Hyman Minsky's Economic Journey." *PIMCO Global Central Bank Focus*, May 2009.

[8] "Shadow Banking: Scoping the Issues." *Financial Stability Board,* 2011.

[9] Claessens, Stijn, and Lev Ratnovski. "What is Shadow Banking?" IMF Working Paper WP/14/25, 2015 at p. 5.

with the emergence of money market mutual funds, which offered deposit-like services without being subject to the same regulations as traditional banks.[10] Over time, the sector expanded to include various entities such as hedge funds, investment banks, and private non-depository lenders. The growth of shadow banks was fuelled by financial innovation, regulatory arbitrage, and investors moving up the risk curve in pursuit of higher risk-adjusted returns. This growth in unregulated financial institutions played a significant role in the build up to the Global Financial Crisis (GFC), as shadow banking entities were increasingly involved in the origination and distribution of complex mortgage-backed securities.[11] The GFC exposed the systemic risks posed by the lack of transparency and regulation in this sector, leading to calls for increased oversight. In response, regulatory bodies such as the Financial Stability Board (FSB) have initiated efforts to monitor and regulate shadow banking activities. For the context of this paper, the use of shadow banks only makes reference to non-depository institutions providing mortgage financing.

Given the significance of shadow banks within the global financial system, their role has been researched extensively, particularly in the context of credit intermediation and financial stability. Pozsar et al.[12] find that shadow banks contribute significantly to the credit supply by engaging in maturity transformation and risk transfer activities. This sector's growth and systemic importance first became evident during the GFC, emphasising the need for a deeper understanding of their operations and impacts.[13]

A critical analysis of shadow banking, however, reveals its dual nature in financial markets. While Gorton & Metrick[14] imply that shadow banks provide essential liquidity and credit to markets that might otherwise be underserved, their reliance on the repo market increases systemic risk. This is supported by Acharya et al.[15] who emphasise that the lack of regulatory oversight creates systemic vulnerabilities which arise from maturity mismatches, leverage, and regulatory arbitrage opportunities that shadow banks exploit. The exponential growth of shadow banking assets, $70.2 trillion globally in 2024,[16] further underpins the sector's significance and potential impact on financial stability.

The rise in shadow banking is partially driven by the originate-to-distribute model that defines much of shadow bank lending. The originate-to-distribute model structurally reduces incentives for long-term risk assessment and enables origination activity up the risk curve. Unlike depository institutions that must manage asset-liability mismatches and retain exposure to credit risk over time, shadow banks generally seek to originate and sell loans within 12 months, often with little intention of maintaining servicing rights. As a result, they are less incentivised to evaluate or respond to slow-onset risks such as floodplain expansion, extreme weather intensification, or shifting regulatory frameworks. This issue is further compounded by the lack of environmental covenants or physical risk factors in the standard underwriting process. Loan origination, even in high-risk areas, therefore, can proceed without penalising terms or higher capital charges.

[10] Gorton, Gary, and Andrew Metrick. "Regulating the Shadow Banking System." *Brookings Papers on Economic Activity*, 2010, pp. 261-312; Luttrell, David, et al. "Understanding the Risks Inherent in Shadow Banking: A Primer and Practical Lessons Learned." *Federal Reserve Bank of Dallas: Staff Papers*, no. 18, 2012.

[11] *The Financial Crisis Inquiry Report: Final Report of the National Commission on the Causes of the Financial and Economic Crisis in the United States*. Financial Crisis Inquiry Commission, 2011.

[12] Pozsar, Zoltan, et al. "Shadow Banking." *Federal Reserve Bank of New York: Staff Reports*, no. 458, 2010.

[13] Adrian, Tobias, and Adam Ashcraft. "Shadow Banking Regulation." *Annual Review of Financial Economics*, vol. 4, no. 1, 2012, pp. 99-140.

[14] Gorton, Gary, and Andrew Metrick. "Securitized Banking and the Run on Repo." *Journal of Financial Economics*, vol. 104, no. 3, 2012, pp. 425-451.

[15] Acharya, Viral, et al. "Securitization Without Risk Transfer." *Journal of Financial Economics*, vol. 107, no. 3, 2013, pp. 515-536.

[16] *Global Monitoring Report on Non-Bank Financial Intermediation 2024*. Financial Stability Board, 2024.

Post-GFC literature has revisited shadow banking as a persistent and evolving feature of global finance. Adrian & Ashcraft[17] argue that despite regulatory reforms aimed at strengthening depository and non-depository institutions, the shadow banking sector is able to exploit regulatory arbitrage opportunities thereby making uneven progress in achieving a more stable shadow banking system. However, it is also demonstrate that regulations designed to enhance stability may also incentivise risk to migrate into less regulated spaces such as shadow banking whilst significantly and silently increasing the concentration of systemic risk in the financial sector.[18] Given their lack of balance sheet lending, shadow banks are able to create and exploit neglected tail risk by generating a facade of safety by pooling together seemingly uncorrelated and diversified assets and originating low risk securities through securitisation.[19] When these tail events are triggered, however, these apparently diversified pool of assets can experience significant losses of potentially systemic nature, making the financial system vulnerable to low probability, high impact events such as those linked to climate change. Similarly, Plantin[20] cautions that the migration to shadow banking may lead to structural opacity and delayed risk recognition, which I argue may be magnified in areas involving long-term environmental exposure.

This interaction is particularly visible in the US mortgage market where, in the aftermath of the GFC, non-bank mortgage lenders have captured a growing share of the market by dollar value. By 2017, shadow banks were responsible for 50% of mortgage originations in the US[21] and have increased further to approximately 60% in 2020.[22] This shift is not only attributed to efficiency gains but also to differences in regulatory oversight. Unlike traditional banks, shadow banks face limited capital requirements and no liquidity coverage mandates. In particular, Buchak et al.[23] find that fintech shadow banks increased their market share in residential mortgage origination to 12% from 3% between 2007 and 2015, with shadow banks overall increasing their share to 50% from 30% during the same period. These features have implications for climate-exposed real estate markets, where flood risk, sea-level rise, and storm intensity increasingly shape default probabilities but remain difficult to integrate into standard underwriting and securitisation models. Building on this, Fuster et al.[24] find that fintech lenders process mortgage applications faster, than traditional banks, and are more responsive to exogenous mortgage demand fluctuations. I argue that while technological advancements could enable better identification and pricing of climate risks, automated underwriting may fail to fully incorporate complex climate risk factors that rely on expert judgement.

While traditional banks are increasingly subject to climate stress testing, shadow banks remain largely outside the scope of supervisory guidance. This creates a regulatory blind spot, especially as shadow banks' asset share has increased to almost half of global financial assets, compared to approximately 40% in 2008.[25] Climate credit risk, unlike conventional credit risk, is characterised by long time horizons, spatial asymmetry, inconsistent data quality, and model uncertainty. These features make it particularly prone to mispricing, especially in markets dominated by institutions that do not

[17] Adrian & Ashcraft (n 13) *supra*.
[18] Acharya et al. (n 15) *supra*.
[19] Gennaioli, Nicola, et al. "A Model of Shadow Banking." *The Journal of Finance*, vol. 68, no. 4, 2013, pp. 1331-1363.
[20] Plantin, Guillaume. "Shadow Banking and Bank Capital Regulation." *The Review of Financial Studies*, vol. 28, no. 1, 2015, pp. 146-175.
[21] Buchak, Greg, et al. "Fintech, Regulatory Arbitrage, and the Rise of Shadow Banks." *Journal of Financial Economics*, vol. 130, no. 3, 2018, pp. 453-483.
[22] Kim et al. (n 2) *supra*.
[23] Buchak et al. (n 21) *supra*.
[24] Fuster, Andreas, et al. "The Role of Technology in Mortgage Lending." *The Review of Financial Studies*, vol. 32, no. 5, 2019, pp. 1854-1899.
[25] "Holistic Review of the March Market Turmoil." *Financial Stability Board*, 2020.

retain loan exposure and lack incentives to assess long-term vulnerabilities.

B. *Physical Climate Risk in Real Estate*

In the last decade, the crossover of finance and climate risk has generated substantial theoretical and empirical work. Physical climate risk, such as sea-level rise (SLR), inland flooding, and extreme weather events, is increasingly recognised as material to asset prices, mortgage default risk, loss given default, and broader institutional lending decisions. The acceleration of climate change impacts, particularly in coastal areas, has created an unprecedented challenge for the US housing market, and over $1 trillion in coastal real estate is now threatened by climate change impacts.[26] This significant exposure, combined with the increasing frequency and severity of climate events, presents an interesting opportunity to examine how different types of financial institutions respond to and price climate risk.

Financial markets are beginning to price in some climate-related risks, but unevenly and often with a focus on transition risk rather than physical risk. In general, results from studies assessing how physical climate risks are being priced into real estate and mortgages are mixed. For example, Bin & Landry[27] find that property values in flood-exposed areas tend to decline immediately after major storm events but gradually recover over time, suggesting that market memory is relatively short and incentives to relocate or mitigate exposure remain weak. Ortega & Taşpınar,[28] on the other hand, present a more nuanced view noting that while some prices recover post-disaster, the trajectory is often partial and uneven. Outside of price recovery, Bernstein et al.[29] demonstrate that homes in coastal areas exposed to SLR trade at a discount only in markets where buyers are informed and express a degree of worry towards global warming. Baldauf et al.[30] add nuance to this by showing that property overvaluation is most acute in regions where climate scepticism is prevalent. These findings suggest that market efficiency in pricing physical climate risk is highly uneven, shaped not just by information availability, but also by human behaviour and cultural beliefs. This is especially problematic given the uneven geography of climate exposure and is echoed by Bakkensen & Barrage[31] who also find significant heterogeneity in risk capitalisation based on local climate risk perceptions and expectations. Additionally, Bakkensen & Mendelsohn[32] use a global panel of tropical cyclone events to document that wealthier, denser regions show a higher degree of climate adaptation. This results in lower relative losses for wealthy areas compared to less wealthy and populated areas. They find no evidence of adaption to damage in the US thus resulting in a damage function that is 14 times greater than other developed countries. I believe that this lack of adaptation is partly driven by climate scepticism, as argued by Baldauf et al.[33] On the contrary, Giglio et al.[34] find evidence that climate risks are increasingly capitalised into asset prices; however, significant mispricing persists, particularly in the long end of the risk curve.

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[26] US Global Change Research Program (n 1) *supra*.

[27] Bin, Okmyung, and Craig Landry. "Changes in Implicit Flood Risk Premiums: Empirical Evidence From the Housing Market." *Journal of Environmental Economics and Management*, vol. 65, no. 3, 2013, pp. 361-376.

[28] Ortega, Francesc, and Süleyman Taşpınar. "Rising Sea Levels and Sinking Property Values: Hurricane Sandy and New York's Housing Market." *Journal of Urban Economics*, vol. 106, 2018, pp. 81-100.

[29] Bernstein, Asaf, et al. "Disaster on the Horizon: The Price Effect of Sea Level Rise." *Journal of Financial Economics*, vol. 134, no. 2, 2019, pp. 253-272.

[30] Baldauf, Markus, et al. "Does Climate Change Affect Real Estate Prices? Only If You Believe in It." *The Review of Financial Studies*, vol. 33, no. 3, 2020, pp. 1256-1295.

[31] Bakkensen, Laura, and Lint Barrage. "Going Underwater? Flood Risk Belief Heterogeneity and Coastal Home Price Dynamics." *The Review of Financial Studies*, vol. 35, no. 8, 2022, pp. 3666-3709.

[32] Bakkensen, Laura, and Robert Mendelsohn. "Risk and Adaptation: Evidence from Global Hurricane Damages and Fatalities." *Journal of the Association of Environmental and Resource Economists*, vol. 3, no. 3, 2016, pp. 555-587.

[33] Baldauf et al. (n 30) *supra*.

[34] Giglio, Stefano, et al. "Climate Change and Long-Run Discount Rates: Evidence from Real Estate." *The Review of Financial Studies*, vol. 34, no. 8, 2021, pp. 3527-3571.

This is primarily true in areas which have faced significant damages, thereby indicating a learning mechanism. All these findings, however, suggest that climate risk is not fully priced into property values to begin with.

Additionally, there is a degree of inconsistency in the findings with regards to lending activity, across both depository and non-depository institutions, following physical climate events. Keys & Mulder[35] observe that mortgage lenders in Florida did not materially change their origination or securitisation patterns despite repeated storm events. Their findings suggest that underwriting practices and securitisation pipelines remain relatively insensitive to physical climate risk, even when historical events suggest long-term threats. They conclude that this is likely a result of prospective buyers being more pessimistic about climate change risk than prospective sellers. In a similar manner, Brei et al.[36] examine the impact of hurricanes on the banking sector in the Caribbean and find that banks respond to funding shocks by reducing lending and drawing on liquid assets rather than expanding credit. This implies that post-disaster recovery is primarily financed through deposits, rather than through an increase in credit availability.

Conversely, other studies highlight more dynamic responses. Cortés & Strahan, Rehbein & Ongena, and Ivanov et al.[37] find that credit is often reallocated after disasters, with banks reducing lending in unaffected areas to meet new demand in impacted areas. These flows are usually rationalised as post-crisis reconstruction support, but they also reflect underlying assumptions about temporary dislocation rather than permanent loss.

In an effort to further understand if flood risk is capitalised into house prices, numerous academics have used the FEMA flood zones as a basis for their research. The literature suggests that house prices inaccurately reflect underlying flood risk with Hino & Burke[38] concluding that house prices in FEMA flood zones are overvalued by $33–56 billion. A more recent study by Gourevitch et al.[39] finds that US housing is overvalued by $121–237 billion due to unpriced flood risk. The latter study also highlights that overvalued properties are particularly common in coastal areas just outside the official FEMA flood zones. Whilst Sastry[40] analyses credit rationing following flood map changes in Florida, they find that mortgage lenders transfer flood risk to the government through flood insurance contracts, and to under-insured households through higher deposit requirements. They conclude that lenders screen for flood risk when they retain exposure to the loan and thereby have a significant impact on household financial health. In a similar manner, Blickle & Santos[41] find that banks are less likely to lend to low-income and low-FICO borrowers following map changes as a result of the added financial burden of insurance. More recently, Blickle et al.[42] find that lenders are unwilling to

[35] Keys, Benjamin, and Philip Mulder. "Neglected No More: Housing Markets, Mortgage Lending, and Sea Level Rise." *National Bureau of Economic Research*, 2020.
[36] Brei, Michael, et al. "The Impact of Natural Disasters on the Banking Sector: Evidence From Hurricane Strikes in the Caribbean." *The Quarterly Review of Economics and Finance*, vol. 72, 2019, pp. 232-239.
[37] Cortés, Kristle, and Philip Strahan. "Tracing Out Capital Flows: How Financially Integrated Banks Respond to Natural Disasters." *Journal of Financial Economics*, vol. 125, no. 1, 2017, pp. 182-199; Rehbein, Oliver, and Steven Ongena. "Flooded Through the Back Door: The Role of Bank Capital in Local Shock Spillovers." *Journal of Financial and Quantitative Analysis,* vol. 57, no. 7, 2022, pp. 2627-2658; Ivanov, Ivan, et al. "Bank Lending Networks and the Propagation of Natural Disasters." *Financial Management*, vol. 51, no. 3, 2022, pp. 903-927.
[38] Hino, Miyuki, and Marshall Burke. "The Effect of Information About Climate Risk on Property Values." *Proceedings of the National Academy of Sciences*, vol. 118, no. 17, 2021.
[39] Gourevitch, Jesse, et al. "Unpriced Climate Risk and the Potential Consequences of Overvaluation in US Housing Markets." *Nature Climate Change*, vol. 13, no. 3, 2023, pp. 250-257.
[40] Sastry, Parinitha. "Who Bears Flood Risk? Evidence from Mortgage Markets in Florida." Columbia Business School Working Paper, 2024.
[41] Blickle, Kristian, and Joao Santos. "Unintended Consequences of "Mandatory" Flood Insurance." *Federal Reserve Bank of New York: Staff Reports*, 2022.
[42] Blickle, Kristian, et al. "Do Mortgage Lenders Respond to Flood Risk?" *Federal Reserve Bank of New York: Staff Reports,* 2024.

originate mortgages that face unmapped flood risk and that shadow banks are more likely to securitise mortgages in flood prone areas.

Part of this inability to accurately price flood risk stems from limitations in flood risk data and insurance underwriting capabilities. The National Flood Insurance Program (NFIP), which underpins most US residential flood insurance, has long relied on outdated maps and subsidised pricing. FEMA's Risk Rating 2.0 reform which was introduced in 2021, after a one-year delay due to poor uptake and teething problems, aims to resolve this by aligning insurance premiums more closely with actual climate risk.[43] That being said, substantial backlash was initially faced as increased premiums based on risk could disproportionately affect low-income households in climate-prone areas,[44] in line with the findings of Blickle & Santos.[45] Private flood insurance markets are thin, fragmented, and often unaffordable. As a result, property-level flood risk remains poorly reflected through insurance pricing, limiting its role in mortgage underwriting or homebuyer decision-making.

For lenders, this creates a distorted risk environment in which loans can be originated on overvalued and underinsured properties without triggering red flags in conventional credit underwriting models. Interestingly, Keenan & Bradt[46] conclude that local lenders are more likely to transfer risk from mortgages in high-risk coastal areas through securitisation, signifying a level of information asymmetry between local lenders and national or global lenders. Their analysis of mortgage origination and securitisation in coastal communities reveals that lending practices shift in response to perceived climate risk, thereby accelerating socio-economic changes in vulnerable communities. The continuation of such lending practices may disproportionately affect climate-vulnerable populations resulting in reduced access to credit and affordable housing and ultimately leading to climate gentrification.[47]

The potential mispricing of real estate has significant implications for household wealth given that real estate is usually the largest component of a household's investment portfolio, and by far the largest component of a household's debt profile.[48] If physical climate risk is not fully priced into house values, and shadow banks underwrite non-conforming mortgages in the absence of traditional banks, this may lead to residential mortgage-backed security investors holding overvalued collateral and underpriced credit risk. These circumstances could result in conditions that may contribute to financial instability in the wake of climate shocks. Therefore, the growing role of shadow banks in financing climate exposed real estate raises concerns about financial stability and market efficiency whilst increasing the need for transparent and consistent regulation.

C. *Regulation & Socio-Economic Impacts*

Whilst regulation for depository institutions increased substantially in the aftermath of the GFC, red tape for non-depository institutions has been a lot slower. Whilst too much regulation may hinder growth, regulatory blind spots may result in the accumulation of risks within the shadow banking sector, particularly when regulatory frameworks fail to account for evolving risks—such as physical climate risks. Banque de France's[49] financial stability review highlights that regulatory oversight of shadow banking remains at a

[43] "FEMA Defers the Implementation of Risk Rating 2.0." *Federal Emergency Management Agency*, 7 Nov. 2019.
[44] Tesselaar, Max, et al. "Regional Inequalities in Flood Insurance Affordability and Uptake under Climate Change." *Sustainability*, vol. 12, no. 20, 2020.
[45] Blickle & Santos (n 41) *supra*.
[46] Keenan, Jesse, and Jacob Bradt. "Underwaterwriting: From Theory to Empiricism in Regional Mortgage Markets in the U.S." *Climatic Change*, vol. 162, no. 4, 2020, pp. 2043-2067.
[47] Keenan, Jesse, et al. "Climate Gentrification: From Theory to Empiricism in Miami-Dade County, Florida." *Environmental Research Letters*, vol. 13, no. 5, 2018.
[48] Jones, John, and Urvi Neelakantan. "Portfolios Across the U.S. Wealth Distribution." *Federal Reserve Bank of Richmond Economic Brief*, 2023.
[49] "Non-Bank Finance: Trends and Challenges." *Banque de France Financial Stability Review*, no. 22, 2018.

formative stage and that a key structural vulnerability lies in the external credit rating process itself. As credit rating agencies continue to operate under an issuer-pays model, where issuers finance the assessment of their own securities, there remains a potential incentive misalignment that may lead to favourable ratings in order to maintain corporate relationships or win business. This dynamic may perpetuate the underestimation of credit and liquidity risk, thereby propagating systemic financial vulnerabilities over the long run. Adding to this, Campiglio et al.[50] emphasise the need for central banks and financial regulators to develop comprehensive analytical frameworks to assess the potential impact of climate change and the low carbon transition on financial stability. Building upon this, I argue that it is becoming increasingly important to extend regulation to cover the activities of shadow banks. This is particularly crucial for flood-prone areas as they have the potential to facilitate the aggregation of unpriced environmental risks within the financial system as a result of high securitisation rates and artificial external credit ratings.

In practice, implementation of climate risk frameworks has been slow. In the US for example, while there has been some progress in integrating climate-related risks into financial stability frameworks, significant gaps remain with regards to non-depository institutions.[51] Even in the European Union, where sustainability disclosure regimes such as the Sustainable Finance Disclosure Regulation (SFDR) have gained traction, coverage of asset-backed securities and private credit markets remains limited and opaque.

One point to note however, is that lenders may misrepresent information about underlying mortgages even if climate regulation was enforced. Piskorski et al.[52] find that financial intermediaries often misrepresent key aspects of mortgages, such as occupancy status and the existence of second liens, in the RMBS market. These misrepresentations led to higher default rates and were not adequately priced into the securities at issuance. Although they do not directly address climate-specific exposure, it underscores how opacity in loan-level data can compromise investor due diligence and risk assessment in securitised products. More specifically, the role of climate risk disclosures has been explored by Ilhan et al.[53] who find that institutional investors have a strong demand for climate risk disclosures, and many actively engage their portfolio firms for improvements. The increasing demand for climate risk disclosures from institutional investors signifies the critical importance of this study. That being said, not all climate risk disclosures are equal. Bingler et al.[54] find that many firms' disclosures are immaterial, with companies cherry-picking to report primarily insignificant climate risk information. This suggests that voluntary disclosure frameworks may be insufficient for ensuring meaningful transparency, particularly in sectors like mortgage financing where climate-related risks are significant.

Whilst expanding and enforcing regulation is one solution, Battiston et al.[55] indicate the importance of climate policy timing and transparency. Their network-based climate stress-test framework reveals how abrupt shifts in climate policy could trigger sudden asset repricing which may cascade losses across portfolios with high exposure to climate-sensitive areas. Ultimately, policy

[50] Campiglio, Emanuele, et al. "Climate Change Challenges for Central Banks and Financial Regulators." *Nature Climate Change*, vol. 8, no. 6, 2018, pp. 462-468.
[51] "FSB Roadmap for Addressing Financial Risks from Climate Change: 2022 Progress Report." *Financial Stability Board,* 2022.
[52] Piskorski, Tomasz, et al. "Asset Quality Misrepresentation by Financial Intermediaries: Evidence from the RMBS Market." *The Journal of Finance*, vol. 70, no. 6, 2015, pp. 2635-2678.
[53] Ilhan, Emirhan, et al. "Climate Risk Disclosure and Institutional Investors." *The Review of Financial Studies*, vol. 36, no. 7, 2023, pp. 2617-2650.
[54] Bingler, Julia, et al. "Cheap Talk and Cherry-Picking: What ClimateBert Has to Say on Corporate Climate Risk Disclosures." *Finance Research Letters*, vol. 47, 2022.
[55] Battiston, Stefano, et al. "A Climate Stress-Test of the Financial System." *Nature Climate Change*, vol. 7, no. 4, 2017, pp. 283-288.

uncertainty could create arbitrage opportunities where agents with information about climate policy could offload their assets ahead of the policy announcement and repurchase their assets after the re-rating. This, however, is unlikely for physical real estate given its illiquid nature and high transaction costs.

Shadow banks appear less responsive to these signals primarily because many do not service loans or hold them on a balance sheet and so they are removed from the feedback loops that might otherwise encourage caution or adjustment. When institutional incentives are aligned toward origination volume and downstream securitisation, the risk of moral hazard increases, particularly in areas where climate risks are slow-moving, probabilistic, and not yet priced into GSE purchasing standards or credit rating methodologies.

The implications of these institutional dynamics extend beyond financial stability, encompassing issues of spatial inequality and adaptive capacity. The concept of climate gentrification stipulates that climate impacts and adaptations may contribute to differences in property values and have socio-economic consequences.[56] In particular, Keenan et al.[57] find that properties at higher elevations appreciate more rapidly than those at lower elevations, suggesting that concerns over sea-level rise were influencing real estate markets. Ultimately, lower-income and historically marginalised communities in climate vulnerable zones may face rising insurance costs, disinvestment, and deteriorating access to credit unless backstopped by state funding. Best & Jouzi[58] review the concept of climate gentrification and highlight the importance of participatory methods and availability of longitudinal data required to fully grasp the multifaceted nature of climate gentrification. I therefore argue that, if shadow banks are more inclined to extend loans in flood-prone areas, they may inadvertently magnify geographic and socio-economic disparities in climate vulnerable real estate markets.

In this context, climate risk can become a form of hidden leverage which is embedded in highly intermediated mortgage finance systems but not accounted for in capital ratios, pricing, or mandatory disclosure requirements. When combined with mispriced collateral and fragile funding structures, the result is a well-balanced house of cards that appears robust until risk crystallises. A correction may be triggered not just through mortgage defaults but also by insurance withdrawal, zoning policy, or shifts in investor sentiment following flood events. At that point, feedback loops can generate sharp corrections in property values, loan performance, and investor sentiment. Demonstrating the complexity of the subject, Murfin & Spiegel[59] find no evidence that seal level rise risk is already affecting residential real estate markets. This may suggest that local residential real estate markets are short-term profit motivated thereby intentionally ignoring long-term climate risk considerations.

In response to the growing recognition of climate-related financial risks, several policy frameworks and analytical approaches have emerged to address potentially systemic climate vulnerabilities such as the Task Force on Climate-Related Financial Disclosures and the Network for Greening the Financial System.[60] Whilst the former aims to

[56] Flavelle, Christopher. "Climate Change is Already Forcing Americans to Move." *Bloomberg,* 31 Oct. 2016; Bolstad, Erika. "High Ground is Becoming Hot Property as Sea Level Rises." *Scientific American*, 1 May 2017.
[57] Keenan, Jesse, et al. "Climate Gentrification: From Theory to Empiricism in Miami-Dade County, Florida." *Environmental Research Letters*, vol. 13, no. 5, 2018.
[58] Best, Kelsea, and Zeynab Jouzi. "Climate Gentrification: Methods, Gaps, and Framework for Future Research." *Frontiers in Climate*, vol. 4, 2022.
[59] Murfin, Justin, and Matthew Spiegel. "Is the Risk of Sea Level Rise Capitalized in Residential Real Estate?" *The Review of Financial Studies*, vol. 33, no. 3, 2020, pp. 1217-1255.
[60] *see* "The Need for Climate-Related Financial Disclosure." *Task Force on Climate-Related Financial Disclosures*, 2022; "NGFS Scenarios for Central Banks and Supervisors." *Network for Greening the Financial System,* 2022.

standardise climate risk reporting across asset classes, the latter highlights the importance of scenario analysis across the entire financial sector. It should be noted that these frameworks have, to some degree, been used by governments as a foundation for reporting obligations. An example of this is the European Union's Corporate Sustainability Reporting Directive (CSRD) which requires reporting under the European Sustainability Reporting Standards (ESRS). These standards go one step further than the TCFD pillars as they require reporting on double materiality—i.e., the impacts on and of the firm—compared to the TCFD which involves only financial materiality. Whilst European nations have warmed to implementing sustainability reporting, the same cannot be said for the United States.

Bolton et al.[61] introduce the concept of green swan events as climate-related financial shocks that are foreseeable in nature but highly uncertain in timing and impact. They argue that central banks and financial regulators should prepare for such systemic events by adopting more robust climate stress-testing frameworks. The effectiveness of these frameworks, however, is limited by the current lack of mandatory climate disclosures and data quality and availability.[62] This gap is particularly problematic in the context of shadow banks as they operate outside the regulatory perimeter yet still hold significant climate-related risk exposure that could echo through the financial markets in the event of a major climate shock.

Comparative studies suggest that some jurisdictions are moving more decisively than others. In the UK, for example, the Prudential Regulation Authority emphasised the importance of climate scenario analysis in its 2024 priorities to banks and insurers.[63] It specifically highlighted that it expects firms to make significant progress on climate scenario analysis and to limit their reliance on off the shelf climate tools which do not provide the level of detail end users need to effectively undertake asset-level risk. Meanwhile, Australia's Prudential Regulation Authority launched climate vulnerability assessments for major lenders, with explicit mandates to incorporate flood and fire risk into capital planning.[64] Yet such practices remain rare in the shadow banking sector, where oversight is fragmented and data often proprietary. The US, in particular, has struggled to translate climate concern into enforceable standards for non-bank lenders, despite their material presence in mortgage origination.

Given these dynamics, shadow banks may not only contribute to the misallocation of credit in climate-prone areas but also play a pivotal role in amplifying systemic fragility. This may occur through multiple channels: (i) origination of high-risk mortgages without long-term accountability, (ii) reliance on opaque securitisation structures that weaken market discipline and transparency, and (iii) insulation from emerging climate risk regulations that apply to banks and insurers but not to non-depository credit providers. The outcome is a financial framework that, whilst efficient in capital allocation and credit provision, may be structurally incapable of internalising and quantifying slow-moving environmental risks.

This institutional fragility is compounded by information asymmetry between originators, investors, and regulators. As Keys & Mulder show,[65] even post-disaster lending patterns may remain unchanged. This is not because climate risk is absent, but because relevant risk signals are not effectively transmitted. If rating agencies do not adjust their criteria, if

[61] Bolton, Patrick, et al. "Green Swans: Central Banks in the Age of Climate-Related Risks." *Banque de France Bulletin*, vol. 229, no. 8, 2020, pp. 1-15.
[62] Monasterolo, Irene, et al. "Climate Transition Risk and Development Finance: A Carbon Risk Assessment of China's Overseas Energy Portfolios." *China & World Economy*, vol. 26, no. 6, 2018, pp. 116-142.
[63] Bailey, David, and Laura Wallis. "UK Deposit Takers Supervision: 2024 Priorities." *Bank of England PRA*, 2024; Gerken, Charlotte, and Shoib Khan. "Insurance Supervision: 2024 Priorities." *Bank of England PRA*, 2024.
[64] "Climate Vulnerability Assessment." *Australian Prudential Regulation Authority*, 2022.
[65] Keys & Mulder (n 35) *supra*.

regulators do not impose disclosure mandates, and if investors continue to demand volume over transparency, then the conditions for mispricing are likely to persist. In effect, the current configuration of mortgage finance incentivises the transferring, rather than the mitigation, of climate risk. In particular, the structural shift towards shadow bank mortgage origination post-GFC raises important questions about how climate risks are being distributed through the financial system.

The contribution of this article lies in addressing this critical blind spot. I propose to empirically examine the relationship between shadow bank mortgage origination and physical climate exposure, with a particular focus on the top three states affected by flood events. Using a staggered difference-in-difference framework, this paper will assess whether the share of shadow banks' mortgage lending changes post high damage flood events. This research is positioned at the intersection of environmental finance, financial stability, and regulation. By linking climate exposure to institutional behaviour across the credit chain, I aim to offer new insights into how systemic risk accumulates in decentralised and opaque parts of the financial system. In doing so, the findings seek to inform ongoing policy debates about the need for climate-aligned financial regulation that goes beyond the traditional, deposit-taking, banking sector and into the structures where credit, risk, and accountability are increasingly fragmented and opaque.

III. **Research Gap, Hypothesis & Contribution**

Given the existing gap in the literature, this paper will address the role of shadow bank lending in US regions impacted by physical climate risks, in particular flood events. The focus on the US is driven by the quality and volume of data available, whilst the focus on shadow banks is driven by a lack of stringent regulatory oversight of the practice in comparison to depository institutions. The lack of shadow banking regulation may lead to varying underwriting standards which could result in inadequately accounting flood risk, which in turn may lead to a systemic event. Evaluating shadow bank activity can provide us with insights into potential vulnerabilities in the housing market and is crucial for several reasons.

Firstly, climate change poses significant and growing risks to the housing market. Properties in areas prone to natural disasters are increasingly at risk of property devaluation, which can undermine the stability of mortgage portfolios. Understanding how shadow banks, as major players in the mortgage market (more than 50% of lending value), address these risks is vital for financial stability and consumer protection.

Secondly, coastal properties are facing growing insurance premiums or even the inability to secure insurance due to climate risks. The unregulated lending and securitisation activity of shadow banks may lead to additional household costs if the property owner cannot afford coverage or is exposed to uninsured losses. This creates further instability in the housing market with the potential for higher default rates.

Finally, this research can inform policymakers by identifying gaps in the current regulatory framework and proposing measures to enhance the resilience of the mortgage market in flood-prone areas. It can also contribute to the broader discourse on climate finance by highlighting how shadow banks integrate flood risk into their decision-making processes.

A. *Data*

This paper relies on two externally verified sources for data: (i) Home Mortgage Disclosure Act (HMDA), and (ii) National Oceanic and Atmospheric Administration (NOAA). Both sources are certified and regulated by US government agencies and thereby provide reliability and consistency to this research. However, the large file sizes present several complexities due to the high processing speed and computational power

requirements. Therefore, selecting the three largest states by flood-related property damage and focusing on the most affected counties within those states, provides a more realistic and manageable approach whilst further justifying the focus of this study. To mitigate the computational power requirements, the raw data from each provider has been cleansed and filtered to ensure that only the relevant and reliable data remains. This is discussed in greater detail below.

1. HMDA (**Figures 1, 2, 3**)
Detailed mortgage-level data is publicly available from HMDA from 2007 to 2024 and includes numerous mortgage details such as the loan amount, type and purpose, the lender's regulator, the loan's state, county and MSA code, and the purchaser type among other application details. To avoid confounding effects, the study is limited to cover the eight years from 2010 to 2017 whilst ensuring it is a long enough time period to observe shadow bank lending activity.

By excluding the 2007 to 2009 data, the study removes the impact of the GFC during which depository institutions reduced their lending as a result of weakening economic conditions and increased regulation. Additionally, I opted to end the data period two years prior to the impact of the COVID-19 pandemic in order to further limit the confounding effects. For illustrative purposes, however, the study covers the 2007 to 2017 time period as it highlights the progression of shadow bank lending since the GFC.

To identify if a lending entity is a shadow bank or depository institution, I use the regulatory classification findings from Buchak et al.[66] HMDA identifies the lender's primary regulator, which provides a useful first cut regarding depository versus non-depository institutions. For regulating entities that govern both depository and non-depository institutions, Buchak et al.[67] manually classify the underlying lenders based on their deposit holdings. Using this proportion of shadow bank lending, I can then measure the impact that flood events have on shadow bank activity.

The HMDA data also provides us with information regarding if the loan has been sold to a different entity within one year of origination highlighting the type of purchaser, i.e., FNMA, GNMA, or private securitisation. This allows us to understand if the mortgages are backed by government agencies and thereby who ultimately bears the credit risk. Given the scope of this article, the securitisation aspect of shadow bank lending will not be discussed further, but I recommend this as a next step for future research.

Analysing the HMDA data, it is noted that there have been over 187.5 million mortgage applications across the time period (2007 – 2017), of which 89.2 million were approved. This resulted in a total of $19.8 trillion in new mortgage issuances, of which shadow banks accounted for $7.1 trillion. The majority of approved mortgage applications related to refinancings (56.2%), while 42.1% related to home purchases, and the remaining 1.6% related to home improvements.

During the period, the share of shadow bank lending, both as a percentage of total approved applications and as a percentage of total loan amounts, increased. I hypothesise that this is a result of reduced lending activity from depository institutions following the GFC, which shadow banks were able to capitalise on. The role of shadow banks was then further entrenched by the enactment of the Dodd-Frank Wall Street Reform and Consumer Protection Act of 2010,[68] which led to traditional banks becoming price uncompetitive due to stricter regulation and more costly capital requirements. As shadow banks were not covered under the same regulatory regimes and capital requirements, they were able to fill the lending gap which was caused by the shrinking of depository institution activity.

[66] Buchak et al. (n 21) *supra*.
[67] ibid.
[68] Dodd-Frank Wall Street and Consumer Protection Act. PL 111-203, 124 Stat 1376, 21 Jul. 2010.

2. NOAA (**Figures 4, 5, 6**)
Natural disaster data is gathered from NOAA, which details climate events by type, year, county and state identification code, and property damage among other event details. Whilst NOAA has annual data from 1950 to 2025, I have elected to use the same time period as the HMDA data for consistency.

I have categorised the subset of unique climate event types into broader groups for ease of comparison. For example, all flood event types such as flash flood, coastal flood, and lakeshore flood, have been aggregated into the broader category of floods for comparative simplicity. For context, the definitions of each flood event type are specified by NOAA[69] and listed below:

- Flash Flood: Caused by heavy or excess rainfall in a short period of time, usually less than six hours.
- Coastal Flood: Inundation of land areas along the coast, caused by higher-than-average high tide and heavy rainfall.
- Lakeshore Flood: Inundation of land areas adjacent to the lake, often due to strong winds pushing water onshore.

A total of 684.4 thousand climate events are observed across the study period, of which 67.8 thousand (9.9% of observations) relate to flood events. For context, these flood events account for $122.8 billion or 55.5% of total property damage experienced. The magnitude of flood-related property damage is significantly larger than other event types such as hurricanes (15.3 thousand observations resulting in $27.5 billion of property damage) and wildfires (3.9 thousand observations resulting in $5.1 billion of property damage). The relative increasing magnitude of flood-related property damage further validates the relevance and focus of this study. The aggregate of all floods, hurricanes, and wildfires accounts for 70.2% of total property damage across the time period studied. The largest spike in flood-related property damage was in 2012 as a result of Hurricane Sandy in New Jersey which accounted for 97.2% of all flood-related property damage in that year. This was followed by Hurricane Harvey in Texas during 2017, which accounted for 95.6% of all flood-related property damage that year. The impact of Hurricane Harvey and 2017 more broadly, however, is not necessarily included in this model in order to avoid spillover effects. The third spike was in Louisiana in 2016, which accounted for 85.9% of all flood-related property damage that year, and was a result of heavy rainfall leading to widespread flash floods and river floods.

It should be noted that, the aforementioned flood-related property damages are heavily concentrated in three states, which account for 79.5% of all flood-related property damage. The three states, in order of damage, are: (i) Texas, (ii) New Jersey, and (iii) Louisiana. Given the significance of these states, the study will focus on these and expand the geographic focus as part of the robustness tests.

For simplicity, I have also only used data relating to the 50 states in mainland US and have not included other overseas territories or states, such as Puerto Rico and Hawaii. The rationale behind this is that the sophistication and maturity of financial markets differ materially outside mainland US and thereby would contaminate the results.

3. Data Cleansing & Filtering
Both the HMDA and NOAA datasets had complexities that needed to be dealt with, however that was made easier by the fact that all files, columns, and definitions were consistent. As both organisations make their data publicly available in comma separated value files, the transfer and reading onto R was smooth. That being said, there were numerous adjustments required prior to testing the hypothesis.

With regards to the HMDA data, I began by filtering for only approved mortgage applications as this will allow us to further

[69] "Severe Weather 101: Floods." *National Oceanic & Atmospheric Administration,* 2025.

analyse the difference in lending attitudes between depository institutions and non-depository institutions. I then proceed to format the loan amounts to be in a consistent format to ensure that all approved mortgage amounts are included. For simplicity and consistency with the NOAA data I format all loan amounts to be in single units. Most importantly, I apply the findings from Buchak et al.,[70] as shown in **Table 1** below, to determine whether a lending entity is a shadow bank or depository institution based on its primary regulator. Whilst a manual classification based on regulating entities may have be more accurate, I believe that the current method is an accurate proxy given that six of the seven regulatory entities either almost solely regulate depository institutions or non-depository institutions.

A similar number of amendments were performed on the NOAA data. For example, I began filtering the data to include only the 50 states of mainland US and remove any overseas territories or states, such as Puerto Rico and Hawaii. I further focused the data from the 50 states to only analyse Texas, New Jersey, and Louisiana as they will be the primary focus of this paper given the high concentration of flood-related property damages in these three states.

Similar to the HMDA data, I ensured consistency in the property damage figures by formatting all amounts to be in single units. Finally, all flood event types are aggregated into one main flood group. This is then replicated for hurricanes and wildfires as these can be used for future research.

IV. **Methodology**

To assess the causal impact of flood exposure on the share of mortgage origination by shadow banks, this study employs a staggered difference-in-difference (DiD) based on model specifications by Sun & Abraham.[71]

The staggered DiD approach estimates causal effects by comparing changes in outcomes between treated and untreated groups before and after a treatment event, in this case the occurrence of a top quartile flood event. By doing so, I am able to control for unobserved, time-invariant county characteristics and common temporal shocks. The staggered implementation allows treatment timing to vary across counties, reflecting the fact that flood event occur in different years and locations. This mitigates the bias of traditional two-way fixed-effect estimators, which can assign negative weights when treatment is not simultaneous across units. A standard DiD that pools all treated counties at a single post-flood date would misstate dynamic effects when counties are treated in different years. The staggered DiD, therefore, provides a more reliable estimate of the dynamic response of shadow bank lending to flood exposure over time.

To determine the treated and control groups, counties are ranked by their cumulative flood damage from 2010 to 2017. The top quartile as then assigned as the treated group and the bottom quartile as the control group. This approach results in counties within the same states being compared thereby increasing the accuracy of the study as state unique characteristics are ignored. More specifically, the use of the bottom quartile for the control group results in nearby counties with no flood damage or with minimal flood damage being used. This may be due to those counties being further from the flood source or due to better flood protection systems, such as flood barriers, and enables for an accurate comparison.

Treated counties then receive a cohort year g_c equal to the first calendar year in which they experienced top quartile flood damage, whilst control counties are assigned a unique key to indicate they were never treated. An event-time variable is then constructed which indexes years relative to the first flood.

[70] Buchak et al. (n 21) *supra*.

[71] Sun, Liyang, and Sarah Abraham. "Estimating Dynamic Treatment Effects in Event Studies With Heterogeneous Treatment Effects." *Journal of Econometrics,* vol. 225, no. 2, 2021, pp. 175-199.

The econometric model is as follows—

$$Y_{clt} = \sum_{\kappa \neq -1} \beta_\kappa 1\{\kappa = g_c - t\} + \gamma_c + \delta_t + \varepsilon_{clt}$$

where:

- Y_{clt} is the shadow bank lending share in county c, for lender type l, in year t;
- g_c is the first treatment year for county c, also known as cohort;
- $1\{\kappa = g_c - t\}$ is an indicator equal to 1 if year t is exactly κ years relative to that county's first flood—for example:
    - when $\kappa = -2$, two years before the flood
    - when $\kappa = 0$, the flood year itself
    - when $\kappa = +2$, two years after the flood
- the sum $\sum_{\kappa \neq -1} \beta_\kappa 1\{\kappa = g_c - t\}$ stacks a full set of event-time coefficients β_κ for κ (excluding $\kappa = -1$), where each β_κ measures the average difference in shadow bank share in treated counties at time κ relative to the year before the treatment ($\kappa = -1$) and relative to the control group;
- γ_t is the area fixed effect (county) to control for time-invariant county characteristics;
- δ_t is the time fixed effect (year) to account for temporal dynamics in mortgage lending;
- ε_{clt} is the error term capturing unexplained variation.

By incorporating staggered treatment timing, this model effectively accounts for heterogeneity in treatment timing and reduces biases arising from dynamic treatment effects. For proof of parallel trends, I test $\beta_\kappa = 0$ for all $\kappa < 0$. Statistical insignificance confirms that treated and control counties exhibit similar pre-flood trajectories in shadow bank lending share. Whilst post-treatment coefficients $\beta_\kappa \geq 0$ track the timing and persistence of any flood-related shift towards non-depository lending.

By identifying the change in lending activity, this study offers valuable insights into the risk transfer mechanisms and systemic vulnerabilities of the US housing market. The findings may play a crucial role in informing policymakers and regulators on the role of shadow banks in amplifying flood-related financial risks.

Overall, I hypothesise that shadow bank lending increases as a proportion of total lending activity following a top quartile flood event. I assume this is driven by the fact that depository institutions are more risk averse given their capital and regulatory requirements as a result of the Dodd-Frank Act. As such, the gap left in the mortgage market is quickly filled by shadow banks who seek to capitalise on higher interest mortgages before packaging them and externalising their risk through securitisation.

This study therefore seeks to test the hypothesis that shadow bank mortgage lending increases, as a proportion of total lending, in treated counties relative to untreated counties.

V. **Results**

This Section presents the empirical results and provides a discussion on the impact of flood-related property damage on shadow bank lending between high flood-damage areas (treated group) and low flood-damage areas (control group).

The estimates in **Table 2**, below, present the staggered DiD results using the Sun & Abraham event-study estimator,[72] with standard errors clustered at the county level. The dependent variable is the proportion of total approved mortgage lending originated by shadow banks, i.e., the shadow bank share of lending. The key parameter of interest is the interaction of a treated-period indicator with the post-flood period.

The row labelled "Shadow Bank Share x Post" in **Table 2** corresponds to the aggregate post

[72] ibid.

treatment indicator. Its estimate indicates that treated counties experience an immediate and persistent increase in shadow bank lending share of 5.3%, on aggregate, relative to the control group. I believe that the use of the bottom quartile flood damage counties for the control group is an appropriate approach as the use of counties with no flood damage at all resulted in a significant reduction in observations.

By construction, the omitted reference period is one year before treatment ($\kappa = -1$), so the coefficient at event time zero (β_0) measures the effect relative to that benchmark. The findings indicate that in the initial flood year itself, there is a 3.8% increase in the shadow bank share followed by a continuous positive and statistically significant increase in every subsequent year, with a peak at 8.6% increase six years post flood event. This pattern suggests not only a contemporaneous shift toward shadow banks in flood-hit counties, but also a cumulative strengthening of that shift in the years following the shock.

These results demonstrate that flood exposure induces a sizable and sustained redistribution of mortgage originations away from regulated depository institutions and toward shadow banks, consistent with the hypothesis that non-bank lenders expand credit supply in regions where traditional banks pull back from following flood events. The implications of these results are discussed in the section below.

A. *Parallel Trends & Robustness Tests*

The parallel trends assumption is a critical requirement to ensure the internal validity of the staggered DiD method. To validate the above results, a parallel pre-trend analysis is conducted and is shown in **Table 2**. Row (1) of the table verifies that no statistically significant change existed in the share of shadow bank lending prior to the flood event and is expressed by the coefficient being near zero and the 95% confidence interval straddling zero. This result indicates that the parallel pre-trend assumption holds true, providing further validity of the empirical method used.

To further evaluate the validity of the findings, I also conducted two additional changes to the base case model. Firstly, I expanded the geographic focus to include all additional states which account for more than 1.0% of annual flood-related property damage. The expanded list of states accounts for 93.9% of all flood-related property damage and include: Texas, New Jersey, Louisiana, Tennessee, Michigan, Iowa, New York, Vermont, Illinois, Florida, Mississippi, and California.

By expanding the geographic scope of the study, I am able to assess if shadow bank activity is consistent across states and verify the common trends assumptions. I hypothesise that, as the geographic focus expands to include states with a proportionally smaller share of flood-related property damage, the change in shadow bank lending post flood event will increase at a lower rate and remain positive but will be smaller compared to the top three states test. I assume this is due to the capital requirements of depository institutions not being linear in nature. The result confirms the existence of parallel trends and is in line with the hypothesis highlighting that the share of shadow bank lending increases by 3.2% (statistically significant at 0.01% level) following a high damage flood event. This finding further validates that the base case results may hold true for the rest of the US.

Secondly, I conducted a placebo test to assess whether the findings truly reflect a causal response between flood events and shadow bank lending. As such, artificial flood dates are randomly assigned to treated counties and re-estimated with the Sun & Abraham[73] staggered DiD model on these placebo cohorts. The result of the placebo test indicates that both pre- and post-treatment coefficients hover closely around zero and none are statistically significant. In particular, there is no shift in shadow bank lending during pre-treatment

[73] ibid.

period and no spurious increase at or after the flood event. These null placebo coefficients confirm that the original staggered DiD results are not driven by idiosyncratic time-trends, seasonal patterns, or other data driven noise. Had there been no actual flood shock, an increase in shadow bank lending share would not have been observed post-flood event. Thus, this robustness test reinforces the credibility of parallel trends and implies that the 5.3% aggregate increase in post-flood shadow bank lending reflects a genuine shift in credit supply.

VI. **Discussion**

The finding that exposure to high damage floods leads to a persistent and economically meaningful shift in mortgage origination toward shadow banks carries several important implications for financial stability, regulatory policy, and household financial health. This is consistent with my hypothesis. The observed increase in the share of shadow bank lending, from 3.8% in the flood year to 8.6% six years afterwards, suggests that non-depository institutions play a vital role in restoring credit flows in areas where traditional banks have withdrawn from. These findings add nuance to the works of Cortés & Strahan, Rehbein & Ongena, and Ivanov et al.[74] who find that credit is often reallocated after disasters, with banks reducing lending in unaffected areas to meet new demand in impacted areas. Whilst traditional banks may reallocate capital towards affected areas after climate events, they do so at a slower rate than shadow banks, thereby allowing the share of shadow bank lending to increase.

In the immediate aftermath of flooding, however, depository institutions may tighten underwriting standards or reduce lending in order to repair capital buffers and manage disaster-related losses. Meanwhile, shadow banks which are unconstrained by the same deposit-funding requirements and regulatory capital ratios, step in to fill this credit gap, thereby maintaining access to mortgage finance for affected homeowners and potential buyers. From a household credit perspective, this substitution could be value accretive if it smooths the supply of credit and prevents material downturns in local real estate markets. In theory, given their unconstrained capital, shadow banks would be able to provide post-flood credit at competitive rates. However, given the lack of credit supply and relatively higher cost of capital compared to traditional banks this is not the case.

The persistent rise in shadow bank lending also raises concerns regarding risk allocation and consumer protection. Non-bank lenders rely on more complex and expensive wholesale funding,[75] employ less standardised and prudent underwriting, and face looser regulatory oversight relative to traditional banks. As a result, households in flood-impacted counties may face higher interest rates or less favourable contract terms, potentially further exacerbating financial vulnerability among already distressed borrowers. Regulators should therefore monitor the post-flood expansion of shadow bank credit to avoid predatory lending practices or an accidental buildup of systemic risk outside the traditional banking system.

The evidence of parallel trends highlights that credit reallocation is neither transient nor anticipated. Instead, it reflects a structural, long-run recalibration of the mortgage finance market in regions subject to flood events. Policymakers aiming at enhancing local real estate market resilience should therefore recognise that simply restoring the physical built environment may not be enough, and that ensuring equitable access to credit post-flood events is equally important. Post-flood programs such as targeted guarantee schemes, disaster-loan assistance, or reinsurance pools could be calibrated to incentivise traditional banks and insurers to maintain lending and insurance coverage even in the face of large losses, thereby mitigating reliance on less regulated and opaque market participants.

[74] Cortés & Strahan (n 37) *supra*; Rehbein & Ongena (n 37) *supra*; Ivanov et al. (n 37) *supra*.

[75] Pozsar et al. (n 12) *supra*.

For example, by deploying targeted guarantee schemes that partially backstop new originations in flood prone areas, a public guarantor (e.g., the Federal Housing Administration) would absorb a pre-specified share of losses and thereby lower the expected loss for households. The success of this scheme, however, relies on robust underwriting, continuous insurance coverage, and lenders caping their interest rates and fees. By lowering the expected loss given default for depository institutions, the funding cost gap to shadow banks should narrow, thereby reducing the spike in post-flood event shadow banking activity. The scheme could also be tailored to favour low- and middle-income households or first-time buyers by tying the guaranteed percentage to borrower income, loan-to-value ratios, or the implementation of property-level mitigation measures.

Similarly, disaster-loan assistance programmes, such as low-interest federal disaster loans that already exist, could be expanded to integrate forecasted climate-related expected losses or refinancing costly post-flood mortgages into more affordable government-backed debt structures. In parallel, the use of re-insurance pools could stabilise primary insurers' capacity and pricing in flood prone regions. As insurers group together to jointly provide reinsurance coverage, this allows them to share the risks they may not have otherwise been able to underwrite alone, increasing their capacity to handle large or unusual events. This approach can already be seen in the UK with the Flood Re scheme.[76]

Additionally, coastal properties are experiencing rising insurance premiums, or in some cases an outright unavailability of insurance coverage, driven by the increasing frequency and severity of flood events.[77] Traditional depository lenders often require borrowers to maintain adequate hazard insurance as a condition of mortgage approval, effectively offloading catastrophic risk to insurers. Shadow banks, however, operate with minimal regulatory requirements and may securitise pools of mortgages without rigorous verification of insurance status or with allowances for expired coverage. When insurers retreat from high-risk coastal zones or impose higher insurance premiums, the homeowners in the affected areas may find themselves unable to secure or afford the policies that banks require. Within shadow banking, such coverage gaps translate into increased exposure to uninsured losses which households must self-fund. The resulting monetary impact on households may diminish their ability to service their mortgage obligations, thereby magnifying default risk in markets struggling to recover from flood events.

These regulatory gaps stem from the design and implementation of the National Flood Insurance Program's (NFIP) Mandatory Purchase Requirement (MPR), established under the National Flood Insurance Act of 1968 and the Flood Disaster Protection Act of 1973.[78] The MPR requires borrowers to purchase and maintain flood insurance only if they have a mortgage from a federally regulated or federally backed lender and the property lies within a FEMA-mapped flood zone. Borrowers outside these zones, with non-federally regulated lenders, such as shadow banks, therefore, are out of scope for MPR.

To correct these shortcomings, the flood insurance requirements could be extended beyond the federally chartered banks to include non-bank mortgage lenders and servicers. Whilst this would help ensure appropriate coverage at origination it would fall short in assessing this requirement during the life of the mortgage. Therefore, it would also be appropriate to strengthen the enforcement by mandating periodic post-origination verification of coverage for all mortgages in specified risk bands. In turn this would require standardised reporting of

[76] Browning, Steve. "Flood Re and Household Flood Insurance." *House of Commons*, 6 Jul. 2023.

[77] Flavelle & Rojanasakul (n 3) *supra*.

[78] PL 93-234; PL 90-448.

insurance status to regulators. To address the equity implications of stricter mandates, these obligations could be paired with means-tested premium subsidies or tax credits targeted at lower-income households in high-risk areas. One feasible option would be to explicitly require both banks and shadow banks to offer loss-mitigation options such as term extensions or rate reductions to borrowers facing large uncovered losses. The financial institutions would then be able to claim the losses back from government agencies or via tax credits.

More importantly, the securitisation of these loans further transmits risk throughout the financial system, making it harder for regulators to track credit risk concentrations. In aggregate, these dynamics have the potential to destabilise local housing markets and threaten systemic financial stability. As mortgage performance deteriorates and foreclosures rise, property values may weaken, further amplified by reduced insurance coverage, thus triggering a feedback loop of tightening credit conditions, especially to the most vulnerable communities ultimately leading to a debt spiral and climate gentrification.

Securitisation based on such weak credit profiles, uninsured properties and increasing climate risk poses a significant threat to the residential mortgage-backed securities (RMBS) market as default rates flow through the tranches. Given that RMBSs are priced and split into tranches at origination, there is potential for risk to have increased in subordinated tranches thereby resulting in investors receiving lower-than-expected risk-adjusted returns. Whilst the argument of geographic diversification does offer some risk relief, the systemic nature of climate events poses a potential threat across all tranches. However, given the scope of this article, securitisation will not be explored any further.

The speed at which credit demand is met by shadow banks reflects positively on the capital allocation efficiency of the market as equilibrium is retained. However, the cost and terms of the new credit may result in market disequilibrium in the long run as losses materialise.

VII. **Limitations & Further Research**

Whilst the study was developed in a rigorous manner, its limitations must be acknowledged when interpreting the results and accounted for appropriately in future research.

Although one of the article's strengths is the fact that it covers the three largest states which account for 79.5% of flood-related property damage, it does not cover the whole US and therefore it cannot be certain that the findings are representative of the wider market. Although one of the robustness tests did expand the geographic focus to the top 12 states (93.9% of flood-related damage), this does not necessarily verify that the model is truly representative. Additionally, the US has a significantly more developed and active shadow banking market compared to other developed economies. These considerations further signify that the findings should also be examined in an international context.

While the parallel trends assumption held true in this study, this could be further improved by accounting for additional independent variables such as applicant FICO score, race and gender, household income, LTV ratio, and delinquency rate. By controlling for these variables, I would be able to strengthen the accuracy of the findings. In particular, I hypothesise that FICO scores and delinquency rates play a significant role as shadow banks are more prevalent at the lower end of the credit score spectrum where delinquency rates are higher. The untreated group could use a blind matching technique based on counties with similar characteristics such as population density, household income, and average FICO score to test the parallel trends assumptions across states in the US. An additional amendment to further assess the validity of the results would be to use other staggered DiD models, such as Callaway &

Sant'Anna.[79] If the results were similar, this would strengthen the validity of the current findings and confirm the appropriateness of the independent variables used.

Regulatory changes to capital requirements and deposit-funding should also be accounted for. Changes in regulation, for both depository and non-depository institutions, can have a significant impact on the interpretation of these findings. Therefore, any actual or potential changes to capital requirements should be accounted for as these may lead to changes in lending patters.

The staggered DiD framework implemented offers a template for evaluating the impact of other climate-related events, such as wildfires and hurricanes, on credit markets. As extreme weather events become more frequent as a result of climate change, further research seeking to understand how different segments of the financial system respond to natural disaster events is essential for designing robust regulatory policy and public-private partnerships. It is also important to note that, climate events rarely occur independently and thereby their true impact is likely to be larger than these findings which only focus on one type of climate event.

An additional area of study would be to assess the sensitivity of shadow banks to FICO scores before and after climate events. This could help inform policymakers about the potential socioeconomic outcomes of climate events and the potential need for shadow bank regulation. Furthermore, the second-round effects of climate events on MBS would allow investors and regulators to get a better understanding of where credit risk truly lies. In the context of investors, such as pension funds, this is crucial as their risk-adjusted returns may be lower-than-expected resulting in an asset-liability mismatch whilst hiding systemic risks. Finally, the duration of shadow bank lending post-flood events should also be examined. Whilst depository institutions may be quick to withdraw from flood-affected areas, it is unclear at what stage depository institutions return to previously flooded areas. By understanding this volatility in lending behaviour, regulators can better seek to protect households and provide stability to local real estate markets.

VIII. **Conclusion**

This article has demonstrated that shadow banking institutions play a distinct role in meeting credit demand for mortgages following flood events in Texas, New Jersey, and Louisiana. The findings show that shadow banks' share of total mortgage originations rises by 5.3%, on aggregate, following high-damage flood events. The findings also highlight how regulatory frictions on depository institutions can leave critical credit gaps which non-depository, unregulated, institutions can fill. This result is economically significant and may have material implications for household finances, financial regulation, and the stability of local real estate markets.

Shadow banks currently originate more than 50% of all US mortgages by dollar value, and my geographic focus accounts for 79.5% of national flood-related property damage. As such, the post-flood lending shift observed represents a sizeable reallocation of credit supply away from traditional, tightly capitalised banks and toward entities that are not subject to comparable risk-management standards or capital requirements. This change in lending behaviour is assumed to be a form of regulatory arbitrage whereby depository institutions retreat after high-damage flood events due to costlier capital requirements, caused by the post-Dodd-Frank regulatory era. In turn, shadow banks step in to fill the newly created credit gap while potentially extending credit to borrowers whose collateral is most exposed to future flood events.

[79] Callaway, Brantly, and Pedro Sant'Anna. "Difference-In-Differences With Multiple Time Periods." *Journal of Econometrics*, vol. 225, no. 2, 2021, pp. 200-230.

By underwriting mortgages on flood damaged or high-risk properties without robust insurance coverage, shadow banks may amplify local housing market volatility and magnify borrower vulnerability to future disasters, beyond flooding. The securitisation of such loans further complicates the tracing and management of geographically concentrated credit risk, thereby raising the possibility of hidden spillovers across the housing market and financial system more broadly.

From a policy perspective, the results suggest that climate resilience in mortgage markets requires more than infrastructure adaptation or floodplain management. It also requires a review of regulatory equivalence across lender types and further implementation of government schemes, such as targeted guarantees, disaster-loan assistance, and reinsurance pools, to support equitable access to credit post-flood events. By aligning capital, disclosure, and insurance requirements to account for climate-driven concentration risks across both banks and shadow banks, regulators could mitigate the rise in shadow bank activity following flood events. Enhancing transparency around post-flood lending practices and insurance coverage may also support more informed origination decisions and consumer protections whilst enforcement of post-origination insurance verification could result in reduced uninsured losses. Additionally, closing regulatory gaps such as the ones present under the MPR currently would not only bring the regulatory requirements up to date with modern finance, but would also enable for a more competitive bidding process between banks and shadow banks that would ultimately benefit consumers.

While this article focused on three high damage states, future work should extend the scope nationwide, and to other climate events such as wildfires and hurricanes. This study contributes to a nascent but growing area of study which is at the intersection of climate risk, mortgage finance, and financial regulatory policy. The research also highlights the urgent need for a coherent framework to govern credit provision in an era of intensifying climate events.

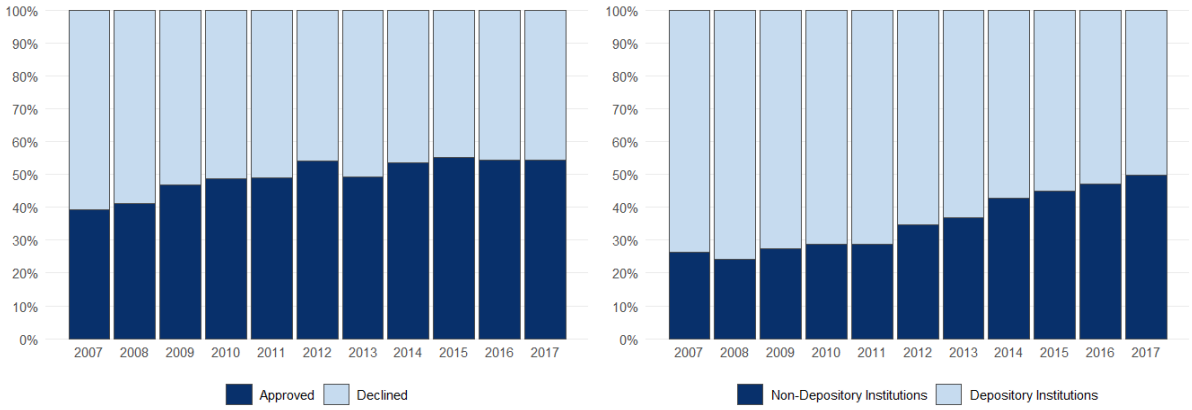
Overall, the findings suggest that flood-exposed credit demand for mortgages can be met by non-depository institutions. However, careful oversight and increased regulatory scrutiny are needed to balance market efficiency with consumer protection and systemic resilience.

Regulatory Agency	**Classification Distribution**	
	Bank	**Shadow Bank**
OCC	100.0%	0.0%
FRS	62.9%	37.1%
FDIC	99.9%	0.1%
OTS	100.0%	0.0%
NCUA	100.0%	0.0%
HUD	0.3%	99.7%
CFPB	97.4%	2.6%

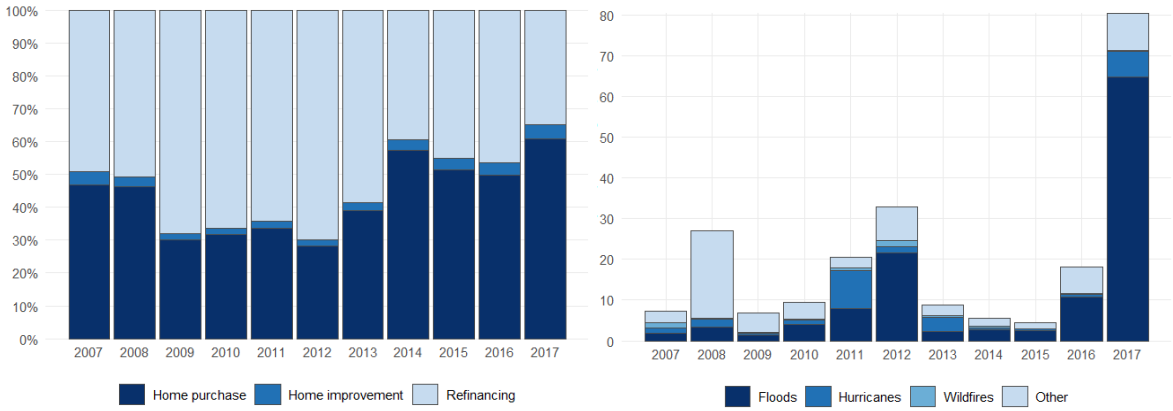
Table 1: Regulatory Agency Classification Distribution (Data Source: Buchak et al.).

	Coefficient	***Standard Error***	***t-value***
Shadow Bank Share	*-0.00970*	*0.02113*	*-0.45920*
Shadow Bank Share x Post	***0.05259******	***0.01251***	***4.20498***
Shadow Bank Share x Post$_0$	*0.03800****	*0.00977*	*3.88871*
Shadow Bank Share x Post$_1$	*0.04644**	*0.01929*	*2.40811*
Shadow Bank Share x Post$_2$	*0.04740****	*0.01138*	*4.16577*
Shadow Bank Share x Post$_3$	*0.05046****	*0.00985*	*5.12111*
Shadow Bank Share x Post$_4$	*0.05536****	*0.01028*	*5.38769*
Shadow Bank Share x Post$_5$	*0.06529****	*0.01495*	*4.36639*
Shadow Bank Share x Post$_6$	*0.08613**	*0.03812*	*2.26027*
Area Fixed Effect		*Yes*	
Time Fixed Effect		*Yes*	
Observations		*26,144*	
R-squared		*0.75643*	

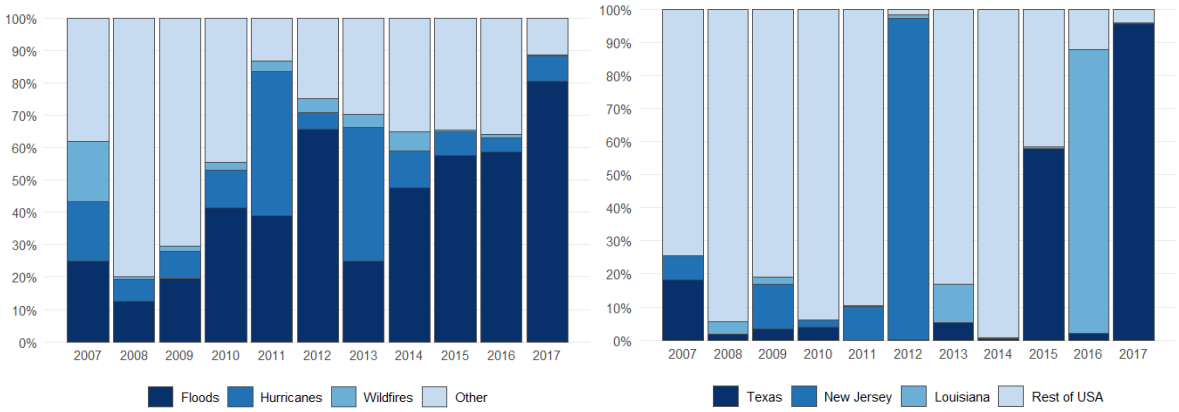
*Table 2: Staggered DiD Results. Notes: * p < 0.05, ** p < 0.01, *** p < 0.001. Standard errors are robust to heteroskedasticity.*



Figures 1 & 2: Mortgage Approval Rate (Transactions, %) (L); Share of Mortgage Lending (Loan Amount, %) (R) (Data Source: Author / HMDA).



Figures 3 & 4: Purpose of Mortgage Undertaking (Loan Amount, %) (L); Total Property Damage by Event (USD bn) (R) (Data Source: Author / HMDA / NOAA).



Figures 5 & 6: Total Property Damage by Event Type (%) (L); Total Flood-Related Property Damage by State (%) (R) (Data Source: Author / NOAA).

Valuing Natural Capital: Reconciling a Right to Development with a Right to a Healthy Environment in the Context of the Climate Crisis

Molly Macleod*

* Law Tripos Student (Emmanuel College), University of Cambridge, UK

KEYWORDS

climate justice, CBDR, valuing natural capital, right to development, right to a healthy environment

ABSTRACT

This article proposes that developed countries bearing the highest historical contribution to global emissions must be held accountable for financing the sustainable development of less economically advanced nations. Drawing upon the international legal concept of Common But Differentiated Responsibility (CBDR), the article argues that developed states have a duty to support developing states. Fundamentally, 'Valuing Natural Capital' aims to fairly compensate developing countries for the natural resources they were unable to exploit due to colonialism and historical economic structures. The article proposes an economic framework, grounded in the assumption of historic responsibility by developed nations for their carbon emissions, which would allow developing nations to seek economic redress under international law. By integrating legal, economic, and environmental considerations, this article will take an interdisciplinary approach, aiming to promote a more equitable global response to climate change which prioritises both ecological sustainability and social justice in international climate policies.

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I. **Introduction**

Among the myriad complexities of the climate crisis, one thing can be asserted as of near-absolute necessity to tackle such an existential issue: a globalised, cooperative response. However, it is clear that in working towards this common aim, States cannot be expected to assume equal burdens. This can be attributed to two key factors: a given State's capacity to enact climate-related measures (due to economic, technological, and population-size disparities), and the historic responsibility borne by States who have contributed to climate change in the past. Of the two, the latter is by far the most contentious. It can be argued that the States that contributed to historic emissions did so unknowingly and it would thus be inequitable to punish this ignorance, rather than those States that continue to emit in full knowledge of the consequences. However, this article will assert that historic responsibility is of fundamental importance in establishing the common but differentiated responsibility which each State must bear. In balancing the competing rights of States, and the individuals within those States, international law must prevent developed States from leveraging their ill-borne strength against the rights of developing States in the name of global

climate action. Instead, economic and legal solutions must be found to value natural capital in order to reconcile the competing rights to development on the one hand, and a healthy environment on the other.

This piece argues that climate change solutions to climate change must be approached from an interdisciplinary perspective, integrating ecological, social, historical, legal, and economic dimensions to analyse the complex climate relationship between developed and developing nations. To do justice to all of these vast considerations being somewhat beyond the scope of this article, the focus is placed on the tension between a right to a healthy environment and a right to economic development—a challenge that many States, if not all, must wrestle with.

II. **A Right to a Healthy Environment**

A right to a healthy environment is becoming increasingly enshrined at international law, and has become a point of significant academic and judicial contention. With climate litigation trends on the rise, international courts including the European Court of Human Rights have increasingly found a right to a healthy environment and a duty to combat climate change as falling under the positive international law obligations of States, such as in the landmark decision of *KlimaSeniorinnen v Switzerland*.[1]

Here, it is important to draw a distinction between those obligations which correspond to rights held by humans (i.e., human rights owed to individuals by States), and obligations which are owed, and rights held, as between States (e.g., as State parties to multinational or international treaties).

There is a wealth of emerging case law concerned with the former: human rights courts, such as the African Commission on Human and Peoples' Rights in *SERAC v Nigeria*,[2] have found States to bear both positive and negative duties in relation to human rights, to protect, preserve, and maintain a healthy environment, from as early as the year 2000. Two decades later, in *Lhaka Honhat Association v Argentina*, the Inter-American Court of Human Rights held that Argentina violated an autonomous right to a healthy environment, and ordered the State to take restitutionary measures for the recovery of the natural resources of the indigenous communities affected.[3] In *La Oroya v Peru*,[4] the autonomous right found in *Lhaka Honhat* was once again engaged, and a new precedent set by the IACHR: an obligation on State parties to "regulate, control and remediate the effects of environmental pollution".[5] Thus, there is an increasingly rich history of global jurisprudence for the right to a healthy environment as it relates to humans or individuals. As of 2021, over 155 States had recognised 'some form' of a right to a healthy environment at a domestic or international level per a Resolution adopted by the Human Rights Council.[6]

In considering obligations owed between States, apart from human rights or the obligations of States to their own people, the development of a global right to a healthy environment is found primarily in international multilateral treaties and conventions. Since the 1990s, international treaties have been signed between hundreds of States acknowledging the climate crisis as a "common concern of humankind"[7] and seeking to implement strategies, mechanisms, and

[1] *Verein KlimaSeniorinnen Schweiz and Others v Switzerland*, 53600/20, Judgment of the Grand Chamber of the ECtHR, 9 Apr. 2024.
[2] *Social and Economic Rights Action Center (SERAC) and Center for Economic and Social Rights (CESR) v Nigeria* (2001) AHRLR 60.
[3] "Inter-American Court Recognizes Right to a Healthy Environment in Indigenous Peoples' First Contentious Case." *IUCN World Commission on Environmental Law*, May 2020.
[4] *Community of La Oroya v Peru*, Judgment of the IACtHR, 22 Mar. 2024, Series C 511.
[5] "Inter-American Court Ruling on La Oroya Case Sets Key Precedent for the Protection of a Healthy Environment." *Interamerican Association for Environmental Defense*, 22 Mar. 2024.
[6] "The Human Right to a Clean, Healthy and Sustainable Environment." UNHRC Res. 48/13, 8 Oct. 2021, UN Doc. A/HRC/RES/48/13.
[7] The Paris Agreement of 12 Dec. 2015, 3156 UNTS 79.

mandates to promote the protection of the environment.

Despite the essential nature of a collective acknowledgement of the importance of the environment, and the preservation of its health, this right must be a tempered one. The Paris Agreement contextualises its environmental objective alongside the concepts of "sustainable development and efforts to eradicate poverty",[8] thus demonstrating that rights and duties borne towards the environment do not surpass the rights of developing States to seek to alleviate poverty among their own population. This distinction is crucial, and it is not simple to reconcile the rights of such States with the right to a healthy environment held by all States, both in the present moment and in looking to the future. It is at this point that the right to development must be examined.

III. **A Right to Development**

The 'right to development' is enshrined at international law under the 1986 UNGA Declaration on the Right to Development.[9] The Declaration conceptualises the right as one owed by States to their citizens and peoples, stating that "[t]he human person is the central subject of development and should be the active participant and beneficiary of the right to development".[10] This centres the human right as the core realisation of the right to development, with obligations being conferred primarily on individuals rather than between States. The Declaration also makes no explicit reference to 'sustainable development', which was first recognised at the 1972 Stockholm Conference, but not popularised until the Brundtland Report in 1987.[11]

The Brundtland Report defined sustainable development as "development which meets the needs of the present without compromising the ability of future generations to meet their own needs",[12] recognising the need for an intersectional approach to the rights to development and a healthy environment. While it is crucial that States prioritise their own development in order to benefit their own citizens, it is also crucial that they do so in a way that is sustainable, and will not threaten the human rights of future citizens.

The Paris Agreement recognises succinctly the "intrinsic relationship that climate change actions, responses and impacts have with equitable access to sustainable development and eradication of poverty",[13] focusing on setting targets to provide a framework for realising the sustainable development goals. Furthermore, the treaty takes 'full account' of the unique situation of developing country parties in achieving this aim. The tension which often arises between the right to a healthy environment for all, and the right to development of developing States can thus be recognised by the principle of sustainable development. What must be further considered is how sustainable development can address, and ultimately rectify, this tension.

IV. **Historic Responsibility**

Analysis by CarbonBrief of the percentage of emissions released between 1850 and 2021 attributable to the "national responsibility" of different States for C02 emitted on their territory found that the US was found to have produced 20% of total global emissions in this period.[14] This staggering figure was followed by China at 11% and Russia at 7%; while at 4% and 3%, Germany and the UK have also produced emissions at a highly population-disproportionate rate. These statistics demonstrate the disproportionate share of historic emissions produced by developed States, who now seek to regulate the

[8] ibid, Art. 2(1).
[9] "Declaration on the Right to Development." UNGA, 4 Dec. 1986, A/RES/41/128.
[10] ibid, Art. 2(1).
[11] "History of Sustainable Development." *Sustainable Development Commission*, 1992.
[12] *Our Common Future*. World Commission on Environment and Development, 1987, at Chapter 2, [1].
[13] The Paris Agreement (n 7) *supra*, preamble.
[14] Evans, Simon. "Analysis: Which Countries Are Historically Responsible for Climate Change?" *CarbonBrief*, 2021.

emissions of developing States to prevent the continual rise of global temperatures. As a result of their own emission 'spending' and the destruction of their own natural resources, developed States are seeking to implement climate-positive restrictions internationally. The EU Deforestation Regulation, for example, seeks to restrict the trade of products resulting from deforestation, and consequently to target those areas of biodiversity loss such as in the Amazon Rainforest in Brazil.[15]

The Amazon Rainforest is the quintessential example of the valuable natural capital possessed by Global South countries: while Global North countries have exploited their own resources, perhaps past the point of no return, and reaped the economic and developmental rewards as a result, they now seek to limit those same actions in other countries as natural capital generally continues to decline.[16] This hypocrisy is clear even without reference to, perhaps even more pertinently, the massive exploitation that those same States enacted on the natural capital of others through the course of colonisation. In imposing trade restrictions on products originating from developing countries, developed States use a 'stick' rather than 'carrot' approach. Instead of facilitating economic and environmental growth, they sanction economic activity, thus restricting the development of such States further and perpetuating the paternalistic cycles of colonialism. This approach is legally moralistic, and may go as far as to contravene the principle found in Article 3(5) of the UNFCCC (1992) which prohibits the use of unilateral (or otherwise) measures from restricting international trade under the guise of combating climate change.[17]

Moreover, it is proposed that, in light of the historic culpability of developed States, the common but differentiated responsibility should be that the developed States facilitate developing States to develop in a manner consistent with the international aims of climate preservation and restoration. Article 3(5) of the UNFCCC supports such a view, promoting party cooperation towards an "open international economic system that would lead to sustainable economic growth and development in all Parties, particularly developing country Parties, thus enabling them to better address the problems of climate change".[18] This construction envisages a 'carrot'-based approach, allowing for developing countries to do so sustainably, both in terms of their own economic development and in the interests of environmental protection.

V. **Economic Solutions to Natural Capital**

At the simplest level, in order to value natural capital the externalities of pollution and biodiversity loss must be internalised into the cost of production. The 'polluter-pays' principle is a mechanism to hold consumers from developed States to account financially for their carbon spending, recognised at international law under Principle 16 of the Rio Declaration (1992), which instructs national authorities to internalise environmental costs "without distorting international trade and investment".[19] This principle reflects the need for economic solutions to place a burden on the consuming States, as well as those involved in the production process, in order to fairly distribute the environmental costs.

However, cost internalisation and pricing policy is only one factor in correctly valuing natural assets. In internalising costs, the depletion of resources continues to occur, just at a higher price point—which should have the effect of limiting overconsumption to a degree. This is, however, an insufficient measure in the face of the existential threat

[15] Regulation (EU) 2023/1115.
[16] Managi, Shunsuke, and Pushpam Kumar. *Inclusive Wealth Report 2018*. United Nations Environment Programme / Kyushu University, 2018.
[17] The United Nations Framework Convention on Climate Change, 1771 UNTS 107
[18] ibid, Art. 3(5).
[19] "The Rio Declaration on Environment and Development." UNGA Res. 47/190, 14 Jun. 1992, at Principle 16.

climate change poses. Cost internalisation serves to correctly distribute the environmental costs found in creating a given product, but fails to treat the issue at the core. It is clear that instead, developing countries must, in exchange for the protection and non-exploitation of their own naturally occurring resources, be in some way compensated by those countries who have already 'grown' and now seek to 'clean up later'.[20] This could take the form of (i) classical compensation in the form of financial contributions, (ii) economic carrots, and indeed sticks, to incentivise climate positive trade and investment, and (iii) technological support and the reduction of the cost of capital in climate positive investment.

A. *Classical Compensation Model*

Classical compensation, while the simplest mechanism to quantify, is difficult to administer. A classical compensation model would seek to provide reparations to developing States, paid by developed States, proportionate to their share of historic responsibility. Though this is in principle an equitable solution, it is inefficient, easily susceptible to corruption, and would be incredibly difficult to enforce at international law.

The systems of international law being predicated on State consent, it is highly unlikely that developed nations would be willing to sign themselves up to make bare reparations without seeking some return on investment for their own economic gain. Without the involvement of all the major emitters, including China and the USA, this system would not yield sufficient investment, and is fundamentally unattractive to the developed countries whose economic burden would be highest. Furthermore, even in a system where it would be possible to require such financial contributions from these wealthier nations, it is inefficient to grant each individual developing State a lump sum to compensate them for the bare cost of their natural resources that they will in turn not exploit. The classical model fails to account for the historic investment into the technology required for the green transition that the developing countries will also benefit from, unlike the climate positive investment approach explored below.

Finally, a fund dedicated to financial reparation for losses suffered, or an inability to exploit a State's own natural resources, necessarily pays out monetary sums without specific direction to those States on how that money must be spent. As the State would have been free to exercise their own total discretion as to the purpose of money generated from the exploitation of their own natural capital, the compensatory value would therefore also be theirs to direct. While this may yield an equitable result, it is extremely difficult to ensure that the restitutionary sum be used efficiently and in a way which ensures sustainable development—with the contributions from developed States likely being conditional on the latter. The administrative difficulties render this model aspirational, but overly complex, and highly unlikely to ever operate in practice. This essay argues that instead, many of these issues may be resolved through a combination of the following two approaches.

B. *Economic Carrot (and Stick) Approach*

The economic carrot and stick approach targets corporations, rather than States, in attempting to incentivise climate positive trade and investment. There are many mechanisms by which economic carrots and sticks can be utilised to facilitate climate positive trade, such as through specific legislation which gives lower carbon products tax benefits (for example Carbon Border Adjustment Mechanisms) and disincentivises the trade of products with higher emissions ratings. However, while this approach can contribute to the lowering of emissions by a given State in line with their emissions

[20] Ekins, Paul, and Dimitri Zhengelis. "The Costs and Benefits of Environmental Sustainability." *The Productivity Institute*, 2021.

reductions goals, this does little to facilitate the green transition of developing countries.

Such an approach may include carbon pricing, such as implementing specific carbon taxes, or cap and trade systems such as the European Emissions Trading Scheme (ETS). The EU ETS is based on the polluter-pays principle, requiring companies to report and monitor their carbon emissions, and pay for a carbon allowance in line with what they emit: failing to do so results in heavy fines.[21] The 'cap' (i.e., the total number of emissions which may be produced and given corresponding allowances for) is reduced every year, with the goal of reducing the EU's total emissions in line with their climate commitments, as well as incentivising companies to reduce their own emissions to escape the carbon price, which affects their profits.

Carbon pricing can thus be effective in reducing emissions and encouraging companies to act in a climate positive way. However, the ETS in this form is only targeting the first part of the dual problem: the right to a healthy environment. In order for an ETS to target the second issue - the right to development - the revenue generated by such a scheme must not benefit the development of renewable energy, energy efficiency improvements and low-carbon technologies only in the home States to which the ETS applies. Therefore, in order to take into account the historic responsibility of the developed States, and the right to development which they should thus be facilitating, a link should be drawn between profits generated from climate positive trade, and economically supporting those developing countries whose own trade will be disadvantaged by such a system. This link could take the form of the classical compensation model described above, with profits going towards simple reparations, but the disadvantages of this have already been laid out. More effective would be to use such profits to fund the development of technologies that facilitate the green transition in these countries.

C. *Technological Support / Reduction of Costs to Facilitate a Green Transition*

In implementing economic tools for the sustainable development of States while valuing natural capital, it will thus be necessary for developed States to support developing States to bypass the infrastructure which has historically been the method of industrialisation at the expense of the environment. The natural cost decline of new technologies such as renewable energy and storage systems is not yet sufficiently low as to incentivise developing countries to choose these systems on the basis of economic cost alone. This choice must therefore be facilitated by developed States, in supporting the large-scale upfront investment required to put in place infrastructure which will have a lesser negative impact on the environment. While cheaper forms of energy production exist, it cannot be the sole responsibility of developing States to finance their development to align with the green transition. Thus, those States which have a capacity to do so should bear a legal duty to facilitate the introduction of such infrastructure.

The support of developed economies, both in technological development and upfront investment, will reduce the cost of capital globally and align with the sustainable development goals. The assurance of investment and financial backing by developed States can also provide private investors with the necessary confidence to invest in developing States deemed to be less stable. This is relevant as it is the transitional costs which will be fundamental in allowing for a green transition to occur across the global stage. Bhattacharya et al.[22] found that investment and spending requirements by emerging and developing economies will

[21] *Report on the Review of The European Union Emissions Trading System (EU ETS)*. European Commission, 2021.

[22] Bhattacharya, Anshuk, et al. "Financing a Big Investment Push in Emerging Markets and Developing Economies for Sustainable, Resilient and Inclusive Recovery and Growth." *Grantham Research Institute on Climate Change and the Environment*, 2022.

require $1500 billion a year on the energy transition alone. This vast and continuing investment through the transitional period demonstrates the requirement for a global, cooperative response. Bhattacharya et al. also found that a further $300bn investment on the same metric would be required to deal with natural capital and sustainable agriculture; a valuation that reflects the significant role played by natural capital in the economics of the climate transition. The Paris Agreement of 2015 sought to strengthen the global response to climate change through ensuring "finance flows consistent with a pathway towards low greenhouse gas emissions".[23] In light of these economic commitments (however vague) it is clear that developed countries have a duty to support developing countries through their economic means if agreements are to be effectively implemented,[24] through direct and indirect investment, as well as technological and trade support.

Ekins and Zhengelis[25] consider the significant structural shift in developing countries under the low-carbon transition as a potential blockade to traditional industrial development routes. They go on to cite evidence that multilateral funding and technological diffusion may allow countries to leverage global finance in the implementation of new, green technologies. This reflects the necessity of economic investment, but also the responsibility of richer countries to support the development of green technologies and trade diffusion beyond their own spheres.

With developing countries less able to rely on public borrowing, high-income countries will be vital in providing access to the finance and technologies necessary to secure sustainable growth,[26] and could be delivered by either new or existing institutions of international law and cooperation.[27]

VI. **Incorporating CBDR**

The principle of common but differentiated responsibility provides the international legal underpinning for the different treatment of States with regard to environmental treaties. Under Art. 3(2) of the UNFCCC, full consideration should be given to "the specific needs and special circumstances of developing country Parties, especially those that are particularly vulnerable to the adverse effects of climate change" when analysing State obligations under the Convention. This is essentially negative in effect ('excusing' developing States of obligations): in order for the principle to have tangible impact, it is necessary that CBDR takes positive effect.

In applying positively, CBDR would apply to actively require developed States to support developing States. A positive incorporation of the principle would thus give a legal basis to the proposed economic framework, wherein those States that are determined to bear historic responsibility for climate emissions are required at international law to contribute to the facilitation of the green transition, through investment and technological support, of developing countries.

CBDR already being an accepted principle of international law, the rule would form a solid legal basis to support the valuation of natural capital and its subsequent reparation, and legitimises the theoretical imposition of such a framework.

VII. **Conclusion**

In considering the unequal opportunities afforded to States throughout history (in particular, those opportunities having been

[23] The Paris Agreement (n 7) *supra*, Art. 2(1)(c).
[24] ibid, Art. 3.
[25] Hidalgo, César, et al. "Climate Change 2007: Synthesis Report." *Science*, vol. 318, no. 5850, 2007, pp. 1-16.
[26] Ekins and Zhengelis (n 20) *supra*.
[27] *see* the World Bank's current approach to concessional financing, that models a similar (but somewhat limited) approach. Although sometimes including grants to facilitate transitional costs associated with global challenges such as climate-associated risks, concessional financing includes low-rate loans and equity investments (all coming from private or non-State investors) and is thus inherently limited under the historic-responsibility and social justice analysis delivered prior. For more information, *see* Duarte, Mafalda. "What You Need to Know About Concessional Finance for Climate Action." *World Bank*, 16 Sept. 2021.

robbed from one State-class by another), it is clear that developing States have neither the capacity, nor the same responsibility, to enact climate measures at the same level as developed States who have already been afforded the opportunity to develop through the exploitation of the globe's natural resources. However, there exists a collective need to prevent the continuing devastation of the rich natural resources the Global South possesses. As a result, while developing States do have a share of the duty under the common aspect of differentiated responsibility, it is equitable that the Global North and developed States contribute economically and technologically to the necessary climate measures outside of their own direct territory, in order to fairly compensate developing countries for the non-exploitation of their natural capital. If such facilitation of the Global South is practically supported, there may be room for optimism that both the right to development and a right to a healthy environment may coexist in the coming decades. This optimism is conditional[28] on a fast, cooperative response as the clock continues to tick on our environmental time bomb.

[28] Stern, Nicholas. "Growth with Decarbonization Is Not an Oxymoron." *Institute for New Economic Thinking*, 3 Mar. 2021.

Bridging Sanctions and Climate Justice: Facilitating Iran's Access to Climate Mitigation Support

Hoda Asgarian*

* PhD Candidate (Faculty of Law), Bond University, Australia

KEYWORDS

sanctions, climate justice, Global South, climate mitigation

ABSTRACT

As a major greenhouse gas emitter and a developing nation in the Global South, Iran faces exceptional challenges in addressing climate change while under international sanctions. These sanctions restrict access to crucial finance and technology, hindering effective mitigation efforts. This article examines the intersection of climate justice and international sanctions, advocating for a balanced approach that maintains the intent of sanctions while introducing humanitarian exceptions for climate relief. Drawing on precedents in medical and humanitarian exemptions, this study explores potential legal mechanisms that could enable Iran's participation in international climate agreements, such as the Paris Agreement, within existing sanction frameworks. Notably, no established precedent currently addresses climate change mitigation within a climate justice framework under sanctions, distinguishing this issue as a niche area of legal and policy inquiry. By bridging this gap, this study contributes to ongoing debates on equitable climate action and the responsibilities of high-emission States facing economic restrictions.

I. Introduction

Climate change mitigation depends on genuine international cooperation, yet global political divisions increasingly obstruct the equitable flow of resources and technologies.[1] Among the most significant of these obstacles are international sanctions, legal instruments intended for political leverage but often producing unintended environmental consequences.[2] While humanitarian carve-outs exist for food and medicine, no parallel framework protects access to climate-related finance or technology. This absence creates a structural blind spot at the intersection of sanctions law and climate justice, which this article seeks to address.

[1] Hallegatte, Stéphane, et al. "Mapping the Climate Change Challenge." *Nature Climate Change,* vol. 6, no. 7, 2016, pp. 663-668.

[2] 'The term 'sanctions' under international law generally refers to coercive measures, taken by one State or in concert by several States, which are intended to convince or compel another State to desist from engaging in acts violating international law. Joyner, Christopher. "Collective Sanctions as Peaceful Coercion: Lessons from the United Nations Experience." *Australian Yearbook of International Law,* vol. 16, 1995, pp. 241-270.

Iran provides an illustrative and urgent case study. It faces one of the world's most comprehensive sanction regimes introduced in response to longstanding concerns about its nuclear programme,[3] including disputes over enrichment levels and compliance with International Atomic Energy Agency (IAEA) safeguards.[4] These sanctions have been imposed primarily by the United States (US)[5] and European Union (EU)[6] since 2010. These measures restrict trade, banking, and technology transfers, affecting even civilian sectors such as renewable energy and environmental management.[7] Simultaneously, Iran ranks among the top ten greenhouse gas (GHG) emitters,[8] and is one of the world's largest oil and gas producers,[9] yet is acutely vulnerable to droughts, desertification, and extreme heat due to its arid geography.[10]

It will be argued that the interaction of these sanctions with Iran's climate obligations locks the country into high-emission pathways and effectively excludes it from mechanisms such as the Green Climate Fund (GCF)[11] and global carbon markets.[12] In recent years, Iran has also positioned itself as a coordinating voice among sanctioned and resource-dependent States in the Global South, seeking partnerships with Latin American and African countries to share strategies for economic resilience and sustainable development.[13] This leadership role refers not to geopolitical dominance but to advocacy for equitable participation in global governance despite systemic economic exclusion.

Iran has submitted conditional mitigation pledges[14] under the Paris Agreement:[15] an unconditional four-percent emissions reduction and a conditional twelve-percent reduction dependent on sanctions relief.[16] It also undertook in its Sixth Five-Year National Development Plan (2016–2021) to increase the share of renewable energy to at least five per cent of national electricity generation by 2021.[17] However, implementation has been constrained by financial isolation and limited access to technology.[18] This dynamic raises a central normative question: if climate change is a collective challenge, can any State justifiably be denied the tools required to address it?

Recent international jurisprudence confirms that climate change is not merely an environmental or economic issue but a profound human rights concern.[19] The

[3] Katzman, Kenneth. "Iran Sanctions." *Congressional Research* Serice, 18 Nov. 2020.
[4] *IAEA Safeguards Glossary: 2001 Edition (Updated July 2017)*. International Atomic Energy Agency, Vienna.
[5] Early, Bryan, and Dursun Peksen. "Does Misery Love Company? Analyzing the Global Suffering Inflicted by US Economic Sanctions." *Global Studies Quarterly*, vol. 2, no. 2, 2022, pp. 1-12.
[6] Druláková, Radka, et al. "Assessing the Effectiveness of EU Sanctions Policy." *Central European Journal of International & Security Studies,* vol. 4, no. 1, 2010, pp. 101-122.
[7] Hafezi, Reza, et al. "Iran in the Emerging Global Natural Gas Market: A Scenario-Based Competitive Analysis and Policy Assessment." *Resources Policy*, vol. 68, 2020, pp. 1-16 at 6, 14.
[8] "Greenhouse Gas Emissions by Country 2024." World Population Review, 2024.
[9] Pistilli, M. "Top 10 Oil-Producing Countries." *Investing News Network*, 2024.
[10] Hadi, M, et al. "Analysis of Scientific Research Trends in the Field of Climate Change in Iran." *Seasonal Journal of Health and Environment*, vol. 15, no. 2, 2022, pp. 361-378 at 362.
[11] "About the Fund." *Green Climate Fund*, 2025.
[12] Masullo, I, et al. "'Direct Access" to Climate Finance: Lessons Learned by National Institutions." World Resources Institute Working Paper, 2015.
[13] Anderson, Maia Golzar. "Bringing Iran to the Climate Action Table." *Middle East Institute*, 22 Sept. 2023. *see also* Khanjani, N. "The Effects of Climate Change on Human Health in Iran." *International Journal of Public Health Research,* vol. 3, no. 1, 2016, pp. 38-41 at 39.
[14] Abdelbary, I, and R Elshawa. "Economic Sanctions as a Foreign Policy Tool: A Case Study of the Iran–West Conflict." *Migration Letters*, vol. 20, no. S7, 2023, pp. 215-237 at 215-16.
[15] The Paris Agreement of 12 Dec. 2015, 3156 UNTS 79.
[16] "Islamic Republic of Iran: Intended Nationally Determined Contribution (INDC)." *UNFCCC*, Nov. 2015, pp. 1-10 at 3-4.
[17] *Sixth Five-Year National Development Plan (2016–2021)*. Iranian Parliament, 2016, at Art. 50.
[18] Pahlavan, S, et al. "Assessing the Current Status of Renewable Energies and Their Limitations in Iran." *International Journal of Renewable Energy Development*, vol. 9, no. 1, 2020, pp. 97-105 at 102.
[19] *see* for example *Verein KlimaSeniorinnen Schweiz and Others v Switzerland*, 53600/20, Judgment of the Grand Chamber of the ECtHR, 9 Apr. 2024; "Human Rights and Climate Change: Grand Chamber of European Court Rules in Three Cases." Cleary Gottlieb, 23 Apr. 2024.

International Court of Justice (ICJ) in its recent Advisory Opinion (AO) held that "the protection of the environment is a precondition for the enjoyment of human rights,"[20] while the Inter-American Court of Human Rights and the International Tribunal for the Law of the Sea (ITLOS) (2024) have similarly recognised States' duties to prevent environmental harm that undermines life, health, and dignity.[21] Thus, international law already acknowledges the indivisibility of environmental protection and human rights, providing a legal foundation for extending humanitarian exceptions to climate action.[22]

Accordingly, this article argues that the absence of climate-related humanitarian exemptions represents a critical normative and practical gap in international law. By drawing on existing humanitarian precedents in medical and food assistance, it develops the case for analogous exceptions enabling sanctioned States to access climate finance, renewable-energy technologies, and adaptation support.

The argument proceeds as follows: Section II elaborates the theoretical basis of climate justice and examines how sanctions impede its realisation; Section III analyses humanitarian-exception frameworks in international law and identifies principles that could guide climate-related exemptions; and Section IV outlines operational pathways and policy mechanisms for enabling climate assistance in sanctioned contexts, using Iran as the principal case study.

II. **Climate Justice in the Context of Sanctions and Mitigation**

A. *Theoretical Foundations of Climate Justice*

Climate change is a governance problem grounded in questions of fairness, responsibility, and allocation, not merely an environmental science issue.[23]

Justice, broadly defined as the fair distribution of rights, duties, and burdens, becomes indispensable in addressing climate change.[24] Climate justice refers to the distribution of the benefits and burdens of climate change[25] and its responses in a way that is fair both within and between States.[26] It asks who caused the problem, who suffers most from its impacts,[27] and who should bear the costs of addressing it.[28]

Four strands of climate-justice theory are particularly relevant to the sanctions context.

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[20] *Obligations of States in Respect of Climate Change*. ICJ Advisory Opinion, 23 Jul. 2025, [371]-[374]. *see also* [202] (holding that Article 4(1) of the UNFCCC establishes legally binding obligations), [205] (finding that Article 4(2) of the UNFCCC establishes legally binding obligations for Annex I parties), [213] (confirming that obligations under Article 4(8) and 4(9) are legally binding notwithstanding party discretion), [234] (interpreting Article 4(2) of the Paris Agreement as containing binding obligations), [255] (clarifying that Article 7 of the Paris Agreement provides context but not binding adaptation obligations), [264] (holding that Article 9 of the Paris Agreement establishes binding obligations on developed States to provide climate finance), [457(a)] ("the climate change treaties set forth binding obligations for States parties to ensure the protection of the climate system and other parts of the environment from anthropogenic greenhouse gas emissions").

[21] The *Environment and Human Rights Advisory Opinion* of the IACtHR, OC-23/17, 15 Nov. 2017) [29], [133], [144]; *Advisory Opinion on Climate Change and International Law* [2024] ITLOS 31, [66].

[22] Rezadoost, V. "Unveiling the 'Author' of International Law—The 'Legal Effect' of ICJ's Advisory Opinions." *Journal of International Dispute Settlement,* vol. 15, no. 4, 2024, pp. 506-533 at 507.

[23] Tosun, Jale. "Addressing Climate Change through Climate Action." *Climate Action*, vol. 1, no. 1, 2022, pp. 1-8 at 4-5.

[24] Bulkeley, Harriet, et al. "Contesting Climate Justice in the City: Examining Politics and Practice in Urban Climate Change Experiments." *Global Environmental Change*, vol. 25, no. 1, 2014, pp. 31-40 at 31-32.

[25] Deivanayagam, Thilagawathi Abi, et al. "Envisioning Environmental Equity: Climate Change, Health, and Racial Justice." *The Lancet*, vol. 402, no. 10395, 2023, pp. 64-78.

[26] Ogunbode, Charles, et al. "Climate Justice Beliefs Related to Climate Action and Policy Support Around the World." *Nature Climate Change*, vol. 14, no. 11, 2024, pp. 1144-1150 at 1148.

[27] von Allmen, Kathrin. "Rethinking Responsibility for Mitigating Climate Change Harm: Advocating Remedial Responsibility." *Ethics, Policy & Environment*, vol. 28, no. 2, 2025, pp. 223-247.

[28] Pottier, Antonin, et al. "A Survey of Global Climate Justice: From Negotiation Stances to Moral Stakes and Back." *International Review of Environmental and Resource Economics*, vol. 11, no. 1, 2017, pp. 1-53 at 3.

Distributive justice focuses on the fair allocation of climate burdens[29] and benefits.[30] Henry Shue argues that those who have historically contributed the most to GHG emissions bear greater moral responsibility for mitigation efforts.[31] The United Nations Framework Convention on Climate Change (UNFCCC)[32] principle of common but differentiated responsibilities (CBDR)[33] formalises this logic by requiring States with greater historical emissions and capacity to shoulder greater costs.[34] When sanctions restrict access to climate finance or technology, they materially prevent the least advantaged States from benefiting from decarbonisation pathways,[35] thereby frustrating Rawls' difference principle in practice.[36] In other words, sanctions convert theoretical distributive justice duties into structural incapacity.

Procedural justice emphasises fair participation in decision-making.[37] Those most exposed to climate harm frequently have the least institutional voice.[38] Exclusion from climate-finance mechanisms or technical networks due to sanctions reduces a State's agency in shaping the mitigation rules that govern its future.

Restorative justice addresses historical responsibility and corrective repair.[39] Henry Shue's 'polluter-pays' principle[40] and Caney's view on this principle imply that high-emitting nations owe assistance to those facing climate losses.[41] Climate assistance to sanctioned States is therefore not charitable generosity but a form of reparative equity.

Cosmopolitan and intergenerational justice extend duties beyond borders and beyond present generations.[42] Preventing a State from pursuing low-carbon development entrenches temporal injustice by limiting the rights of future citizens to climate stability.[43]

Sanctions that obstruct access to climate finance, technology, or participation therefore do not merely inconvenience sanctioned States, they undercut the core distributive, procedural and reparative duties recognised in climate justice theory itself and convert those normative commitments into a legally structured incapacity to mitigate.

Taken together, these strands of climate-justice theory clarify why sanctions design cannot be separated from global mitigation responsibilities. They demonstrate that equitable climate governance requires preserving every State's practical capacity to

[29] Paavola, Jouni. "Seeking Justice: International Environmental Governance and Climate Change." *Globalizations*, vol. 2, no. 3, 2005, pp. 309-322 at 313.
[30] Page, Edward. "Fairness on the Day after Tomorrow: Justice, Reciprocity and Global Climate Change." *Political Studies*, vol. 55, no. 1, 2007, pp. 225-242 at 226-27.
[31] Shue, Henry. *The Pivotal Generation: Why We Have a Moral Responsibility to Slow Climate Change Right Now*. Oxford University Press, 2021, at 32.
[32] The United Nations Framework Convention on Climate Change, 1771 UNTS 107.
[33] Common but Differentiated Responsibilities (CBDR) is a principle that acknowledges all countries are responsible for addressing environmental degradation, but not equally; developed nations bear greater responsibility due to their higher contributions to global emissions. *see* Fisher, S. "The Emerging Geographies of Climate Justice." *The Geographical Journal*, vol. 181, no. 1, 2015, pp. 73-82 at 74.
[34] Zeb Khan, Bushra. "Common but Differentiated Responsibilities: A Shield for Equity or Barrier to Global Climate Action?" *Journal of Asian Development Studies,* vol. 13, no. 4, 2024, pp. 1159-1166 at 1159–1160.
[35] Abdelbary & Elshawa (n 14) *supra* at 216.
[36] Premchand, Lakshmi. "Social Justice and Rawls' Difference Principle." *Essex Student Journal*, vol. 9, no. 1, 2017, pp. 1-6.
[37] Klinsky, Sonja, and Hadi Dowlatabadi. "Conceptualizations of Justice in Climate Policy." *Climate Policy*, vol. 9, no. 1, 2009, pp. 88-108 at 93.
[38] Kashwan, Prakash. "Climate Justice in the Global North: An Introduction." *Case Studies in the Environment*, vol. 5, no. 1, 2021, pp. 1-13 at 5.
[39] Walker, Margaret Urban. "Restorative Justice and Reparations." *Journal of Social Philosophy*, vol. 37, no. 3, 2006, pp. 377-395.
[40] Shue, Henry. *Climate Justice: Vulnerability and Protection,* Oxford University Press, 2014, at 21.
[41] Caney, Simon. "Climate Change and the Duties of the Advantaged." *Critical Review of International Social and Political Philosophy* vol. 13, no. 1, 2010. pp. 203-228 at 205.
[42] Campos, André Santos. "Intergenerational Justice Today." *Philosophy Compass*, vol. 13, no. 2, 2018, pp. 1-12 at 2-3.
[43] Bessant, Judith, et al. "Intergenerational Climate Justice: Applying Theory to Policy in the Anthropocene." *Journal of Applied Youth Studies*, 2025.

decarbonise. Climate justice principles therefore underpin the argument advanced in this article: that narrowly tailored climate-related exemptions are needed to ensure sanctions do not impede essential mitigation efforts.

B. *Sanctions and Iran's Mitigation Capacity*

The promise of climate justice is particularly complex for countries under international sanctions. Sanctions, whether trade, financial, or technology restrictions,[44] extend far beyond their political purpose and reshape environmental capacity.[45] They limit cooperation, finance, and technology transfer, creating systemic obstacles to mitigation and adaptation.[46]

Iran is one of the world's largest oil and gas producers[47] and ranks among the top ten GHG emitters,[48] leaving it economically dependent on fossil fuels.[49] At the same time, it remains acutely vulnerable to climate impacts, which threaten agriculture, livelihoods, and urban populations[50] through droughts, floods, and severe water scarcity.[51] In Khuzestan province, water shortages have driven internal migration and heightened social tension,[52] while Tehran and other densely populated cities suffer heat stress and air pollution,[53] further affecting public health.[54] These pressures are exacerbated when sanctions block renewable-energy investment and finance.[55]

After the 1979 Revolution, sanctions against Iran began with the freezing of approximately USD 12 billion of Iranian assets during the hostage crisis and evolved into a progressively layered regime.[56] UN sanctions, initially imposed over its nuclear programme,[57] introduced trade and financial restrictions. By 2006, the United Nations Security Council (UNSC) adopted Resolution 1737,[58] followed by Resolutions 1747,[59] 1803,[60] and 1929,[61] which collectively imposed export bans on sensitive nuclear-related items, restricted support for Iran's ballistic-missile programme, and authorised travel bans and asset freezes.[62] Although the 2015 Joint Comprehensive Plan of Action (JCPOA)[63] suspended many of these multilateral

[44] Caldwell, Z. *International Sanctions: Do They Work?* CQ Press, 9 Dec. 2022.
[45] Hesarzadeh, Reza. "Unintended Environmental Sustainability Ramifications of US Sanctions." *International Political Science Review*, Apr. 2025, pp. 1-21 at 17.
[46] Sharma, Y. "Trends in Political Science Research: Economic Sanctions." *International Political Science Abstracts*, vol. 74, no. 6, 2024, pp. 897-909 at 898.
[47] "Country Analysis Brief: Iran." *US Energy Information Administration*, 10 Oct. 2024.
[48] Filonchyk, Mikalai, et al. "Greenhouse Gas Emissions and Reduction Strategies for the World's Largest Greenhouse Gas Emitters." *Science of the Total Environment*, vol. 944, 2024, pp. 1-11 at 5.
[49] Aien, M, and O Mahdavi. "On the Way of Policy Making to Reduce the Reliance of Fossil Fuels: Case Study of Iran." *Sustainability*, vol. 12, no. 24, 2020, pp. 1-28 at 2-4.
[50] *see* Ondiko, Jackob Haywood, et al. "A Review of the Anthropogenic Effects of Climate Change on the Physical and Social Environment." *OAlib*, vol. 9, no. 2, 2022, pp. 1-14.
[51] Broberg, Morten. "State of Climate Law: The Third Pillar of International Climate Change Law: Explaining 'Loss and Damage' after the Paris Agreement." *Climate Law*, vol. 10, no. 2, 2020, pp. 211-223 at 217.
[52] *see* Hejazi, Seyed Jafar, et al. "Assessment of Social Vulnerability in Areas Exposed to Multiple Hazards: A Case Study of the Khuzestan Province, Iran." *International Journal of Disaster Risk Reduction*, vol. 78, 2022, pp. 1-21.
[53] Mansouri Daneshvar, M, et al. "An Overview of Climate Change in Iran: Facts and Statistics." *Environmental Systems Research*, vol. 8, no. 7, 2019, pp. 1-10 at 1.
[54] Alizadeh Choobari, O, and M Najafi. "Extreme Weather Events in Iran under a Changing Climate." *Climate Dynamics*, vol. 50, 2018, pp. 249-260 at 253.
[55] Balali, H, et al. "Economic Sanctions, Energy Consumption, and CO_2 Emissions in Iran: A System Dynamics Model." *Policy Studies*, 2024, pp. 718-747.
[56] Hewitt, Kate, and Richard Nephew. "How the Iran Hostage Crisis Shaped the US Approach to Sanctions." *Brookings Institution,* 12 Mar. 2019.
[57] Borszik, Oliver. "International Sanctions against Iran and Tehran's Responses: Political Effects on the Targeted Regime." *Contemporary Politics*, vol. 22, no. 1, 2016, pp. 20-39 at 24.
[58] UNSC Res. 1737, 23 Dec. 2006, UN Doc SC/8928.
[59] UNSC Res. 1747, 24 Mar. 2007, UN Doc S/RES/1747.
[60] UNGA Res. 1803, 14 Dec. 1962, UN Doc A/RES/1803(XVII).
[61] UNSC Res. 1929, 9 Jun. 2010, UN Doc S/RES/1929.
[62] Taylor, Brendan. *Sanctions as Grand Strategy*. International Institute of Strategic Studies Adelphi Paper No. 411, 2010, pp. 65-66.
[63] The JCPOA is a 2015 agreement between Iran and world powers to limit Iran's nuclear program in exchange for sanctions relief.

measures,[64] the snapback mechanism created persistent regulatory uncertainty, discouraging re-engagement by international financial institutions even where suspensions formally applied.[65] The EU largely mirrored these measures, implementing autonomous restrictive measures in 2007 to reinforce UNSC sanctions,[66] including prohibitions on assistance to Iran's nuclear programme, travel bans, asset freezes, and an arms embargo.[67] The US simultaneously expanded unilateral sanctions through the Department of the Treasury's Office of Foreign Assets Control (OFAC) under the Iran Sanctions Act and successive executive orders, extending restrictions to banking, shipping, insurance, and energy.[68] These measures amplified the de-risking behaviour of international banks,[69] producing a de facto embargo on financial flows even in areas that are technically exempt.[70] The combined effect of UN, US, and EU measures is therefore not only legal prohibition but structural exclusion; Iran is formally isolated from the global financial system,[71] and informal market behaviour (particularly banks refusing to process lawful transactions) further entrenches this exclusion.

These restrictions have direct environmental and social consequences. Projects such as the Karun River Basin restoration[72] and solar and wind developments have been delayed or cancelled for lack of financing.[73] Exclusion from the GCF and global carbon markets further blocks Iran from participating in collective mitigation efforts.[74] The result is a cycle of structural vulnerability in which citizens bear the cost of policies they cannot influence.

C. *Linking Sanctions to Justice Theory*

Viewed through climate justice theoretical lenses, sanctions intensify inequalities in distributive and procedural terms: they shift the burden of climate inaction onto those least responsible for emissions and exclude them from decision-making processes.[75] Restorative and cosmopolitan perspectives extend this critique, framing climate assistance as a global moral duty that cannot be suspended for political reasons.[76]

Sanctions, therefore, produce a dual deficit; practical and moral. Practically, they obstruct mitigation and adaptation efforts; morally, they contradict the core principles of climate justice.[77] Integrating equity considerations

[64] Caba-Maria, Flavius, and Radu-Cristian Mușetescu. "The Impact of International Economic Sanctions on National Economies: The Islamic Republic of Iran—A Case in Point." *Proceedings of the International Conference on Business Excellence*, vol. 14, no. 1, 2020, pp. 1011-1023 at 1018.

[65] "United States Fails to Secure Multilateral Snapback Sanctions against Iran." *The American Journal of International Law*, vol. 115, no. 1, 2021, pp. 140-146 at 142.

[66] Portela, Clara. *European Union Sanctions and Foreign Policy: When and Why Do They Work?* Routledge, 2010, pp. 19-20.

[67] Bassiri Tabrizi, Aniseh, and Ruth Hanau Santini. *EU Sanctions against Iran: New Wine in Old Bottles?* Istituto per gli Studi di Politica Internazionale Working Paper No. 97, Mar. 2012, pp. 1–7 at 1–2.

[68] Thomas, Clayton. "U.S. Sanctions on Iran." CRS In Focus Working Paper No. IF12452, 20 Jul. 2023.

[69] De-risking refers to the phenomenon where financial institutions terminate or restrict business relationships with clients or categories of clients to avoid, rather than manage, risk: *Guidance on Correspondent Banking Services*. Financial Action Task Force Guidance Paper, Oct. 2016, at 3.

[70] de Koker, Louis and Pompeu Casanovas. "De-Risking, De-Banking and Denials of Bank Services: An Over-Compliance Dilemma?" *Financial Crime, Law and Governance: Navigating Challenges in Different Contexts*, edited by Doron Goldbarsht and Louis de Koker, Springer, 2024, pp. 45-70 at 46.

[71] Reynaud de Sousa, Bruno. "Beating the (White) House: How a 'Rogue' Iran Broke Free from the 'Axis of Evil' and Became an Antifragile State." *The Geopolitics of Iran*, edited by Francisco José B S Leandro et al., Palgrave Macmillan, 2023, pp. 117-142 at 126.

[72] *see* Olson, K, and S Chernyanskii. "Karun and Shatt Al-Arab River System: Historic and Modern Attempts to Manage Iran's Lifeline." *Open Journal of Soil Science*, vol. 14, no. 7, 2024, pp. 416-447.

[73] Harshan, A. "Go Green with GBO: Iran Transitions Rapidly to Renewable Energy Despite US Sanctions." *Global Business Outlook*, 10 Nov. 2023.

[74] Erdoğan, S, et al. "An Investigation of Iran's Banking System: Challenges and Remedies." *Bilimname*, no. 41, 2020, pp. 957-990 at 963-964.

[75] Caney, Simon. "Cosmopolitan Justice, Responsibility, and Global Climate Change." *Leiden Journal of International Law*, vol. 18, no. 4, 2005, pp. 747-775 at 749.

[76] ibid at 750.

[77] Peksen, Dursun. "Political Effectiveness, Negative Externalities, and the Ethics of Economic Sanctions."

into sanctions design—for example, by embedding explicit climate exceptions—would reconcile international security objectives with global environmental responsibility. The following Sections develop legal and operational pathways for such reform.

The lack of equity considerations reflects a critical failure in the global governance of climate mitigation. While CBDR and distributive justice principles emphasise fairness in responsibility and resource allocation,[78] the interaction of sanctions with climate obligations undermines these principles in practice. Vulnerable nations may be expected to reduce emissions and build resilience without access to the tools, finance, and knowledge required to do so effectively.[79] In other words, sanctions inadvertently contradict the ethical and legal commitments underpinning international climate agreements.

Addressing this missing link requires reframing climate justice to explicitly incorporate sanctions as a structural barrier. Such an approach recognises that equitable climate governance cannot be achieved without ensuring that all nations, including those under political or economic constraints, have meaningful access to mitigation support.[80] The idea of climate-conscious sanctions highlights the need to adapt sanction regimes so they do not hinder global climate goals, which could involve creating financial mechanisms or broadening exemptions within existing frameworks.[81] Operationally, this could include targeted exemptions for sanctioned nations, enabling access to renewable energy technologies, climate finance, and technical assistance, much as humanitarian exceptions exist for medicine and food.[82]

III. **Legal Frameworks and Precedents for Humanitarian Exceptions**

Economic sanctions are often imposed to exert political pressure, but their unintended humanitarian consequences have led to the development of humanitarian exceptions within many sanction regimes.[83] These exceptions typically allow for the delivery of essential goods such as medical aid, food, and disaster relief to prevent disproportionate civilian harm.[84] Although these provisions recognise the moral and legal need to avert humanitarian crises, they rarely extend to another critical sphere: climate-related aid and technology transfer. Focusing on Iran, this Section examines how existing humanitarian exceptions could inform mechanisms for climate finance, renewable energy technology, and adaptation support in sanctioned nations.

A. *Humanitarian Exceptions in Medical Aid*

Most international sanction regimes include carve-outs for medical supplies and humanitarian assistance.[85] For example, the UN, the US, and the EU have all developed procedures allowing the export of life-saving

Ethics & International Affairs, vol. 33, no. 3, 2019, pp. 279-289.

[78] Meckled-Garcia, S. "Two Concepts of Justice—And of Its Scope." *Critical Review of International Social and Political Philosophy*, vol. 19, no. 5, 2016, pp. 534-558 at 538.

[79] Godin, M. "Fossil Fuels Are Propping Up Autocracies—And the Climate Crisis." *The Guardian*, 18 Jul. 2025.

[80] Mackey, Brendan, and Nicole Rogers. "Climate Justice and the Distribution of Rights to Emit Carbon." *Access to International Justice*, edited by Phillip Keyzer et al., Routledge, 2015, pp. 225-240 at 225-226.

[81] Aryanpour, M. "Energy Transition in the Middle East and North Africa Region: Regional Solutions for Climate Change Challenges Amid Economic Sanctions." *Journal of Sustainable Development Law and Policy*, vol. 15, no. 2, 2024, pp. 162-185 at 178-179.

[82] UNHRC Res. 7/23, 28 Mar. 2008, UN Doc A/HRC/RES/7/23. The UN Human Rights Council has adopted multiple resolutions recognising the link between climate change and human rights. These resolutions affirm that climate change impacts fundamental rights, particularly for vulnerable populations, and call for stronger international action to address these challenges.

[83] Bílková, V. "Humanitarian Exceptions and Sanctions." *International Sanctions and Human Rights*, edited by P Šturma, Springer, 2024, pp. 97-115 at 100-101.

[84] Brubaker, R, and S Huvé. "Conflict-Related UN Sanctions Regimes and Humanitarian Action: A Policy Research Overview." *International Review of the Red Cross*, vol. 103, 2021, pp. 385-402 at 395.

[85] Musmeci, D. "UN Targeted Sanctions, Counter-Terrorism Measures and Standing Humanitarian Carve-Out: A Lesson Learned?" *International Organizations Law Review*, vol. 21, 2024, pp. 527-561 at 540.

medications and equipment to sanctioned States.[86] However, in practice, these exceptions are often frustrated by secondary financial barriers.[87]

Banks, insurers, and freight companies frequently engage in de-risking behaviour, declining even lawful transactions due to zero risk appetite.[88] For example, the US imposed a record US$8.9 billion fine on BNP Paribas in June 2014 for breaching sanctions relating to Sudan, Cuba and Iran, a case which made global financial institutions far more risk averse.[89] Correspondent banking relationships are withdrawn, letters of credit cannot be issued, and payments stall in compliance reviews.[90] Thus, financial restrictions can continue to block access despite the goods themselves being exempt. Even humanitarian actors are caught in this dynamic; they often find over-compliance deeply unethical because it results in denying aid to populations in need, yet they lack the legal capacity and compliance resources to contest banks' decisions and may also be reluctant to disclose beneficiary lists for protection reasons.[91]

Closing this implementation gap is essential if climate-related exemptions are to operate in practice. Robust, predictable financial channels, perhaps through designated humanitarian banks or, for example, clearing mechanisms overseen by a neutral multilateral institution such as the International Monetary Fund (IMF),[92] would be necessary to operationalise climate assistance in sanctioned jurisdictions.[93] These dynamics are instructive for the present analysis, as the operational logic that enables medical-aid exemptions also illuminates how climate-related assistance could be accommodated within sanctions regimes.

B. *Towards Climate-Related Humanitarian Exceptions*

The inclusion of medical-aid exemptions stems from the recognition that access to healthcare is a fundamental human interest.[94] Climate change poses comparably grave risks to health, survival, and security,[95] particularly in sanctioned States such as Iran, where water scarcity and extreme heat already endanger vulnerable populations.[96] Yet current sanction regimes provide no exemptions for climate finance, renewable-energy technology, or adaptation projects.[97] A carefully designed

[86] UNSC Res. 2664, 9 Dec. 2022, UN Doc S/RES/2664; "Fact Sheet: Provision of Humanitarian Assistance and Trade to Combat COVID-19." *US Department of the Treasury*, 2023; "FAQs: Application of EU Sanctions in the Medical Sector." *European Commission*, 2023.
[87] de Koker & Casanovas (n 70) *supra* at 46.
[88] Durner, Tracey, and Liat Shetret. *Understanding Bank De-Risking and Its Effects on Financial Inclusion: An Exploratory Study*. Global Center on Cooperative Security, Nov. 2015, at 5.
[89] Borchert, Lea, et al. *Broken Relationships: De-Risking by Correspondent Banks and International Trade*. Leibniz Centre for European Economic Research Discussion Paper No. 23-064, 2023, at 9.
[90] Early, Bryan, and Timothy Peterson. "The Enforcement of U.S. Economic Sanctions and Global De-risking Behavior." *The Journal of Conflict Resolution*, vol. 68, no. 10, 2024, pp. 2048-2075 at 2059.
[91] Giumelli, Francesco, and Michal Onderco. "States, Firms, and Security: How Private Actors Implement Sanctions, Lessons Learned from the Netherlands." *European Journal of International Security*, vol. 6, no. 2, 2021, pp. 190-209 at 203-204.
[92] The International Monetary Fund (IMF) is an intergovernmental organisation established in 1944 to promote global monetary cooperation, ensure financial stability, facilitate international trade and maintain a stable system of exchange rates. "About the IMF." *International Monetary Fund*, 2025.
[93] Megersa, Kelbesa. *Alternative Systems for Managing Financial Transactions in Humanitarian Crises*. Institute of Development Studies, 13 Apr. 2021, at 1-2.
[94] *Declaration of Alma-Ata at the International Conference on Primary Health Care, Alma-Ata, USSR*. World Health Organization, 1978, [I].
[95] Paavola, Jouni. "Health Impacts of Climate Change and Health and Social Inequalities in the UK." *Environmental Health*, vol. 16, suppl. 1, 2017, pp. 61-68 at 61-62.
[96] Khine, Myo, and Uma Langkulsen. "The Implications of Climate Change on Health among Vulnerable Populations in South Africa: A Systematic Review." *International Journal of Environmental Research and Public Health*, vol. 20, no. 4, 2023, pp. 1-19 at 2.
[97] *see* for example "Top 10 Things You Need to Know About Sanctions and the Energy Sector." Burness Paull, 8 Oct. 2024. The United Kingdom has implemented its own sanctions regime under the Sanctions and Anti-Money Laundering Act 2018 (SAMLA), targeting areas such as the energy sector and financial transactions. While there are provisions for humanitarian exceptions, these do not explicitly extend to climate finance or renewable energy projects. Similarly, the European Union's sanctions in response to geopolitical events, such as Russia's invasion

"climate-aid" exception could permit technology transfer, climate-finance flows, and technical cooperation without undermining the political purposes of sanctions.

Under the principle of CBDR, wealthier States bear a duty to assist developing nations in addressing climate challenges.[98] Sanctions that impede such support risk weakening existing human-rights and environmental obligations. More precisely, by limiting access to clean-energy technologies and adaptation resources, they constrain a sanctioned State's capacity to realise its own positive duties, such as protecting the rights to health, food, and an adequate standard of living.[99] This distinction aligns with recent jurisprudence and Advisory Opinions, including the 2024 AO of the ITLOS on States' obligations regarding climate change[100] and the 2025 AO of the ICJ. Both of these AOs recognise the shared responsibility of States to avoid transboundary environmental harm and to cooperate in enabling other States to fulfil their environmental and human-rights obligations. Accordingly, it is more accurate to say that restrictive measures may undermine the enjoyment of human rights within sanctioned States rather than automatically constitute violations by sanctioning States themselves.[101]

In Iran's case, restrictions on importing environmental-monitoring equipment, renewable-energy components, and related spare parts have delayed modernisation efforts and hampered climate adaptation.[102] The effects of such restrictions are felt more stronger by low-income communities, women, and children, highlighting the distributive inequities that climate justice theory seeks to remedy.[103]

Expanding humanitarian exceptions to encompass climate-related goods and services would therefore represent both an ethical and legal evolution of existing practice. The precedent of medical exemptions confirms that sanctions policy can accommodate essential human-security objectives without eroding its political rationale.[104] Integrating a climate-aid exception would similarly align sanctions regimes with global mitigation goals and human-rights principles, a matter explored further in Section IV.B.

C. *Legal Precedents Supporting Humanitarian Exceptions*

Sanctions regimes, while designed to achieve foreign policy and security objectives, often intersect with fundamental human rights and humanitarian imperatives.[105] Over time, international law and State practice have established legal precedents allowing exemptions to protect human welfare.[106] For instance, the Oil-for-Food Programme (OFF) was established by the UN in 1995 under Security Council Resolution 986 to permit Iraq to export oil on the international market in exchange for food, medicine, and other essential humanitarian goods for its civilian

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of Ukraine, have focused on sectors like energy, imposing import bans on Russian oil and coal, and restrictions on EU exports and investments in energy projects. These measures aim to exert pressure on the targeted nation's energy sector, with limited exceptions for certain areas like civil nuclear energy and specific energy products: *see* "Sanctions on Energy." *European Commission*, 18 Jul. 2025.

[98] Brunnée, Jutta, and Charlotte Streck. "The UNFCCC as a Negotiation Forum: Towards Common but More Differentiated Responsibilities." *Climate Policy*, vol. 13, no. 5, 2013, pp. 589-607 at 590.

[99] The International Covenant on Economic, Social and Cultural Rights, 993 UNTS 3, 3 Jan. 1976, Art. 2(1).

[100] ITLOS AO (n 21) *supra*.

[101] Peksen, Dursun. "Better or Worse? The Effect of Economic Sanctions on Human Rights." *Journal of Peace Research*, vol. 46, no. 1, 2009, pp. 59-77 at 68-69.

[102] Hazrati, Mohammad, and Zeynab Malakoutikhah. "An Unclear Future for Iranian Energy Transition in Light of the Re-Imposition of Sanctions." *Oil, Gas & Energy Law Intelligence*, vol. 17, no. 1, Feb. 2019, pp. 1-17 at 11.

[103] "The Relationship between Economic Sanctions and Respect for Economic, Social and Cultural Rights." Committee on Economic, Social and Cultural Rights General Comment No. 8, 12 Dec. 1997, UN Doc E/C.12/1997/8, [7].

[104] Bílková (n 833) *supra* at 110.

[105] Marks, S. "Economic Sanctions as Human Rights Violations: Reconciling Political and Public Health Imperatives." *American Journal of Public Health*, vol. 89, no. 10, 1999, pp. 1509-1513 at 1509.

[106] Seatzu, F, and P Vargiu. "Is the UNSC Resolution No. 2664 (2022) on Humanitarian Exemption a Paradigm Shift for Sanction Regimes?" *Paix et Sécurité Internationales*, no. 11, 2023, pp. 1-22 at 3.

population.[107] Similarly, regarding the asset freeze measures, UNSC Resolution 2664 (2022) introduced a cross-cutting humanitarian exemption, affirming that funds, goods, or services necessary for humanitarian assistance do not violate such sanctions.[108] The EU implemented this through Council Regulation (EU) 2023/331 (14 February 2023), which inserted humanitarian-exemption provisions across several restrictive-measures frameworks.[109]

However, even where such exceptions exist, implementation is often constrained by the financial sector's fear of secondary sanctions and regulatory risk.[110] This leads to a chilling effect, where banks, insurers, and suppliers avoid legitimate transactions to minimise exposure.[111] The practical scale of this problem is considerable; humanitarian organisations frequently report delays or refusals of lawful payments, leading to interrupted medical and food deliveries.[112] Yet these challenges do not negate the value of humanitarian exceptions; rather, they reveal the need for stronger operational safeguards and clearer compliance guidance. In this sense, the chilling effect limits but does not invalidate the effectiveness of existing exemptions.

Such precedents illustrate that sanctions are not absolute and that targeted exceptions can mitigate civilian harm while maintaining policy objectives.[113] The structural logic is similar; both medical and climate-related assistance concern essential, life-preserving support that cannot be meaningfully delayed by restrictive measures. In the climate context, this would require clearly defined exemptions for mitigation and adaptation activities, supported by secure financial channels or licensing mechanisms that shield authorised transactions from sanctions risk. These operational pathways would allow climate finance, technology transfers, and adaptation projects to proceed without undermining the broader foreign-policy purposes of the sanctions regime. Building on this logic, the same legal rationale should be extended to the climate domain. Existing humanitarian-exemption models provide a persuasive normative basis for developing climate-related carve-outs that enable access to finance, technology, and adaptation support in sanctioned contexts.[114]

Recent jurisprudence further supports this argument by recognising that inadequate climate action can engage obligations under international human rights law. Courts and treaty bodies increasingly affirm that climate change poses risks to protected interests such as life, private life, and health, thereby triggering positive duties on States. Key examples include the Dutch Supreme Court in *Urgenda v The Netherlands*,[115] the German Constitutional Court in *Neubauer v Germany*,[116] and the European Court of Human Rights in *KlimaSeniorinnen v Switzerland*,[117] collectively confirming that insufficient climate action may breach existing rights

[107] UNSC Res. 986, 14 Apr. 1995, UN Doc S/RES/986.
[108] UNSC Res. 2664, 9 Dec. 2022, UN Doc S/RES/2664; UNSC Res. 2761, 6 Dec. 2024, UN Doc S/RES/2761, [1].
[109] Council Regulation (EU) 2023/331, 14 Feb. 2023; "Australia Implements Humanitarian Exemption to UN Security Council Sanctions in Relation to the Taliban." Australian Department of Foreign Affairs and Trade, 11 Jan. 2022.
[110] *Correspondent Banking*. Bank for International Settlements, Jul. 2016, at 11.
[111] Musmeci (n 855) *supra* at 528.
[112] Megersa (n 93) *supra* at 2.
[113] Aryanpour (n 81) *supra* at 183.
[114] Such measures could give countries like Iran the opportunity to shift toward low-emission development and upgrade their climate policies and infrastructure, all without running afoul of international sanctions: *see* Hafezi, R, and A Souhankar. "Energy Security in a Resource-Rich Economy: Case of Iran." *The Handbook of Energy Policy*, edited by Farhad Taghizadeh-Hesary and Dayong Zhang, Springer, 2023, pp. 97-127 at 123.
[115] *Urgenda Foundation v The Netherlands*, 20 Dec. 2019, ECLI:NL:HR:2019:2007; Spier, Jaap. "The 'Strongest' Climate Ruling Yet: The Dutch Supreme Court's Urgenda Judgment." *Netherlands International Law Review*, vol. 67, no. 2, 2020, pp. 319-391 at 320.
[116] Neubauer & Ors v Germany, 24 Mar. 2021, 1 BvR 2656/18. The German Constitutional Court held that Germany's climate targets were unconstitutional because they imposed a disproportionate burden on younger generations. Kotzé, L. "Neubauer Et Al. versus Germany: Planetary Climate Litigation for the Anthropocene?" *German Law Journal*, vol. 22, no. 8, 2021, pp. 1423-1444 at 1424.
[117] *KlimaSeniorinnen* (n 19) *supra*.

obligations.[118] Similarly, in *Teitiota v New Zealand*,[119] the UN Human Rights Committee (HRC) acknowledged that climate-induced harm can activate non-refoulement duties[120] under the International Covenant on Civil and Political Rights (ICCPR).[121] Finally, the 2025 ICJ AO affirmed that States have binding obligations under international law to mitigate climate change and protect present and future generations, identifying the environment as "the foundation for human life, upon which the health and well-being of both present and future generations depend".[122] Taken together, this body of jurisprudence underscores that climate-related harms are not external to human rights law but fall within its protective scope, providing a credible normative foundation for expanding humanitarian exceptions in sanctions regimes to encompass climate assistance. The next subsections analyse how these precedents, and related legal frameworks, can inform the development of targeted climate-specific exemptions that reconcile sanctions policy with global mitigation objectives.

1. United Nations Security Council Sanctions and the Human Rights Basis for Exceptions

The UNSC has established clear precedents for incorporating humanitarian exceptions within sanctions frameworks, particularly to safeguard civilian well-being.[123] Critics of comprehensive sanctions note that such measures often harm populations with little political agency, prompting the development of 'smart sanctions'; restrictions designed to target ruling elites while minimising collateral harm.[124] For example, UNSC Resolution 2134 (2014)[125] imposed targeted sanctions on the Central African Republic while expressly permitting humanitarian assistance,[126] demonstrating that sanctions can coexist with protections for vulnerable population.[127]

The ongoing negotiations concerning snapback mechanisms further underscore the flexibility of the UNSC framework. If sanctions can be rapidly re-imposed when States breach obligations,[128] then parallel mechanisms could also be designed to trigger humanitarian or climate-related exemptions automatically when civilian harm becomes disproportionate. Such an approach would align the design of sanctions with the evolving recognition of humanitarian imperatives in international law.

The humanitarian rationale becomes even more compelling where sanctions coincide with armed conflict. In such contexts, the combined effects of conflict, displacement, and environmental degradation magnify civilian vulnerability.[129] International humanitarian law (IHL) already provides a framework ensuring that aid must continue to flow even amid hostilities.[130] Article 70 of Additional Protocol I to the Geneva

[118] Hoffmann, Anna. "Five Key Points from the Groundbreaking European Court of Human Rights Climate Judgment in Verein KlimaSeniorinnen Schweiz v. Switzerland." *Environmental Law Review*, vol. 26, no. 2, 2024, pp. 91-99 at 92.
[119] *Teitiota v New Zealand*, 7 Jan. 2020, UN Human Rights Committee, CCPR/C/127/D/2728/2016.
[120] ibid.
[121] The International Covenant on Civil and Political Rights (ICCPR), 999 UNTS 171, 23 Mar. 1976, Art. 6.
[122] ICJ AO (n 20) *supra* at [155]-[157], [182], [273], [373]. The Court further recognised that States must take measures within their jurisdiction to prevent activities that cause environmental harm, including harm contributing to climate change, and to cooperate internationally in addressing this global challenge. It also reaffirmed the principle of intergenerational equity, emphasising that present generations have duties to protect the environment for future generations through effective mitigation measures: [187]-[191], [193]-[195].
[123] Brubaker & Huvé (n 84) *supra* at 391.
[124] Shagabutdinova, Elmira, and Jeffrey Berejikian. "Deploying Sanctions while Protecting Human Rights: Are Humanitarian 'Smart' Sanctions Effective?" *Journal of Human Rights*, vol. 6, no. 1, 2007, pp. 59-74 at 61.
[125] UNSC Res. 2134, 28 Jan. 2014, UN Doc S/RES/2134.
[126] *Central African Republic, February 2014 Monthly Forecast.* Security Council, Feb. 2014.
[127] Sponeck, Hans. "Sanctions and Humanitarian Exemptions: A Practitioner's Commentary." *European Journal of International Law*, vol. 13, no. 1, 2002, pp. 81-87 at 85.
[128] UNSC Res. 2231, 20 Jul. 2015, UN Doc S/RES/2231, at [11]-[12].
[129] Wong, C. "Climate Policies and Financing for Conflict and Displacement-Affected Contexts: Closing the Capacity and Education Gaps." *Current Issues in Comparative Education*, vol. 27, no. 1, 2025, pp. 172-196 at 173.
[130] *IHL and Humanitarian Assistance.* International Committee of the Red Cross Casebook, 2024.

Conventions obligates parties to an international armed conflict to 'allow and facilitate the rapid and unimpeded passage of humanitarian relief for civilians in need', subject to their right of control.[131] Article 18 of Additional Protocol II extends this requirement to non-international armed conflicts.[132] These provisions underscore a consistent legal duty to ensure that humanitarian assistance reaches affected populations despite political or military impediments. Extending this reasoning to climate-related assistance ensures that vulnerable populations are not doubly penalised by both sanctions and environmental stress. The International Committee of the Red Cross (ICRC) has reaffirmed that "parties to an armed conflict must allow and facilitate the rapid and unimpeded passage of humanitarian relief for civilians in need",[133] a principle that remains critical for climate-related support where environmental degradation compounds humanitarian crises. Together, these UNSC and IHL frameworks form a coherent legal and moral foundation for designing targeted exemptions, confirming that sanctions can be both effective and consistent with humanitarian imperatives.

2. US and EU Sanctions: Humanitarian and Developmental Exceptions

The US OFAC exemplifies how sanctions regimes can incorporate flexibility through General Licenses, which authorise humanitarian and medical transactions even under comprehensive embargoes.[134] These licenses serve as a policy tool for selectively enabling essential support while maintaining pressure on targeted actors.[135] For instance, OFAC's General License E authorises specific humanitarian exports to Cuba[136] and other sanctioned States. Similarly, the EU implements sector-specific exemptions in its restrictive measures on Iran and North Korea.[137] As Portela emphasises, minimising humanitarian harm is central to the sustainability of sanctions,[138] which further supports the argument that exemptions must not be merely symbolic but genuinely operable. Although the EU is often criticised for gold-plating sanctions; extending them beyond UNSC requirements,[139] the EU has broadened exemptions to facilitate humanitarian aid to align with UNSC Resolution 2664 (2022).[140]

In this context, the concept of a snapback mechanism again becomes highly relevant. If automatic triggers for humanitarian or climate-related exemptions were incorporated, they would reduce the uncertainty faced by organisations fearing penalties and create a predictable, rules-based channel for delivering climate finance and technology assistance under both US and EU regimes. Sanctions practice in both jurisdictions demonstrates that humanitarian flexibility can coexist with policy discipline.

3. Convention on the Elimination of All Forms of Racial Discrimination (CERD)

The Convention on the Elimination of All Forms of Racial Discrimination (CERD)[141] primarily addresses racial discrimination but its jurisprudence and monitoring practice also

[131] Protocol Additional to the Geneva Conventions, 1125 UNTS 3, 8 Jun. 1977, Art. 70.
[132] ibid, Art. 18.
[133] *Humanitarian Access: What the Law Says*. International Committee of the Red Cross, 1 Aug. 2023.
[134] Hoye, J. "OFAC, Famine, and the Sanctioning of Afghanistan: A Catastrophic Policy Success." *New Political Science*, vol. 46, no. 2, 2024, pp. 150-170 at 167.
[135] Manfredi, S, and M Jugl. "Tackling Unintended Consequences of EU Sanctions: NGOs' Advocacy for Humanitarian Exceptions." *Journal of Common Market Studies*, vol. 62, no. 6, 2024, pp. 1519-1537 at 1526.
[136] "Cuba Sanctions." US Department of the Treasury, 2022.
[137] See Taylor (n 62) *supra*; Council Decision 2010/413/CFSP [2010] OJ L195/39; Council Regulation (EU) 267/2012 [2012] OJ L88/1.
[138] Portela, Clara. *The EU's Use of 'Targeted' Sanctions: Evaluating Effectiveness*. CEPS Working Document No. 391, 2014, at 37.
[139] ibid at 8.
[140] Council Decision 2023/726/CFSP [2023] OJ L94. It permits the provision of funds, goods, and services necessary for humanitarian assistance or activities supporting basic human needs, stating such actions are not in violation of imposed asset freezes.
[141] The International Convention on the Elimination of All Forms of Racial Discrimination (CERD), 660 UNTS 195, 4 Jan. 1969.

provide insight into protecting vulnerable populations from disproportionate external harm.[142] In parallel, the Committee on Economic, Social and Cultural Rights has warned that economic sanctions have "a dramatic impact" on rights and must be designed so that they do not harm vulnerable groups.[143] Where sanctions or resource blockages exacerbate the climate-related vulnerability of marginalised groups, they may trigger concerns under Articles 2 and 5 of CERD, which require States to prevent policies that result in discriminatory effects and to secure the equal enjoyment of socio-economic rights.[144]

This interpretation strengthens both the ethical and legal basis for creating climate-related humanitarian exceptions. By recognising that structural inequities, including those reinforced by sanctions, can translate into differentiated climate burdens, CERD complements the broader climate-justice rationale underpinning the call for targeted exemptions.

4. Other Legal Precedents

IHL's humanitarian-access doctrine recognises that life-preserving assistance cannot be subordinated to coercive aims, even in situations of armed conflict.[145] In the sanctions context, this logic is sharpened by Judge Robinson's Separate Opinion in *Certain Iranian Assets*, where she rejects "unfettered resort to unilateral economic sanctions" that override fundamental rights, and stresses that sanctions must remain bounded by humanitarian and human-rights constraints.[146] Read together, this jurisprudence indicates that there are legal ceilings on how far sanctions may frustrate essential needs.

CBDR provides the climate law analogue to this constraint.[147] It acknowledges unequal capacity and historical emissions, and allocates differentiated mitigation burdens accordingly.[148] For sanctioned nations, access to climate finance and mitigation technology is therefore not discretionary "development assistance" but a precondition for fulfilling their share of the global mitigation effort.[149]

Climate-related exemptions within sanctions regimes would thus maintain the integrity of sanctions' core strategic objectives while avoiding breaches of established humanitarian-access doctrine, and would operationalise CBDR rather than reducing it to rhetoric.[150]

IV. **Operational Pathways for Climate Assistance under Sanctions Outcomes**

Providing financial and technological assistance to Iran for climate change mitigation and adaptation is a complex

[142] Yilmaz, M. "Protection of Non-Citizens under the International Convention on the Elimination of All Forms of Racial Discrimination." *International Journal of Discrimination and the Law*, 2025, at 13. Thornberry, Patrick. "The Committee on the Elimination of Racial Discrimination (CERD)." *The United Nations and Human Rights: A Critical Appraisal*, 2nd edn, edited by F Mégret and P Alston, Oxford University Press, 2020, pp. 309–338.

[143] Committee on Economic, Social and Cultural Rights (n 103) *supra* at [3].

[144] CERD (n 141) *supra*, Art. 2(1)(c), 5(e).

[145] The Geneva Conventions and Additional Protocols outline the obligation to provide humanitarian assistance to civilians during conflict and allow third-party aid when the party responsible is unable to provide it themselves. For instance, Article 55 and related sections of the Fourth Geneva Convention acknowledge that States (or occupying powers) must facilitate humanitarian relief and accept assistance when needed: *see* Stoffels, R. "Legal Regulation of Humanitarian Assistance in Armed Conflict: Achievements and Gaps." *International Review of the Red Cross*, vol. 86, no. 855, 2004, pp. 515-546.

[146] *Certain Iranian Assets (Islamic Republic of Iran v United States of America) (Preliminary Objections)* [2023] ICJ Rep 85 (Separate Opinion of Judge Robinson) at [24].

[147] Pauw, Pieter, et al. "Different Perspectives on Differentiated Responsibilities: A State-of-the-Art Review of the Notion of Common but Differentiated Responsibilities in International Negotiations." *International Environmental Agreements: Politics, Law and Economics*, vol. 14, no. 3, 2014, pp. 407-426.

[148] UNFCCC, Art. 3(1); Paris Agreement, Art. 2(2).

[149] Batista-Pritchard, Lívia Regina. "Climate Justice in the Intersection between the CBDR&RC Principle and Intellectual Property Rights: A Critical Reading of International Cooperation." *Journal of Global Ethics,* vol. 20, no. 2, 2024, pp. 179-194 at 180.

[150] Deleuil, Thomas, and Tuula Honkonen. "Vertical, Horizontal, Concentric: The Mechanics of Differential Treatment in the Climate Regime." *Climate Law*, vol. 5, no. 1, 2015, pp. 82-93 at 86.

challenge due to the constraints imposed by international sanctions. Nevertheless, given Iran's vulnerability to climate impacts, it is crucial to explore strategies that allow support while remaining compliant with sanction policies. While this article focuses on Iran, the operational pathways and policy mechanisms identified here are not limited to this case. They provide a framework for reconciling climate justice obligations with legal and political realities in any sanctioned or politically constrained context, thereby offering insights with global relevance.

A. *Ethical and Humanitarian Considerations*

Climate justice provides the ethical foundation for treating climate assistance to sanctioned States as a moral necessity rather than a discretionary favour.[151] Drawing on Henry Shue's fairness principle, which holds that those who benefit most from pollution bear the greatest duty to prevent harm,[152] and Thomas Pogge's argument that global institutions perpetuating deprivation generate remedial obligations,[153] the inequities created by sanctions assume both moral and legal significance. Amartya Sen's capability approach reframes this further; justice is not only about distributing burdens but also about safeguarding the capabilities of all peoples to live dignified lives.[154] Applied to climate change, this means ensuring every nation retains the ability to mitigate and adapt, even when political restrictions are in place.

High-emission nations possess an ethical duty, grounded in distributive and corrective justice, to ensure that sanctions do not block access to the means of survival.[155] As Stephen Gardiner notes, climate injustice is an intergenerational moral storm where the powerful externalise costs onto the powerless and the future.[156] Basing sanctions policy on these insights transforms the exemption question from political expediency into a matter of rectifying structural harm.

Sanctions that impede climate finance or clean-technology transfer exacerbate inequality[157] in two dimensions: (a) between States, because sanctioned nations remain locked in fossil-fuel dependence while others decarbonise;[158] and (b) within States, because the poorest communities bear the highest adaptation costs.[159] This is simultaneously a justice concern, implicating fairness and proportionality, and a rights concern, implicating the basic entitlement to life, health, and security, consistent with scholarship emphasising the moral priority of protecting the most vulnerable.[160] By contrast, climate-related exemptions would not guarantee environmental improvement per se, their empirically supportable effect, according to the UNEP 2024 Adaptation Gap Report, is to enable vulnerable countries to build the

[151] Cameron, Edward. "Human Rights and Climate Change: Moving from an Intrinsic to an Instrumental Approach." *Georgia Journal of International and Comparative Law,* vol. 38, 2010, pp. 673-716 at 686.
[152] Shue, Henry. "Subsistence Emissions and Luxury Emissions." *Law & Policy*, vol. 15, no. 1, 1993, pp. 39-60 at 49.
[153] Pogge, Thomas, and Mitu Sengupta. "Assessing the Sustainable Development Goals from a Human Rights Perspective." *Journal of International and Comparative Social Policy*, vol. 32, no. 2, 2016, pp. 83-97 at 85.
[154] Sen, Amartya. *The Idea of Justice*. Belknap Press of Harvard University Press, 2009, pp. 31-33.
[155] Will, U, and C Manger-Nestler. "Fairness, Equity, and Justice in the Paris Agreement: Terms and Operationalization of Differentiation." *Leiden Journal of International Law*, vol. 34, no. 2, 2021, pp. 397-420 at 400–401.
[156] Gardiner, Stephen M. *A Perfect Moral Storm: The Ethical Tragedy of Climate Change*. Oxford University Press, 2011, at 22-23.
[157] Ikporukpo, C, and N Ikporukpo. "Climate Change and the Struggle for Climate Justice." *Advances in Social Sciences Research Journal*, vol. 11, no. 11, 2024, pp. 43-61 at 45.
[158] Hatipoglu, Emre, et al. "Environmental Consequences of Geopolitical Crises: The Case of Economic Sanctions and Emissions." *Resources Policy*, vol. 85, 2023, 104011, at 2.
[159] Jamieson, Dale. *Reason in a Dark Time: Why the Struggle against Climate Change Failed and Why Our Choices Still Matter*. Oxford University Press, 2014, at 214.
[160] McKinnon, Catriona. "Climate Justice in the Endgame for 2 Degrees." *British Journal of Politics and International Relations*, vol. 21, no. 2, 2019, pp. 279-286 at 282; Pogge, Thomas. "Shue on Rights and Duties." *Global Basic Rights*, edited by Charles Beitz and Robert Goodin, Oxford University Press, 2009, at 107-108.

institutional capacity required for mitigation and resilience.[161] In this light, blocking access to climate mitigation technologies through sanctions does not merely disadvantage Iran economically, it interrupts the realisation of reparative justice by preventing the polluter-pays principle from being operationalised in practice.

Humanitarian reasoning reinforces the ethical one. Analogous to medical aid exceptions, climate aid addresses existential threats. If international law already recognises that sanctions must yield to essential health needs, it follows by parity of reasoning that life-preserving environmental support deserves similar accommodation.[162] The ethical and humanitarian imperatives outlined here underscore that climate assistance is a condition for survival and justice, not merely a policy choice.[163] This ethical reasoning naturally connects to international human-rights law. The duties of fairness, capability, and corrective justice outlined above correspond to the positive obligations recognised in human-rights instruments to safeguard life, health, and a safe environment.

B. *Legal Considerations*

Climate-related assistance cannot be viewed purely as a policy choice. Human rights bodies have increasingly recognised that environmental degradation undermines a wide range of rights. They have effectively "greened" existing human rights by clarifying that States' duties to respect, protect and fulfil those rights apply equally in environmental contexts.[164] The ICJ in its 2025 AO, affirmed that the adverse effects of climate change may impair the enjoyment of the right to life and that States have duties to prevent activities within their jurisdiction from causing environmental harm.[165] The right to life enshrined in Article 3 of the Universal Declaration of Human Rights,[166] Article 6 of the ICCPR and Article 6 of the Convention on the Rights of the Child,[167] has been interpreted by the HRC to encompass protection against environmental degradation and climate-related threats.[168] From this standpoint, when sanctions impede access to climate finance or technology essential for adaptation and mitigation, sanctioning States may indirectly contribute to conditions that compromise the right to life.

Authoritative interpretations further clarify this nexus, as discussed previously. In *Teitiota v New Zealand*,[169] the HRC held that exposure to life-threatening climate impacts could engage non-refoulement obligations under the ICCPR.[170] This reasoning suggests that States must not create or maintain regimes such as sanctions, that foreseeably worsen such exposure. Likewise, the UN Human Rights Council, in Resolutions 27/21 (2014) and 45/5 (2020), underscored that unilateral coercive measures can have "far-reaching implications for the human rights of the general population", particularly the rights to food, health, and an adequate standard of living.[171] The Committee on Economic, Social and Cultural Rights has similarly stressed that sanctions cannot render human-rights obligations inoperative and that the international community must protect at least the core content of those rights.[172]

The UN Human Rights Council's Resolution 16/11 (2011) recognises that a clean, healthy,

[161] *Adaptation Gap Report 2024*. United Nations Environment Programme, 2024, at 74.
[162] Sardo, M. "Responsibility for Climate Justice: Political Not Moral." *European Journal of Political Theory*, vol. 22, no. 1, 2023, pp. 26-50 at 27.
[163] Grasso, Marco. "An Ethical Approach to Climate Adaptation Finance." *Global Environmental Change*, vol. 20, no. 1, 2010, pp. 74-81 at 78.
[164] Boyd, David and John Knox. "Report of the Special Rapporteur on the Issue of Human Rights Obligations Relating to the Enjoyment of a Safe, Clean, Healthy and Sustainable Environment." UN Doc A/73/188, 2018, at 6, [13].
[165] ICJ AO (n 20) *supra*, [377]-[378].
[166] UNGA Res. 217(A)(III), UN Doc A/RES/3/217 A (UDHR), Art. 3, 25, 27.
[167] The Convention on the Rights of the Child (CRC), 1577 UNTS 3, 2 Sept. 1990, Art. 6.
[168] ibid; UDHR (n 166) *supra*, Art. 3; ICCPR (n 121) *supra*, Art. 6.
[169] *Teitiota* (n 119) *supra* at [9]-[11].
[170] UNHRC (n 82) *supra*.
[171] UNHRC Res. 27/21, 2 Oct. 2014; UNHRC Res. 45/5, 6 Oct. 2020.
[172] Committee on Economic, Social and Cultural Rights (n 103) *supra*.

and sustainable environment is indispensable to the enjoyment of fundamental rights such as life, health, and dignity;[173] consequently, blocking access to climate-related support risks contravening these principles. Therefore, although sanctions restricting climate action may not themselves be unlawful *per se*, they may undermine the enjoyment of protected rights within sanctioned States.[174] The human consequences are concrete; sanctions can weaken public services, limit economic opportunity, and restrict access to renewable-energy and adaptation technologies, disproportionately affecting vulnerable populations while insulating political elites.[175]

In heavily sanctioned contexts like Iran, this dynamic creates structural vulnerability; populations already facing drought, heat stress, and pollution are further constrained by financial restrictions that obstruct environmental governance.[176] As one Special Rapporteur has observed, such effects are deeply disturbing in their cumulative impact on rights to life, food, housing, and development.[177] Accordingly, sanctions design must integrate humanitarian and climate-related carve-outs consistent with the principle of proportionality in international law.[178]

The jurisprudence and resolutions above collectively support a duty of due diligence requiring States to anticipate and mitigate the adverse human rights consequences of their measures.[179] They also complement humanitarian law's acceptance that, even in conflict, life-preserving aid must continue flowing.[180]

C. *Potential Policy Recommendations*

Human conditions in sanction-affected States highlight the urgent need for legal and procedural reform to ensure that sanctions deter abuses without creating new ones.[181] The following policy pathways address Iran's climate vulnerabilities while offering a replicable framework for other sanctioned or politically constrained nations. By drawing on legal precedents for humanitarian exceptions (as discussed in Section III), ethical imperatives in climate justice, and practical mechanisms for financing and technology transfer, these recommendations show that effective climate action remains possible even under restrictive political conditions.

1. Extending Humanitarian Exceptions to Climate Aid

Humanitarian exceptions in sanction regimes have historically facilitated medical, food and disaster-relief transactions.[182] As discussed in Section III.B, these carve-outs show that sanctions are not absolute and can accommodate life-preserving needs under certain circumstances.[183] Applying the same rationale to climate assistance would recognise renewable-energy technology, adaptation projects, and environmental restoration as essential for human survival. This approach builds upon UNSC Resolution

[173] UNHRC Res. 16/11, 24 Mar. 2011, UN Doc A/HRC/RES/16/11.
[174] Tang, K, and O Spijkers. "The Human Right to a Clean, Healthy and Sustainable Environment." *Chinese Journal of Environmental Law*, vol. 6, no. 1, 2022, pp. 87-107 at 103-104.
[175] Moret, Erica. "Humanitarian Impacts of Economic Sanctions on Iran and Syria." *European Security*, vol. 24, no. 1, 2015, pp. 120-140 at 124-125.
[176] Tahbaz, Morad. "Environmental Challenges in Today's Iran." *Iranian Studies*, vol. 49, no. 6, 2016, pp. 943-961 at 944.
[177] Douhan, Alena. "Report of the Special Rapporteur on the Negative Impact of Unilateral Coercive Measures on the Enjoyment of Human Rights." UN Doc A/HRC/51/33, 2022.
[178] Owen, Mallory. "The Limits of Economic Sanctions Under International Humanitarian Law: The Case of the Congo." *Texas International Law Journal*, vol. 48, no. 1, 2012, pp. 103-123 at 117.
[179] Gutmann, Jerg, et al. "Economic Sanctions and Human Rights: Quantifying the Legal Proportionality Principle." ILE Working Paper No. 12, 2018, at 6.
[180] Protocol Additional to the Geneva Conventions (n 131) *supra*, Art. 69(1).
[181] Sponeck (n 127) *supra* at 87.
[182] Huvé, S, and R Brubaker. *Humanitarian Exemptions in UN Sanctions Regimes*. United Nations University / UN Sanctions & Humanitarian Action Policy Memo Series, 2022.
[183] Rodenhäuser, Tilman, and Gilles Giacca. "The International Humanitarian Law Framework for Humanitarian Relief during Armed Conflicts and Complex Emergencies." *Research Handbook on Disasters and International Law*, edited by Susan Breau and Katja Samuel, Edward Elgar, 2016, pp. 132-152 at 138.

2664 (2022) and subsequent EU regulations, extending their humanitarian logic to climate security.[184]

Evidence from the period after Resolution 2664 shows that clearer carve-out procedures reduce over-compliance among banks; 43.75% of institutions surveyed reported greater comfort in processing humanitarian transactions as a result.[185] A parallel model for climate goods, solar components, water-management systems, or drought-resistant agriculture inputs could yield similar predictability. However, these benefits are not automatic; studies of humanitarian banking corridors indicate that unless liability shields and simplified due-diligence documentation are provided to financial institutions, risk-aversion and sanctions over-compliance can still significantly impede the practical delivery of exempted goods.[186] Framing climate support as essential rather than discretionary transforms it from a goodwill gesture into a rights-based obligation consistent with the CBDR principle.[187]

2. Leveraging Multilateral Climate Funds and Mechanisms

Building on Section III.C's analysis of legal precedents, multilateral climate funds such as the GCF, the Adaptation Fund,[188] and UNFCCC's Technology Mechanism (TEC and CTCN)[189] can provide lawful and neutral channels for supporting sanctioned States.[190]

However, recurring obstacles must be acknowledged. The first is financial-compliance risks as discussed previously. In Syria, 2020 INGO data shows that 12% of humanitarian transfer requests were rejected, a further 12% ultimately failed, and 32% were delayed by three to ten months; and the Association of Certified Anti-Money Laundering Specialists (ACAMS)[191] dialogue indicates rejection rates for Iran are likely even higher.[192] The second obstacle is institutional conditionality. International agencies sometimes impose Western-centric reporting or governance standards, which can inadvertently reproduce neo-colonial asymmetries by subordinating local priorities.[193] The third obstacle concerns empirical performance. Recent portfolio assessments similarly show delivery constraints; a 2024 G20 high-level expert review reported that the GCF's disbursement-to-approval ratio is roughly 31%, indicating slow conversion of approved finance into operational delivery;[194] the GCF's own 2023 Annual Results Report likewise emphasises gradual portfolio rollout.[195] Thus, without substantive procedural reform, exemptions on

[184] Seatzu & Vargiu (n 106) *supra*.
[185] Subramanian-Montgomery, Ashleigh. *A Study on the Impacts of UN Security Council Resolution 2664 on Financial Institutions & Donors*. Charity & Security Network, 3 Dec. 2024, at 6.
[186] Moret, Erica. *Safeguarding Humanitarian Banking Channels: How, Why and By Whom?* Norwegian Refugee Council, Jan. 2023, at 10.
[187] Schapper, Andrea. "Climate Justice and Human Rights." *International Relations*, vol. 32, no. 3, 2018, pp. 275-295 at 278.
[188] The Adaptation Fund was established in 2001 to finance concrete adaptation projects and programmes in developing country Parties to the Kyoto Protocol that are particularly vulnerable to the adverse effects of climate change. "Adaptation Fund." *UNFCCC*, Oct. 2025.
[189] The Technology Mechanism, created in 2010 under the UNFCCC, has two parts: the Technology Executive Committee (TEC), which develops policy advice and briefs, and the Climate Technology Centre and Network (CTCN), which delivers technical assistance, capacity-building, and networking support. "Report of the Conference of the Parties on Its Seventeenth Session, Held in Durban from 28 November to 11 December 2011. Addendum. Part Two: Action Taken by the Conference of the Parties at Its Seventeenth Session." 15 Mar. 2012, UN Doc FCCC/CP/2011/9/Add.1.
[190] Oh, Chaewoon. "Evaluation of the UNFCCC Technology Mechanism's Contribution to an International Climate Policy Framework." *International Environmental Agreements: Politics, Law and Economics*, vol. 22, no. 3, 2022, pp. 527-542 at 528-529.
[191] For further information on the ACAMS International Sanctions Compliance Task Force Humanitarian Workstream, see "ACAMS International Sanctions Compliance Task Force: Humanitarian-Sanctions Technical Dialogue Forum." *ACAMS Sanctions Space*, 1 Mar. 2021.
[192] Walker, Justine. "The Public Policy of Sanctions Compliance: A Need for Collective and Coordinated International Action." *International Review of the Red Cross*, vol. 103, no. 916-917, 2022, pp. 705-716 at 707.
[193] *Pathways Towards Effective Locally Led Development Co-Operation: Learning by Example*. OECD, 2024, at 13.
[194] "Review of the VCEF Investment Framework." G20 Working Paper, Sept. 2024, at 11
[195] *Annual Report 2023*. Green Climate Fund, Sept. 2024, at 8.

paper may fail to translate into material impact in practice. Comparable bottlenecks have already been observed in sanctioned jurisdictions in the humanitarian context, which suggests that climate-specific carve-outs are likely to encounter similar implementation friction without concurrent streamlining. To address these weaknesses, the GCF and similar bodies could authorise neutral implementing partners (e.g., UNDP, UNEP, IRENA) to vet and channel climate finance into sanctioned contexts; simplify fiduciary standards for low-risk climate goods while maintaining transparency; and establish a dedicated "sanctions-context window" to fast-track mitigation and adaptation proposals verified through multilateral oversight. These adjustments would operationalise the humanitarian-exception logic without compromising accountability.

3. Third-Party and Regional Intermediaries

Where multilateral funds face procedural inertia, intermediary institutions can provide an operational bridge between donor finance and on-the-ground implementation in sanctioned environments. International organisations,[196] regional banks, and NGOs[197] can act as intermediaries that separate humanitarian intent from political risk.[198] They may receive funds from donors,[199] procure renewable-energy equipment,[200] or manage adaptation projects on behalf of sanctioned States.[201] Yet experience reveals implementation barriers. Studies of humanitarian access constraints show that excessive vetting and delayed approvals often erode the timeliness of relief.[202] Evaluations of similar third-party structures in high-risk jurisdictions suggest that although intermediary models improve legal compliance, they do not consistently improve delivery speed or project completion rates unless there are dedicated local implementation partnerships in place.[203] Furthermore, accountability frameworks imported from donor countries sometimes ignore local social norms, leading to community resistance or perceptions of paternalism.[204]

To mitigate these risks, intermediaries should prioritise co-governance arrangements with local institutions to ensure cultural

[196] For further information, *see* Chaudhury, A. "Role of Intermediaries in Shaping Climate Finance in Developing Countries—Lessons from the Green Climate Fund." *Sustainability*, vol. 12, no. 14, 2020, pp. 1-17.

[197] This is about using intermediaries to ensure funds reach the local level efficiently and in ways that reduce bureaucratic or political risk. While not about sanctions, it's directly relevant to how neutral / multilateral / NGO actors are already proposed as essential channels, especially in complex political environments. Grutter, N, et al. *Shifting Climate Adaptation Finance to Local Communities through Effective Intermediaries*. IIED, 2025.

[198] The GCF has explicit policies on anti-money laundering, countering financing of terrorism, "prohibited practices", integrity, risk management etc., which suggests that the GCF is structured to mitigate legal risks, including those arising from working in difficult / high-risk jurisdictions. That framework could constrain or facilitate work involving intermediaries: *see Anti-Money Laundering and Countering the Financing of Terrorism Policy*. Green Climate Fund, 2 Oct. 2017.

[199] *Managing Aid: Practices of DAC Member Countries.* OECD, 2009, at 47-58. For example, The Global Fund relies heavily on Local Fund Agents (independent intermediaries) to monitor allocation of donor money in politically sensitive countries: *see* "The Global Fund's Monitoring and Evaluation Framework." *The Global Fund to Fight AIDS, Tuberculosis and Malaria*, 2025.

[200] In sanctioned / fragile settings, WHO and partners provide technical assistance, training, and capacity building for national health staff and NGOs to implement aid. *Global Health Cluster Guide: A Practical Guide for Country-Level Implementation of the Health Cluster*. WHO, 7 Jul. 2009, WHO/HAC/MAN/2009.7, at 178. *see also* Brinkerhoff, Derick. "Capacity Development in Fragile States." *ECDPM*, 1 May 2007; Wignaraja, Kanni, *Capacity Development: A UNDP Primer*. UNDP, 2009.

[201] *Humanitarian Access in Situations of Armed Conflict: Handbook on the Normative Framework*. Swiss Federal Department of Foreign Affairs, 2011; Gillard, Emanuela-Chiara. "Humanitarian Exceptions: A Turning Point in UN Sanctions." *Chatham House International Law Programme*, 20 Dec. 2022; "How U.S. Economic Sanctions Work: Tools, Targets, and Trade-offs." *GovFacts*, 30 Aug. 2025.

[202] *Guidance: Understanding and Addressing Bureaucratic and Administrative Impediments to Humanitarian Action—Framework for a System-Wide Approach*, Inter-Agency Standing Committee, Jan. 2022, at 7, 9.

[203] Stoddard, Abby, et al. *Efficiency and Inefficiency in Humanitarian Financing*. Humanitarian Outcomes, Dec. 2017.

[204] Turner, Ellen, et al. "Accountability and Objectivity: Humanitarian Narratives at the Intersection of Evidence and Localisation." *Journal of International Humanitarian Action*, vol. 9, no. 1, 2024, pp. 1-18 at 2-3.

relevance,[205] draw on regional development banks (such as the Islamic Development Bank or the Asian Infrastructure Investment Bank) to pool risk-sharing guarantees for climate projects,[206] and shift transparency requirements towards results-based monitoring rather than prescriptive procedural control.[207] Such hybrid governance arrangements strike a balance between compliance, legitimacy, and sensitivity to context, enhancing the credibility of climate-aid delivery.[208]

4. Bilateral and Technical Agreements

Targeted bilateral arrangements between Iran and climate-committed States (e.g., Germany, Norway, France), limited strictly to environmental cooperation, could supplement multilateral channels. Examples might include renewable-energy joint ventures, water-management exchanges, or carbon-capture research partnerships.[209]

However, empirical lessons from previous bilateral environmental accords show uneven outcomes; capacity-building projects often falter when embedded within wider diplomatic tensions.[210] In addition, comparative case studies in EU–MENA[211] energy cooperation suggest that bilateral climate agreements are unusually sensitive to changes in in donor-state political leadership, policy reversals or shifts in foreign-affairs priorities can abruptly terminate projects even where technical delivery is satisfactory.[212]

To remain viable, such agreements must be narrowly scoped to climate objectives; include sanction-compliance clauses and third-party auditing; and guarantee knowledge reciprocity, avoiding one-way technology transfer that reinforces dependency. Even where bilateral climate partnerships do yield positive outputs, effects do not automatically scale. Indonesia's bilateral CASE cooperation with Germany rapidly increased installed solar capacity (from ~9MW to over 240MW in two years), yet programme evaluations note that broader penetration remains constrained by supply-chain cost shocks and political cycles, illustrating how bilateral climate cooperation can deliver project-level gains without structural transformation.[213]

5. Multilateral Climate Cooperation and Knowledge Transfer

Organisations such as International Renewable Energy Agency (IRENA)[214] and United Nations Environment Programme

[205] McNaught, Rebecca. "The Application of Collaborative Governance in Local Level Climate and Disaster Resilient Development—A Global Review." *Environmental Science & Policy*, vol. 151, 2024.

[206] Zeng, Weishen. "Climate Finance and New Multilateral Development Banks: Approaching Co-Productive Dynamics?" *Climate Policy*, vol. 25, no. 8, 2025, pp. 1117-1130 at 1117-1119.

[207] *see* Goodwin, Sean, and Marta Olazabal. "Revisiting the Challenges to Monitoring, Evaluation, Reporting, and Learning for Climate Adaptation." *Environmental Science & Policy*, vol. 172, 2025, 104199.

[208] Huvé, Sophie, et al. *Unblocking Aid: The EU's 2023 Shift in Sanctions Policy to Safeguard Humanitarian Efforts*. International Committee of the Red Cross, 23 Jan. 2024.

[209] Shokri, Umud. "COP29 and Iran: Overcoming Sanctions, Fossil Fuel Dependence, and Harnessing China's Role in the Clean Energy Transition." *TRENDS Research & Advisory*, 9 Dec. 2024

[210] *UNDP Country Programme (2017–2022) Evaluation, Islamic Republic of Iran: Final Report*. UNDP, 31 Mar. 2022, at 32; Bianco, Cinzia. *A New Climate for Peace: How Europe Can Promote Environmental Cooperation Between the Gulf Arab States and Iran*. European Council on Foreign Relations, Oct. 2022, at 3.

[211] The Middle East and North Africa (MENA) region includes countries across the Middle East and North African areas (e.g. Iran, Iraq, UAE, Saudi Arabia, Egypt, Morocco, Tunisia, etc.).

[212] Schmitt, Thoma. "Why Did Desertec Fail? An Interim Analysis of a Large-Scale Renewable Energy Infrastructure Project from a Social Studies of Technology Perspective." *Local Environment*, vol. 23, no. 7, 2018, pp. 747-776 at 765-766; Urbasos, Ignacio. *Lessons Learnt from the Failure of the Mediterranean Solar Plan for the Success of a Mediterranean Green Hydrogen Partnership*. Euro-Mediterranean Study Commission Policy Brief No. 145, Jun. 2024; Leonard, Mark, et al. *The Geopolitics of the European Green Deal*. Bruegel Policy Contribution No. 04/2021, Bruegel, Feb. 2021.

[213] Hariyadi, Firsty Afrilia, and Dadan Suryadipura. "Indonesia and Germany Bilateral Cooperation Towards Renewable Energy Transition Through Clean, Affordable and Secure Energy (CASE)." *Jurnal Ilmu Sosial*, vol. 21, no. 2, 2022, pp. 145-160 at 148-150.

[214] IRENA is an intergovernmental organisation that supports countries in their transition to a sustainable energy future. It serves as a principal platform for

(UNEP)[215] are positioned to operationalise climate-related exceptions.[216] IRENA's regional hubs already coordinate technical training and grid-integration programs across West Asia;[217] UNEP has supported Iran in hazardous waste management and environmental law capacity-building.[218]

Nevertheless, governance asymmetries persist. Host-country agencies often lack decision-making power once donor funding begins, and project evaluation metrics may prioritise efficiency over equity.[219] Moreover, UNFCCC's TNA guidance notes that technology transfer must be aligned with national development priorities and institutional capacities in order to be sustainable, meaning that without an enabling environment, transfer alone is unlikely to translate into effective mitigation outcomes.[220] Embedding local academic and governmental partners into project steering committees can counteract this bias and reinforce ownership.

UNEP's 2022 Adaptation Gap Report shows that 84 per cent of countries now maintain at least one national adaptation planning instrument (up from 79 per cent in 2021), underscoring that nationally anchored governance is increasingly recognised as a prerequisite for effective adaptation.[221] This trend reinforces the broader point that institutional ownership structures matter, which, in the Iranian context, supports embedding domestic research institutes and NGOs into any future climate-aid carve-out.

6. Innovative Financial Mechanisms

In response to the persistent inefficiencies of traditional aid mechanisms, innovative finance tools have been proposed to widen access to climate funding in high-risk or sanctioned environments; yet their practical efficacy remains uncertain. Alternative finance tools including blockchain-based traceability systems, blended-finance platforms, and crowdfunding can circumvent traditional banking barriers.[222] However, regulatory volatility and verification challenges limit their scale. A World Bank brief notes that crypto- and token-based climate finance pilots face conversion, compliance, and implementation bottlenecks[223] underscoring that without institutional anchoring, such mechanisms cannot reliably function as primary delivery channels.

A pragmatic model could involve hybrid financing, where crowdfunding[224] mobilises small contributions for micro-solar or water-harvesting projects;[225] and multilateral

international cooperation, a centre of excellence, and a repository of policy, technology, resource, and financial knowledge on renewable energy.

[215] The UNEP is the leading global environmental authority that sets the global environmental agenda and promotes the coherent implementation of the environmental dimension of sustainable development within the United Nations system.

[216] Uzondu, Nwankwo Charles, and Dominic Dummene Lele. "Multifaceted Impact of Renewable Energy on Achieving Global Climate Targets: Technological Innovations, Policy Frameworks, and International Collaborations." *International Journal of Applied Research in Social Sciences*, vol. 6, no. 7, 2024, p. 1521.

[217] "Iran, IRENA Discuss Expanding Cooperation on Renewable Energy." *Tehran Times*, 17 Jan. 2025.

[218] *Strengthening Institutional Capacity for the Sustainable Sound Management of Chemicals and Waste throughout Cleaner Production Approach in Order to Implement the Multilateral Environmental Agreements in the Islamic Republic of Iran Oil Industry.* United Nations Environment Programme, 2024.

[219] *Donor Support for Institutional Capacity Development in Environment: Lessons Learned: Evaluation and Aid Effectiveness No. 3*. OECD, 2000, pp. 1-225, at 13-15, 63.

[220] "Technology Needs Assessments (TNAs)." *UNFCCC*.

[221] *Adaptation Gap Report 2022: Too Little, Too Slow*. UNEP, 2022, at 10.

[222] Agustí Strid, Alma, et al. *Innovative Financing Series: Introduction to Innovative Financing*. Donor Tracker, 1 Jul. 2025.

[223] *Does Blockchain Have a Role in the Financing of Infrastructure?* PPIAF & IPG Global Practice, May 2023, at 48; *Security Token Offerings: Regulatory Approaches and Lessons from Global Case Studies*. World Bank, Nov. 2024, at 9-10, 21.

[224] Crowdfunding is an online method of raising funds from many small contributors (using crowdsourcing principles without traditional financial intermediaries). Shneor, Rotem, and Natalia Maehle. "Editorial." *Baltic Journal of Management*, vol. 15, no. 2, 2 Jun. 2020, pp. 141-147.

[225] Maehle, Natalia, et al. "Crowdfunding for Climate Change: Exploring the Use of Climate Frames by Environmental Entrepreneurs." *Journal of Cleaner Production*, vol. 314, 2021, at 2.

agencies or philanthropic funds match verified outcomes using blockchain-recorded proof of emission reduction.[226]

This structure enhances transparency while maintaining alignment with anti-money-laundering standards, thus addressing donor concerns about legitimacy and traceability.

7. Diplomatic Advocacy

Long-term change depends on policy reinterpretation within major sanctioning coalitions. Engagement in United Nations General Assembly (UNGA) debates, G20 processes, and regional climate summits can reframe climate aid as a humanitarian necessity rather than a political concession. For instance, UNSC Resolution 2664 already embeds flexibility for humanitarian delivery.[227] A practical illustration is the EU introduction of a general humanitarian exemption in its Syria sanctions regime in 2023, now extended to facilitate aid-related transactions. Yet independent analyses continue to report bank de-risking and over-compliance that impede transfers, meaning that although legal reinterpretation has eased the procedural architecture, a demonstrable increase in actual approvals is not established in publicly available data.[228] In practice, normative progress has not consistently yielded operational reform, necessitating direct engagement with bureaucratic inertia and risk-averse compliance cultures.[229] Diplomatic strategy should therefore anticipate opposition rooted in national-security rhetoric and emphasise shared interest in climate stability, supported by data on transboundary climate risks such as dust storms, migration, and regional water scarcity.[230]

D. *Potential Benefits for Regional and Global Environmental Outcomes*

Iran's inclusion in structured climate-assistance mechanisms could yield conditional yet measurable gains, though projections must remain evidence-based. At the regional level, enhanced cooperation on water-management, renewable-energy grids, and sustainable agriculture could alleviate competition over transboundary resources and support conflict-prevention.[231] Comparable oil-dependent economies in the region face similar transition pressures, reinforcing that Iran's predicament reflects a broader structural challenge rather than an anomaly.[232] Empirical evidence supports this link. World Bank analysis shows that climate-resilient, cooperative water-sharing scenarios in the Mashreq reduce macroeconomic damage from water scarcity by c.60 percent compared with non-cooperative baselines,[233] and UNESCO reports that only 32 of 153 transboundary-water States currently have operational cooperation arrangements, underscoring how institutionalised cooperation remains the exception rather than the norm.[234]

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[226] *Strengthening Transparency of Non-State Actors: How National Experiences and New Digital Technologies Can Strengthen the Transparency Efforts of Non-State Actors.* UNEP, 26 Oct. 2023.

[227] UNSC Res. 2664 (n 108) *supra*.

[228] *The Future of EU-India Relations*. European Parliamentary Research Service Briefing EPRS BRI 749765, 2023, pp. 1-12 at 5–7; Human Rights Watch. "Questions and Answers: How Sanctions Affect the Humanitarian Response in Syria." 22 Jun. 2023.

[229] Obrecht, Alice, et al. *The State of the Humanitarian System 2022*. ALNAP / ODI, 2022, pp. 1-357 at 114-115.

[230] "Overlooked and Underestimated: Sand and Dust Storms Wreak Havoc across Borders." *UN News*, 25 Jul. 2025; *Sand and Dust Storms in the Middle East and North Africa (MENA) Region: Sources, Costs, and Solutions.* IBRD / The World Bank, 2019; "Tracking Sand and Dust Storms." *UNEP*, 16 Feb. 2024.

[231] Al-Manji, Suad, et al. *Troubled Waters in Conflict and a Changing Climate: Transboundary Basins Across the Middle East and North Africa.* Carnegie Endowment for International Peace, 12 Feb. 2024; *Regional Initiatives: Middle East*. Blue Peace Initiative; Schaefer, Paula. "Climate Change as an Opportunity for Cooperation in the Middle East." Heinrich-Böll-Stiftung, 30 Mar. 2023.

[232] *MENA Economic Update: Trading Together—Reviving Middle East and North Africa Regional Integration in the Post-COVID Era.* The World Bank, 2023, at 17–19; "World Energy Outlook 2024." IEA, 2024*; Adaptation Gap Report 2023: Too Little, Too Slow*. UNEP, 2023, at 56-59; "Iran's Government Plans to Increase Taxes Amid Economic Crisis." *Iran International,* 23 Nov. 2023*;* Salhani, Justin. "Iraq's Overreliance on Oil Threatens Economic, Political Strife." *Al Jazeera,* 28 Mar. 2024; "How Is Libya Reacting to Low Oil Prices?" *The World Bank,* Jul. 2016.

[233] Zhang, Fan, and Christian Borja-Vega, *Water for Shared Prosperity*. The World Bank, 2024, at 14, 29.

[234] "The Role of Transboundary Cooperation." *UNESCO*, 2024.

Domestically, Iran's 4–12 percent emission-reduction pledge under the Paris Agreement[235] could expand significantly with sanctions relief enabling technology imports and financing.[236] Using 2022 generation data (oil ≈8% of total ≈361 TWh) and standard oil-fired emission factors (~0.77 tCO_2/MWh), Energy Information Administration (EIA) data suggest that replacing roughly one-fifth of Iran's oil-fired electricity with solar would avoid approximately 4–5 $MtCO_2$ per year, a non-trivial, but not transformational, mitigation gain.[237] This quantitative estimate operates as a modelled scenario, not an *a priori* prediction of actual future outcomes. Nonetheless, outcomes would depend on governance quality,[238] transparency, and maintenance capacity.[239] Hence, claims of automatic environmental improvement are avoided here; rather, the evidence suggests a plausible, conditional pathway to emissions reduction if financial and technological access is restored.

Regionally, spillover effects may include joint adaptation projects in the Persian Gulf and Central Asia, expansion of renewable-supply chains, and diversification of climate-finance flows. Yet equity safeguards are necessary to prevent wealthier partners from capturing disproportionate value. The OECD notes that in developing countries, private-finance mobilisation is constrained by weak enabling conditions, high due-diligence costs, and climate projects that are often too small to secure significant commercial funding, meaning that large actors with lower transaction costs are better positioned to benefit.[240]

At the global level, integrating Iran into climate finance frameworks would reaffirm the universality of climate-justice principles, ensuring that political isolation does not translate into environmental exclusion. Empirical evidence from comparable contexts, notably Sudan's 2022 UNDP solar-irrigation program, shows that climate-aid carve-outs can deliver verifiable emission reductions while maintaining sanctions compliance.[241] These examples demonstrate feasibility rather than certainty, reinforcing that a climate-action exception can be both ethical and practicable within existing international law parameters.

V. **Conclusion**

In an era of escalating climate crises, ensuring that vulnerable nations have the resources to mitigate and adapt to climate change is not only a moral imperative but also a matter of legal responsibility grounded in equity and human rights.[242] As evidenced by the comparative analysis of humanitarian-exception practice in the medical domain, exemptions can be, and have been, operationalised without collapsing the integrity of sanctions regimes. Drawing on existing humanitarian-exception precedents and legal analyses, this article has argued that international sanctions, though designed for political objectives, can inadvertently hinder access to essential climate finance and technology.[243] Therefore, existing humanitarian exceptions for medical aid provide the most compelling operational and normative model for extending similar mechanisms to climate-related assistance.

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[235] Mahoozi, Sanam. "Why Iran Did Not Give a Plan for Climate Action at COP29." *Forbes*, 22 Nov. 2024.
[236] Shokri, Umud. "Iran's Renewable Energy Prospects and Challenges." *Stimson Center*, 23 Oct. 2024.
[237] US EIA (n 47) *supra* at 10.
[238] Choe, Byeong-Hak, and Tilsa Ore-Monago. "Governance and Climate Finance in the Developing World." *Climate Change and Energy Transition*, Springer, 2024, pp. 1-40 at 1.
[239] *Reference Guide for Climate-Smart Public Investment*. IBRD / The World Bank, 2022, at 113.
[240] *Scaling Up the Mobilisation of Private Finance for Climate Action in Developing Countries: Challenges and Opportunities for International Providers*. OECD, 2023, pp. 1-28 at 14.
[241] "Terminal Evaluation Report for the Project 'Promoting the Use of Electric Water Pumps for Irrigation in Sudan' (Award No 00087168, UNDP, 30 December 2022)." *UNDP*, 2022, at 50-52.
[242] Dehm, Julia. "Climate Change, 'Slow Violence' and the Indefinite Deferral of Responsibility for 'Loss and Damage'." *Griffith Law Review*, vol. 29, no. 2, pp 220-252 at 221-2.
[243] Moret, Erica. "Humanitarian Impacts of Economic Sanctions on Iran and Syria." *European Security,* vol. 24, no. 1, 2015, pp. 120-140 at 121.

Incorporating sanctioned nations into global climate initiatives could, where supported by procedural safeguards and transparent oversight, enhance domestic resilience and contribute to regional cooperation on shared environmental risks.[244] The Iranian case illustrates both the obstacles created by current restrictions and the opportunities that a targeted exemption could unlock for equitable climate action. No deterministic claim is made here regarding environmental outcomes; rather, the argument suggests that a climate carve-out is a plausible and legally coherent pathway whose effects would ultimately depend on governance capacity, implementation integrity, and verified mitigation performance.

Ultimately, a climate-just approach demands that high-emitting nations recognise their differentiated responsibilities and ensure that coercive economic measures do not obstruct collective climate goals.[245] Aligning humanitarian, ethical, and legal principles with practical sanction-design reforms can transform existing constraints into pathways for cooperation. The pursuit of climate justice amid sanctions is not aspirational; it is a prerequisite for a sustainable and genuinely inclusive global climate regime.

[244] Arts, Karin and Atabongawung Tamo. "The Right to Development in International Law: New Momentum Thirty Years Down the Line?" *Netherlands International Law Review,* vol. 63, no. 3, 2016, pp. 221-249 at 228.

[245] Falkner, Robert. "The Unavoidability of Justice—And Order—In International Climate Politics: From Kyoto to Paris and Beyond." *The British Journal of Politics and International Relations,* vol. 21, no. 2, 2019, pp. 270-278 at 270.

Securitising Climate Change: Pacific Island States as Norm Entrepreneurs in the UN System

Siyue (Grace) Tang*

* MPhil Candidate (Department of Land Economy), University of Cambridge, UK

KEYWORDS

PSIDS, norm entrepreneurs, climate security, international relations, UN

ABSTRACT

From extreme storms, coastal erosion, to marine ecosystem collapse, Pacific Island states are at the frontline of climate change disruption. Despite their limited material power, Pacific Small Island Developing States (PSIDS) have emerged as one of the earliest and most influential actors to engage with the climate change issue. In the UN arena, PSIDS have shaped global climate responses by securitising climate change, proposing binding emission targets, and securing consensus on global warming limits.

This article engages with international relations theories on the framework of the United Nations (UN) system, the constructivist theory of norm formation, and the Copenhagen School's theory of securitisation to examine how the Pacific Small Island Developing States (PSIDS) have advanced climate security norms within the UN system and steered global climate responses. Using case studies including the establishment of the United Nations Framework Convention on Climate Change (UNFCCC), the 1997 Kyoto Protocol, and the 2015 Paris Agreement, the article argues that the PSIDS' success in exerting disproportionate influence over UN climate agreements should be credited to their skilful leveraging of norm entrepreneurship, and their procedural excellence at forging broad coalitions under their normative authority. The article proposes that the PSIDS campaign illustrates an alternative pathway through which small States can exert meaningful influence in global climate governance, despite the enduring power asymmetries of the international system.

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I. Introduction

Pacific Small Island Developing States (PSIDS) are uniquely exposed to climate change. As some of the world's most geographically isolated states with small land area, small population sizes, and constrained resources, they have long been recognised as one of the most vulnerable areas to global warming.[1]

Despite accounting for only 0.02 percent of global emissions, PSIDS face existential threats from global warming and rising sea levels. The low-lying Pacific atoll islands

[1] "Status of Coral Reefs of the World 2020." *UN Environment Programme*, 2021

average just one to two meters of elevation above the sea level, 90 percent of Pacific island populations live within five kilometres of the coast, and half the infrastructure is within 500 metres of the sea.[2] Should the current emission pathway continue, Pacific small islands could face permanent submergence, frequent coastal flooding, extreme storm surges, and the loss of freshwater and land in the coming decades.[3] Even if Pacific small islands could avoid the extreme weather events for now, global warming is already impacting the coastal ecosystem that the island nations rely on. The 2022 IPCC Report confirmed that the highly productive coral reef ecosystems were devastated by rising water temperatures and ocean acidification.[4] The 2024 World Meteorological Organisation (WMO) report recorded unprecedented marine heatwaves in the region, compounded by extreme tropical cyclones in the coastal region.[5]

However, despite their limited material power and acute vulnerability, the Pacific Small Island Developing States (PSIDS) have emerged as disproportionately influential agents in the UN climate diplomacy. They have been one of the earliest actors to reframe climate change as a security issue, advocate for global climate responsibility, drive binding emission targets, and secure consensus on global warming limits. From the establishment of the United Nations Framework Convention on Climate Change (UNFCCC), the 1997 Kyoto Protocol, to the 2015 Paris Agreement, Pacific Small Island Developing States (PSIDS) have consistently punched above their weight.

This paper argues that the Pacific Small Island Developing States (PSIDS) were able to exert a disproportionate influence on the global climate responses because of their skilful leveraging of norm entrepreneurship and their procedural excellence at forging broad coalitions attracted by their normative authority. Through procedural mastery and strategic diplomacy, PSIDS leaders reframed climate change as an acute security threat, mobilised broad coalitions around this norm, and embedded it within a compelling moral narrative of survival and justice. Using case studies of the pre-1990 framing of the climate security issue, the negotiations leading up to the Kyoto Protocol (1997), and the strategic diplomacy that shaped the Paris Agreement (2015), this article aims to analyse how the PSIDS employed norm entrepreneurship to steer the UN climate response. This study examines how PSIDS advanced the norm of climate security, and how they leveraged the moral authority of their normative consolidation to forge broad coalitions in support of their initiatives.

In Section II, I will examine the theoretical framework of the UN system, dissecting the way in which power is exerted by weak States and non-State diplomatic agents. Building on this framework, Section III will examine constructivist theories to understand the use of norm entrepreneurship in creating rational-legal authority within a specific institutional context. Section IV will focus on the theory of securitisation, as proposed by the Copenhagen School, and delineate the theoretical amplitude of the climate security agenda. Section V will focus on the history of PSIDS' climate security agenda, using selected case studies of UN climate negotiations to delineate how normative power is used to drive climate negotiations in practice.

Building on the theoretical framework of international relations, this paper aims to situate the case study analysis within a nuanced theoretical space. In this paper, the PSIDS grouping is occasionally referred to as the Pacific islands. The UN system recognises PSIDS members as the Federated States of Micronesia, Fiji, Kiribati, Marshall Islands,

[2] *State of the Climate in the South-West Pacific 2023*. WMO Paper No. 1356, 2024.
[3] "Small Islands." *Climate Change 2022 – Impacts, Adaptation and Vulnerability: Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, 2023, at 2043-2122.
[4] ibid.
[5] *State of the Climate in the South-West Pacific 2024*. WMO Paper No. 1374, 2025.

Nauru, Palau, Papua New Guinea, Samoa, Solomon Islands, Tonga, Tuvalu, and Vanuatu. In parts of the article, the PSIDS group is discussed within the broader alliances of AOSIS (Alliance of Small Island States), through which the Pacific islands have conducted active collective diplomacy, especially in the negotiations for the Kyoto Protocol.

II. **The Theory and the Practice of Power in the United Nations**

Since norm entrepreneurship is fundamentally shaped by institutional structure, an analysis of PSIDS' climate diplomacy must first begin with an examination of the UN system. In international relations theories, this is predominantly approached through the framework of the liberal international order. In the liberal account, international order is not just an equilibrium condition, nor is it the natural crystallisation of power distribution.[6] On the contrary, international orders are actively constructed by strong States and created in a system of organising principles, authority relations, functional roles, shared expectations, and settled practices.[7] Ikenberry defines the UN system as the institutionalisation of the American-led post-1945 liberal order.[8] In this conception, the UN is the active construct of major States, and was designed to anchor the American-led post-1945 order in a framework of rules and institutions. It functions as a mechanism for collective security, legitimacy, and cooperation. Leading States restrain themselves within the constitutional order to reassure weaker members of the threat of unilateralism.[9] In return, the UN system legitimises the power of leading States in the shared rules and multilateral frameworks. By framing their power within universal and institutional terms, strong States lock in the compliance of weaker States and secure a more cooperative international environment where their leadership is legitimised through institutional means. In this liberal institutionalist view, the United Nations embodies the multilateral face of American and Western leadership in a framework of universal rule-based cooperation, legitimacy, and collective security.[10]

While the UN system remains the active construction of powerful States, weaker States still actively benefit in the shared liberal framework. The UN system provides a means for weaker States to insulate themselves from the arbitrariness of great-power politics. The institutional framework embeds member states in legal-rational norms, predictable procedures, and protects weaker States from the power asymmetries of material power.

Ikenberry's construct provides a strong theoretical basis for the study of the UN system. Nevertheless, such broad-stroked theories leave unresolved how power is exercised in practice in the UN system. While the institutional structure of the United Nations remains skewed by the legacy of its great-power origins, most evidently in the Security Council Permanent Five (P5) Members, outcomes in the UN system often correlate poorly with the asymmetries of material power.[11] Certain States appear surprisingly weak in multilateral negotiations despite their material strength, while others exert influences far beyond their material size. What makes one country more influential than the other in multilateral diplomacy? What allows Pacific Small Island Developing States (PSIDS) to punch above their weight in climate diplomacy?

The structural accounts of traditional international relations theories would not suffice to answer these questions. To truly exercise influence in the UN system, State and

[6] Ikenberry, G John. *After Victory: Institutions, Strategic Restraint, and the Rebuilding of Order after Major Wars, New Edition.* Princeton University Press, 2019.
[7] ibid.
[8] Ikenberry, G John. *Liberal Leviathan: The Origins, Crisis, and Transformation of the American World Order.* Princeton University Press, 2011.
[9] Ikenberry (n 8) *supra.*
[10] ibid.
[11] Adler-Nissen, Rebecca, and Vincent Pouliot. "Power in Practice: Negotiating the International Intervention in Libya." *European Journal of International Relations*, vol. 20, no. 4, 2014, pp. 889-911.

non-State agents need to be adept at navigating the legal procedures, institutional rules, and frameworks that crisscross the UN system. Power, then, can be developed not only from material State capacity, but also through rational-legal authority. In this light, it becomes necessary to investigate the constructivist theory, which studies not only where power is formally located, but also how authority, legitimacy, and persuasion are created in the practice of politics. Such constructivist theories do not displace the institutionalist theories of rule-based cooperation nor the structural constructs of the liberal order. Rather, constructivist theories operate at a different analytical scale, investigating how power is generated in rational-legal authority and technical competence that defines institutional interaction. Thus, power in multilateral negotiations rests not in the structural resources of state agents, but in how these resources are locally generated in the UN system of diplomacy itself. Control over technical expertise, information, and skills, then, generates an implicit claim of authority: the ability to decide "how things are done".[12] In this fine-grained level of politics, power manifests in the socially recognised competence or mastery in a certain practice. Being recognised as this authority allows state or non-state agents to wield a context-specific power of influence; that is, a non-coercive power derived not from material strength but technical competency. Once recognised as a source of authority, agents can then decide how this game of social interactions is played out, structure how other players behave, and thereby shape the outcome of the game.[13]

III. **Norm Entrepreneurs in the UN System**

This fine-grained dissection of power broadens the key players of the UN system from great States to any State or non-State agents that know how to play their cards right.

Much of the emergent power is wielded by non-State agents that sit at the negotiation tables, draft its legal proceedings, and define its norms and principles. The ecology of knowledge producers, career diplomats, and legal scholars interacts with the intergovernmental machinery of the UN Member States to create and refine UN decisions at key junctures of its policy processes.[14] They formulate and refine the norms, principles and standards used to influence how issues are perceived, how states understand their interests, and how UN policy recommendations function at local, national, regional, and international levels. It is these agents who wield the rational-legal authority of norm entrepreneurs.

Following Martha Finnemore, we can understand a norm as a three-stage life cycle, beginning with the first stage "norm emergence", the second stage of "norm cascade" in which the norm is broadly accepted, and finally the third stage of "norm internalisation" where it becomes embedded as a taken-for-granted truth.[15] Yet norms do not appear out of thin air. Instead, they are the active construct of agents with strong notions of the appropriate or desirable action in their community. Norms that medical personnel and those wounded in war should be treated as neutral noncombatants are traced to Henry Dunant, a Swiss banker who founded an organisation that would later become the International Committee of the Red Cross.[16] The international campaign for women's suffrage can be traced back to the initial leadership of Elizabeth Cady Stanton and Susan B. Anthony in the United States and Millicent Garrett Fawcett and Emmeline Pankhurst in England.[17] Both cases are consistent with what Ethan Nadelmann

[12] ibid at 893.
[13] Barnett, Michael, and Raymond Duvall. "Power in International Politics." *International Organization*, vol. 59, no. 1, 2005, pp. 39-75.
[14] Carayannis, Tatiana, and Thomas Weiss. *The "Third" United Nations: How a Knowledge Ecology Helps the UN Think*. Oxford University Press, 2021.
[15] Finnemore, Martha, and Kathryn Sikkink. "International Norm Dynamics and Political Change." *International Organization*, vol. 52, no. 4, 1998, pp. 887-917.
[16] ibid at 897.
[17] ibid.

termed "transnational moral entrepreneurs" who engage in "moral proselytism".[18]

Norm entrepreneurs actively identify or "create" issues by naming, interpreting, and dramatizing them.[19] In other words, they construct specific cognitive framings that firmly embed alternative framings to challenge existing norms. Norm entrepreneurs classify the world, creating categories of actors and action, and fix meanings in the social world. They articulate and diffuse new norms, principles, and goals, so that the increasingly technical demands of modern politics can continue in a stable, predictable, and nonviolent way.[20]

However, norm entrepreneurs are not just non-State actors. The ecology of professional knowledge producers and diplomacy enactors can exist both alongside and within State entities. One prominent strategy of modern norm entrepreneurs is to train and recruit like-minded bureaucrats to help or block the promotion of new norms in standing organisations.[21] Peter Haas's study on the Mediterranean cleanup shows that the ecologists' success in promoting their norms was largely contingent on how they persuaded governments to create new agencies to deal with the cleanup and staff those posts with like-minded ecologists.[22] This ecology of non-State professionals is crucial to the agenda of environmental security because their legal-rational authority provides the scientific background and moral weight for PSIDS campaigns.

IV. **Securitisation Theory and the Climate Security Agenda**

The uniqueness of the PSIDS' strategy in the United Nations is its emphasis on the climate security agenda. Analysing this strategy, however, requires a theoretical foundation in security studies. What makes it worthwhile to frame an issue as a matter of security? What quality makes something a security issue? How are security issues different from other pressing agendas, and how has the climate security concept been framed and created?

Security issues are unique because they elevate the threat from the normal policy space into a prioritised security sphere where extraordinary action is justified and expected.[23] In international relations, security studies have been traditionally understood as a State-centric concept focused on military threats. This tradition, created under the dominance of realist and neorealist theorists, sees the state as the referent object of all security discourse. Threats are defined in military terms, and made against the State's sovereignty and survival. Security, in this framework, equals simply the absence of military threat and the preservation of territorial sovereignty.[24]

The end of the Cold War brought an intellectual shift in the definition of security. In the late 1980s and early 1990s, the Copenhagen School emerged as a part of the broader IR response to the end of bipolar confrontation.[25] The Copenhagen School, founded by the seminal works of Wæver, Buzan, and de Wilde,[26] conceptualises security as a discursively constructed concept, rather than an objective reality. Their central argument is that issues only become "security" issues when they are successfully framed as existential threats through "speech acts", the process where a securitising agent declares that an issue poses an existential threat requiring extraordinary means. The essence of a speech act is not so much about the objective reality of a threat, but the

[18] Nadelmann, Ethan A. "Global Prohibition Regimes: The Evolution of Norms in International Society." *International Organization*, vol. 44, no. 4, 1990, pp. 479-526.
[19] Finnemore & Sikkink (n 15) *supra* at 897.
[20] Barnett, Michael, and Martha Finnemore. *Rules for the World: International Organizations in Global Politics.* Cornell University Press, 2004.
[21] Finnemore & Sikkink (n 15) *supra*.
[22] Haas, Peter M. *Saving the Mediterranean: The Politics of International Environmental Cooperation.* Columbia University Press, 1990.
[23] Buzan, Barry, et al. *Security: A New Framework for Analysis*. Lynne Rienner, 1998.
[24] Waltz, Kenneth. *Theory of International Politics.* Addison-Wesley, 1979.
[25] Buzan et al. (n 23) *supra*.
[26] ibid.

performative construction of it.[27] By extension, the scholarship also argued for a multi-sectoral analysis of security, encompassing military, political, societal, economic, and, as the latest addition, environmental terms. Along with the liberal and constructivist critiques of Nye & Lynn-Jones,[28] Mathews,[29] and Crawford,[30] the Copenhagen School sought to broaden and deepen the concept of security from the State-centric, military-focused conception that dominated the Cold War period.

The scholarship is both informed and enabled by a paradigm shift in the structure of international relations. The close calls with nuclear annihilation made the flaws of a State-obsessed security strategy evident. The apparent stability of the American-led post-1990 order rendered actual warfare in the Global North unlikely. Instead, emerging transnational risks, from civic violence, economic vulnerability, to political repression, captured political salience. In this apparent moment of US unipolarity, the UN Secretariat and its knowledge producers sanctified a shift in both the referent object and the sectoral scale of security studies. The 1994 United Nations Development Programme Human Development Report codified this pivotal shift of security paradigms with the introduction of "human security".[31] Ordinary people, not nation-States, became front and centre of the security agenda. With this pivot of referent object came a sectoral broadening of the security analysis. As the scholarship indicates, ordinary people are not only threatened by military threats, but also by multi-sectoral, non-military issues. In response, human security considers a broad range of threats to human development, including protection from non-military threats such as famine, disease, poverty, crime, social conflict, political repression, and environmental hazards.

While the Copenhagen School presents securitisation as an analytically neutral tool, the theory nevertheless raises at least three political and normative concerns.

First, by removing issues from normal democratic politics and into the realm of extraordinary security response, securitising agents risk abusing the process of depoliticization. The successful securitisation of an issue renders it urgent, existential, and its countermeasures beyond debate. Depoliticization, then, shrinks the space of democratic discourse, and allows the executive or technocratic authority to act without democratic checks and balances.[32]

Second, the primacy of performative speech acts encourages actors to instrumentalise security rhetoric to attract attention, authority, and resources.[33] This induces a moral hazard of security framing, where securitising agents are readily incentivised to inflate the threat language to gain material concessions beyond the issue context.

Third, securitisation's logic of existential threats tends to privilege responses in military terms even if the original issue area is not.[34] Despite the sectoral expansion of security issues, the logic of existential threat could readily pull issues towards a militarised framing. Climate change, migration, and global health crises are frequently framed

[27] Wæver, Ole. "Securitization and Desecuritization." *On Security*, edited by Ronnie Lipschutz, Columbia University Press, 1995, pp. 46-86.
[28] Nye, Joseph, and Sean Lynn-Jones. "International Security Studies: A Report of a Conference on the State of the Field." *International Security*, vol. 12, no. 4, 1988, pp. 5-27.
[29] Mathews, Jessica Tuchman. "Redefining Security." *Foreign Affairs*, vol. 68, no. 2, 1989, pp. 162-177.
[30] Crawford, Neta. "Once and Future Security Studies." *Security Studies*, vol. 1, no. 2, 1991, pp. 283-316.
[31] *Human Development Report 1994: New Dimensions of Human Security*. United Nations Development Programme, 1994.
[32] Huysmans, Jef. "Security! What Do You Mean? From Concept to Thick Signifier." *European Journal of International Relations*, vol. 4, no. 2, 1998, pp.226-255.
[33] Balzacq, Thierry. "The Three Faces of Securitization: Political Agency, Audience and Context." *European Journal of International Relations*, vol. 11, no. 2, 2005, pp. 171-201.
[34] Bigo, Didier. "Security and Immigration: Toward a Critique of the Governmentality of Unease." *Alternatives*, vol. 27, no. 1, 2002, pp. 63-92.

through the lens of national security and defence. Migration securitisation often legitimises border militarisation and detention regimes.[35] Climate change securitisation risks condoning militarised disaster planning or geopolitical resource grabs.

Nevertheless, it is within the Copenhagen School's theoretical construct that one should understand the PSIDS' climate security campaign. PSIDS primed their campaign on framing climate change as an existential threat to island States' environmental viability, socio-economic stability, and physical statehood. Using a deeply moralistic speech act, such as the "1.5 to stay alive" slogan in the Paris talks, PSIDS exemplified the performative aspect of securitisation throughout climate negotiations. Through this discursive campaign, PSIDS directly identified multiple referent objects: the physical survival of the low-lying atoll states, the human security of populations who depended on the fragile ecosystems, and the sovereignty of states whose very existence could be swallowed up by the rising sea.

However, simply defining climate security within the regional context would not be enough. Securitisation is a relational process, and the success of a security claim depends on the acceptance of a sufficient audience that endorses and internalises the concept.[36] For the PSIDS, the broad acquiescence of the UN Member States would be necessary to legitimise the move to securitise climate change and transform it into an authoritative reordering of political priorities. This would prove to be the main challenge for PSIDS. By the time the Pacific Islands began their campaign for climate security in the UN arena, the world had only just realised the threat to the natural environment. The scientific consensus on global warming was not reached until the 1970s-80s. The UN first considered the deterioration of the natural environment an issue in the 1972 United Nations Conference on the Human Environment.[37] Few States viewed climate change with the same urgency as PSIDS, and many held conflicting interests in greenhouse gas emissions. Winning over such a wide range of State actors, would take more than constructing a rhetoric wholly framed around the Pacific islands themselves.

To an extent, PSIDS would succeed in its mission. In practice, it took strong diplomatic and procedural excellence to form large negotiating blocs, win over sympathetic developed States, and generate moral authority in the international civil society. In the meantime, PSIDS would usher in a process that embeds climate security in a broad array of global issues, from the disruption of ecosystems, the depletion of energy and resources, the instability of national socio-economy, and the threats to human well-being.

Admittedly, the PSIDS' definition of the climate referent object would not be unique. The modern UN arena houses numerous alternative definitions and contesting interpretations of what climate security ought to protect. Some theorists regard the ultimate referent object as the environment itself, while others consider it the risk of losing the achieved levels of civilisation and a forced return to barbarism.[38] In the rapid succession of post-Cold War talks, climate security discourse would borrow the logic of the anti-nuclear movement and its imagery for civilisational success. Implicit in this framing was the suggestion that the true motive for climate security was not environmental preservation, but the protection of "local and planetary biosphere as the essential support system on which all other human enterprises depend".[39] Such a conception would make the moral concern for the planet a mere veneer for

[35] McDonald, Matt. "Securitization and the Construction of Security." *European Journal of International Relations* vol. 14, no. 4, 2008, pp. 563-587.
[36] Buzan et al. (n 23) *supra* at 72.
[37] ibid at 73.
[38] Wæver (n 27) *supra*.
[39] Buzan, Barry. "New Patterns of Global Security in the Twenty-First Century." *International Affairs*, vol. 67, no. 3, 1991, pp. 431-451.

the human enterprise and risk critiques of moral hypocrisy.

The challenge to preserve the moral value of climate security would be compounded by the deliberate ambiguity of its discourse. UN climate security advocates often kept its definitions deliberately obscure to accommodate the divergent interests of endorsing States. While the PSIDS' positions are consistently clear in the survival of the physical islands and their cultural legacy, the reason for European, American, or Chinese support could be a mixture of moral obligation, realist bargaining, or strategic compliance. Therefore, debates on the proper place for the climate security agenda would continue, with some theorists describing environmental security as the "ultimate security",[40] and others as an intellectual distraction.[41]

Nevertheless, it is important to note that the academic advocacy for a climate security agenda largely coincided with, or was guided by, the Pacific diplomats' campaign for climate security in the UN system. When the PSIDS began framing the climate security issue in the late 1980s, they had entered a competitive normative arena with few established frameworks to support their advocacy. Yet, with sustained diplomacy, skilful coalition building, and strong moral appeal, they managed to become one of the key actors in defining and drafting the global climate response.

V. **Case Studies: History of PSIDS in the UN Systems**

The PSIDS' engagement in international climate diplomacy is both extensive and longstanding. They were one of the earliest actors to shape the global climate responses by framing climate change through the security lens, proposing binding emission targets, and securing consensus on global warming limits. As Morgan et al. outline, the evolving influence of PSIDS could be categorised in a "thick history" of distinct phases:[42]

1. Pre-1990. Following growing scientific recognition of global warming, PSIDS began framing climate change as an urgent security crisis in the UN system. The global coalition of island nations, AOSIS, was created to lobby for the climate security agenda.
2. 1991-7. PSIDS steered climate negotiations in the search for a global climate agreement. The group's persistence in building binding protocols eventually paved the way for the 1997 Kyoto Protocol.
3. 1998-2015. The Kyoto Protocol failed to create lasting results in global emission cuts. Recognising stalled talks with major emitters, key Pacific leaders created broad coalitions to secure the 2015 Paris Agreement and codify the 1.5°C global temperature limit.

A. *1985-90*

The scientific consensus on global warming emerged in the mid-1980s, as extensive empirical studies showed that greenhouse gas emissions, caused by the burning of fossil fuels, had serious and irreversible consequences for the planet's climate system. In 1985, a WMO report on greenhouse gases warned that "in the first half of the next century a rise of global mean temperature could occur which is greater than any in man's history".[43] In 1988, a Toronto Conference on the Changing Atmosphere sponsored by the UNEP and the WMO warned that global warming has become "an unintended, uncontrolled, globally pervasive experiment whose ultimate consequences could be second only to a global nuclear war".[44] In the same year, the Intergovernmental Panel on Climate

[40] Myers, Norman. *Ultimate Security: The Environmental Basis of Political Stability*. WW Norton, 1994.
[41] Deudney, Daniel. "The Case Against Linking Environmental Degradation and National Security." *Millennium*, vol. 19, no. 3, 1990, pp. 461-476.
[42] Morgan, Wesley, et al. "Leading from the Frontline: A History of Pacific Climate Diplomacy." *The Journal of Pacific History*, vol. 59, no. 3, 2024, pp. 353-374.
[43] *Report of the International Conference on the Assessment of the Role of Carbon Dioxide and of Other Greenhouse Gases in Climate Variations and Associated Impacts*. WMO, 1985.
[44] *Conference Proceedings: The Changing Atmosphere, Implications for Global Security*. WMO, 1988.

Change (IPCC) was formed to equip policymakers with regular assessments of the scientific information available on climate change.

By the late 1980s, growing scientific and political concern had alarmed the PSIDS. In 1987, tidal waves caused massive flooding in Malé, the capital of the Maldives, prompting global coverage and a UN General Assembly (UNGA) resolution to assist the Maldives in strengthening coastal defences.[45] A 1988 technical report prepared for the South Pacific Regional Environment Programme warned that "global warming threatens the physical and cultural survival of several Pacific societies".[46] In the 1988 South Pacific Forum, PSIDS leaders expressed "concern about climatic changes in the South Pacific" and the threat of "serious social and economic disruption in countries of the region".[47] Kiribati President Ieremia Tabai told reporters of the conference, "if what the scientists are saying is true, within 50–60 years there are countries like my country which will no longer be there".[48]

The Pacific islands convened a series of multilateral meetings to discuss the existential risks climate change posed for small island nations. At the South Pacific Forum in July 1989, leaders "expressed concern about the possible effects on island countries of rising sea levels" and agreed to "take decisive action to draw world attention to the way the environmental problem affected the South Pacific".[49] In November the same year, the Small Sates Conference on Sea Level Rise in Malé focused the discussion on "the need for a common strategy on sea level rise and on how to protect the SIDS [small island States] from the effects of global warming".[50] The ensuing Malé Declaration on Global Warming and Sea Level Rise called for the establishment of a UN convention on climate change and for negotiations to start as soon as possible.[51]

In 1990, the first IPCC assessment report was released at the Second World Climate Conference in Geneva. The report confirmed that global warming was driven by anthropogenic emissions of greenhouse gases and predicted global sea levels to rise by 20cm by 2030.[52] This would mean that low-lying Pacific islands that "lie almost entirely within three metres of sea level, such as the Maldives, the Marshall Islands, Tuvalu, Kiribati, Tokelau and other archipelagos and island nations in the Pacific ... could lose much of their beaches and arable lands".[53] In response to the IPCC report, a UNGA resolution was passed in December 1989 to formally launch negotiations for a UN climate convention.[54]

Alarmed by the urgency of the threat, the PSIDS began framing global warming as an urgent crisis that required immediate action, especially from the developed states. In the 1990 World Climate Conference, Tuvalu's Prime Minister Bikenibeu Paeniu stated that the Pacific islands were "extremely vulnerable to the environmental hazards and dangers of the greenhouse effect and sea level rise. These are problems which we have done the least to create but now threaten the very heart of our

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[45] UNGA Res. 42/202, 1987.
[46] Hulm, Peter, et al. *A Climate of Crisis: Global Warming and the Island South Pacific*. Association of South Pacific Environmental Institutions, 1989.
[47] "Annex 5: Forum Communiqué." *Nineteenth South Pacific Forum, Nuku'alofa, Tonga, 20–21 September 1988: Agreed Record*, South Pacific Forum, SPEC(88)Rep, at 57.
[48] Scott, David. "Shoring Up Regional Interests in South Pacific." *Christian Science Monitor*, 22 Sept. 1988.
[49] "Annex 6: Forum Communiqué." *Twentieth South Pacific Forum, Tarawa, Kiribati, 10–11 July 1989: Agreed Record*, South Pacific Forum, SPFS(89)Rep, at 55–56.
[50] Ronneberg, Espen. "Small Islands and the Big Issue: Climate Change and the Role of the Alliance of Small Island States." *The Oxford Handbook of International Climate Change Law*, edited by Kevin Gray et al., Oxford University Press, 2016.
[51] "Malé Declaration on Global Warming and Sea Level Rise." *Commonwealth Law Bulletin*, vol. 16, 1990.
[52] *IPCC First Assessment Report: Policymaker Summary of Working Group I: Scientific Assessment of Climate Change*. WMO, 1990, pp. 63-64.
[53] *see* Ashe, John, et al. "The Role of the Alliance of Small Island States (AOSIS) in the Negotiation of the United Nations Framework Convention on Climate Change (UNFCCC)." *Natural Resources Forum*, vol. 23, no. 3, 1999, p. 210.
[54] UNGA Res. 45/212, 21 Dec. 1990, UN Doc A/RES/45/212.

existence".[55] Broad coalitions with global small island States were pursued. At the Second World Climate Conference in Geneva, 1990, the PSIDS joined forces with their counterparts in the Indian Ocean and the Caribbean to establish the Alliance of Small Island States (AOSIS). AOSIS was created with the mission to continue the initiative laid forth in the 1989 Malé Declaration and to represent the shared global demand of small island developing states (SIDS) in UN negotiations.[56] Through AOSIS, Pacific Island states would later propose a binding cut of emissions by 20 percent on all developed countries and set the precedent of legally binding emission cut protocols.

In constructivist terms, 1985-90 is best characterised as the stage of norm emergence. In this period, the PSIDS acted as key norm entrepreneurs in reframing climate change as an existential threat to territorial survival and sovereignty. They were among the first UN actors to emphasise the asymmetric distribution of climate risks, which disproportionately falls on the smaller, developing States in the Global South. The early articulations of their entrepreneurship, most notably the 1989 Malé Declaration, constituted some of the earliest normative innovations in a discursive landscape that had yet to recognise climate change as a global responsibility.

In time, the growing momentum of their norms would help justify the creation of the UNFCCC negotiating process and logic of differentiated responsibilities for developing and developed States. While the PSIDS had yet to consolidate true engagement in the Security Council or begin their push for binding emission cuts, they had succeeded in establishing themselves as the moral authorities in the emerging climate regime.

B. *1991-97*

In the early 1990s, UN negotiations became increasingly divided by a North-South faultline. Developing countries argued that developed States, which had burned fossil fuels for centuries, had the obligation to cut emissions first.[57] Within the Global North, fissures emerged between European States, which were more conciliatory to clear emissions targets, and the United States, which initially opposed any binding targets.[58] During this period, the PSIDS remained vocal for ambitious climate action. The existential threat posed by global warming helped the PSIDS to be seen as the 'international conscience' on the issue, allowing them to exert considerable moral pressure in UN climate negotiations.[59]

In the lead-up to the 1992 Earth Summit, negotiations culminated in the creation of a UN Framework Convention on Climate Change (UNFCCC), through which Pacific islands joined the unified front of the AOSIS coalition. In the 1992 Summit in Rio, AOSIS advocated to impose emission limits on developed countries, and proposed a global compensation fund to pay for the loss and damage of climate change.[60] Under strong American opposition, the targets failed to obtain official UN ratification, and the convention signed in Rio only made an ambiguous reference to emissions reduction and made no mention of compensation for loss and damage. However, the advocacy did force the UNFCCC to establish a shared objective to prevent "dangerous anthropogenic interferences with the climate system" and recognised the unique position of small island developing states, who were given specific seats on various UN bodies established during the convention.[61] In the 1992 South Pacific Forum, convening island leaders described the convention as "an important first step" that

[55] *see* Barnett, Jon, and John Campbell. *Climate Change and Small Island States: Power, Knowledge and the South Pacific*. Earthscan, 2010, at 87.
[56] Morgan et al. (n 42) *supra*.
[57] ibid at 360.
[58] Bodansky, Daniel. "The History of the Global Climate Change Regime." *International Relations and Global Climate Change*, edited by Urs Luterbacher and Detlef F Sprinz, MIT Press, 2001.
[59] Morgan et al. (n 42) *supra* at 360.
[60] Morgan et al. (n 42) *supra* at 361.
[61] The United Nations Framework Convention on Climate Change, 1771 UNTS 107.

would pave the way for tougher negotiations on the climate security protocol.[62]

In September 1994, AOSIS submitted a draft protocol under the UNFCCC framework, calling for a binding commitment for all developed countries to reduce greenhouse gas emissions by at least 20% below 1990 levels by 2005.[63] First drafted by the Pacific island nation Nauru, the proposal was submitted by Trinidad and Tobago, then the chair of AOSIS, and introduced to the UN session by Samoa's ambassador to the UN, Tuiloma Neroni Slade.[64] The meticulous coordination of the Pacific island alliance helped the AOSIS protocol become an important reference point in ensuing climate negotiations. The ambitions of the target were justified as a historical responsibility: since it is the developed countries that are historically responsible for most greenhouse gas emissions, they should also bear the most immediate responsibility in cutting them.[65]

While this proposal did not pass in its original form, its framing of climate security and the introduction of binding targets were subsumed in later UN climate negotiations.[66] In the First Conference of the Parties to UNFCCC (COP 1) in April 1995, the AOSIS protocol was brought to the floor and won the support of most developing countries, with China and India adopting the AOSIS text as the basis for a negotiating proposal.[67] While the AOSIS protocol failed to gain formal adoption at COP 1, it succeeded in catalysing the adoption of the Berlin Mandate, a political compromise inheriting the protocol's framing of global climate security, and advancing its call for stronger commitment from the developed states. The mandate established the Ad Hoc Group on the Berlin Mandate (AGBM) to draft a legally binding protocol that would establish stronger, quantified, legally binding commitments for developed countries to reduce greenhouse-gas emissions to 1990 levels by 2000, and hit further reduction targets by 2005, 2010, and 2020.[68] In the 1995 COP 1, Report Decision 1/CP.1 Section III.5, the Berlin Mandate directly referenced the AOSIS protocol, affirming that "the protocol proposal of the Alliance of Small Island States (AOSIS), which contains specific reduction targets ... should be included for consideration in the process".[69]

The precedents set by the Berlin Mandate would eventually lead to the 1997 signing of the Kyoto Protocol. In the negotiations leading up to Kyoto, AOSIS consistently presented itself as a cohesive, moralistic developing-country coalition pressing for legally binding, clear, and quantifiable emission-reduction commitments from the developed countries. Their framing of climate action as a matter of moral and political urgency had anchored their moralistic authority in the negotiations, allowing Pacific Island states to form flexible coalitions with the European Union and the Group of 77 and China (G77 / China).[70]

During the Kyoto negotiations, sharp faultlines over emissions reduction responsibilities materialised between the Annex I Parties, the 37 individual industrialised countries and economies in transition and the European Union, and the non-Annex I Parties, the developing countries asserting that they have no legally binding reduction targets. Between these faultlines, PSIDS delegations formed strategic alliances to borrow the power of major developing states and conciliatory developed nations. The dual moral authority AOSIS members

[62] South Pacific Forum (n 49) *supra*.
[63] *Draft Protocol to the United Nations Framework Convention on Climate Change on the Reduction of Greenhouse Gas Emissions*. Alliance of Small Island States (AOSIS), 1994.
[64] Morgan et al. (n 42) *supra* at 361.
[65] ibid at 361.
[66] Klöck, Carola, et al. "AOSIS in the UNFCCC Negotiations: From Unity to Fragmentation?" *Climate Policy*, vol. 12, 2012, pp. 591-613.
[67] Morgan et al. (n 42) *supra* at 361.
[68] *Press Backgrounder: A Brief History of the Climate Change Convention*. UNFCCC, 1997.
[69] *Report of the Conference of the Parties on Its First Session, Held at Berlin from 28 March to 7 April 1995. Decision 1/CP.1: The Berlin Mandate.* UNFCCC, 7 Apr. 1995.
[70] Betzold, Carola. "Borrowing Power to Influence the World: Small States in Multilateral Negotiations." *International Negotiation*, vol. 15, no. 3, 2010, pp. 131-148.

command as a small developing state and a global warming victim allows delegations to retain alliances while acting as a "vanguard subgroup" in the G77 / China bloc.[71] The wider G77 / China bloc consisted of low-income developing States that sought to emphasise development over immediate climate mitigation. While AOSIS members consistently pushed the G77 / China bloc towards stronger language in mitigation and climate ambition, they were cautious not to openly challenge major developing states such as China or India. Instead, Pacific island delegations adopted a flexible coalition strategy, speaking through the G77 / China platform to pressure climate commitment from the Global North, and acting as the independent AOSIS to not contradict the developmental ambitions of major Global South powers.

AOSIS's other significant ally in the Kyoto negotiations was the European Union, which supported binding targets for developed countries and held a notably conciliatory position compared to the United States and Japan. In this coalition borrowing, the EU complemented the AOSIS bloc's moral credibility with practical political, economic, and diplomatic leverage to push less-ambitious major emitters like the US. While this alliance remained informal, the technical proficiency of the AOSIS delegation allowed the island States to insert their proposals into negotiations led by other penholders. Their strategy proved successful, as the Kyoto Protocol set binding targets to reduce Annex I Parties' emissions by an average of 5% below 1990 levels while imposing no mitigation commitments on non-Annex I Parties.

During the 1991-97 period, climate security entered the stage of early norm cascading. While PSIDS remained norm entrepreneurs on promoting binding emission reductions and asymmetric burden sharing, the general acquiescence of climate responsibility had already spread to a heterogeneous grouping. In this cascading landscape, PSIDS increasingly assumed the role of norm sponsors to support ideas already accepted within the G77 / China coalition and the emerging United Nations Framework Convention on Climate Change. During the Kyoto negotiations, these sponsored norms include, most notably, the principle of Common But Differentiated Responsibilities (CBDR), the expectations for financial and technology transfer obligations of the Global North, and the absence of binding mitigation commitments for developing countries.

Admittedly, the outcomes of the Kyoto Protocol were largely determined by the G77 / China coalition and intra-OECD bargaining. Nevertheless, the PSIDS' interventions locked in a strong securitising frame that conditioned how climate change was interpreted in the negotiations and widened the political space for more stringent mitigations. While sponsoring the norms promoted by the G77 / China bloc, the PSIDS also acted as the hardline vanguard of climate action that advocates a moral imperative for deeper emission cuts. Their persistent security framing challenged the predominantly technocratic emissions-trading language favoured by many Annex I states. In this sense, the PSIDS' distinct normative influence helped entrench a moralised sense of responsibility for the Global North, which ultimately informed the normative foundations of the Kyoto Protocol.

C. *1998-2015*

Global climate action proved to be disappointing in the decade that followed the Kyoto Protocol. The United States, then the world's largest emitter, withdrew from the Kyoto Protocol in 2001. By the early 2000s, a growing recognition emerged that significant climate impact was likely and imminent. UN climate talks are increasingly focused on climate adaptation and financing for developing nations to deal with the consequences of climate change. At the same time, Pacific diplomats continued lobbying the UN to consider climate change as a primary security threat with limited success. In 2004, the Tuvalu Ambassador called for the UN Security Council (UNSC) to include climate

[71] ibid at 141.

change in the reformed UNSC agenda. During the first UNSC debate on climate change in 2007, Papua New Guinea's ambassador argued that climate change was "no less threatening to small islands" than "guns and bombs … to large nations".[72] These securitisation efforts were met with strong opposition from permanent Security Council members, including China, Russia, and the United States, who argued that climate concerns were inconsistent with the UNSC's responsibilities.[73]

The UNSC opposition opened a new battleground for codifying the climate security agenda. By 2009, Pacific island ambassadors successfully sponsored the first UNGA resolution on climate change and security, titled *Climate Change and Its Possible Security Implications*. The UNGA was chaired by Miguel d'Escoto Brockmann, a Nicaraguan diplomat and long-time advocate for decisive climate action. The 2009 UNGA resolution "invites the relevant organs of the United Nations", including the Security Council, "to intensify their efforts in considering and addressing climate change, including its possible security implications".[74] The resolution was adopted unanimously, with more than 100 countries as co-sponsors by the time it was passed.[75]

Despite the success in the UN normative space, by the early 2000s, PSIDS had realised the vast inadequacies of the existing climate agreement. The Kyoto Protocol failed to credibly constrain global greenhouse emissions, especially as developing countries and the United States were not required to cut emissions. This reflected poorly on the emission reality then. By 2007, China had become the world's largest emitter, and the United States was in favour of creating a new deal including emission cuts from major developing States.[76] The global climate response became increasingly shaped by the balance of American and Chinese interests. Following the 2009 Copenhagen Climate Summit (COP 15), American diplomats pressed UN climate negotiations to move away from binding targets and shift to a flexible regime that would allow countries to set nationally determined commitments.[77] This shift received reluctant support from China, and the bilateral cooperation set the tone for a new global climate treaty.

With stalled global climate action, PSIDS began to press for a legally binding agreement that would limit global warming to 1.5°C. At the 2008 COP14 climate talks, AOSIS argued that any new climate agreement must limit global warming to 1.5°C above the pre-industrial average to ensure the security of small island States. In the 2009 Copenhagen COP 15, both AOSIS and the Southern Pacific island nation of Tuvalu proposed a legal text for a new Copenhagen Protocol that would limit global warming to 1.5°C and require global emissions reduction of 85%, compared to 1990 levels, by 2050.[78] This proposal failed to win over the developed States or the major developing countries such as China and India.[79] However, commitment to obtain a 1.5°C limit pushed PSIDS to form new coalitions across the traditional South-North divide, the most notable of which would be the High Ambition Coalition (HAC), led by the Marshall Islands, which would help seal the 2015 Paris Agreement.[80]

HAC began as a quiet alliance. In 1994, Marshall Islands Foreign Minister Tony de Brum began quietly convening with a core group of foreign ministers from developed and developing States to discuss a common

[72] "Security Council Holds First-Ever Debate on Impact of Climate Change on Peace, Security, Hearing over 50 Speakers." United Nations Security Council Press Release SC/9000, 17 Apr. 2007.
[73] Morgan et al. (n 42) *supra*.
[74] UNGA Res. 63/281, 3 Jun. 2009, A/RES/63/281.
[75] Morgan et al. (n 42) *supra* at 364.
[76] ibid.
[77] ibid at 366.
[78] Bascombe, Michael. "AOSIS Release: Islands Propose 'Survival' to COP15." *Climate Pasifika*, 11 Dec. 2009.
[79] Komai, Makereta. "AOSIS Shakes, Goliath Stirs: US, China Hands Off on '1.5 to Stay Alive' Call at COP15." *Climate Pasifika*, 11 Dec. 2009.
[80] Manoa, Fulori. "The New Pacific Diplomacy at the United Nations: The Rise of the PSIDS." *Pacific Diplomacy*, edited by Greg Fry and Sandra Tarte, ANU Press, 2016, pp. 89-98.

position on ambitious global climate goals.[81] Meetings were often conducted in secret, and sensitive communications were handwritten to avoid being leaked to the wider assembly.[82] During the Paris talks, Marshall Islands negotiator Dean Bialek recalled that new members had to approach de Brum in person: "[t]o all those who wanted to be part of us, this was personal. No emails, you had to come to our delegation office, shake hands and look at us in the eye".[83] In the 2015 Paris negotiations, this secret alliance was finally announced publicly.

Throughout the Paris negotiations, HAC remained an informal but broad alliance aligned on ambitious provisions of climate response. It steadily attracted partners from Europe, Africa, the Caribbean, and the Pacific, including France, Germany, Chile, Jamaica, New Zealand, Sweden, and the United Kingdom. Within the Coalition, Marshalls Minister de Brum found a valuable ally in the EU Climate Commissioner Michel Canete, his European counterpart, committed to advancing the continent's response to the climate emergency. Eventually, the Coalition succeeded in winning over two heavyweight actors: the United States and Brazil. The membership of Brazil was especially crucial, as it had already been in the coalition of BASIC, a negotiating pact with South Africa, India, and China.[84] Tough negotiation points had surrounded India and China's reluctance to comply with stricter transparency measures and climate plan reviews every five years.[85] Brazil's partnership proved to be a pivotal point. Minister de Brum and Commissioner Canete had met with São Paulo's experienced Environment Minister Izabella Teixeira frequently throughout the year, and were both impressed by Brazil's commitment to a national, absolute emissions reduction target. "It was a game changer", Commissioner Canete commented to reporters, "as they [Brazil] were part of BASIC, seen as hardline".[86]

The Brazilian negotiator's decision to break with the BASIC allies provided the Coalition with the momentum to keep pushing for a tougher deal. The final Agreement, committed to keeping global warming "to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels".[87] The inclusion of the 1.5°C pathway was a key success for Pacific islands: the warming limit, lower than the commonly accepted 2°C threshold agreed at the Copenhagen talks, would be one safer for small island States.

At the signing of the Agreement, Marshall Islands negotiator Bialek recalled "strong resistance to the language on a long-term goal", and a number of developing countries "wanted to strip out aspects of the agreement particularly on the ambition side".[88] Eventually, the rough edges were smoothed out, and the Coalition won over even the hardliners of climate talks—Canada and Australia, which had until then been major blockers of UN negotiations. Once inaugurated, the Paris Agreement codified a functioning, adaptive, global climate response after three decades of scientific consensus on the issue. The agreement still allowed nations to pledge new, adaptive emission reduction targets every five years, so that the international society might work together to decarbonise the global economy by 2050.

By the post-Kyoto and Paris era, the PSIDS' campaign for climate security increasingly operated within a maturing normative space with limited space for the invention of new ethical categories. Consequently, PSIDS diplomats were engaged primarily with sponsoring and amplifying existing norms and pushing them towards more ambitious goals. These sponsored norms include the vision of a

[81] ibid.
[82] Goodell, Jeff. "Will the Paris Climate Deal Save the World?" *Rolling Stone*, 13 Jan. 2016.
[83] King, Ed. "Foie Gras, Oysters and a Climate Deal: How the Paris Pact Was Won." *Climate Home News*, 14 Dec. 2015.
[84] ibid.
[85] ibid.
[86] ibid.
[87] The Paris Agreement of 12 Dec. 2015, 3156 UNTS 79.
[88] King (n 83) *supra*.

net-zero global emission endpoint, and the formal recognition of climate change as a legitimate object of security governance. These norms had predominantly originated in activist, scientific, or selected political circles, but were not yet institutionalised within the UN framework. In the Paris negotiations, the PSIDS' sustained coalition building helped move these norms from diffuse advocacy into formal institutional campaigns, and ultimately embedded them into the legal architecture of the Paris Agreement.

Nevertheless, PSIDS remained the principal norm entrepreneurs for the 1.5°C threshold when most negotiating states favoured the 2°C benchmark. By framing 1.5°C as the survival threshold for small island states, PSIDS secured an unlikely cross-bloc support owed in large to their diplomatic leadership in the High Ambition Coalition. Thus, by 1998-2015, even as PSIDS had largely assumed the role of norm sponsors to facilitate norm cascade and legal internalisation, they nonetheless preserved their hardline ambition to lock in deeper climate commitments in a maturing climate response regime.

VI. **Conclusion**

This article has examined how Pacific Small Island Developing States served as norm entrepreneurs and shaped the global climate response. Tracing from the emergence of the global warming consensus in the 1980s to the codification of the Paris Agreement in 2015, the article investigated the nuanced ways in which the PSIDS steered UN action with a combination of normative authority and diplomatic mastery.

Considering their limited material power, the PSIDS' success in manoeuvring the UN system to ratify ambitious climate agreements is nothing short of an impressive feat. Following the 2015 Paris Agreement, countries have taken concrete action to consolidate the new climate regime. However, the tenacity of the Paris Pact continues to be tested under the global hegemons' reluctance to sacrifice development goals. The future of the UN climate regime remains unclear under the power asymmetries of the international system.

While the Pacific islands continue to face the worsening impacts of climate change, their persistence has embedded the norm of climate security within the UN system, and the language of climate security has been internalised even in the Security Council. In 2021, US Special Envoy for Climate John Kerry told the UN Security Council that failing to address the threats of climate change "is almost tantamount to a mutual suicide pact".[89] In the same year, UK Prime Minister Boris Johnson, who was then serving as the chair of the UNSC, asserted that "it is absolutely clear that climate change is a threat to our collective security and the security of our nations".[90]

Identifying and framing climate change as an existential threat to island States and as a security matter to the international society gave Pacific leaders the role of norm entrepreneurs early in climate discussions. As one of the first movers to push for the climate security concept, key Pacific actors came to be recognised as the moral authority and technical leadership in climate negotiations. The inaugural role of the Marshall Islands in securing the Paris Agreement evidences that. Beyond setting the space of normative discourse, the procedural excellence and strategic diplomacy of the Pacific negotiators exemplifies constructivist theories on emergent power and influence.

Despite the current roadblocks to the Paris Agreement, the PSIDS' campaign in climate diplomacy presents an alternative pathway for small, vulnerable states in the UN system. Regional challenges such as food security or climate-induced migration may be well-positioned to adopt similar strategies. Conflict-driven food insecurity could be readily securitised and elevated into an

[89] Sengupta, Somini. "Biden's Climate Envoy, at U.N., Likens Global Inaction to a 'Suicide Pact'." *The New York Times*, 23 Feb. 2021.

[90] Goering, Laurie. "Small Island States, Britain Warn U.N. of Climate Threats to Security." *Reuters*, 24 Feb. 2021.

international security and humanitarian issue. The current legal and normative vacuum around climate-induced migration could be tackled by strong issue-framing that integrates the protection of climate-displaced population within the existing refugee framework. In practice, broad coalition-building and procedural excellence would be necessary to define international obligations, support mechanisms, and lock in the Member States' acquiescence. While small States would still face an uphill battle in advancing these agendas, the Pacific islands' experience provides a valuable example that small States can drive global action even when it is beyond the agenda of the major powers.

In conclusion, this article has analysed the way in which small States can leverage UN institutional frameworks, using international relations theories in both the liberal and constructivist traditions. Despite the enduring power asymmetries that define the international system, the success of the PSIDS in achieving climate talks breakthroughs should serve as encouragement that weak, small States can exert meaningful influence in the global climate response.

Reading the Rain with All Senses: Exposure to, Use of, and Trust in Climate Information in Colombia

Laurel DiSera,* Carolina Hernández Rodríguez,† Flora Lecomte‡

* Postdoctoral Fellow (Department of Earth and Environmental Sciences; International Research Institute for Climate and Society), Columbia University, US; Abdus Salam International Centre for Theoretical Physics, Italy

† PhD Candidate (Department of Geography), National University of Colombia; Centre de Recherche et de Documentation sur les Amériques, Sorbonne Nouvelle University, France

‡ PhD Candidate (Centre de Recherche et de Documentation sur les Amériques), Sorbonne Nouvelle University, France

KEYWORDS

climate information, climate communication, climate change adaptation

ABSTRACT

Climate information is a critical tool for climate change adaptation. However, not all communities use and trust scientific information. This research aims to understand how farmers in Colombia build knowledge of their environment, how they experience and are responding to climate change, and what climate information they are using to make decisions about farming and other practices.

Farmers in two regions are studied here: the mountainous, coffee growing department of Huila, and the low-lying wetlands of La Mojana in northern Colombia. Results suggest that most farmers experience some impacts of climate change, though some are worried less about impacts than others. Farmers use WhatsApp groups, radio communication, published bulletins, and regional agricultural meetings to receive and learn about scientific climate information. In addition to—and often in place of—provided climate information, farmers use natural indicators such as birds, insects, clouds, and the Moon to make decisions about farming and other daily practices.

Generally, there is low trust of climate information provided by the official meteorological institute in Colombia; however, younger generations are beginning to use and trust climate forecasts from Google and the government more than their parents' generation.

I. **Introduction**

The utility of climate services[1] is only as beneficial as the information that is provided to decision makers and end users. This is true, but what defines good information? The first step in assessing this issue is to understand which tools and information and at what timescale the end users desire. Second, it is important to identify if end users trust such information and tools and if they would use them when making decisions about agriculture and other day-to-day practices. Following these user-focused processes, however, is not canonical climate service research method.

Historically, scientific fieldwork has frequently involved extracting knowledge and data from local communities, transporting it back to laboratories in developed nations for analysis, and providing little or no results to the communities studied.[2] More recently, there have been efforts to include communities in research endeavours through requirements of grant proposals, and many more research projects focus on the co-production of climate tools for communities.[3] However, one central issue that confronts co-production research originates from the lack of time scientists are given to learn about the communities and groups with which they are working. Grant proposals require initial research to be completed without financial support to substantiate the credibility of the work, but without funding support and time to adequately understand needs and prior knowledge of communities, the current form of grant proposal writing precludes the ability to truly integrate and work co-productively.[4]

Efforts to effectively work with and co-produce tools with communities have been studied both through theoretical and practical lenses.[5] However, there is still an existing underlying epistemic asymmetry in understanding the needs of communities. Local knowledge of the climate is often undervalued, and is not effectively included in the co-production process. For example, the language (often English) and methodologies used in research are primarily rooted in Western science. Additionally, the local rhythms of day-to-day lives and productive cycles are subsumed in the common timescales of climate forecasts (e.g., seasonal or subseasonal timescales). For instance, Bremmer and Wandekker[6] present the different particularities of time and rhythm practiced by communities around the world and the tacit knowledge built accordingly. Similarly, Venning and Bushaka[7] find that participants in their study view seasonal rhythms differently than the scientifically defined three-month climate season, suggesting that local rhythms for agricultural practices preclude the use of traditional three-month forecasts. Therefore, it is evident that

[1] Dilling, Lisa, and Maria Carmen Lemos. "Creating Usable Science: Opportunities and Constraints for Climate Knowledge Use and Their Implications for Science Policy." *Global Environmental Change*, vol. 21, no. 2, 2011, pp. 680-689; Goddard, Lisa. "From Science to Service." *Science*, vol. 353, no. 6306, 2016, pp. 1366-1367; Brasseur, Guy, and Laura Gallardo. "Climate Services: Lessons Learned and Future Prospects." *Earth's Future*, vol. 4, no. 3, 2016, pp. 79-89.

[2] *see*, for example, Toomey, Anne, et al. "A Question of Dissemination: Assessing the Practices and Implications of Research in Tropical Landscapes." *Ambio*, vol. 48, no. 1, 2019, pp. 35-47; Minasny, Budiman,et al. "Global Soil Science Research Collaboration in the 21st Century: Time to End Helicopter Research." *Geoderma*, vol. 373, 2020, 114299.

[3] "Research Partnerships." *National Science Foundation*, 2025; "Smart and Connected Communities (S&CC)." *National Science Foundation*, 2025; "Community Engagement and Knowledge Coproduction in NSF Arctic Research—Office of Polar Programs (GEO/OPP)." *National Science Foundation*, 2025; "Tackling Helicopter Research." *Nature Geoscience*, vol. 15, no. 8, 2022, pp. 597.

[4] Lamber, W Marcus et al. "Ending 'Domestic Helicopter Research'." *Cell*, vol. 187, no. 8, 2024, pp. 1823-1827.

[5] Vogel, Coleen, et al. "Climate Services in Africa: Re-Imagining an Inclusive, Robust and Sustainable Service." *Climate Services*, vol. 15, 2019, 100107; Vincent, Katharine et al. "What Can Climate Services Learn from Theory and Practice of Co-Production?" *Climate Services*, vol. 12, 2018, pp. 48-58; Grossi, Amanda, and Tufa Dinku. "Enhancing National Climate Services: How Systems Thinking Can Accelerate Locally Led Adaptation." *One Earth*, vol. 5, no. 1, 2022, pp. 74-83.

[6] Bremer, Scott, and Arjan Wardekker. *Changing Seasonality: How Communities Are Revising Their Seasons*. De Gruyter, 2024.

[7] Venning, Mathias, and Bizuneh Bushaka. "Co-Ordinating Agricultural Adaptation: Seasonal Forecasts and Their Influence on Rural Agricultural Rhythms in Ethiopia." *Time & Society*, 2024, 0961463X241260554.

there are gaps in understanding the complex systems and needs of end-users when attempting to co-produce services.

The objective of this research is to understand what participants know about the climate of their region, how and if local farmers trust scientific climate information, and what tools or knowledge they use on a regular basis for agricultural decision-making. Such information will help to provide the foundation for assessing what climate services are needed and what steps need to be taken to co-produce useful climate services for communities.

This research focuses on a particular case study in Colombia, where field work was conducted in two different regions: the Huila department and La Mojana.[8] Prior research on the use of climate information in Colombia has found that those who utilise climate information are able to more successfully reach their greatest potential in agricultural production. However, there are many channels of climate information that are not being fully utilised, such as roundtable discussions, due to lack of opportunity and access.[9] Other studies have suggested new tools or analyses for improving forecasts in Colombia, such as new agroclimatic forecasts for crop modelling;[10] however, direct modelling studies often fall short in directly connecting their tools to communities and participating in evaluation and co-production processes that would facilitate more useful end products.[11] Few studies have successfully co-produced tools and services with communities and find that the best results come from constant incorporation of user requirements and evaluation of tools with communities.[12] Thus, we suggest that there is still work to be done to better connect with communities and facilitate a co-productive process in the design of climate services in Colombia.

The focus of this research targets the initial phase of co-productive research to understand the needs of farmers in two regions of Colombia. Much of this research was funded by small grants and support from associated institutes, as this mission focused on building relationships, forming networks, and understanding individual knowledge and histories, to better contextualise how climate services might be most helpful in the two areas of interest. Effectively, this research is a litmus test to understand the current trust in, perspectives of, and utility of climate information and tools in Colombia to bridge the gap of knowledge between local farmers and scientific researchers, both within and outside of Colombia.

II. **Data and Methods**

This work was conducted in two regions of Colombia, the Huila department and La Mojana (**Figure 1**, below). La Mojana (**1**a), located in northern Colombia, comprises lowlands and the Magdalena River basin, with many *cienagas* (wetland ecosystems) and flooded regions often spilling into towns creating crop losses and difficulties for infrastructure and transportation (**Figure 2**a). The communities in La Mojana rely on fishing and rice growing and depend heavily on rainfall for rainfed agriculture and in river floods for artisanal fishing activities. Huila (**1**b) is a mountainous and the most important department in coffee production in southwestern Colombia (**Figure 2**b), where many farmers grow coffee alongside subsistence farming to support their families,

[8] Colombia is divided into 32 departments. The Huila is one of them. For its part, La Mojana is not a political-administrative division, but rather a biocultural region, formed by 11 municipalities of 4 departments.

[9] Loboguerrero, Ana Maria, et al. "Bridging the Gap between Climate Science and Farmers in Colombia." *Climate Risk Management*, vol. 22, 2018, pp. 67-81; Bouroncle, Claudia, et al. "A Systematic Approach to Assess Climate Information Products Applied to Agriculture and Food Security in Guatemala and Colombia." *Climate Services*, vol. 16, 2019, 100137.

[10] Ordoñez, Leonardo, et al. "Applying Agroclimatic Seasonal Forecasts to Improve Rainfed Maize Agronomic Management in Colombia." *Climate Services*, vol. 28, 2022, 100333.

[11] Esquivel, Alejandra, et al. "Predictability of Seasonal Precipitation across Major Crop Growing Areas in Colombia." *Climate Services*, vol. 12, 2018, pp. 36-47.

[12] Sotelo, Steven, et al. "Pronosticos AClimateColombia: A System for the Provision of Information for Climate Risk Reduction in Colombia." *Computers and Electronics in Agriculture*, vol. 174, 2020, 105486.

but is also home to commercial coffee growers (20% of Colombian coffee is produced in the Huila).[13]

Methods used for this research were based on methodologies presented in Bremmer et al.,[14] which utilized semi-structured interviews to elicit narratives from primarily adult participants. In addition, three workshops were conducted with high-school students to understand the differences in local knowledge, trust, and use of scientific knowledge across generations. For this, we used social mapping and a serious game[15] about the growing cycle of rice. Finally, we participated in guided tours in the wetlands with fishers, that allowed us to better understand situated knowledge on weather, climate, and seasonal flooding in La Mojana.

The interviews took place in Neiva, Gigante, Garzón, Timaná, Pitalito, and La Plata in the Huila department. In La Mojana, interviews were conducted in Montería (department of Córdoba), San Marcos, and Sucre (department of Sucre). This research was conducted in a transdisciplinary team with two human geographers who had in-depth knowledge of the regions of study and one climate scientist. All researchers spoke Spanish, two of the researchers had conducted research in one of these two areas prior to the current fieldwork expedition, and one of the researchers was a Colombian national. These established connections facilitated the trust building process with the inhabitants and enhanced deeper and more intimate conversations.

Sixteen interviews were conducted (**Table 1**, below). Participants were mostly men (with the exception of one of the associations of coffee growers, women led) and ranged in age from early twenties to late seventies. Farmers either cultivated coffee or rice, along with sustenance crops.

Research questions for the interviews focused on two areas. First, how communities experience climate: (i) what climate cycles and climate events are remembered through personal and / or collective memories, and what indicators are used to identify them; and (ii) what does climate change mean to communities? Are wetland (rice growers and fishers) and mountain (coffee growers) farmers experiencing similar or different effects of climate change? The second was focused on understanding how communities are informed about climate and how they react in response to scientific climate information: (iii) where do community members receive their weather / climate information and how do they use it; and (iv) what changes are the communities experiencing and how are they adapting?

In addition to structured interviews, we conducted three workshops with high school aged students in two different towns in the department of Sucre, Sucre and San Marcos. The workshops were aimed at (i) teaching students about the difference between climate variability and climate change; and (ii) acquiring a baseline understanding of student knowledge on climate through their schooling and collective memories of their communities, their exposure to agriculture and environmental changes in their area, and how they understand climate impacts in their communities. Students were asked to participate in several activities where they answered questions about climate: how do you know when it is going to rain? In La Mojana, when is it summer and when is it winter? What is the phenomenon of El Niño? What are the effects of rain in your town? They also identified how much rain they would expect during different stages of the crop growing season and drew maps identifying well-known flooding zones in their town during extreme rainfall events.

[13] *Municipality Agricultural Evaluations*. Office of Agricultural Planning (UPRA).

[14] Bremer, Scott, et al. "Narrative as a Method for Eliciting Tacit Knowledge of Climate Variability in Bangladesh." *Weather, Climate, and Society*, vol. 9, no. 4, 2017, pp. 669-686.

[15] Flood, Stephen, et al. "Adaptive and Interactive Climate Futures: Systematic Review of 'Serious Games' for Engagement and Decision-Making." *Environmental Research Letters*, vol. 13, no. 6, 2018, 063005.

III. **Findings and Discussion**

In the following Section, results are based around the four central research questions. Any direct quotes have been translated from Spanish to English. The goal of these findings was to (i) assess local climate knowledge and the use of scientific climate knowledge and information; and (ii) understand if and how such perceptions of climate knowledge and information have been impacted by interventions from public or university interventions which have influenced the flow of climate information and knowledge in the region.

A. *What Climate Cycles and Climate Events Are Remembered through Personal and / or Collective Memories, and What Indicators Are Used to Identify Them?*

1. Memorable Historical Events

When asked what historical climate events participants remembered, a majority did not speak at length, with surprisingly no climate or weather events described before 2010. The most noteworthy event recalled by several participants in the region of La Mojana was the 2010–2011 La Niña event.[16] In the town of Sucre, Sucre, locals recalled 2010–2011 to be the years of the worst floods in recent history, receiving approximately 30 cm of rainfall, so much so that they needed canoes to move around the town in areas that did not normally flood.

In response to the catastrophic floods of 2010–2011, a national emergency was declared in Colombia, and the Adaptation Fund was created as the entity responsible for the recovery of the most affected areas through four macro-projects, La Mojana being one of them. The Regional Centre for Forecasts and Early Warning (CRPAT) was created in San Marcos as part of the La Mojana macro-project, providing a regional weather and climate centre to help protect the general population in the event of another catastrophic La Niña event. In addition to the created climate and weather centre, participants in La Mojana discussed other mitigation efforts for disaster prevention, such as raising the level of the houses above the 2010 flood level, to reduce their likelihood of reliving the fooding disasters.

In addition to 2010–2011, participants also described the abundance of rainfall and lower temperatures they had experienced more recently, specifically during the three year-long La Niña event between 2020–2023.[17] In La Mojana, this period has been also marked by a non-climatic related event: the rupture of the marginal dike on the Cauca River border, which has created floods in the region even in the absence of above normal rainy seasons. However, participants described temperatures from 2020–2023 to be normal when compared to other rainy seasons in both the Huila and La Mojana regions. In regard to agriculture, one participant from Sucre (M4) described how there were very few fish to be caught in 2022, the opposite of what they experienced in 2010. The reason for this difference is the source of the flooding. While the floods of 2010–2011 were stronger, the flood waters were the result of interseasonal rainfall patterns, which is linked to the reproductive and migration cycles of fish, while the 2022 floods were related to the rupture of the dike, not related to other biological cycles.

Additionally, some of the farmers discussed the current conditions they were experiencing (those of July 2024) to be wetter than normal or even having too much water due to rainfall, with one coffee farmer from Gigante (Huila; H1) noting a recent hurricane with 35 kmh winds that impacted their farm.

Based on the participant responses, it is clear that living and actionable memory in both regions only recalls the most recent extreme rainfall events and less extreme events within

[16] Vargas, Germán, et al. "La Niña Event 2010–2011: Hydroclimatic Effects and Socioeconomic Impacts in Colombia." *Climate Change, Extreme Events and Disaster Risk Reduction*, edited by Suraj Mal et al., Springer, 2018, pp. 217-32; Camargo, Alejandro. "Disastrous Waters, Renascent Lands: Politics and Agrarian Transformations in Post-Disaster Colombia." Ph.D. Thesis, Syracuse University, 2016.

[17] "El Niño / La Niña Update." WMO, 2023.

the last five years, similar to other findings.[18] Even CRPAT did not have a record of major rainfall and flooding events in the area due to their short presence in the region (since 2011). Therefore, very little information appears to be carried over from generation to generation both in an oral and recorded manner. However, the catastrophic floods in La Mojana have created a permanent mark in the collective memory and even in the landscapes[19] (the level of the houses, the water marks in the walls). Such indicators of extreme events have become a reference for what is considered a strong rainy season and how they can be prepared in the event of another.

2. Natural Indicators

Throughout the two regions studied, participants described a strong relationship between climate cycles and their natural environment, or natural indicators, that have been historically marginalised by European / Western paradigms[20] qualifying them as anecdotical. Specifically, many locals discussed their dependence on animals, plants, clouds, and the Moon to make decisions about planting their crops, understanding the upcoming weather events, or identifying annual or interannual fish abundance cycles. The farmers and fishers understand the related rhythms of rain and other biological cycles, like the reproductive cycles of the fish, the migratory patterns of the birds, the physiological rhythms of the plants, etc., and so they adapt their productive practices to those rhythms and cycles.[21]

In regard to animals, participants spoke mostly of birds and the songs that they sing to predict the upcoming weather or season. Coffee farmers in Gigante (Huila; H1) spoke of the Chistosa birds that fly to a green tree if it is going to rain or a dry tree if it is going to be dry. Farmers in La Plata (Huila; H8) described the song of the Noche Larga (also named Chachalaca, *Ortalis columbiana*) bird that signals if it will rain in the morning or the evening (**Figure 3**a). Similarly, in La Mojana, many participants spoke of birds that sing to predict the rain, such as the carrao (*Aramus guarauna*) and chavarri (*Chauna chavaria*) birds (**Figure 3**b; M1, M4). However, such birds of wisdom are not present in every region. In fact, farmers in Garzón (Huila; H2) mention that these birds no longer live in their area and inhabitants in La Mojana say that the carrao populations have decreased because of the degradation of the wetland ecosystems. This ecological alteration has diminished the accuracy of the singing of these birds, with many now stating that the carrao are no longer accurate at describing upcoming seasonal rainfall predictions.

In addition to birds, other animals indicating patterns of rains, flooding or droughts include fish, molluscs, and insects. For example, an abundance of butterflies in Sucre, or the increased activity of the snails, suggests an imminent rainfall event.

Other animals, such as fish, are tied to seasonal rhythms. Fishers in Sucre and San Marcos (La Mojana; M4) discussed the natural cycle of fish in the region. La Mojana is a wetland region that hosts many migratory fish. At the beginning of the *verano* (the dry season) the fish often leave *cienagas* for cooler waters, and return at the beginning of the rainy season. This migratory cycle is related to the cycle of rains and floodings, and marks not only the moments, but the places for the fishing activity.

Locals also rely on snails to anticipate the level of the floodings. A snail laying eggs higher in elevation suggests an above normal rainfall

[18] Harley, Trevor. *The Psychology of Weather*. 1st edn, Routledge, 2018.

[19] Ingold, Tim. *The Perception of the Environment: Essays on Livelihood, Dwelling and Skill*. Routledge, Taylor & Francis, 2002.

[20] Chilisa, Bagele. "Decolonising Transdisciplinary Research Approaches: An African Perspective for Enhancing Knowledge Integration in Sustainability Science." *Sustainability Science*, vol. 12, no. 5, 2017, pp. 813-827.

[21] Bremer & Wardekker (n 6) *supra*; Forigua-Sandoval, Juliana, et al. "The Synchronization of Hydrotemporalities in Fishing Territories: Debating Time and History in the Llanito Swamp, Magdalena River (Colombia)." *Geoforum*, vol. 165, 2025, 104381.

season, thus requiring a safer location for eggs (**Figure 4**, below). A fisherman in Sucre (La Mojana; M4) explained that "snails are the most accurate of all, the snail does not make mistakes". Snails, along with other animal indicators driven by the climate, have been documented by research scientists at the National Federation of Rice Growers (Fedearroz) in Montería, Colombia, who have conducted hundreds of interviews to understand the natural indicators people use to understand weather and climate in Colombia and have published their findings.[22]

Plants and fungi also act as indicators to predicting climate in an upcoming season. One coffee farmer (H8) discussed the importance of fungi as an indicator of rain and humidity in the region and its utility in predicting upcoming rainfall events.

Clouds, though part of the climate system, were also heavily discussed as indicators to predict rainfall. One farmer in Pitalito (Huila; H7) mentioned that he uses clouds over certain parts of the mountains to be an indicator for rainfall. Also, in Gigante (Huila; H1) another participant stated that "when it rains in Bogota, it rains here two days later". Others in La Mojana evaluated clouds based on their colour and position (H4). Dark clouds suggest rain—depending on where they are in the sky—and thunder was described to be the sound of summer, with thunderstorms often being associated with hurricanes. In San Marcos (La Mojana), one farmer (M4) described that depending on if the clouds are on one side of the Moon or the other, it could indicate upcoming rainfall.

When speaking with the younger generation in the school workshops in La Mojana, students shared a similar narrative as their parents and elders about natural indicators. Students referenced songs from the carrao and chavarri birds, along with sounds from crickets and beetles, and low flying formations of dragonfly groups to indicate rainfall. They also explained that worms will burrow deeper into the Earth before it rains. In regard to the sky, many students discuss abundant and dark clouds, distant thunderstorms with thunder and lightning, strong winds, and clouded night skies as indicators of rainfall.

Beyond the Earth, many participants also described their relationship with the Moon's use; not to predict the weather, but for longer rhythms, such as those of planting and harvesting seasons. Farmers in Garzón (Huila; H2) stated that the Moon is the most important indicator for determining when to plant and harvest crops. Many participants, both in Huila and La Mojana (H1, H2, M1, M3, M4), described the best time to plant based on the Moon phase. For example, bananas, beans, and onion are best planted during the waxing phase of the Moon. However, some farmers (H7, H8) dismissed or rebuked the reading of the Moon (and its relationship to crops) and suggested that such methods are only utilised by older generations or that they no longer used such practices that their parents and grandparents had passed down. **Table 2**, below, summarises the indicators used in both regions.

3. Impacts of Seasons and Climate Variability

There are two seasonal states observed by the participants in Colombia that can vary from month to month: *verano* (summer) and *invierno* (winter). *Verano* is described as a period of warmth and little rain, while *invierno* is typically referred to as periods of lower temperature and more abundant rainfall. The fickle fluctuation of these two states is due to Colombia's location in the equatorial region, often impacted by the shifting of the Inter-Tropical Convergence Zone, which leads to less rigid definitions of seasons than what might be experienced at higher latitudes.

When speaking to farmers in the Huila region, many discuss how *verano* is observed between August and the end of the first half of September, and December–March. *Invierno* is often observed in late September, parts of

[22] Saavedra, Enrique, et al. *Bioindicadores Climáticos Usados Por Los Agricultores Arroceros En El Caribe Húmedo Colombiano*. Fedearroz / Universidad de Córdoba, 2022.

October–November, as well April–July. However, in la Mojana, adult participants agree that *verano* is described as December–April, while *invierno* is observed May–November, with a few suggesting that *invierno* can begin as early as April and last through November with the occasional *verano* month in between. Such characterisations of the seasons in La Mojana were validated by students in both Sucre and San Marcos (La Mojana), suggesting that they have a strong understanding of seasonal changes in their area. This consensus is reasonable as the seasonal changes in the levels of the *cienagas* allow for different productive activities: in the rainy season, mounting water levels enables increased fishing, while in the dry months, the lower water levels open space for rice and other sustaining crop production.

Students also had a firm understanding of the impacts of rainfall, or lack thereof, on their communities. They stated that rainfall was beneficial for crops, animals, plants, strengthening of trees, abundance of fish, and waterways, while being detrimental by causing floods in towns (**Figure 5**, below), reducing crop production, damaging natural and electric systems, causing deaths of diverse species, and impacting daily life. The students were also able to accurately draw the most flood-prone regions in their towns.

Adult participants discussed the impacts of rainfall on both coffee and rice crops. In Pitalito, Timaná, and La Plata (Huila), farmers explained that a surplus of sun restricts coffee growth, as excessive heat negatively impacts the flowering of the coffee plants, while an overabundance of rain can also negatively impact flowering by knocking flowers off the coffee plants. Additionally, three weeks of consistent rain and humid conditions can provide a suitable environment for infection, such as coffee rust, to grow on the plant and destroy the harvest, while 15–20 days without rain can dry the coffee plant, impacting coffee production. Drier months, however, are often a relief to most farmers, as diseases, such as coffee rust, and insects are often no longer an issue. Though, generally, one coffee farmer in Timaná (Huila; H3) claimed that "there is a very tempered climate here with no strong winds and it rains most of the time so they [farmers] are able to plant whenever they want to", suggesting that through seasonal variations, there are fewer dynamic shifts of climate in coffee growing regions.

Rice growing in the lowlands, on the other hand, is a "crop of water"[23] and is less impacted by humidity but greatly dependent on rainfall. According to farmers in Sucre (La Mojana; M3), it only takes four hours for rice crops to dry out if there is no standing water present; so, farmers work with the rainfall and forecasts to protect their plants and harvest. Additionally, farmers in San Marcos (La Mojana; M1) discussed how rice seeds will not grow if it does not rain for a month after planting. Such alignment of farmers to the hourly dependence of rice on water and rainfall suggests that farmers in La Mojana have a stronger dependence on weather related forecasts than farmers in the Huila region, thus leading farmers to use rainfall prediction products more seriously in making decisions about agricultural practice.

Predicting rainfall and drought in Colombia becomes less challenging during El Niño and La Niña years. During La Niña events, high quantities of rainfall and flooding are experienced across the country, with firsthand accounts provided in Pitalito (Huila) and San Marcos and Sucre (La Mojana), which have impacts on agriculture. In Huila and La Mojana, El Niño events are characterised by drought. Poor quality coffee is reported during El Niño years due to heat stress on the plant during flowering in Timaná (Huila; H3). Additionally, drier conditions impact rice crop production all La Mojana region, alter the migration cycles of fish, and cause forest fires in the high grounds. However, more descriptive depictions of El Niño events were

[23] Castillo, Laura. "La Vida Social de la Inundación: Experiencias de Pequeños y Medianos Cultivadores de Arroz Frente a la Inundación de Caregato, Ayapel, Colombia." Master's Thesis, Erasmus University Rotterdam, 2023.

provided by students in La Mojana, who often characterised them as long periods of drought, destruction of species and crops, high temperatures and prolonged heat waves, and water shortages.

It is evident that both adult and student participants have a clear understanding of climate cycles and events that impact their communities. They use different indicators, such as plants, animals, clouds, and other environmental features to understand climate cycles, but not all indicators are equally trusted or available in all regions. The impacts of El Niño and La Niña events are well understood and participants could articulate the most recent catastrophes experienced in their regions; however, there was very little discussion of climate variability at longer time scales. Only two participants in La Mojana (M3, M5) recognized long term variability, one citing stronger solar insolation now, compared to insolation in the 1980s, and the second discussing the existence of century cycles, claiming every century experiences different rainfall frequency and intensity. Therefore, short-lived memory of changes in climate is prevalent in both regions, leaving farmers with only the understanding of the current state and less of the greater picture of the region's climate history, which may impact their ability to contextualise changes they are experiencing.

B. *What Does Climate Change Mean to Communities? Are the Wetland (Rice Growers and Fishers) and Mountain (Coffee Growers) Farmers Experiencing Similar or Different Effects of Climate Change?*

1. Impacts on Crops and Farming

Farmers in both Huila and La Mojana described various changes in weather and climate in their regions; however, the majority of coffee farmers discussed changes in rainfall patterns, frequency, and intensity during *invierno*, while rice farmers in La Mojana focused on the changes in sun intensity during months of *verano*. This difference is logical, as farmers are preoccupied with the season where crops are most vulnerable to climate-related changes in each region.

For towns in the Huila region, such as Gigante and Pitalito, farmers cite additional cool and wet days due to climate change, which can be problematic for coffee plants. As one farmer (H8) described this double-edged sword, they need rainfall to feed the coffee plant, but rainfall comes at the cost of more frequent cooler and humid days, which can lead to the loss of the flowering of the coffee plant and the invasion of pests or diseases, leading to lower crop production and lower coffee quality. Diseases (such as coffee rust), pests, and insects pose a great threat to crops.[24] However, these concerns were only recognised in Pitalito (Huila), suggesting that other areas might not be experiencing these issues to the same degree. Pitalito was the highest elevation municipality studied in this research (1,348 meters above sea level); therefore, it is possible that it has unique climate challenges that other regions do not.

Changing rainfall frequency and intensity was also discussed by many coffee farmers. In Pitalito (Huila), one well-known coffee farmer owner noted that rainfall had been particularly high between 2013–2019, while a representative from Las Rosas Coffee Association in La Plata (Huila; H8) stated that she had observed rainfall changes starting around 20 years ago (early 2000s) in addition to more frequent cloud cover in the region.

Farmers also commented that additional and more frequent rainfall is changing the way that the water is absorbed, specifically when considering soil drainage. With increasing soil moisture content, ventilation of the ground is decreasing, impacting plant health by

[24] Bustillo, Álex Enrique. "El Manejo de Cafetales Su Relación Con El Control de La Broca Del Café En Colombia." *Federación Nacional de Cafeteros de Colombia*, 2007; Lu, Li, et al. "Comprehensive Review of Fungi on Coffee." *Pathogens*, vol. 11, no. 4, 2022, p. 411; Góngora, Carmenza, et al. "Sustainable Strategies for the Control of Pests in Coffee Crops." *Agronomy*, vol. 13, no. 12, 2023, p. 2940; Salazar-Navarro, Alexis, et al. "Coffee Leaf Rust (Hemileia Vastatrix) Disease in Coffee Plants and Perspectives by the Disease Control." *Phyton*, vol. 93, no. 5, 2024, pp. 923-949.

waterlogging coffee plants roots.[25] While most conversations in Huila focused on rainfall, one famer in Garzón (H2) did mention that he had noticed more intense and extreme heat in January, which also impacted the flowering and overall health of the coffee plant.

In contrast to coffee farmers, most farmers in La Mojana spoke about the changing intensity of the sun during drier months. In Sucre, one participant noted that during the 1980s the sun had weaker intensity than it does now (M3). Another farmer corroborated this statement by commenting that summer heat has become stronger and more intense since 1992 (M4). Additionally, some farmers discussed seeing changes in rainfall patterns, specifically in Sucre, Sucre (M3, M4).

When speaking with a representative from Fedearroz (M5), it became apparent that traditional indicators of climate that have been used by rice growers for decades are changing, making it more difficult for farmers to use traditional climate knowledge. Therefore, with a lack of climate indicators, farmers have needed to become more familiar with climate information from Fedearroz, IDEAM (the National Institute of Hydrology, Meteorology and Environmental Studies), and other forecasting services.

2. Perspectives from Communities

While most participants knew of climate change, some of them were less concerned about it than others, specifically in coffee growing regions, such as Garzón and Timaná (Huila), where farmers described very little impact of climate change on their farms. On the other hand, rice growers, who are much more dependent on rainfall, appeared to be more openly invested in using climate information provided by organisations such as CRPAT and IDEAM. However, one young rice farmer in San Marcos (La Mojana; M1) admitted that he had never heard of such climate information and services before, but seemed very interested and was later able to get in contact with CRPAT. It is therefore evident that farmers of similar or different crop types have different needs for climate information, which was also echoed by representatives from CRPAT (M6) who mentioned that Indigenous communities also needed different climate information than the rice growers in the area.

Students in Sucre (La Mojana) were all very aware of the dangers associated with climate change. They described climate change both in regard to changing rainfall and temperature, with one student identifying that "climate change is something that affects *our* environment". Some students did not know how to articulate the difference between climate change and changes seen between *verano* and *invierno*, but understood that we as humans are contributing to the issue.

One student wrote:

> *"Climate change can be defined as when it rains one day and not the next, when the sun comes out and it is said to be a rainy sun and this is due to the great damage and impact that we humans cause by throwing garbage."*

Generally, most students understood that climate change produced more wet and hot days in La Mojana when compared to their traditional seasonality.

C. *Where Do Community Members Receive Their Weather / Climate Information and How Do They Use It?*

In addition to the natural indicators mentioned in Section III.A.2, participants mentioned several other sources of climate information that disseminate relevant data through the various channels described below. General trust in climate forecasts and other

[25] León-Burgos, Andrés Felipe, et al. "Soil Waterlogging Conditions Affect Growth, Water Status, and Chlorophyll 'A' Fluorescence in Coffee Plants (Coffea Arabica L.)." *Agronomy*, vol. 12, no. 6, 2022, p. 1270; Toral-Juárez, Marco, et al. "Drought-Tolerant Coffee Plants Display Increased Tolerance to Waterlogging and Post-Waterlogging Reoxygenation." *Environmental and Experimental Botany*, vol. 182, 2021, 104311.

information produced by IDEAM in Colombia is also discussed.

1. Distributors of Climate Information

Several regional and national level organisations were frequently mentioned by participants when asked from where they receive their climate information, including IDEAM and regional climate centres (like CRPAT), the National Federation of Coffee Growers of Colombia (FNC) and local coffee associations, and Fedearroz.

For the coffee farmers interviewed, many were part of a local coffee association and had some level of interaction with the FNC. Participants in Neiva and Gigante (Huila) discussed their use of information disseminated by FNC, which they received from a platform created in collaboration between the FNC and IDEAM. This platform was also described to have the functionality of contacting the farmers to provide additional climate information. Participation in local coffee associations, such as ISEG or Global Cafe, were mentioned by participants in Neiva, Gigante, and Timaná (Huila). These regional associations hold frequent meetings in cooperation with the FNC, with which they have a strong relationship, to provide and translate climate information to local communities. In Pitalito (Huila), one coffee association is made up of 18 families; however, farmers explained that they do not use climate information from IDEAM or other information distributors, but rather use weather information from Google or look to the mountains to determine if it is going to rain (H7). Similarly, a separate large coffee association in Pitalito utilises channels of communication to receive and communicate climate information amongst members, but they also do not use information from IDEAM. This lack of connection between IDEAM and communities in Pitalito (the original municipality in coffee production in the country),[26] likely due to the lack of extension services located in the area, as mentioned by a participant in Pitalito (H7), appears to have contributed to a stronger fortification of local coffee associations and networks, but less knowledge of climate services and tools.

When IDEAM was mentioned during interviews in both Huila and La Mojana, most farmers had strong opinions on the utility of information they have and currently receive from IDEAM. Most know how to access or already receive some sort of climate information from IDEAM through various channels, but many do not use it. One coffee farmer in Garzón (Huila; H2) explained that he does not use climate information from IDEAM because he does not believe that it is local enough to be relevant to his farming practices. The lack of trust of the information provided by IDEAM may be related to the traditional lack of state presence in many territories in Colombia,[27] which has created an extensive lack of trust in the state services and its relevance to local realities.

Other farmers in La Plata (Huila) and Sucre, Sucre (La Mojana) continue to resist the use of scientific forecasts and prefer to use natural indicators to understand weather and climate or use other resources on their phones. One coffee farmer in La Plata (Huila; H8) described that she typically only uses the official ENSO forecast (which describes if conditions are El Niño, neutral, or La Niña) from IDEAM, but knows how to manage her crops for the remainder of the season just knowing the ENSO forecast. In La Mojana, there is greater utilisation of climate information from IDEAM to monitor rainfall, and one rice miller (M3) mentioned that of the small population of farmers who use climate information, many of them use information from IDEAM.

The effective distribution of climate information within La Mojana has a particular advantage with the presence of the Regional Centre for Forecasts and Early Warning (CRPAT). After the devastating 2010–2011 La

[26] UPRA (n 13) *supra*.

[27] Serje, Margarita. "El Mito de la Ausencia Del Estado: La Incorporación Económica de las 'Zonas de Frontera' en Colombia." *Cahiers Des Amériques Latines*, no. 71, 2013, pp. 95-117.

Niña event,[28] local government officials realised that there was a need to bring regional climate information to La Mojana for better prediction of temperature, rainfall, and impacts of climate change. Though it lacks the capacity to carry out climate-related research due to capacity restraints, CRPAT focuses on the creation and dissemination of climate forecasts for the region. Additionally, CRPAT works jointly with IDEAM, the Ministry of Agriculture and Rural Development (MADR), the Food and Agriculture Organization (FAO) and the United Nations Development Programme (UNDP) to provide relevant information and resources to communities in La Mojana.

Fedearroz also has a strong presence in La Mojana, as it is one of the largest rice growing regions in the country.[29] Representatives from Fedearroz (M5) demonstrated the climate tools on their platform (clima.fedearroz.com.co) that can be used by anyone with access to the internet to retrieve climate and weather forecasts, along with historical climate information and bulletins published by the organisation. They explained that the platform has forecasts of lead times up to six months, but that the first three months are most reliable.

Though climate information is communicated from large bodies like IDEAM, CRPAT, FNC, and Fedearroz, farmers and regional climate information distributors frequently mentioned their use of local weather stations. Some farmers have their own or multiple weather stations. One participant in Gigante (Huila; H1) described that he has ten weather stations on his property collecting data that is shared with neighbours that he has used to monitor changes in climate over the last 15-20 years (**Figure 6**, below). Some other towns have local weather stations, such as in Timaná and Pitalito (Huila), but it was unclear how easily local farmers could gain access to such weather information. In La Mojana, Fedearroz explained that they have ten of their own weather stations throughout the region. There is a larger network of >30 weather stations monitored by IDEAM across the country, but only two are located in La Mojana. In San Marcos (La Mojana), CRPAT does not have any weather stations that they own; however, they have accumulated 24 volunteer weather stations—with 19 currently functional—throughout the region where they can gather local data. In the Huila department, there are also stations installed by other actors to monitor important weather and climate indices, such as the electric company Enel Colombia. Enel Colombia constructed a hydroelectric dam El Quimbo, close to Gigante and Garzón (Huila), and installed six weather stations around the hills above the dam to measure the climate impacts produced by the dammed lake.

In addition to station and forecast-based types of climate information and natural indicators, some farmers mentioned other methods that they use to understand upcoming weather or climate events. In Pitalito (Huila; H7) and San Marcos (La Mojana; M1), some farmers discussed the use of Google and other search engines to find weather information, though they did not disclose what sources they were using. Additionally, other forms of information like the local Farmer's Almanac (the Bristol Almanac) and, sometimes, the Mayan calendar were mentioned, though these sources did not seem to be used by most of the participants (M3).

2. <u>Forms of Communication</u>

Four main forms of communication and dissemination of climate information were identified during the interviews and are used most frequently across Colombia: WhatsApp group messages, radio broadcasts, bulletins, and agroclimatic roundtable meeting (MTAs).

[28] Vargas, Héctor, et al. "La Mojana 2030: Un País Posible: Propuestas Para Ordenarla Alrededor Del Agua." *Planeación & Desarrollo*, 2023.

[29] *III Censo Nacional Arrocero Zona Centro No. 3*. Fedearroz, 2008; Castro-Llanos, F, et al. "Climate Change Favors Rice Production at Higher Elevations in Colombia." *Mitigation and Adaptation Strategies for Global Change*, vol. 24, no. 8, 2019, pp. 1401-1430.

The use of WhatsApp groups was pervasive within the two areas of study, with specific groups mentioned by farmers in Neiva, Timaná, and Pitalito in Huila and Montería, San Marcos, and Sucre in La Mojana. Many messaging groups have well-known names, such as CLAP, used by farmers in Timaná (Huila), or Cafe al Dia, used by farmers in Pitalito (Huila). Some of the WhatsApp groups are used to communicate solely amongst the farmers to share information, while others are run by Fedearroz or CRPAT as a primary way to distribute climate information or information about MTA meetings. For smaller coffee associations, some of the groups are private, while others can amass great numbers of members. CRPAT alone mentioned that they have around 30 different WhatsApp groups based on region and other factors that they send information out to daily (M6).

However, even with the abundance of WhatsApp groups available to farmers in both regions, invitations to such groups and, therefore, access to local climate information, do not always find their way into the hands of all farmers. For example, at the time of the interview, one participant in San Marcos (Huila; M1) was not a member of any WhatsApp groups that discussed the climate. He mentioned that he speaks to neighbours about what weather they are experiencing, but had no formal connection to IDEAM or CRPAT. Even with the pervasiveness of CRPAT's operations in the San Marcos region, this demonstrates how difficult it can be to connect small farmers to the network of climate information.

Additionally, in both the Huila and La Mojana regions, organising bodies like the local coffee associations and CRPAT use radio broadcasts to reach farmers to provide more general weather and climate information. Such broadcasts were mentioned with farmers in Pitalito and Timaná (Huila), with one particularly useful channel called Canal Clima which is used to provide information on rainfall. In La Mojana, CRPAT has a radio broadcast sent out to the region daily at 9am with hydraulic, meteorological, and early warning information. In Garzón (Huila), where there is no local coffee association, radio broadcasts from the federal government transmit climate information and changes in coffee prices, along with information about hurricanes on the coast and other country-wide weather impacts.

As regards written and published material, weekly and monthly virtual bulletins are available through some organising bodies. Some local coffee associations, like in Pitalito (Huila), distribute a bulletin that provides information about weather and climate, regional fires, harvesting seasons, and updates on the abundance of crop infections in a region. Bulletins are also distributed by Fedearroz and CRPAT in La Mojana. CRPAT has two forms of bulletins, one that is published daily and a second that is published monthly. The monthly publication provides information at a higher scientific level, proving to be less accessible to some farmers. However, the forecasts published by CRPAT include two-month forecasts and agricultural information which complement the information provided by IDEAM.

Finally, in addition to broadcast or written materials, MTAs are used in La Mojana to communicate and educate farmers and locals on climate information. MTAs in Sucre and other parts of La Mojana were added based on interest from participants in surrounding regions, such as Córdoba[30] and are hosted monthly in Sucre and Córdoba (Huila) by Fedearroz and the FAO. Meetings are attended by 20-22 participants from all of the sectors in the department who receive forecasts from IDEAM—including representatives from CRPAT—and learn about interpreting the forecasts for agricultural purposes. Fedearroz noted that fishers do not typically attend the meetings, but they see stronger attendance from rice farmers in the region; however, as with the WhatsApp groups, the MTAs are not known to all, as one rice farmer only learned of the MTAs during the interview in Sucre (La Mojana; M4).

[30] Loboguerrero et al. (n 9) *supra* at 67-8.

3. Trust in and Use of Climate Information

Throughout the field study, all farmers discussed their use of some sort of climate information, whether it was provided by IDEAM, from natural indicators, or had been passed down generationally from their parents and grandparents before them. Many farmers were still sceptical of forecasts from IDEAM or other regional climate offices, citing a lack of resolution and claiming that climate and weather forecasts were unable to achieve the spatial resolution of their particular land area, making forecasts unusable. One farmer in Timaná (Huila; H3) claimed they only needed weather and climate forecasts with a 1–2-month lead time, so seasonal forecasts were irrelevant to them. On the other hand, one rice farmer in Sucre, Sucre (La Mojana; M3) said that he personally uses information from IDEAM and finds it to be 70% accurate, suggesting there still exists a wide range of opinions on the information provided by IDEAM and other regional climate offices.

Additionally, results suggest that participants of different ages are using climate information differently. For example, many younger farmers (less than 50 years of age: e.g., H7, M1) no longer use historical indicators from their parents' generation and believe that forecasts are important to protect the plants, while older participants spoke more on the use of natural indicators or practices passed down from previous generations. Students, on the other hand, are developing new technologies to help plant and harvest crops with the changing climate and are creating new materials, such as paper, constructed with waste produced by agricultural practices. Therefore, the different mindsets of how to interact with the environment and climate change are shifting between the generations and will likely continue to adapt as climate change increasingly impacts the natural rhythms of rains, animals and agricultural activities in Colombia.

To better understand what information the farmers could benefit from, participants were asked what their ideal weather or climate forecast would look like. Like many participants mentioned with their current use of climate information, most were looking for forecasts in the 1–2-month range, with some interested in shorter, subseasonal, timescales of 2–3 weeks. Farmers were particularly interested in variables such as temperature, precipitation, humidity, and wind to assist in the mitigation of pest invasions in crops and to understand if the upcoming month(s) would be *verano* or *invierno*. Some farmers in San Marcos (La Mojana) also expressed interest in better ENSO state forecasts throughout the year. Farmers therefore see the importance and value of forecasts, but still appear to lack trust in the information that is currently available. Additionally, farmers noted the need to better match the timescales of provided forecast (often three-month forecasts) to the timescales used in local practices.

D. *What Changes Are the Communities Experiencing and How Are They Adapting?*

1. Climate Change in Huila

Many participants discussed the changes they were observing due to climate change (Section III.B). However, there were surprisingly fewer observations than expected in coffee growing regions, and participants rarely elaborated on what they were doing to actively combat climate change in their farming practices. Only one farmer in Pitalito (H4) was able to articulate a change in coffee from climate change by lamenting that coffee quality was good until around 2008, when they started to see more impacts of climate change.

Coffee farmers generally agreed that changing temperatures were impacting their ability to grow coffee. In Garzón, one participant estimated that they have seen a 2–4°C increase in temperature, with warmer night-times, while farmers in Pitalito discussed more frequent cooler days in *invierno*. Additionally, increasing intensity of the rains in July and August is leading to issues with flowering and the proliferation of coffee rust disease on coffee plants in Gigante and other surrounding towns. However, at higher elevations in Pitalito, farmers are experiencing issues with dry conditions, with one farmer (H5) noting that they recently lost a whole harvest of

coffee due to dry conditions and have noticed that rivers are drier than normal.

To combat the accumulation of coffee rust and other pests on their plants, farmers are being forced to move their farms to higher elevations. The increasing altitude of coffee farms reduces temperature and capacity for the air to hold moisture, reducing coffee rust cases. Farmers from most regions agreed that the minimum elevation to successfully grow coffee falls somewhere between 1100–1300 meters above sea level, with most suggesting that 1300–1800 is the best range, and 1900 is the maximum. A farmer in Gigante (H1) suggested a lower elevation of 800 meters, and some farmers in Pitalito explained that the altitude varies based on the variety of coffee one is interested in growing. However, moving coffee farms to higher elevations comes at the cost of deforestation to clear land for the coffee plants, an issue discussed by several farmers in Neiva and Pitalito. To combat the deforestation, there are efforts in Neiva, Gigante, Timaná, and other towns in the Huila department to reforest the lower altitudes the old coffee farms once inhabited.

Additionally, coffee growing seasons are also changing. One farmer in La Plata (H8) observed that the shorter growing season (October–November) is more susceptible to climate change, creating inconsistency in crop yield. This inconsistency of crop production due to climate change is also felt between the different harvests, impacting overall crop production. In Pitalito, farmers (H4, H7) described that they are receiving 70–75% of their harvest during the second harvest, and only 25–30% in the first harvest. Therefore, farmers are increasingly experiencing unpredictability in crop yield leading to greater concerns about year-round economic security.

To add to the complexity of the economic stability of crop yields, participants also noted changes in animals and insect populations. For example, the death of 70–80% of bees was observed in Pitalito in 2024, which impacted the pollination of the coffee and other plants in the region. Additionally, one coffee farmer in La Plata (H8) observed that many plants are not growing and birds are no longer migrating to their area. Animals were also described to be very disoriented and do not appear to know how to interpret the weather. Systemic ecosystem changes will continue to affect the pollination and health of the coffee farms, which are often out of the control of the farmers, but impact the livelihoods of communities.

2. Climate Change in La Mojana

In La Mojana, climate is also impacting the planting season and crop yield. A representative from Fedearroz (M5) mentioned that, due to climate change, some farmers were unable to plant seeds in the early months of 2024. However, with the empowerment of readily available climate information from Fedearroz, CRPAT, and the MTAs, there has been an increase of visible awareness of climate change impacts in La Mojana among rice growers. Representatives from CRPAT (M6) mentioned that before 2011, and the creation of CRPAT, weather and climate information was not coordinated or well understood by the general public. Now, however, after years of MTAs, consistent climate information distribution, and an increased demand for climate information, CRPAT finds that locals use more technical language when discussing weather and climate and the community as a whole is better prepared for climate-related disasters. This is a relative success for the MTAs and other regional projects, that have been active in the region.

IV. **Conclusion**

This article focused on the local climate knowledge of and use of climate services, tools, and forecasts in two regions of Colombia: Huila and La Mojana. Huila, a mountainous department in Colombia, is the largest coffee-producing region and produces coffee year-round. La Mojana is a large expanse of rivers and wetlands in northern Colombia and is home to rice farmers and fishers. Interviews were conducted in both regions to understand how participants

interact with their environment and how they are responding to climate change.

Results suggest that there is very little memory of strong climate events before 2010, but greater memory of conditions over the last five years. Additionally, farmers use their knowledge on biological rhythms of animals such as birds, insects, fish, clouds, the Moon, and other natural indicators to understand rainfall and make decisions on planting and harvesting crops. This varies by region, with some regions no longer trusting the natural indicators that their parents once used.

In regard to climate change, most farmers expressed some level of impact on their farms, but farmers in Huila appeared to be seeing fewer changes than those in La Mojana. However, coffee farmers find that they need to shift the altitude of their farms higher to combat pests brought in by increasing temperatures. Additionally, farmers are seeing changes in the productivity of their two growing seasons, creating greater economic imbalances between harvests. Warming temperatures in La Mojana are impacting rice yield and requiring better utility of forecasts to ensure successful planting and harvesting.

Many farmers received climate information from Institute of Hydrology, Meteorology and Environmental Studies (IDEAM). However, many do not trust or use this information, especially in the coffee growing regions. Climate information is also provided by the National Coffee Federation (FNC), the National Rice Association (Fedearroz), local coffee associations, and regional climate offices (e.g., CRPAT). In most regions, climate information is communicated to farmers through the use of WhatsApp groups, often managed by local coffee associations or by community members themselves. Communication also reaches more rural farmers by radio, often daily, depending on the region. For published material, bulletins are distributed virtually in most regions and contain information ranging from planting practices to climate forecasts. Such material is also communicated at MTA meetings once a month in regions that host MTAs, often facilitated by Fedearroz, FNC, and IDEAM.

Generally, few people trust the information provided by IDEAM, stating that forecasts do not have the spatial resolution or accuracy to be helpful to their farms. But the way farmers are using climate information is changing. Younger generations of farmers are turning more towards forecasts, whether from IDEAM or Google, are gaining confidence in using climate information through training at MTAs, and are rebuking the generational knowledge passed down to them from their parents.

Thus, a few questions remain: do all communities want or need access to additional climate information? And how could this be assessed and what resources can be used to conduct this research and implementation? Most farmers seemed interested in *reliable* forecasts with 1–2-month or 2–3-week lead time for temperature, precipitation, humidity, and wind variables, the important timeframes of their planting and harvesting cycles. However, trust in forecasts is generally low, and with farmers retaining little memory from year to year to validate forecasts, additional efforts need to be made to build trust between scientific and local communities. Such trust-building will allow farmers to gain confidence in the provided tools, resources, and forecasts, help farmers train younger generations on the use of climate information in farming practices, and facilitate scientists' understanding of local climate indicators. However, this will only be possible with the appropriate distribution of resources.

These results have given us a better understanding of how Colombian farmers use climate information. As mentioned in the Introduction, a better understanding of users' needs, in terms of climate information and access to it, can enable future work not only to formulate research projects that are more in line with the needs and expectations of the population, but also to produce information and forms of communication that will be more widely used. Therefore, it is imperative that grants enable researchers to spend time in the

field collecting this information before, during, and after research to inform the co-production of climate services to produce the most useful tools for society. This, however, will require a fundamental shift in the grant proposal and research process, which, we argue, is imperative to improving the ethics of climate research.

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Region	Type of Actor	Places	Number of Interviews	Interviewee Reference
Huila	Coffee Farmer	Gigante, Garzón, Pitalito, Timaná, La Plata	6	H1–H6
	Coffee Associations	Pitalito and La Plata	2	H7–H8
	National Coffee Growers Association	Neiva	1	H9
	Fisherwoman	Neiva	1	H10
La Mojana	Rice Farmers	San Marcos	2	M1–M2
	Rice Farmer and Miller	Sucre	1	M3
	Fisherman	Sucre	1	M4
	National Rice Association	Montería	1	M5
	Regional Centre for Forecasts and Early Warning (CRPAT)	San Marcos	1	M6
Total			**16**	

Table 1: Interviews Conducted in the Huila Department and the La Mojana Region.

Region	Number of Participants	Indicators Used
Huila	18-29: - 30-49: 4 50-69: 7 70+: 2	18-29: - 30-49: Information from Google or other smartphone weather applications, information from IDEAM, mountains, clouds 50-69: Weather stations, the Moon, weather patterns in other parts of the country, birds, clouds, wind patterns, ENSO forecasts, information from IDEAM 70+: The Moon, birds
La Mojana	18-29: 2 30-49: 3 50-69: 3 70+: -	18-29: Information from Google or other smartphone weather applications, information from IDEAM, clouds, birds 30-49: Information from IDEAM, birds, insects, 50-69: Clouds, breezes, insects, fish, slugs, birds, the Moon 70+: -

Table 2: Description of Interview Participants by Age and Types of Indicators Used to Understand the Weather and Climate in Their Region.

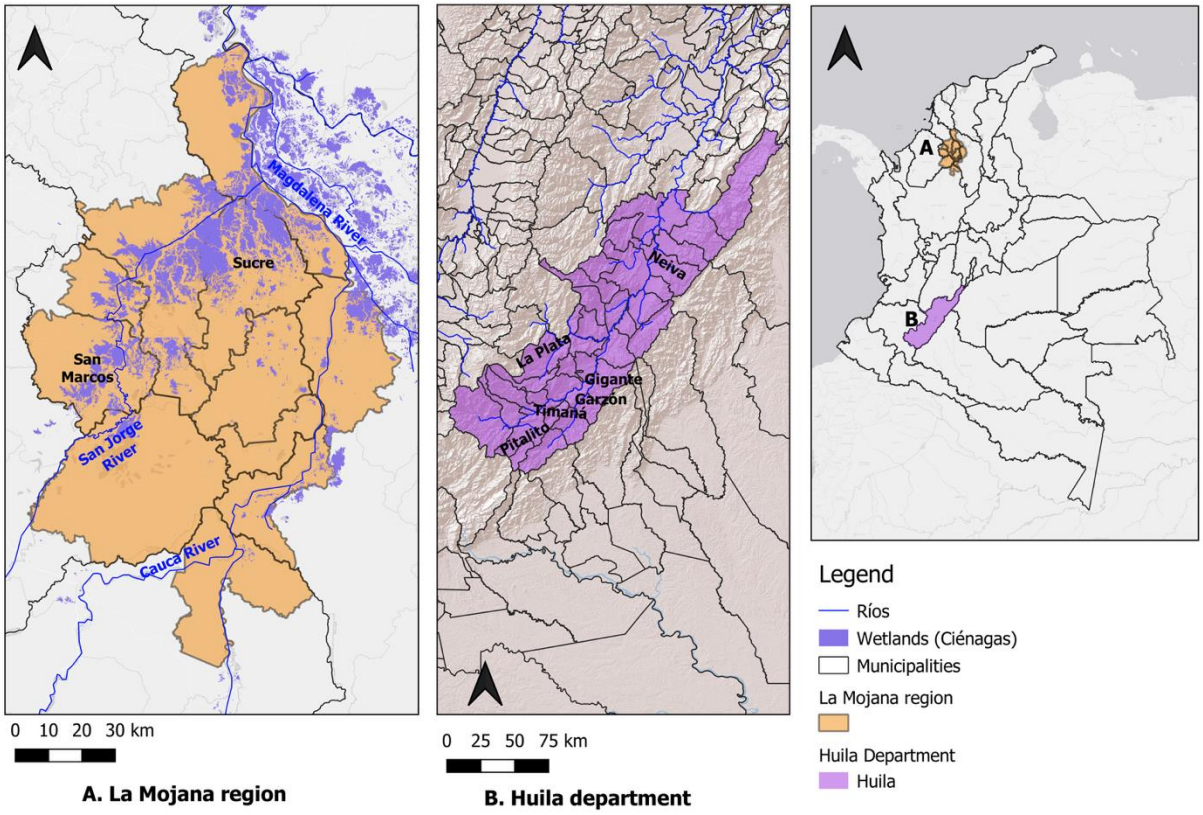


Figure 1: Regions of Study. *Notes: The top region (1a, L) is La Mojana, the low-lying wetland region. The bottom region (1b, M) is Huila, the mountainous and coffee growing department. The two regions are also within Colombia (1c, R).*



Figure 2: La Mojana Lowlands and Wetlands Regions (2a, L) and the Mountainous Coffee Growth Department of Huila (2b, R).



*Figure 3: The Chachalaca (*Ortalis Columbiana*) (3a, L) and the Carrao (*Aramus Guarauna*) (3b, R) (Source: NaturalistaCo / Christof Moning / David Monroy).* *Notes: Birds that announce the rain with their singing in the Huila department and in La Mojana.*



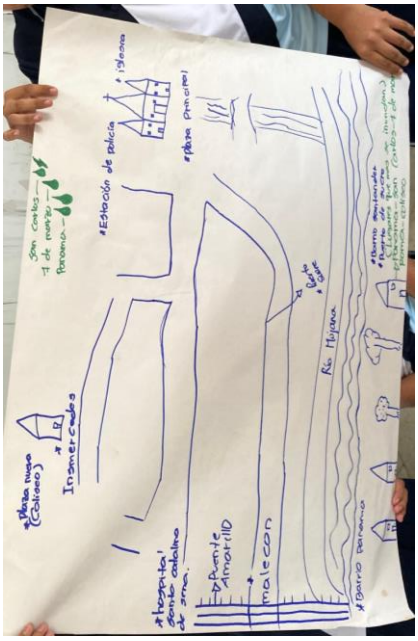


Figure 4 (TL): Snail's Eggs Marking the Maximum Level of Flooding in Sucre, La Mojana (Source: Authors).
Figure 5 (B): Map which Localises the Inundations in the Village of Sucre, Realised by a Group of Students during the Workshop (Source: Authors).
Figure 6 (TR): Enel Weather Station in a Coffee Farm in Gigante (Huila) (Source: Authors).

Iberian Weather Soundings: Climate Knowledge in the *Repertorio de los Tiempos*

Juan Fernando León Báez*

* Postdoctoral Teaching Fellow (Chabraja Center for Historical Studies), Northwestern University, US

KEYWORDS

climate history, past climate change, weather theorisation, vernacular meteorology, repertorio

ABSTRACT

Despite the centrality of weather to early modern life, little is known about how Iberian thinkers conceived the atmosphere during the Little Ice Age. The repertorio de los tiempos, a widely circulated genre that blended religious thought and scientific inquiry with the rhythms of daily experience, provides a unique window into investigating weather prediction and climate knowledge in the Iberian world. This article draws on close textual analysis of Spanish and Portuguese repertorios to reconstruct how early modern authors integrated Aristotelian meteorology, astrometeorology, and empirical observation into adaptive systems for theorising and forecasting weather under volatile climatic conditions. Incorporating environmental knowledge gathered through the transatlantic expansion, figures such as Rodrigo Zamorano, Jerónimo Chaves, Andrés de Avelar, and Enrico Martínez reinterpreted classical ideas of the atmosphere to account for regional variability, hemispherical asymmetries, and an emerging sense of global climatic interconnection. Situating this corpus within the broader history of climate knowledge, the article demonstrates that Iberian weather theorists developed a pluralistic and anticipatory meteorology that transformed natural philosophy into a pragmatic framework for understanding and navigating past climate change.

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I. **Introduction**

In 1585, Rodrigo Zamorano, the royal cosmographer of the *Casa de la Contratación*, compiled a comprehensive catalogue of practical knowledge for everyday life, which included a direct challenge to Aristotle's meteorological theory of winds.[1] Aristotle had

[1] In the *Meteorologica*, Aristotle develops weather theory through observation and *empeiria* (experience) but often subordinates empirical data to teleological reasoning. Defining wind as Earth's heated exhalations, he overlooks topographical factors. His flexible yet inconsistent method—balancing induction and deduction—invited later empiricists to challenge and revise Aristotelian meteorology. For his deductive method, *see* Frisinger, H Howard. "Aristotle and His *Meteorologica*." *Bulletin of the American Meteorological Society*, vol. 53, no. 7, 1972, pp. 634-638. For a counterargument, showing Renaissance Aristotelianism as a pliable and inductive knowledge system capable of integrating new experiences, *see* Martin, Craig. "Experience of the New World and Aristotelian Revisions of the Earth's Climates during the Renaissance." *History of Meteorology*, vol. 3, 2006, pp. 1-15.

asserted that *all* "Western Winds" were "universally cold and humid" regardless of location. However, Zamorano, drawing on his expertise in weather phenomena and his access to the vast knowledge influx from the New World through the *Relaciónes Geográficas*, argued against such crude generalisation. He emphasised that the behaviour of these winds is highly variable and deeply influenced by regional conditions, making their effects far more complex and localised than Aristotle had proposed. As Zamorano pointed out:

> *"According to Aristotle, all Western Winds are universally cold and humid, but the Coro (a Western wind) starts dry and ends wet. Thus,* everything said about the Winds must be regulated according to the nature of each land because they do not have the same effect everywhere*; as we can see with the Solano (an Eastern wind), which in Castile is a beautiful Wind, very temperate, hot and dry; in Murcia, [the Solano] brings rains; in Andalusia, during spring and summer, it is the worst of all, very wearing, hot, and everything that sprouts on the ground withers, breakdowns, and dies; and in the Bay of Cádiz you cannot disembark a Nao, Galera or Boat without wrecking and sinking."*[2] [emphasis added]

These observations, detailed in Zamorano's *Chronographia y Reportorio de la Razón de los Tiempos* (1585), underscore a crucial aspect of Iberian meteorology: the need to adapt theoretical climate knowledge and weather predictions to local ecosystems to ensure their utility.

Zamorano's focus on observing localised atmospheric changes, as we will see in more detail below, reflects a broader trend—thus far unrecognised—within Iberian weather theorisation to refine and diversify forecasting methods in light of erratic climate conditions. While Aristotle's theories offered an initial framework for understanding weather phenomena—attributing them to stratified layers of wet, warm, dry, and hot evaporations rising from the Earth due to the sun's heat—Zamorano and other weather theorists began to view atmospheric patterns as dynamic planetary systems, interconnected and responsive in ways that went beyond the mere mixing of exhalations.[3] They realised that region-specific weather patterns were influenced not only by local topographical features—a departure from the Greco-Roman latitudinal climate model—but also by hemispherical differences and global shifts in previously predictable climate patterns.[4] By illustrating how the Solano wind's impact varied from temperate in Castile to tempestuous in Cádiz, Zamorano described an early attempt to re-evaluate classical meteorological theories (especially zonal climate theory) in practical, place-specific contexts.

The value of this type of perspectival approach becomes even more discernible when considering the broader climate variability of the period. As atmospheric patterns grew increasingly unpredictable, the ability to interpret and forecast these changes became

[2] Zamorano, Rodrigo. *Chronographia y Reportorio de la Razón de los Tiempos*. Andrea Pescioni and Juan de León, 1585. Libro Primero, Cap. 38, "De los Vientos Occidentales." fols. 76-77.

[3] Aristotle was deeply committed to his theory of exhalations, which he used to explain variability of weather on Earth. He believed that the sun's heat caused two types of evaporation from the Earth: one wet and warm, which produced clouds and rain, and the other dry and hot, which generated wind and thunder; *see* Frisinger (n 1) *supra* at pp. 635-36. For Medieval and Renaissance enrichments of Aristotle's theory of exhalations, *see* Lawrence-Mathers, Anne. *Medieval Meteorology: Forecasting the Weather from Aristotle to the Almanac*. Cambridge University Press, 2020; Martin, Craig. "The Ends of Weather: Teleology in Renaissance Meteorology." *Journal of the History of Philosophy*, vol. 48, no. 3, 2010, pp. 259-282.

[4] *see* Taub, Liba. *Ancient Meteorology*. Routledge, 2003; Bakker, Frederik. *Epicurean Meteorology: Sources, Method, Scope and Organization*. Brill, 2016.

essential. Iberian weather theorists, noting deviations in seasonal patterns, promoted the integration of various weathercasting techniques into their reimagined almanac-like *repertorios*.[5] By compiling a variety of phenological markers and decadal climate predictions based on calendrical systems and environmental indicators, they moved beyond the local weather information everyone valued to produce something slightly more sophisticated: localised anticipatory weather knowledge. This equipped *repertorio* readers with critical information to navigate unseasonal weather and climatic anomalies more effectively. *Repertorio* writers offered a readily accessible compendium of strategies for understanding and later managing immediate and long-term atmospheric patterns. As a synthesis of theoretical and vernacular meteorology, the *repertorios* contributed to a more dynamic understanding of climate, surpassing latitudinal restrictions. This literary project reflected a nuanced grasp of the need for flexible, localised anticipatory weather methods that could account for phenological disturbances, especially those linked to global changes in seasonal climate patterns.

In this regard, the *repertorios* should be regarded as a valuable evidentiary base for climate history, as they contain qualitative data; narratives detailing disrupted seasonal rhythms. In fact, this genre has been ignored as a source of information for reconstructing the history of early modern climate change and its historical understanding in the Iberian Atlantic. As a genre that evolved beyond the confines of classical natural philosophy, the *repertorios* have recently drawn scholarly attention.[6] However, much of this research focuses only on their astrological elements and provenance, often disregarding their directive to examine the environment for clues to future weather conditions.[7] Building on the work of Orozco-Echeverri, Avalos-Flores, and Lanuza-Navarro—who have demonstrated that the *repertorios* were more than just collections of Greco-Roman ideas and underscored their authors as empirical thinkers—my study shifts the focus to the genre's weather prediction strategies.[8] In doing so, I am breaking new ground to show how *repertorio* writers meticulously crafted observations and carefully curated environmental indicators to anticipate atmospheric variations across the vast and diverse landscapes of the Iberian world, thereby demonstrating the depth and adaptability of their meteorological expertise. Unlike Craig Martin's analysis of Girolamo Cardano's meteorological predictions in sixteenth-century Italy, which focuses on revising traditional understandings of winds and their impact on health and disease,[9] I contend that the distinct climate conditions

[5] I use the term "weathercasting", which closely resembles Theophrastus's weather predictions in *On Weather Signs*, to differentiate this method from modern "forecasting", which now suggests data-driven and computational modelling of future atmospheric conditions.

[6] *see* Martins, Roberto de Andrade. "André do Avelar and the Teaching of Sacrobosco's *Sphaera* at the University of Coimbra." *De Sphaera of Johannes de Sacrobosco in the Early Modern Period*, edited by Matteo Valleriani, Springer Open, 2020, pp. 313-358; Ribeiro, Luís Campos. "The Bounded Heavens: Defining the Limits of Astrological Practice in the Iberian Indices." *Annals of Science*, vol. 77, no. 1, 2020, pp. 50-70.

[7] *see* Orozco-Echeverri, Sergio, and Sebastián Molina-Betancur. "A Mestizo Cosmographer in the New Kingdom of Granada: Astronomy and Chronology in Sánchez de Cozar Guanientá's *Tratado* (c. 1696)." *Annals of Science*, vol. 78, no. 3, 2021, pp. 295-333; Albisson, Mathilde. "En Mala Estrella: Los Pronósticos Astrológicos y Repertorios de los Tiempos Censurados por la Inquisición Española (1632–1707)." *Studia Historica: Historia Moderna*, vol. 41, no. 2, 2019, pp. 249-274; Alonso Rojo, José Miguel. "Rodrigo Zamorano, el Riosecano: Matemático y Piloto Mayor en la Época de Felipe II." Ph.D. Dissertation, Universidad de Valladolid, 2019; Tappan Velázquez, Maria. "La Representación del Tiempo en un Género de Escritura del Siglo XVI: Los Repertorios de los Tiempos." *Fuentes Humanísticas*, vol. 35, no. 24, 2012, pp. 3-49.

[8] *see* Orozco-Echeverri (n 7) *supra*; Ávalos-Flores, Ana Cecilia. "As Above, So Below: Astrology and the Inquisition in Seventeenth-Century New Spain." Ph.D. Dissertation, European University Institute, 2007; Lanuza-Navarro, Tayra M C, and Ana Cecilia Ávalos-Flores. "Astrological Prophecies and the Inquisition in the Iberian World." *The Global and the Local: The History of Science and the Cultural Integration of Europe: Proceedings of the 2nd ICESHS*, Cracovia, 2006, pp. 681-688.

[9] Martin, Craig. "Girolamo Cardano's Meteorological Predictions: Hippocratism, Weather Signs, Winds, and the Limits of Astrology." *Perspectives on Science*, vol. 30, no. 5, 2022, pp. 851-873.

influencing the work of Iberian weather theorists established the *repertorios* as productive textual spaces where early modern weather theorisation was redefined to serve practical purposes.[10] More directly, my analysis centres on a specific subsection of the *repertorios,* typically titled *Señales o Pronósticos de las Mudanças del Tiempo* ("Signs or Forecasts of Weather Changes"), referred to hereafter as *señales*. Focusing on the *señales* reveals how weather theorists wove together various strands of meteorological knowledge to improve weathercasting techniques for premodern Iberians grappling with the climatic challenges of the Little Ice Age. This research thus directly responds to Deborah Coen's call to rethink the history of ideas and science through "perspectival and pluralistic" histories that reconfigure the "scalar imagination" needed to understand knowledge production during climate crises.[11] The *repertorios* are a *new* historical vantage point for rethinking contemporary forecasting practices. Their pluralistic, observation-driven methods anticipate the logic of today's multi-model climate ensembles (e.g., the Coupled Model Intercomparison Project), which similarly integrate heterogeneous sources of information to predict past, present, and future climates. Moreover, the *repertorio* approach to weathercasting resonates with ongoing forms of non-instrumental forecasting that place local environmental knowledge at the centre. Viewed in this light, the *repertorios* trace deeper genealogies of anticipatory reasoning, demonstrating that cross-scalar, experiential insight has long been crucial for interpreting atmospheric change—even within increasingly sophisticated, yet still fundamentally interpretive, predictive systems used today.

Section II traces the evolution of the *repertorio*, outlining its key authors and the enduring significance of meteorological judgements within the genre.

Section III examines the *señales* sections in Spanish, Portuguese, and Mexican *repertorios*, identifying the theoretical frameworks and phenological indicators that informed efforts to forecast both short-term weather and longer-term climate patterns.

Section IV situates these predictive practices within the context of the Little Ice Age, showing how climatic variability influenced *repertorio* writers' observational methods and strengthened the capacity of early modern communities to anticipate and respond to environmental uncertainty.

Taken together, these analyses challenge the notion that Iberians passively endured climatic fluctuations.[12] Instead, they fashioned an approach of localised, adaptive meteorological reasoning that expanded the epistemic boundaries of climate knowledge. By foregrounding *repertorios* as experimental textual spaces where weather and climate were theorised and managed, this study establishes early modern Iberian meteorology as a pivotal—yet largely overlooked—contribution to the history of climate prediction.

My overarching goal is to demonstrate how textual forecasts and vernacular practices within the *repertorios* bridged environmental epistemes, offering new insights into how societies have historically sought to interpret, forecast, and confront past climate change.

[10] Within the *repertorio* scholarship, only Carmen Gozalo de Andrés has paid critical attention to the climate content of the *repertorios*. While Gozalo de Andrés acknowledges the Little Ice Age and its potential impact in generating weather predictions in a literary manner, she never pursues that line of inquiry historically nor provides a sustained analysis of how readers could have used the weathercasting knowledge to address irregular weather. See Gozalo de Andrés, Carmen. "La Predicción del Tiempo en el Siglo de Oro Español (s. X–XVII)." *Revista al Aficionado a la Meteorología*, no. 2, 2002, pp. 1-7.

[11] Coen, Deborah. "Big Is a Thing of the Past: Climate Change and Methodology in the History of Ideas." *Journal of the History of Ideas*, vol. 77, no. 2, 2016, p. 309.

[12] The notion that Europeans, especially peasants, passively endured nature's fury is a myth rooted in the interpretations of collapse literature writers, which includes the works of Joseph A Tainter (1988), Jared Diamond (2005), and more recently Philipp Blom (2019).

II. 'Contingent Futures and Chance Events': The *Repertorio de los Tiempos* and the Survival of Meteorological Judgements

The *repertorio* genre occupies a unique space between specialised ephemerides, popular almanacs, and books of secrets. As a vernacular miscellany, it translates complex astronomical, geographical, and cosmological knowledge into accessible formats for everyday use.[13] The word *repertorio*—from the Latin *repertorium*, "to find"—signalled a practical inventory: a text to consult, copy from, and act upon.[14] Its success stemmed from its ability to adapt scholarly, devotional, and empirical traditions to the diverse needs of cosmographers, physicians, priests, sailors, and peasants.[15] In the Iberian Peninsula, printers and authors, building on earlier literary traditions of borrowing from classical sources, turned medieval knowledge into widely used tools for timekeeping, natural observation, and weather prediction.

For instance, the earliest known example, Andrés de Li's *Repertorio de los Tiempos* (1495), incorporated Bernat de Granollachs's *Lunari* (1485), a lunar chart for prognostications widely reprinted across Europe.[16] Initially designed as modest, ready-to-use compilations, these works organised calendars, feast days, and celestial cycles in a manner that harmonised religious devotion with agricultural and medical practices. Over time, the *repertorios* expanded in size and scope—from seventy-page almanacs to quarto volumes of several hundred pages—absorbing a vast range of practical and speculative knowledge.[17] This growth, easily attributed to the arrival of the printing press, clearly mirrors their intended audience. Literary historian Jaime Moll famously describes these texts as *"libros para todos"*—books for all—because they circulated across social hierarchies and professions.[18] Cosmographers consulted them to align navigation with celestial timekeeping; physicians and barbers used their bloodletting charts to balance the humours; priests and parishioners followed their feast-day calendars; and peasants looked for their weather signs during cultivation and harvest. In short, the *repertorio* was a shared reference source for those seeking to understand how the heavens shaped earthly rhythms.

The genre's diffusion across Iberia and the Americas testifies to this versatility.[19]

[13] The knowledge amalgamation of the *repertorios* also included medicine, history, mythology, and theology.
[14] Ribeiro (n 6) *supra* at 64. *see also* Blair, Ann M. *Too Much to Know: Managing Scholarly Information before the Modern Age*. Yale University Press, 2010, Chapter 3, "Reference Genres and Their Finding Devices."
[15] For a historiography study on the *repertorio* genre, see Haro Cortés, Marta. "Una Nueva Edición del *Repertorio de los Tiempos* de Andrés de Li." *Boletín de la Real Academia Española*, vol. 101, no. 324, 2022, pp. 449-492.
[16] Delbrugge, Laura. "From Lunar Charts to Li: Considerations of Marketability and Concepts of Authorship in the Evolution of Bernat de Granollachs' *Lunari*." *Catalan Review: International Journal of Catalan Culture*, vol. 22, 2008, pp. 219-226 at 220.
[17] Blair (n 14) *supra* at 173-229. *see also* Delbrugge, Laura. "Ties That Bind (and Print): Pablo Hurus and Andrés de Li." *La Corónica: A Journal of Medieval Hispanic Languages, Literatures, and Cultures*, vol. 31, no. 1, 2002, pp. 41-47; "Capitalizing on the Stars: Medieval Almanacs as Popular Science." *VI Trobada d'Història de la Ciència i de la Tècnica*, edited by Josep Batlló Ortiz et al., Societat Catalana d'Història de la Ciència i de la Tècnica, 2002, pp. 301-305.
[18] Moll, Jaime. "Libros para Todos." *Edad de Oro*, vol. 12, 1993, pp. 191-202.
[19] While tracing the genre's exact dissemination patterns—including cost, pricing, and consumption—lies outside this article's scope, the editorial evolution of the *repertorios* provides valuable insights. As mentioned earlier, the genre grew from modest almanacs to large quarto collections produced mainly by court cosmographers, a change that based on paper alone probably increased production costs and, consequently, prices. Since these larger editions were intended as reference books for artisans, apothecaries, mariners, and supplier farmers, it is clear they were commercially produced with both utility and profit in mind. The fact that the genre later contracted into smaller, more affordable pamphlets also indicates that the reversal may have been caused by market saturation, increased competition among printing presses, the elevated costs associated with larger volumes, or an epistemic shift. Essentially, although the encyclopaedic editions were likely priced beyond some readers' reach, their eventual return to cheaper almanacs in the later stages of their evolution made the *repertorios* increasingly accessible to formerly excluded audiences. For the Spanish book trade, including book prices, *see* Maillard Álvarez, Natalia, and Rafael M Pérez García. "Printing Presses in Antequera in the Sixteenth Century." *Print Culture and Peripheries in*

Between 1485 and 1621, more than a hundred editions appeared, authored by figures such as Jerónimo de Chaves, Rodrigo Zamorano, André do Avelar, Manuel de Figueiredo, and Enrico Martínez.[20] In the hands of these cosmographers and weather theorists, the *repertorio* became a textual device: a portable archive through which old and new geographic, meteorological, and cosmological knowledge could be translated into vernacular form for a wide range of applications. The most sought-after material was meteorological judgements—empirical insights about the present and future behaviour of the atmosphere and its relation to human affairs. Grounded in Aristotelian physics, Ptolemaic cosmology, Hippocratic medicine, and Theophrastan weather signs, meteorological judgements were reformulated in plain Castilian or Portuguese and stripped of scholastic technicalities for practical use.

Rodrigo Zamorano's *Chronographia y Reportorio de la Razón de los Tiempos* (1585–1621) epitomised this knowledge synthesis. Responding to the request of "people keen on the public good", Zamorano set out to produce a *repertorio* that would "explain the reasons of the times and how they should be used from here on".[21] In doing so, he brought together a wide range of techniques for interpreting phenological indicators. These techniques reflected the revised date of the Vernal Equinox (21 March instead of 11 March), established by the new Gregorian calendar, and incorporated "signs written by philosophers", which at the time were used to forecast rains, droughts, and other atmospheric disturbances. Because his work urged readers to observe changes in clouds, wind patterns, and animal conduct as dependable clues of forthcoming weather alterations, *repertorio* consumers had at their fingertips the knowledge and methods to detect unusual shifts in seasonal weather.[22] *Repertorio* instructions then not only brought their users closer to their natural ecosystems but also made them more aware of what Sarah Dimick refers to as "climate arrhythmias"; "environmental pulses experienced as disturbingly premature or delayed, pronounced or absent".[23]

It is worth noting that when early modern writers described the "arrhythmias" of the Little Ice Age, they were not identifying a physical change in climate as we would today but diagnosing a disturbance in the moral and environmental order of the cosmos. This distinction reflects a different epistemic regime: for early modern thinkers, weather referred to short-term fluctuations governed by providence and celestial influence, whereas climate denoted the stable, divinely and geographically fixed character of a place. Persistent deviations from this stability signalled less an environmental transformation than a rupture in the harmony between heaven and earth—a moral as much as a meteorological deviation. A *repertorio* writer's account of a drought, frost, or storm was therefore never a neutral observation; it was an interpretive act seeking to restore meaning within a disrupted cosmos. Although these authors recorded unseasonable weather to interpret divine or astrological order rather than to measure variability, their accounts preserve the texture of environmental experience—the qualitative evidence that enables historians to reconstruct the timing, scale, and geography of past climatic disturbances.[24] Tracing this interpretive

Early Modern Europe: A Contribution to the History of Printing and Book Trade in Small European and Spanish Cities, edited by Benito Rial Costas, Brill, 2013, pp. 271-302.

[20] Chabás, José, and Bernard Goldstein. "Syzygies." *A Survey of European Astronomical Tables in the Late Middle Ages*, Brill, 2012, pp. 153-154; Chabás, José, and Antoni Roca. "The Early Printing of Astronomy: The *Lunari* of Bernat de Granollachs." *Centaurus*, vol. 40, no. 2, 1998, p. 125; Hurtado Torres, Antonio. *La Astrología en la Literatura del Siglo de Oro*. Instituto de Estudios Alicantinos, 1984, pp. 135-136; Alonso Rojo (n 7) *supra* at pp. 23-24.

[21] Zamorano (n 2) *supra*, "Al Curioso y Discreto Lector."

[22] ibid.

[23] Dimick, Sarah. *Unseasonable: Climate Change in Global Literatures*. Columbia University Press, 2024, "Introduction."

[24] The climate irregularities recorded in the *repertorios* constitute an underutilised documentary source for reconstructing past climate change. These texts vividly capture the human experience of weather, often

labour then exposes the precarious balance early modern climate knowledge maintained between theology and natural philosophy. It is precisely within this liminal space that the *repertorio* emerged as a sanctioned instrument of prognostication—one that could translate atmospheric disturbance into intelligible order without overstepping into forbidden divination.

Consequently, as a readily deployable prognostication system, its usefulness in detecting anomalous phenological events meant that meteorological judgements could skirt ecclesiastical constraints in the interest of the public good. While Church authorities condemned the divinatory branches of astrology that claimed foreknowledge of human destiny, they tolerated "natural judgements" that served navigation, agriculture, and medicine. The 1612 *Index* of Grand Inquisitor Bernardo de Sandoval y Rojas drew this distinction clearly, prohibiting predictions of "contingent futures or human actions" while allowing knowledge of "rains, winds, and other alterations of the air" to continue insofar as it derived from natural causes.[25] The Portuguese *Index* of 1624 reaffirmed this distinction with even greater precision, stating that:

> *"... in the treatment of the weather and Revolutions of the years, although all judgements on things dependent on human will are forbidden, contingent futures, and chance events, the judgment of rains, winds, storms, serenities, mists, droughts, and all other alterations of the air are allowed, and according to them to predict what can be expected of fertility or sterility, good or bad success in harvest, and cattle."*[26]

Here, as in the Spanish case, the *revedor de livros* (book reviewer) for the Portuguese Inquisition, Baltasar Álvares, clarified that meteorological prognostication did not fall within the domain of illicit divination, but rather within the realm of legitimate natural knowledge. Like Sandoval y Rojas's ruling, Álvares's declaration reaffirmed the legitimacy of meteorological judgements as effective and publicly beneficial methods for anticipating bountiful and meagre harvests without violating doctrinal boundaries. Together, these Iberian rulings established a sanctioned domain of climate knowledge that allowed practitioners to investigate atmospheric phenomena through empirical observation while adhering to the evolving moral and theological landscape of Counter-Reformation orthodoxy.

In this sanctioned space between orthodoxy, science, and superstition, *repertorios* flourished. Their authors curated environmental intelligence for a society whose survival depended on anticipating the weather. Farmers used them to schedule planting and harvests; merchants and soldiers relied on them to plan journeys; and physicians synchronised bleeding and purging with the rhythms of the atmosphere. By vernacularising and democratising weather

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detailing unseasonable events such as extended droughts or unusual precipitation, including hail, rain, or snow. Because *repertorio* writers frequently document these phenomena with exceptional temporal and spatial precision, their accounts provide crucial clues about how climatic instability affected specific communities and industries, such as salt, gypsum, olive oil, and merino wool producers. Climate historians and palaeoclimatologists can leverage established analytical methods—like temporal displacement or ordinal scales, commonly applied to rogation and harvest records, as well as techniques from dendrochronology and sedimentary analysis—to cross-reference this information and develop serial indexes of irregular and worsening climate variability. When these indexed time series are correlated with natural proxies, they have the potential of yielding high-resolution insights into historical periods when climate predictability—a cornerstone of societal stability—was compromised, diminished, or functioning optimally.

[25] Sandoval y Rojas, Bernardo de. "Regla IX." *Index Librorum Prohibitorum et Expurgatorum*, edited by Bernardo de Sandoval y Rojas, Lvdovicvm Sanchez, 1612, pp. 5-6.

[26] Álvares, Baltasar. *Index Auctorum Damnatae Memoriae*, edited by Fernão Martins Mascarenhas, Pedro Craesbeeck, 1624, pp. 84-85.

climate expertise, *repertorios* bridged observation and action—what might be called an early form of anticipatory literacy. This mediating role blurred the line between clusters of expertise, bringing together learned and artisanal knowledge in a productive dialogue.

The producers of the *repertorios*—whether cosmographers, physicians, printers, or autodidacts—found themselves at the intersection of this dynamic, interconnected intellectual world. Many held academic or imperial posts: Sancho de Salaya taught theology at Salamanca; Cristóbal Ponce de León, medicine at Alcalá; André de Avelar and Manuel de Figueiredo lectured on mathematics and astronomy at Coimbra and Lisbon; and Jerónimo Chaves and Rodrigo Zamorano served as cosmographers to the *Casa de la Contratación* in Seville, where they trained pilots for the *Carrera de las Indias* and compiled geographical data for the *Padrón Real*, the empire's master map. As María Portuondo observes, these figures were "compilers of information": state scientists who also wrote—although in a diminished form—for public instruction.[27] Others, however, were self-taught authors who leveraged their social status and the print press to claim intellectual authority. In his *Fabrica del Universo También Llamada Repertorio Perpetuo* (1563), for example, Pérez de Vargas identifies himself as a "*cavallero*" [sic] (possibly a *hidalgo*) and a lover of astrology.[28] From his other writings, we know he worked as an alchemist, possibly a metallurgist, and a tax collector in Toledo and Madrid. Although no formal training records exist, his social status likely afforded him access to books and libraries. Similarly, in his *Chronographia, y Repertorio de los Tiempos* (1585), Vicente de Tornamira describes the significant "time" and "effort" he invested in "cooking" this work, spending many "sleepless nights" because it was a "very difficult matter" to master.[29] Such confessions of humility were clearly formulaic, yet they reveal how autodidacts entered natural philosophy through their social position and editorial ambition—as both a means of learning and a path to upward social mobility. It should be noted that, even as autodidacts broadened the genre's social base, the *repertorios* they produced often bore the imprint of their social background and uneven training. Their desire to project academic authority encouraged the uncritical reproduction of inherited knowledge rather than sustained interpretation or methodological rigour. This variation, however, is itself illuminating: it shows how climate knowledge circulated across Spanish social strata and how the *repertorio* became a space where aspirational writers negotiated expertise as much as they conveyed it—sometimes introducing moments of epistemological overreliance and oversimplification that highlight the contested nature of authority in early modern weather prognostication.

By the eighteenth century, the genre's spread of weather knowledge was not only well entrenched but already losing its novelty. The *Diccionario de Autoridades* (1737) defined *repertorio* authors as *ganapanes*—"bread-earners"—who produced small, portable books that could be easily carried under one's arm.[30] This image captured the genre's transformation from the encyclopaedic compendia of court cosmographers to the inexpensive almanacs of common printers and self-taught writers. Returning to its modest, utilitarian origins as a people's weather guide, the *repertorio* bridged the divide between expert and lay knowledge. Mediating between textual tradition and lived experience, it

[27] Portuondo, María. *Secret Science: Spanish Cosmography and the New World*. University of Chicago Press, 2013, at 65.
[28] Pérez de Vargas, Bernardo. *Fabrica del Universo También Llamada Repertorio Perpetuo*. Juan de Ayala, 1563, title page and "Al Lector." For the role of the "caballeros" in the history of the Spanish Renaissance, *see* Nader, Helen. *The Mendoza Family in the Spanish Renaissance: 1350–1550*. Rutgers University Press, 1979.
[29] Vicente de Tornamira, Francisco. *Chronographia, y Repertorio de los Tiempos, a lo Moderno, el Qual Trata de Varias y Diversas Cosas*. Thomas Porràlis de Savoya, 1585, "Al Pio Lector."
[30] *Diccionario de Autoridades, Tomo V, 1737*. Real Academia Española.

rendered the heavens legible to those who laboured on land and sea—people whose lives unfolded at the mercy of the weather. More than mere repositories of climate prediction, these books became textual instruments for thinking with the weather—teaching early modern readers to read the shifting sky while navigating a world increasingly shaped by climate uncertainty.

III. 'Rustic Astrology': The Art of Iberian Weathercasting through '*Señales*', '*Pronósticos*' and '*Mudanças del Tiempo*'

The craft of Iberian weather prognosis differs from one *repertorio* to another. This variation stems from how early weather theorists generated forecasts by understanding classical cosmological models, while also inconsistently integrating Islamic advancements in astrometeorology, particularly intricate tables and calculations of planetary alignments and celestial entities.[31] For example, Andrés Li's *Reportorio* (1495) interlaces the Sun and Moon revolutions with planetary movements and zodiacal information to project latitudinal climate and the onset and end of the rainy season across zones. "When the Sun enters [Aquarius] in January", Li writes, "it brings weather full of water and rain, which demonstrates the power of the Sun. Neither water nor rain would come to the Earth if the Sun did not [heat up] the upper parts, which reaction [in the form of exhalations] causes rain".[32] Similarly, Saturn—with its "airy nature" and "hot and humid quality"—needs to be carefully monitored because it exerts influence over Aquarius in January and February. For Li, celestial dynamics make these two months "dangerous for foot diseases" but suitable for using "the baths and bloodlettings", "eating hot and clear stews", "digging vines", "planting all kinds of legumes", and "rotating the fallowlands".[33] Readers of this *repertorio* could then observe the location of the Sun during the day and Aquarius and Saturn at night to anticipate specific weather conditions, specifically seasonal precipitations, ordering life routines during the first two months of the year. Because Li's predictions were rooted in astrometeorology, they offered broad generalisations and low-resolution atmospheric readings. In practice, these served as celestial indicators of future seasonal weather, necessitating an understanding of how to calculate and interpret superlunary movement and its influence on sublunary activity.

Despite numerous revisions and additions to Li's *Repertorio* by the Salamancan astrologer Sancho de Salaya in 1536, 1542, and 1546, the new material contributed little to the field of weather prognosis. If anything, it preserved Li's organisation and thematic approach. Unlike later publications, neither of Salaya's editions dedicated substantial space to weathercasting. The most discernible development of the weathercasting subgenre in Spain can be credited to Jerónimo Chaves, with his *Chronographia o Repertorio de Tiempos* (1548). In the "summary of contents" Chaves describes the final section of the *Chronographia* as follows:

> *"The fourth and final [book] focuses on observing the seasons and their divisions. It emphasises the importance of knowing the critical days or judgements that physicians consider in treating human diseases. Additionally, it discusses weather conditions favourable for purging and bloodletting, along with natural predictions (also known as rustic astrology)* [sic] *concerning weather changes. This includes*

[31] Lawrence-Mathers (n 3) *supra* at 68. One such innovation, or knowledge enrichment from the Islamic Arab world, was the introduction and use of the Alchandrean Corpus. This body of astrometeorological works, Lawrence-Mathers writes, "included text on astronomical tables and the more detailed calculations of planetary positions; the making and uses of astrolabes; and medical and astrological applications of this data".

[32] Li, André de. *Reportorio de los Tiempos*, edited by Laura Delbrugge, Tamesis, 1999 at fol. 122r, p. 68.

[33] ibid at fols. 123r and 124r, 69-70.

> *knowledge of fair weather, rain, winds, storms, cold fronts, earthquakes, pestilences, and famines."*[34]

Chaves's summary presents two categories of weather forecasts: (i) "judgements" and "determinations": these anticipate cyclical climate patterns based on seasonal and astronomical data, which proved advantageous for physicians and patients; and (ii) "natural predictions" or "rustic astrology": this forecasts meteorological phenomena by observing environmental changes, offering valuable and sensitive information to the broader society. *Repertorio* weathercasts emerged from the "natural predictions" category, from a "rustic" method of prediction that Chaves labels *Señales de las Mudanças de los Tiempos* ("weather changing signs").

These *señales* combined bookish (classical) and experiential (rustic / vernacular) knowledge to predict future atmospheric conditions, namely "fair", "windy", "rainy", "cold", and "tempestuous" weather. To determine each atmospheric state, Chaves introduces ten methods for forecasting the weather. These can be understood as subtle variations within a region's usual phenological patterns.

1. "Signs by stars or exhalations" (Señales por Estrellas o Exalaciones);
2. "Signs by the Sun" (Señales por el Sol);
3. "Signs by the Moon" (Señales por la Luna);
4. "Signs by clouds" (Señales por nuves);
5. "Signs by mists" (Señales por neblinas);
6. "Signs by the rainbow" (Señales por el arco del Cielo);
7. "Signs by lightning and thunders" (Señales por relampagos y truenos);
8. "Signs by birds and fishes" (Señales por aves y pesces);
9. "Signs by terrestrial animals" (Señales por animales de tierra);
10. "Signs by inanimate bodies" (Señales por cuerpos inanimados).

Some methods and indicators were more effective than others in determining specific weather conditions. "Signs by mists", for instance, were inadequate in forecasting "windy", "rainy", "cold", or "tempestuous" weather. That approach only seemed to work for anticipating "fair" weather: "[w]hen mist gradually descends from above like a cloud and does not rise again, it means fair weather. Small mist in the spring means fair weather, and the same if it happens in autumn".[35] Why does this approach not predict other weather conditions? Chaves does not tell us. However, the underlying assumption is that *all* phenological indicators require careful monitoring and close examination of the local environment and atmosphere to approximate weather variability.

To forecast "windy" weather by using "signs of clouds" and "signs of exhalations", for example, the reader must identify the movement, size, colour, and composition of clouds and exhalations: "[w]hen exhalations are clear and run all over the place, it means prevailing winds from multiple places"; "[w]hen exhalations come from the four cardinal points, it means tempestuous winds with lightning and thunders"; "[i]f before the Sunrise, red clouds are to the East, it denotes winds, and if any black clouds are among them, it means rain now".[36] Accurate sensory perception is also needed when predicting "rainy" weather using visual and auditory signs, like "signs of the rainbow" and "signs of inanimate bodies": "[w]hen two rainbows appear together, it denotes rain. If the rainbow appears before noon, it means rain in the afternoon with winds"; "[w]hen bells sound louder than usual, without [the amplification of] wind, it denotes flash rains"; "[w]hen salted meat is wet, it denotes rain". Mastery of these signs opened a world in which weather prediction depended on the keen attunement of the senses to the affordances of the skies.

[34] Chaves, Jerónimo de. *Chronographia o Repertorio de Tiempos, el Más Copioso y Precisso que Hasta Agora ha Salido a Luz*. Fernando Díaz, 1580 [1548].

[35] ibid at fol. 265v.

[36] ibid at fols. 266r; 268v.

To forecast "tempestuous" weather by using "signs of the Sun" and "signs of the Moon", the reader must consider the little nuances of the sky surrounding the Sun and the Moon: "[i]f the sky is clear when the Sun rises, and it appears big and yellow, it means a hailstorm with lightning and thunder that day"; "[i]f the full moon had two or three intersecting circles and enclosed within them a black cloud, it means a severe rainstorm with winds".[37] As for "cold" weather using "signs of birds", the forecasting technique involves observing avifauna behaviour and murmuration: "[w]hen many small birds congregate, even if they are from different species or the same species, and look for food in the field, not far from the town, it is a sign of cold and frost, and at times, storms".[38]

The signs discussed here represent but the visible edge of a far broader landscape of rustic phenological insight cultivated by Iberian weathercasters. Chaves's *señales* combine general and specific clues that *anyone* could find in their surrounding ecosystems. He explains that "general señales are recognised across an entire region, while specific señales are understood within ten to fifteen leagues".[39] Readers of the *Chronographia* could thus select the relevant *señal* according to geographic scale or weather state to forecast conditions at any time. These techniques taught users that weather's apparent irregularity could be tracked, interpreted, and anticipated as both beneficial and dangerous, giving individuals and communities tools for protection against worsening variability. As the most refined version of the *repertorio* genre, the *Chronographia* instructed readers to read the sky attentively, discerning meaning from subtle and fleeting details in constant flux. Some *señales* clearly proved more effective than others at interpreting local atmospheric shifts. This raises a larger question: did other Spanish *repertorios* interpret *señales* and *pronósticos* through the same logic, or craft distinct methods of weather reckoning?

A. *Lesser-Known* Repertorio *Writers and the Re-Grounding of Weather Prognosis*

Like Chaves, Bernardo Pérez de Vargas dedicated several sections to *señales* in his *Fabrica del Universo También Llamada Repertorio Perpetuo* (1563). Leading up to that section, he introduces foundational chapters on fire and water and their "accidents" and "impressions" on weather. Drawing from Aristotelian theory, Pérez de Vargas explains phenomena such as the Northern Lights, rainbows, wind, hail, snow, rain, earthquakes, comets, and lightning. For instance, he describes lightning and thunder as follows:

> *"When vapour and exhalation rise to the middle air region, called the interstice, they thicken and produce clouds. The cold air, feeling the heat from the exhalation, tightens and strengthens at the cloud's edges, igniting energy. If trapped, this force ruptures the cloud, causing thunder and lightning. If another cloud sits above, the thunder is greater and more violent. Sometimes, especially in summer, lightning is visible, but thunder is not heard, as the sound is too faint and dissipates before reaching the ground."*[40]

[37] ibid at fols. 274v; 275r.

[38] ibid at fol. 277r.

[39] ibid at fol. 278v. Chaves consistently frames *región* (region) as a meso-scale sphere of atmospheric coherence: large enough for "general señales" to hold across a lunation but smaller than any truly global frame, and always contrasted with the tighter *comarca* (municipal district) of ten to fifteen leagues where only highly local *señales* apply. While articulated in formally Aristotelian terms, this schema strongly underscores the observer's situatedness, since both weather signs and celestial phenomena must be interpreted from a specific horizon. Thus, in the eclipse tract (fols. 253r–253v.) he verifies all computations for "nuestra patria y región" (Seville's meridian and horizon), while providing longitude tables for readers in "otras regiones y climas" (other regions and climates) to recalibrate predictions. Across these discussions, *región* becomes an interpretive band that links spatial and temporal reach to the observer's exact location, making accurate forecasting a matter of knowing where one stands.

[40] Pérez de Vargas (n 28) *supra* at fols. LV-LVI.

Pérez de Vargas's account of thunder and lightning exemplifies early modern efforts to naturalise meteorological phenomena within an Aristotelian framework. By portraying the "interstice" as a zone where fire and water interact through compression and ignition, his explanation links atmospheric tension to seasonal variability, anticipating later physical theories of heat, sound, and air pressure. Notably, his weather theories also incorporate elements of rustic astrology, asserting that weather could be predicted by observing "comets and stars", "clouds", and "animals". While Chaves proposed ten such predictive methods, Pérez de Vargas limited his system to these three signs for determining weather.

Observing "comets and stars", "clouds", and "animals", readers of the *Fabrica del Universo* could forecast weather conditions, from "hot and dry" to "cold and icy", "snow and hail", and "lightning and thunder". To predict "snow and hail" by using the signs of "clouds", the reader had to scan the sky for a specific type of cloud formation and temperature changes occurring in or out of the season: "[w]hen the air is disturbed, and white and clear clouds are stationary, it is a sign of snow. And when in winter it is not cold and suddenly feels hot, it is a sign of snow nearby … Ordinarily, snow is generated in winter in the northern regions and hail in temperate territories during the summer and autumn, when the fruits of the trees ripen. Rarely in winter and summer".[41]

As we can see, Pérez de Vargas's approach to weather prognosis blends awareness of the seasonal climate with local atmospheric disturbances. He notes the importance of interpreting rapid temperature changes in the air while observing the onset of convection and the movement and colour of clouds for the clues they provide in predicting snow or hail. This constant weather reckoning placed *repertorio* readers in a position to spot when atmospheric patterns shifted. Clearly, if *repertorio* writers observed and recorded changes in local weather patterns, as we will see below, it is more than likely that perceptive readers skilled in constant weather soundings could have just as easily recognised climate arrhythmias. If they noticed changes in the timing, intensity, and duration of precipitation regimes, they could also adjust and improve their techniques accordingly as they adapted to these changes.[42]

Following the 1564 prohibitions on astrology and divination by the *Index* and Rule IX of the Council of Trent, specifically targeting printed astrological judgements and *señales*, the *repertorios* published in the 1580s faced significant challenges. Not only did they have to contend with the editorial impact of these prohibitions, but they also had to adapt to the sweeping changes brought by the overhaul of the Julian Calendar in 1583 and the issuance of *Coeli et Terrae* by Pope Sixtus V in 1585, which solidified the Church's stance against judiciary astrology.

Consequently, it is unsurprising that weathercasting *señales* became notably scarce in works like Victoriano Zaragozano's *Lunario, Reportorio de los Tiempos que Sirve a Toda la Europa* (1583) and Bartolomé Valentín de la Hera y de la Varro's *Repertorio del Mundo Particular* (1584).

The effects of these prohibitions emerge clearly in Zaragozano's introduction to the *Lunario*'s weather section. Aware of disputes among astrologers over "astronomical judgements", he grounds his prognostications in observable phenomena—comets, halos, and stars—deemed, following Ptolemy, the most trustworthy indicators of atmospheric change. Although meteorological forecasting was gradually moving away from Ptolemaic reasoning, celestial and atmospheric signs still retained epistemic authority. Yet Zaragozano tempers this inheritance with theological caution, declaring that his pronouncements are conjectural and subordinate to divine

[41] ibid at fol. LRVII.

[42] This challenges an earlier academic perspective that underestimated premodern societies' ability to perceive and interpret climate change, often portraying them as lacking the necessary tools to detect long-term climate shift: *see* (n 12) *supra*.

will.[43] This rhetorical gesture delineates the delicate boundary between licit *señales* and illicit judgements, natural causes and providential acts. By invoking ancient authority while privileging empirical observation, Zaragozano recasts observation as a disciplined and permissible form of foresight—one that Iberian weathercasters increasingly cultivated to navigate the shifting epistemological terrain of the period.

Despite these constraints, Zaragozano compiled weathercasting techniques for interpreting "the alteration of the air", which he noted benefited "physicians", "surgeons", "people who labour in agriculture", and "all common folk".[44] To know the quality of the weather, he encouraged readers to notice: "[w]hen the lamps flicker a lot, [when] ponds or cut weed appear black or light-coloured, when cattle eat voraciously, and when roosters crow at unusual times, and frogs sing profusely, it is a sign of water. When the Sun, one hour after rising and one hour before setting, radiates sunbeams, it is a sign of water". Furthermore, he continued, "air permutations" could also be retrieved from "stones", "minerals", and "metals". No specifications are given as to how that occurs, however. In fact, it seems that Zaragozano hesitantly endorses such a practice: "[s]o as not to trouble the reader, I refrain from writing further".[45] Zaragozano's reticence about predicting weather via "stones", "minerals", and "metals" may reflect concerns about the practice being too rudimentary, complex, or esoteric for general readers, or possibly to avoid association with alchemists, soothsayers, and folk healers. Alternatively, he may have wished to avoid scrutiny from Church authorities. In the end, Zaragozano revitalised weather prognosis by streamlining theoretical and experiential climate knowledge. Drawing on both classical theory and rustic *señales*, he refined the syncretic model pioneered by earlier *repertorio* writers—those who, balancing reader expectations and censorship, grounded meteorology in practical, observable weathercasts.

Similarly, Bartolomé Valentín de la Hera, in his *Repertorio del Mundo Particular*, reduced the scope of weathercasting by adopting the "new meteorological doctrine of the passions of the air", which emphasised the limited influence of celestial bodies over the elements and reflected ecclesiastical prohibitions against calendric and divinatory practices. Unlike Zaragozano, Valentín de la Hera examined the roles of "wind", "water", and "fire" in shaping weather variability, arguing that their interactions revealed the underlying dynamics of the atmosphere.[46] Drawing on peripatetic meteorology, he described all "water meteors"—including dew, frost, windfall, manna, honey, rain, snow, and hail—as forms of vapour whose characteristics corresponded to their position within a stratified atmosphere. His weather signs rested on a Theophrastan foundation that encouraged careful observation of the sky to discern reliable patterns of change. When "two halos appear around the Moon, or three or more", he wrote, "the ensuing rain will be tempestuous and windy", whereas halos "reddened, broken, or surrounded by thick and hazy nimbuses" signalled snow; and when halos around other stars appeared "black, purple, tawny, or smudged", they indicated the same.[47] Such attention to the visual language of the heavens made the upper atmosphere a key site for anticipating snow and precipitation. At the same time, ground-level observation remained essential for identifying dew and frost. Without standardised methods for evaluating these meteorological *señales*, Spanish weather theorists developed forecasts in an ad hoc manner. Their approaches varied and often lacked reproducible consistency. Yet, they remained deeply attuned to place-based

[43] Zaragozano, Victoriano. *Lunario, Repertorio de los Tiempos que Sirve a Toda la Europa*. Juan Altarach, 1583, fols. 54v-55r.
[44] ibid, "Al Rey."
[45] ibid, "De la Mutacion del Ayre, Segun las Meteorologicas Impresiones." fols. 56r-57v; 57r-58v.
[46] Valentín de la Hera y de la Varro, Bartolomé. *Repertorio del Mundo Particular*. Guillermo Druy, 1584, "Al Prudente y Curioso Lector."
[47] ibid at Libro II, "De la Tierra y de la Água." fols. 61r-62v; 62r-63v.

knowledge and to the interplay between theory and practice—a defining feature of Iberian weather sounding everywhere it went.

B. *Iberian Weather Soundings: From the Old to the New World*

From the inkwells of André de Avelar, Manuel de Figueiredo, Rodrigo Zamorano, and Enrico Martínez—operating in Coimbra, Lisbon, Seville, and Mexico City, respectively—we see that geography and acquired expertise, both bookish and experimental, played a crucial role in shaping how these writers crafted weathercasting signs. To accurately predict meteorological conditions in Portugal, Spain, and Mexico, these theorists recommended that readers immerse themselves in their local environments to extract anticipatory climate knowledge. Encounters with disturbed weather undeniably informed their recommendation, as their *repertorios* document numerous instances of unseasonal climate patterns—now linked to the Little Ice Age.

In the *Chronographia, Ou Reportorio dos Tempos que te Agora Sayo a Luz* (1585), Portuguese astrologer André de Avelar offers "some necessary warnings to aptly forecast the changes of the air". After establishing that weather variability follows a set of divine principles and natural patterns, outlined in the writings of Hippocrates, Pythagoras, and Egyptian and Hebrew scholars, readers must understand the correlation between weather signs, geography, and timely prediction: "[f]irst, any *sinaes* [weather signs] will be accurate if what they forecast does not extend beyond the horizon, which is as far as the eye can see ... around forty-five miles, or eleven leagues in Spain"; "[s]econd, it is important to note the geography of the place of prognostication, both concerning the sky and the layout of the land, because naturally humid lands are more susceptible to rains than droughts, [and] mountainous lands to snow, thunderstorms, lightning, and more"; lastly, "it must be acknowledged that winds—despite their nature—sometimes become dry and other times wet according to the regions and places through which they pass".[48]

Avelar's "warnings to aptly forecast" serve as guidelines to recognise the capabilities of weather signs, the influence of the landscape, and the limits of the human senses in detecting and predicting the state of the local atmosphere. Understanding the mechanics and forces behind weather formation through ancient theories and concrete principles became foundational steps leading weathercasters and weather watchers to monitor their immediate environment for subtle insights and features, working as *sinaes* and clues of rain, snow, or lightning. In this approach, it is not enough to identify wind zones, their inherent quality, and their impact area. That was already built into classical meteorology. Qualitative data points must be curated according to the region's geography because trade and prevailing winds change with orographic features, acquiring new convective properties along the way. A prime example of this—now fully incorporated into modern meteorology—is the study of orographic effects, which alter air masses travelling from the east coast of North America and contribute to heavy precipitation in the Spanish Pyrenees.

Building on this lasting insight, Avelar introduces sensory techniques to determine the arrival and end of winter and storms. "Democritus", he says, "predicted winter by noticing the day the Sun reached the Tropic of Capricorn". Weathercasters and practitioners are urged to observe the Sun's shorter trajectory along the horizon and the diagonal direction of the sunlight to know the arrival of "cold and frost": "[w]hen the northern winds blow hard, even if there are clouds, it will be cold"; "[w]hen little birds at the beginning of winter seek shelter among bushes and woods, and gather in flocks, or seek food far from houses, the end of the great cold is near"; "[w]hen Sovereign Pin Oaks and other similar trees have many acorns, it means a great winter"; "[i]f ants are visibly lazy, secluded,

[48] Avelar, André do. *Chronographia, Ou Reportorio dos Tempos que te Agora Sayo a Luz*. Simão Lopez, 1594, Livro III, ch. 1, fols. 121r, 122v, 123v. For an alternative view of region, *see* Chaves (n 39) *supra*.

or sticking out their ears, it denotes wind and storm"; and "if the currents of the sea or rivers make noise during fair weather, it will be a storm".[49]

As we can see, Avelar encourages readers to grasp basic astronomical principles while integrating multiple sensory observations from different perspectives. By firmly tracking the Sun's position, its seasonal variations, wind patterns, topography, animal behaviour, and hydrological shifts, Avelar's method weaves localised environmental cues into the broader latitudinal climate framework he inherited from Democritus—significantly sharpening his *sinaes*' capacity to forecast local weather and future climate. His method, which anticipates Humboldtian meteorology, offers a rich dataset of atmospheric *sinaes* that demand a deep, sustained engagement with the surrounding environment to refine forecasting accuracy.[50] Despite its predictive capacity, this approach was progressively targeted by censorship regimes and a growing number of university-trained specialists, particularly physicians from the *Academia Médica Matritense*. These experts, following the technification of scientific inquiry, began to demand systematic and instrumental recordings of atmospheric phenomena for medicinal purposes, casting new doubt on the effectiveness of rustic methods and weather signs.[51]

That rustic methods for predicting weather futures were to be taken with a grain of salt was not a modernist critique. It was already evident in the work of Portuguese cosmographer Manuel de Figueiredo's *Chronographia, Reportorio dos Tempos* (1603). In his "da mudanças do tempo" chapter, Figueiredo provides a lucid—though by now familiar—description of rustic astrology in the art of weather prognosis.

> *"Astrologers and natural philosophers who write rustic literature—such as Ptolemy, Albert the Great, Bede, Aristotle, Virgil, Columella and others—affirm that the prediction of weather changes—like rain, serenity, winds, earthquakes, storms, cold, famine, pestilence—is more accurate by natural signs and stars [or atmospheric signs], which Ptolemy called secondary because they proceed from the first, than by any other signal obtained from experience. These [atmospheric signs], which Ptolemy calls secondary, are the signs that appear in the air, like the circles sometimes seen around the Sun, moon, and stars, and all [celestial] impressions, like comets. Astrologers call this type of prediction rustic astrology because those who do not know the science of Astrology predict by it."*[52]

[49] ibid at fols. 238v-238r; 242v; 247v.

[50] Cushman, Gregory. "Humboldtian Science, Creole Meteorology, and the Discovery of Human-Caused Climate Change in South America." *Osiris*, vol. 26, no. 1, 2011, pp. 19-44.

[51] In mid-eighteenth-century Spain, royal physician Francisco Fernández Navarrete (1680–1742) spearheaded one of the first institutional efforts to systematically record atmospheric phenomena. After moving from Granada to Madrid to serve Philip V, he presented a research program to the Academia Médica Matritense in 1737 that linked meteorological observation to medical practice. His plan required members to submit monthly reports on diseases and local weather, which were compiled and published as the *Ephemérides Barométrico-Médicas Matritenses*. Using "the common barometer of England and the Florentine thermometer", Fernández Navarrete conducted the initial measurements until October 1737, when José Hortega, the Academia's perpetual secretary, took over and continued the work until 1746. *see* Rico y Sinobas, Manuel. "Estudios Meteorológicos y Topográficos-Médicos en España en el Siglo XVIII." *Siglo Médico*, no. 215, 1858; Alberola Romá, Armando. "Tiempo, Clima y Enfermedad en la Prensa Española de la Segunda Mitad del Siglo XVIII: Diarios Meteorológicos y Crónicas de Desastres en el *Memorial Literario*." *El Argonauta Español*, no. 12, 2015; García Hourcade, Juan Luis. *La Meteorología en la España Ilustrada y la Obra de Vicente Alcalá Galiano*. Academia de Artillería de Segovia, 2002.

[52] Figueiredo, Manuel. *Chronographia, Reportorio do Tempos, no Qual se Contem VI Partes*. Jorge Rodriguez, 1603, Quarta Parte, ch. 3, "Da Mudanças do Tempo," fols. 151r-152v.

Except for the last comment, Figueiredo repeats Chaves and Pérez de Vargas's use of "rustic astrology" almost verbatim to describe weather prognosis beyond astronomical methods. He breaks weathercasting indicators into "natural signs", "rustic astrology" (or atmospheric signs), and "sign[s] obtained by experience". Without a complete profile of each category, we can only assume that "natural signs" are astronomical / astrological and handled by trained experts, "rustic astrology" is a more accessible forecasting method that relies on closely examining atmospheric phenomena, and "sign[s] obtained by experience" are understood to be traditional, heuristic techniques obtainable on demand and confined to the customs and traditions of a group or community. It is unclear if Figueiredo targets a specific group when he contrasts "rustic astrology" with "the science of Astrology" and, by extension, those who practice it. At the very least, he seems to be drawing a line between astrologers and natural philosophers who sensibly curate this knowledge and the consumers and practitioners who take this information and apply it freely—and perhaps recklessly—in their contexts.

Figueiredo's objections that predictions based on "rustic astrology" should not be regarded as "the science of Astrology" did not prevent him from creating *sinaes* that ground weathercasters in their local ecosystems. He often encouraged them to closely observe local atmospheric and environmental phenomena—an aspect more commonly linked to "rustic astrology". Moreover, while crafting the *sinaes*, he even references the region's historical meteorological events, directing *repertorio* readers to recall past climatic experiences when pursuing weather soundings:

> *"When the northeast wind blows, and clouds near the horizon are a mixture of black, red, or white, it means snow for three days, and if it occurs during autumn or summer, it is a sign of hail and frost. In the high plains, the effects will be greater. The snow will last longer, as in Salamanca in 1589, [when] snow began to fall on St. Lucia Day [13 December] and ended on Palm Sunday [2 April]. During that time, the majority of the Tormes froze, allowing students to cross on foot over it. And it also rained all day with hail, in such quantity that on the street where pipes empty stormwater, great piles of hail formed, that people filled [many] sacks. These signs will not be as effective for those who [predict] in warm lands because the cold does not work rigorously there."*[53]

Like Avelar, Figueiredo developed weathercasts that blend the region's climate change history and embed practitioners in their local environment. He integrates trade winds and topography with past meteorological events to demonstrate the wisdom and value of localised weather information. This approach enhanced practitioners' anticipatory capacity, especially in regions known for their climate variability. Positioned on a plateau by the Tormes River, Salamanca is depicted not only as a region prone to cold fronts and heavy precipitation but also as one that has recently experienced unusual and severe snowfalls followed by severe subzero temperatures. Figueiredo recalls the freezing of the Tormes and the heavy accumulation of hail on the streets to illustrate the dangers posed by these elements, the importance of selecting the correct *sinaes* for accurate weather prediction, and, more intriguingly, the idea that the duration and intensity of these climate events (~110 days of snow, hail, and rain) signal broader climatological shifts rather than typical seasonal variations.

[53] ibid at fols. 163v-163r.

Avelar and Figueiredo were not unique in tailoring their forecasting techniques to the region's topography and past climate experiences; their Spanish counterparts followed similar paths. They curated meteorological content, urging readers to engage with their ecosystems judiciously and sensorially to extract anticipatory weather knowledge. Rodrigo Zamorano improved upon Aristotle's theoretical framework of "occidental winds" by combining new climatological data from the *Relaciónes Geográficas* with a nuanced understanding of how Iberian phenological and environmental systems influence these winds. Building on the classical classification of winds, Zamorano emphasised the need to adjust these basic concepts using empirical and experiential data. "Everything said about the Winds must be regulated according to the nature of each land because they do not have the same effect everywhere", he observed. By revising the theoretical assumption that the "Western Winds" were "universally cold and humid", as discussed in the Introduction, Zamorano shifts the focus to their complex global trajectory. This approach emphasises how the winds' characteristics evolved in response to local geography, allowing him to reassess the nature of the "Oriental", "Meridian", and "Septentrional" winds as well.[54]

For the "Meridian" winds, Zamorano compared their characteristics across the Atlantic. He notes that these winds go by many names: the Greeks called them "Noto", the Romans "Austro", sailors referred to them as "Sur", and in Castile, they are commonly known as "Abrego". While these winds are often described as "hot and humid" and "withering, noxious, and pestilent" in "southern regions like Chile, their effects in Castile resemble those of the Cierzo, bringing ice and lots of snow".[55] Linking the reverse effects of the Abrego across hemispheres conveyed the idea that *repertorio* weathercasts were curated with global weather patterns and local environmental factors in mind. His claim that the Abrego brings "ice and snow" to Castile while generating "heat and humidity" in Chile signalled a new phase in early modern weather theorisation—one attuned to the dynamics of atmospheric circulation and hemispheric pressure systems. This insight gave *repertorio* weather soundings a transregional dimension.

His proto-description of the Coriolis effect—caused by Earth's rotation, which makes trade winds swerve left in the southern hemisphere and right in the northern—reveals the evolving nature of Iberian weather theorisation in light of new information from the New World. Understanding the opposing directions of the trade winds across the Atlantic and their changing characteristics in relation to the landscape was foundational to Zamorano's work in the *Casa* and to the creation of his navigation manual, *Compendio del Arte de Navegar* (1588). He recognised the critical importance of translocal atmospheric data for updating the *Padrón Real* and improving the forecast quality of future droughts and famines for the Spanish Crown.[56]

Zamorano's pursuit of high-resolution *señales* reflected a broader ambition to harness applicable meteorological insights for the common good, particularly to safeguard agriculturalists and their harvests. He emphasised the harmful effects of irregular weather on soil fertility, warning that "too much rain in spring and summer causes [soil] sterility" and that "frequent and heavy hail throughout the year usually destroys trees, vineyards, wheat, and causes [soil] sterility". He also noted that when the seasons are "deprived of their own qualities", likely indicating the presence of abnormal weather leading to crop failures, "it signals scarcity".[57] Zamorano identified some causes of soil erosion, such as excessive rain and heavy hail, but he did not clarify what led the seasons to be "deprived" of their usual characteristics. Was he merely recording rare occurrences of unseasonal weather, a common practice among weather chroniclers, or were these

[54] Zamorano (n 2) *supra* at fols. 76v-77v.
[55] ibid at fols. 77v-77r.
[56] Portuondo (n 27) *supra* at 96-101.
[57] Zamorano (n 2) *supra* at fols. 278v; 278r; 279v.

observations subtle acknowledgements of climate change?[58] To confront such unseasonable variability, Zamorano advised using long-range, annual prognostication methods like the *cabañuelas*—weather soundings based on the atmospheric conditions of specific days.

Traditionally, Zamorano explained, *cabañuelistas* observed the sky during predetermined times of the year—typically the first twelve days of January or August, coinciding with the winter and summer solstices—to predict the weather for the following year. He favoured the winter solstice over the summer solstice, aligning with ancient writers like Democritus and Apuleius rather than the summer solstice preferred by the "vulgo" (ordinary people).[59] Both *señales* and *cabañuelas* were grounded in sensory expertise and emphasised the importance of annual climate change awareness. Tracking annual shifts in atmospheric conditions through changes in phenological rhythms provided essential information for planning crop rotations, managing supplies, and determining relocation strategies. Rooted in the belief that knowing the land meant knowing the weather, long-range prognostications forged a vital bond between local ecological knowledge and predictive insight—a notion often eclipsed by technocratic visions of climate action.

For weather theorists and practitioners, the unfamiliar environments of the New World posed significant challenges. Gathering meteorological data required creative adaptation and the development of new texts and techniques, regardless of their origin. Enrico Martínez, the "king's cosmographer", illustrates this in his *Reportorio de los Tiempos, y Historia Natural desta Nueva Espana* (1606). He writes, "I wrote this repertorio because the books brought to these parts (Mexico) from the Kingdom of Spain do not suit the Meridian and Climate of this land".[60] To address this apparent gap in theoretical latitudinal climate, Martínez combined relevant astronomical calculations with local climate data in a detailed "Lunario y Pronóstico de los Temporales" ("Lunary and Weather Forecast") covering the years 1606-1620.[61] The "Lunario" features solar and lunar conjunctions, quadratures, and oppositions, tailored explicitly to the meridian of Mexico City, making the *Reportorio*'s forecasts more accurate and valuable for weather-dependent activities in New Spain.

Before offering nearly thirty folios of weather predictions, Martínez opens with a "warning" urging readers to ensure accurate prognostications by observing "the signs the Moon gives before and after the first quarter and full conjunction". When lunar and solar signs align with the forecast, he writes, "one could be sure that the effects will be effective because these are signs that the air is willing to receive such quality; but if the signs are different, the effects will be delayed". For instance, "the May 1606 conjunction" promised humid and stormy weather, confirmed when "the Sun rises or sets more than ordinary" or when the Moon's crescent appears thick-horned and dimly greenish. If instead "the weather shows signs of serenity", the outcome would differ. Martínez further cautions that local conditions—especially in regions as climatically diverse as New Spain—make uniform predictions arduous, since "it is impossible that one natural cause affects equally all these regions".[62] His "warning" thus encapsulates both the promise and the limits of Iberian weathercasting: it invites farmers and sailors to test prognostications empirically by comparing celestial configurations with visible atmospheric cues,

[58] Dimick (n 23) *supra* in the introduction considers these sorts of acknowledgements in literary sources as discursive and real reflections of disrupted phenological patterns associated with climate change. I agree: this is the literary evidence, akin to rogation ceremonies, that people were not unaware of climate change but highly attuned to it and its transregional spread during this period.

[59] Zamorano (n 2) *supra* at fol. 279v.

[60] Martínez, Enrico. *Reportorio de los Tiempos, y Historia Natural desta Nueva España*. Henrico Martínez, 1606, "Prólogo."

[61] Martínez's second edition extends the "Lunary and Weather Forecast" all the way to 1640.

[62] Martínez (n 60) *supra* at fols. 55v-55r.

bridging theory and observation. By foregrounding environmental diversity and local verification, Martínez reveals a crucial insight—that European astrometeorology, though theoretically refined, required adaptation to the distinct ecologies and meteorological systems of the Americas.

Whereas a broader regional sensibility underpinned the weathercasts of Chaves, Avelar, and Figueiredo—who integrated seasonal rhythms, past climate anomalies, and spatial demarcations directly into their systems of signs—Martínez handles local variability at the level of practice.[63] His warning urges readers to verify whether their own region's "disposition of the air" corresponds to the celestial indications and to adjust their expectations when it does not, placing localisation not in the design of the method but in its moment of application. Thus, while all four assume that forecasting is necessarily situated, they distribute the work of localisation differently: Chaves, Avelar, and Figueiredo embed it in method, whereas Martínez delegates it to use.

Indeed, during the 1607 effort to drain Lake Texcoco and mitigate flooding around Mexico City, Martínez, the recently appointed chief hydraulic engineer for the *Desagüe* project encountered the Valley of Mexico's unforgiving and diverse hydrological system, starkly different from those he encountered in Europe.[64] Working on the *Desagüe*, he faced the challenges of unfamiliar precipitation patterns, complex water tables, seasonal and elevational variability that triggered meltdowns, and intertropical convergence zones that spawned tropical storms and hurricanes.[65] These conditions proved daunting for Martínez and other European hydraulic engineers who attempted to apply Old World, geographically specific agrosystems and waterworks as universal solutions to the new ecosystem they encountered.[66] Despite its limitations, Martínez's weather forecasts offered the most up-to-date (though not the most regarded) meteorological intelligence available to Spaniards and local residents of this region. For instance, his November 1607 forecast, which coincides with the start of the *Desagüe* construction, reads:

> *"Saturday, 3 November, the Moon opposes at 2:48 [pm] in the afternoon at eleven degrees of Taurus, with cool and cloudy weather at the beginning and end of the quarter.*
> *Sunday, 11 November, the Moon makes the third quarter at 8:04 [am] in the morning at 20 degrees of Leo. This shows humid weather.*
> *Monday, 19 November, the Moon is new at 5:13 [am] in the morning at 27 degrees of Scorpio, temperate and dry weather.*
> *Monday, 26 November, the Moon is in the first quarter at 3:08 [am] in the morning at 4 degrees of Pisces; it will be windy and cloudy weather."*[67]

These weathercasts were carefully thought out and informed approximations rather than exact predictions. They were well-structured meteorological judgements outlining possible atmospheric futures for weather-dependent readers and sectors of society. They were not definitive or high-resolution forecasts.

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[63] *see* (n 39) *supra*.

[64] Martínez travelled extensively throughout Europe before coming to the New World. Born in Germany between 1550 and 1560, he moved to Seville at a young age, possibly due to the Martins, a German printing family that had settled there at the time. As a young adult, he left Seville to study liberal arts in Germany and mathematics in Paris. He travelled to Poland and Eastern Europe and, finally, settled in Madrid, where he was appointed as a translator of German texts for the Inquisition. *see* Mathes, Valerie. "Enrico Martínez of New Spain." *The Americas*, vol. 33, no. 1, 1976, pp. 62-71.

[65] Leffler, Robert. "Is the Meltdown of Tropical Glaciers a Signal of Climate Change?: Going, Going, Gone." *Weatherwise*, vol. 58, no. 3, 2005, pp. 36-42.

[66] For the *Desagüe*, *see* Candiani, Vera. *Dreaming of Dry Land: Environmental Transformation in Colonial Mexico City*. Stanford University Press, 2014.

[67] Martínez (n 60) *supra* at fol. 61v.

Instead, they were localised, pliable, and contingent weather projections—"weather soundings"—requiring more atmospheric data to enhance accuracy. Recognising the need for additional information, Martínez refined his weathercasting methods by adopting two principles from his observations in New Spain. The first is the twelve-day method for predicting long-term weather, known as the *cabañuelas*. As noted earlier, this was Zamorano's preferred approach because it relied on sensory expertise and underscored the importance of observing year-to-year climatic variation. In contrast, the second considers the weather variability on the day the *Pleiades* set into the horizon as the Sun rises, a phenomenon typically observed in Mexico on 17 November.

On that day, we can imagine weathercasters from all walks of life going outdoors to scan the sky for atmospheric variabilities: "[i]f the weather is mild, foggy, or rainy, the first three months of the year will be mild", but "if it is dry and fair, it denotes three months of cold and harsh weather"; moreover, "if it rains a day before or after this day (17 November), it is a sign that the rainy season will arrive on time the following year", and "if it doesn't rain 17 November or for many days afterwards, it will be a sign of drought or intemperate weather for the following year".[68] Martínez's November *señales* added redundancies and layers of specificity, which prudent and curious readers combined with the results of other weather predictions to compose a more detailed forecast. Martínez's *Reportorio*, as the other *repertorios* written by Iberian weather theorists, equipped readers with a catalogue of textual tools and techniques to predict short and long-term climate. Many tactics presented in these vernacular texts required astronomical knowledge and a set of working principles that insisted on engaging with the natural world in all its unfamiliarity and variability.

Martínez and the other weather theorists discussed offered essential meteorological insights to regions and audiences struggling with the climatological challenges of the Little Ice Age. By encouraging *repertorio* users to immerse themselves in their local environments and gather anticipatory weather knowledge by observing phenological changes, instances of climate change were inevitably documented. Incorporating this information into their weather soundings successfully turned theoretical ideas into actionable strategies that *repertorio* consumers could deploy to anticipate climate irregularities. Iberian weather soundings then amalgamated weather intelligence from across the Atlantic, capturing the first murmurs of a changing climate.

IV. 'It Used to Be Temperate': The Climate Change of the *Repertorios*

Global meteorological patterns began to change as the warmer climate of the Medieval Climate Anomaly began to cool in the thirteenth century.

This shift, driven by periods of increased volcanic activity, low solar radiation, and changes in air chemical composition and atmospheric feedback mechanisms, resulted in a 0.6ºC drop in average annual temperatures. These cooler conditions triggered intense and irregular climate variations, particularly in the Northern Hemisphere. The temperature decline affected major atmospheric systems, such as the Northern Atlantic Oscillation and the Global Conveyor Belt, which are crucial for shaping European weather patterns. These changes disrupted polar wind patterns, altering surface currents and the temperature and salinity of ocean waters that regulate deep currents and upwelling.

In the Pacific, these disruptions also contributed to potentially abnormal El Niño Southern Oscillation events. Global climate alterations caused unseasonable and extreme weather events, including hailstorms, downpours, floods, blizzards, heatwaves, and droughts across Europe and, to a lesser but still significant extent, throughout

[68] ibid at fol. 74v.

intertropical convergence zones.[69] Elsewhere, I have explored climate shift awareness through weather practices and infrastructure on both sides of the Atlantic.[70] Here, however, my focus is on demonstrating how *repertorio* writers recorded the unseasonable weather brought on by the Little Ice Age.

Following the catastrophic flood of 1629 that inundated Mexico City, a *junta* was assembled to confront the aftermath and address the failure of the *Desagüe* drainage system. Among the experts invited was Andrés de San Miguel, an Andalusian architect and hydraulic engineer with a long history of projects for the crown and the Carmelites in New Spain, dating back to the 1590s. During his evaluation of the 1629 flood, Andrés criticised Martínez's (the same Martínez of the *repertorios*) handling of the desiccation project. Not only did he narrow the problem to infrastructural design issues, but, more importantly for us, he recognised a "change in weather in the last few years"; more precisely, "the way it rains" in the region.[71] He noted:

> *"It used to be temperate, raining most always by day, beginning at one or two until four or five in the afternoon, such that one day's rainfall would be cleared up by the next, causing little rise in the lake [Texcoco]. Nowadays it rains at all hours, and more commonly at night than day … While in years past the torrential downfalls did not remain on the ground long after the Sun came out to clear up the land and make it ready for more rain, the rains these last years … are continuous, drench the land and greatly enrich and augment the springs … such that one day of these rains has a greater effect than a month of crazy downpours."*[72]

Andrés's description reveals his deep awareness that Mexico's weather had changed between his arrival in the 1590s and his evaluation of the *Desagüe* in 1630. As he remembered, "it used to be temperate", rain evaporated daily and caused "little rise in the lake", but in "these last years", "it rains at all hours" and continuously, which has impacted evapotranspiration and increased the water levels in springs and rivers. Extraordinarily, his explanation fits within the timeframe of the so-called Colonial Mexican Pluvial, when polar air outbursts caused by low solar activity and volcanism injected moisture into intertropical zones, changing precipitation patterns from convective to cyclonic rainfall. As Bradly Skopyk writes, the Colonial Mexican Pluvial, the most critical wet and cold period in Mexico's climate history in the last seven hundred years, was fully underway during the first half of the seventeenth century.[73] I argue that its effects align with those recorded by Andrés and later by Martínez.

To presume that Andrés conceived climate change, its causes, and weather effects as we do now would be wrong.[74] Yet during his tenure in New Spain, he detected fluctuations in precipitation regimes and moisture saturation in natural water runoff systems, leading to cataclysmic events. Shifting

[69] Aberth, John. *An Environmental History of the Middle Ages: The Crucible of Nature*. Routledge, 2012, at 50. *see also* White, Sam. "The Real Little Ice Age." *The Journal of Interdisciplinary History*, vol. 44, no. 3, 2013, pp. 327-352; Grove, Jean. *The Little Ice Age*. Routledge, 1988; Skopyk, Bradley. *Colonial Cataclysms: Climate, Landscape, and Memory in Mexico's Little Ice Age*. University of Arizona Press, 2020; Degroot, Dagomar, et al. "Towards a Rigorous Understanding of Societal Responses to Climate Change." *Nature*, vol. 591, 2021, pp. 539-550; and Oram, Richard. *Where Men No More May Reap or Sow: The Little Ice Age, Scotland 1400–1850*. John Donald, 2024.

[70] León Báez, Juan Fernando. *Weather Soundings: Vernacular Meteorology in Spain and Mexico during the Little Ice Age*. Northwestern University, 2025.

[71] For Andrés's criticism of Martínez's building a drainage tunnel, instead of a trench as he proposed, *see* Candiani (n 66) *supra* at 83.

[72] Archivo General de la Nación, *Desagüe: Fray Andrés de San Miguel Regarding the Drainage of Mexico City,* vol. 3, 1631, fols. 333v–34v. *see* Skopyk (n 69) *supra* at 31.

[73] ibid at 31.

[74] *see* (n 58) *supra*.

atmospheric patterns that disrupt quotidian activities and waterworks projects have the added benefit of amplifying people's capacity to perceive unseasonal climate variability. A shifting climate also tests people's ability to scan the skies for signs of bad weather, forcing improvisation and triangulation to attain better weather futures. *Repertorio* weather theorists, in this regard, had to adjust to their changing environment by fine-tuning and multiplying alternative ways to decipher abnormal meteorological phenomena.

Martínez, for example, notes that "experience has shown a change in the temperament (temperature) of these lands in New Spain, as in other parts of the world, such that some [lands] that used to be hot are now temperate or almost cold".[75] Just like his critic, Andrés, Martínez admits—based on what "experience has shown"—that regional and global climate patterns had shifted from "hot" to "temperate" and "almost cold". Reacting to these climatological shifts, Martínez's annual forecasts account for the Little Ice Age's forcings on Mexico's rainy season. Recognising this early form of climate consciousness is essential for understanding how past climatic shifts informed literary production, especially vernacular weathercasts designed for readers seeking regionally attuned forecasts.

In his 1606 forecast, Martínez boldly predicted "heavy rains", "downpours", and "tempestuous rainstorms" for May—a month earlier than the usual onset of Mexico City's rainy season, which typically spans from June to September. The following year, his 1607 forecast anticipated "cold" and "cold winds" for August and September. A comfortable, mild inland climate and hot, sweltering conditions on the coast usually characterise these months. Yet Martínez described them as being "cloudy with cold winds", "temperate with low humidity and cold", "humid and cold", and "cloudy and cold".[76] These fine-tuned weathercasts reflected a deeper consciousness of decadal climate shifts, overlapping with detailed guidance on interpreting atmospheric and phenological signs of early winter and rainfall. This knowledge sharpened both individual and communal foresight in anticipating weather changes, proving indispensable across a wide range of sectors, including censored fields such as folk healing and weather exorcism.

Andrés and Martínez's observations of a shift toward colder and wetter convective systems in New Spain went beyond speculative corrections to developing region-specific weathercasts. Their writings captured tangible environmental changes that directly influenced local labour, health, and colonial settling. *Repertorio* weathercasts likely assisted settler communities in adapting to the unfamiliar climate variability of Mexico's central valley. As Georgina Endfield explains, building dams, developing irrigation systems, and managing food distribution networks in regions already facing severe climate pressures require reliable weather information.[77]

Just as the *Relaciónes Geográficas* were deliberately crafted as weather intelligence briefs for colonial agents and settlement strategies, this newly uncovered evidence shows that *repertorios* similarly rose to prominence across the Atlantic by offering those same actors the critical weather information and strategic guidance they relied upon.

Indeed, local inhabitants and Spaniards turned to the calendric, weathercasting, and medicinal information of the *repertorios* to navigate not only unseasonal weather but also climate-induced health challenges. In most *repertorios*, calendric, zodiac, and lunar charts were strategically placed alongside weather predictions. This arrangement was deliberate, enabling readers to use these resources in tandem to determine the optimal times and atmospheric conditions for medical procedures such as bloodletting and

[75] Martínez (n 60) *supra* at fol. 172v.
[76] ibid at fol. 60v.
[77] Endfield, Georgina. *Climate and Society in Colonial Mexico: A Study in Vulnerability*. Blackwell, 2008, at 102.

purgations and to identify periods of low "seasoning sickness."[78]

As Lori Diel illustrates in *The Codex Mexicanus: A Guide to Life in Late Sixteenth-Century New Spain*, contributors to the *Mexicanus*—a pictorial manuscript created by Christian Nahuas—did more than merely borrow meteorological information from Spanish *repertorios*. They skilfully combined and synthesised this knowledge into images and charts tailored for a local audience.[79] Attempting to extract astromedical knowledge from these sources while ignoring weathercasting signs and predictions was possible but impractical. The overlap, seepage, and connective tissue between these sections were too extensive for colonial and local agents to disregard. Doing so would have deprived physicians, healers, farmers, and settler communities of high-impact anticipatory knowledge—essential for their survival in a region where the still-unfamiliar environment remained unpredictable to them. The interplay between weathercasts, decadal climate predictions, and astromedical information in the *repertorios* created a redundancy effect that served as a cultural safety net. When one theory, technique, or indicator failed to diagnose or forecast accurately, the others could still effectively approximate and even record different atmospheric events and conditions. The proliferation of weathercasting signs within these texts hints at a shared understanding among authors—and the readers seeking this knowledge—that irregular climate variability disrupted accurate weather prognosis. Iberian weather theorists recognised that the "prudent and curious reader" to whom they addressed their work would carefully triangulate and integrate every available piece of information, strategy, and prediction to manage climate risk, though not always with complete success or precision.[80] Notably, this is the kind of cross-referencing at the heart of building climate proxies.[81]

Just as the "prudent peasant" of the Middle Ages mitigated environmental risk by distributing agricultural plots across diverse microclimates, early modern individuals employed similar strategies to enhance decision-making during weather extremes.[82] The *repertorios*, with their miscellaneous and referential nature, facilitated cross-sectional associations between time-sensitive, ready-to-use, and do-it-yourself forecasts, enabling the development of practical and complex adaptation strategies. In this context, we are witnessing a premodern form of weather knowledge integration, finely tuned to the disturbances characteristic of the Little Ice Age and capable of fostering individual and communal resilience in the face of climate impacts.

The wide distribution and diverse readership of the *repertorios* across different Iberian contexts indicate that these texts' references to irregular, severe, or changing weather reflect communities actively confronting hazardous conditions and searching for ways to anticipate and reduce their impact. We have already seen examples of this when Figueiredo developed weathercasts by blending well-established environmental indicators with the region's climate history. By documenting events like the "freezing of the Tormes" and the "heavy accumulation of hail on the streets of Salamanca" alongside wind, cloud, and rain indicators, Figueiredo connected disturbances

[78] For "seasoning sickness", *see* Seth, Suman. *Difference and Disease: Medicine, Race, and the Eighteenth-Century British Empire*. Cambridge University Press, 2018.

[79] Diel, Lori Boornazian. *The Codex Mexicanus: A Guide to Life in Late Sixteenth-Century New Spain*. University of Texas Press, 2018, at 61-66.

[80] Inspiration for this paragraph came from Grau-Satorras, Mar, et al. "Prudent Peasantries: Multilevel Adaptation to Drought in Early Modern Spain (1600–1715)." *Environment and History*, vol. 27, 2021, pp. 3-36. The authors use the idea of "redundancy" as "safety-net" when talking about the wide range of adaptation and mitigation strategies seventeenth-century peasants families in Catalonia developed overtime to cope with climate change, especially drought.

[81] *see* (n 24) *supra*.

[82] For the idea of the "prudent peasant" and "scattering plots across micro-climates" as a "risk avoidance" tactic to cope and adapt to environmental stressors, *see* McCloskey, Donald. "The Prudent Peasant: New Findings on Open Fields." *The Journal of Economic History*, vol. 51, no. 2, 1991, pp. 343-355. McCloskey is mainly interested in the Middle Ages, but his findings can be applied to the early modern period.

typical of the Little Ice Age to observable, ground-level weather patterns.

Weathercasts integrating socioecological elements—bridging theory and nature and classical and rustic signs—are essential in confronting disrupted climate patterns. Annual, seasonal, and daily weather prognosis has been shown to enhance resilience by equipping societies with the skills to interpret the skies and predict unseasonal occurrences. These weather working skills enable vast sectors of the population to anticipate and respond to the impacts of climate change more effectively.[83] The *repertorio* weathercasts enthusiastically confirm that idea, even though it is only partially articulated in the textual record.

For instance, Pérez de Vargas noted unusual air circulation and atmospheric qualities—describing conditions as "windy", "dusty", "dry", and "hot" during winter—as early signs of scarcity, pestilence, and intense heat in the upcoming spring and summer. Similarly, Zaragozano interpreted natural phenomena such as the flickering of lamps, the colour changes in ponds, the unusual crowing of roosters, and the shimmering of sunbeams as indicators of unseasonal rain and rising water levels. Avelar emphasised the importance of observing the behaviour of "little birds," "Sovereign Pin Oaks", and "ants" to predict a "great winter" and the "end of the great cold". Chaves, on the other hand, offered a comprehensive method to forecast five types of weather—"fair", "windy", "rainy", "cold", and "tempestuous"—by interpreting a combination of astronomical, atmospheric, biological, and material signs.

In directing practitioners into their local, climate-affected environments to collect anticipatory weather data, these *señales* inadvertently heightened awareness of climatic shifts.

Far from abandoning classical explanations of climate and weather, Iberian theorists braided them with insights drawn from lived experience—whether gathered in distant seas or in their own fields—and with the enduring stock of European rustic lore. As Stuart Schwartz notes, moments of climatic strain often cast into relief "alternative beliefs and lore about wind and weather, which, combined with prayer, rites, relics, and Church liturgies, provided a sense that men and women were not entirely powerless in the face of natural phenomena".[84] Set within this cultural landscape, the *repertorio* approach emerges as a distinctly Iberian response to unseasonal variability: a malleable, time-tested weathercasting method that spoke to communal needs and met the growing pressures of climate arrhythmia.

V. **Conclusion**

The *repertorio* genre illustrates how Iberian weather theorists developed and circulated diverse, localised forms of anticipatory climate knowledge. Emerging at the intersection of New World discoveries, classical and vernacular meteorology, and the climatic volatility of the Little Ice Age, these texts reveal a dynamic and pluralistic landscape of weather expertise. People from all social backgrounds turned to the *repertorios* for their accessible forecasts and practical guidance. Though their theoretical and empirical *señales* or *sinaes* were designed for specific contexts and professions, their flexibility encouraged improvisation and adaptation amid censorship and shifting market demands.

Li introduced the genre with Aristotelian astrometeorology, which predicted seasonal precipitation through close observation of celestial bodies, such as the Sun, Saturn, and Aquarius. Chaves expanded its predictive range by encouraging readers to select geographically relevant phenological

[83] *see* Eakin, H. "Seasonal Climate Forecasting and the Relevance of Local Knowledge." *Physical Geography*, vol. 20, 1999, pp. 447-460; and Camacho-Villa, Tania Carolina, et al. "Mayan Traditional Knowledge on Weather Forecasting: Who Contributes to Whom in Coping with Climate Change?" *Frontiers in Sustainable Food Systems*, vol. 5, 2021, 618453.

[84] Schwartz, Stuart. *Sea of Storms: A History of Hurricanes in the Greater Caribbean from Columbus to Katrina*. Princeton University Press, 2015, at 12.

indicators to forecast favourable or hazardous weather for specific communities and regions. His framework was later refined by Pérez de Vargas, Zaragozano, and Valentín de la Hera, who worked under Inquisitorial scrutiny and adapted to new reforms, including the adoption of the Gregorian calendar. Despite ecclesiastical restrictions on "judiciary astrology", meteorological judgements persisted through censorship waves owing to their practical utility in agriculture, navigation, and medicine.

Portuguese figures like Avelar and Figueiredo localised their *sinaes* by integrating ecological observation and regional climate history, linking weather prediction to sustained environmental engagement. Spanish contemporaries such as Zamorano and Martínez further refined these methods by incorporating insights from the transatlantic exchange. The distinct ecologies of the New World—shifting winds, topographical diversity, and hemispheric asymmetries—made it clear that no single natural cause could explain weather everywhere. Martínez thus advised practitioners to cross-reference astronomical data with rustic, environmental, and phenological signs to produce reliable, site-specific forecasts.

Over time, *repertorio* authors fused astrometeorological theory with time-sensitive observations of Little Ice Age disturbances. This synthesis, fuelled by new geographic information and climatic pressures, made their forecasts indispensable to a wide range of users—from sailors and peasants to engineers and administrators—who relied on them to anticipate droughts, hailstorms, and frosts. By blending classical, empirical, and vernacular traditions, these texts and their weather *señales* transformed Iberian meteorology into a pragmatic, participatory science rooted in everyday experience—a vital perspective that has remained largely overlooked in *repertorio* studies. By foregrounding the *señales* as dynamic tools of environmental interpretation, the *repertorios* emerged as central to the history of anticipatory weather reasoning during periods of climate stress. Their authors responded to shifting conditions by integrating sensory expertise, inherited meteorological lore, and nascent observational practices. This approach bears a striking resonance with contemporary multi-model forecasting systems: much like modern methods that weigh probabilistic models against experiential judgements and local ecological cues, the *repertorios* relied on pluralistic ways of identifying and interpreting unseasonable weather.

My analysis then invites a reimagining of how Iberian thinkers redefined weather observation as a flexible, experiential, and locally grounded science of the sky. Their integrative approach bridged the gap between natural philosophy and environmental practice. By teaching an expanding audience to read the heavens alongside the landscape, this study reveals how these texts made meteorology participatory and adaptive, responsive to cosmic rhythms, terrestrial affordances, and climate change. In documenting atmospheric irregularities and ecological disruptions, *repertorio* authors not only registered the material effects of the Little Ice Age but also forged a new understanding of human–weather relations. The *Repertorio de los Tiempos* contains crucial information for rethinking how premodern societies used vernacular texts to navigate a world—not unlike ours—increasingly shaped by climate uncertainty.

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Dams, the Dust Bowl, and Dispossession: Climate Security through Hydropower Construction in the Early American West

Dover Sikes*

* MPhil Candidate (Department of Land Economy), University of Cambridge, UK

KEYWORDS

climate security, dam construction, hydropower, Bonneville Dam, sociotechnical futures

ABSTRACT

Our climate crisis poses twin challenges that may contribute to increased investment and reliance on hydropower. Meeting the Paris Climate Agreement requires that renewable energy must provide 65% of the world's energy supply by 2050. Growing unpredictability in rainfall patterns also make advanced water management for agriculture and drinking water paramount to health and economic wellbeing.

To understand the possibilities and limitations of the growth of hydropower and large-scale environmental infrastructure projects, this article examines the cultural and political history of dam building in the North American West in the early 20th century. It takes the construction of the Bonneville Dam (1933-1937) as a case study to examine how environmental crises shape hydropower and infrastructure development writ large.

Employing the framework of "sociotechnical futures", the article undertakes a comparative analysis of President Franklin Roosevelt's speeches, Woody Guthrie's Bonneville Power Administration-commissioned songs, and Chief Johnny Jackson's oral history. It argues that politicians and cultural leaders leveraged narratives of environmental mismanagement from the devastation of the Dust Bowl to imagine federal dam-brought prosperity in the Pacific Northwest. In doing so, they developed clear images of the settler American who would benefit.

Analysing these perspectives can reveal how ideas about the Dust Bowl and regional identity transformed the physical landscape of the Columbia River Basin. Engaging with this history highlights how political contexts and environmental anxieties may legitimise infrastructure projects that advance dominant groups' interests while harming the interests of others.

I. **Introduction**

"We like Oregon. It's green and cool and there's not so much dust", recounted a recent migrant to Oregon to a reporter in the summer of 1938. Speaking from a "half-tent, half-shack home", the mother of two had fled with her family from Kansas, joining tens of thousands of refugees escaping the disastrously dry plains of the "Dust Bowl" of the North American Midwest for the safer climate and employment opportunities of the Pacific Northwest.[1] While the state's economy struggled to accommodate the sudden influx in farming hopefuls, an article in the Medford Mail Tribune brought some reason for optimism: with accelerated construction and the use of proper "irrigation, drainage, clearing and flood control" migrants and residents could benefit from an additional 10 million acres of farmland across Oregon, Washington, and Idaho. Oregon's reputation as a "land of promise" would thus depend on its water management.[2]

Dams likely figured as a crucial component of the technological mastery envisioned by the Tribune. Less than a year prior, the Bonneville Dam on the Columbia River had begun operation as the first federally-sponsored dam on the river. Today, it is one of the 470 dams on the river's main stem and tributaries that make it one of the most hydroelectrically developed river systems in the world.[3] The scale of such a project is difficult to overstate. Crossing more than 1,200 miles from the snow-capped mountains of British Columbia to the Oregon coast, the Columbia drains more water into the Pacific than any other river in North or South America. Its traditional nomenclature pays homage to its magnitude—in the language of the Chinook tribe who live near the lower Columbia, the river is "Wimahl", meaning "the big river".[4] For millennia, it has also been a hub of human and animal life; human presence dates back to 9,000 BP and its waters once boasted the largest Chinook, coho, and steelhead runs on Earth.[5] The Bonneville's appeal was varied: the dam promised rural electrification, easier navigation, continued employment opportunities, and, at least during the years in which the Dust Bowl raged, climate security. This development has come at a steep environmental, social, and spiritual cost—devastating salmon populations, halting the flow of sediment, and inundating settlements and sacred sites.

The damming of the Columbia was not done in one blow. Instead, over 42 years from 1933 to 1975, federal and state governments supported the construction of a number of dams.[6] Such dams now offer cheap, renewable electricity to more than 60% of people in the Pacific Northwest—an increasingly valuable asset in the era of the climate crisis.[7] Simultaneously, these dams are the subject of legal action.[8] In November of 2023, the White House agreed to settle a lawsuit led by Nez Perce, Yakama, Warm Springs, and Umatilla tribal nations over restoring northwestern

[1] My use of the term "climate" follows present-day scholarly conventions rather than the categories available to the Americans of this period. The documents I engage with reveal they did not understand their environmental uncertainties through a lens of "climate" or "climate change". However, their worries about potentially permanent drought, desiccation, and shifting seasonal patterns align closely with contemporary meanings of climate, justifying this anachronism for analytical clarity.

[2] "New Pioneer from Dust Bowl Finds Life Hard, Rough in Oregon." *Medford Mail Tribune*, 7 Jun. 1938. *Historic Oregon Newspapers*, University of Oregon.

[3] "Columbia Basin: Dams and Hydroelectricity." *Columbia Basin Trust,* 2018.

[4] "Naming the Columbia." *National Park Service,* 4 Jun. 2021. For Sahaptin-speaking peoples in present-day Washington, it is the "Nch'i-Wàna", also meaning "big river". Carriker, Robert, and William Lang. *Great River of the West: Essays on the Columbia River*. University of Washington Press, 2013, at 4.

[5] Early archaeological evidence of fishing communities points to human settlement having been established at least 9,000 years before present (before January 1, 1950): Carriker & Lang (n 4) *supra* at 8. *see also* Brown, Bruce. *Mountain in the Clouds: A Search for the Wild Salmon.* University of Washington Press, 1995, at 25.

[6] "Dams: History and Purpose." *Northwest Power and Conservation Council*, 2023.

[7] Wendel, JoAnna. "Hydropower Generation Projected to Rise, but Climate Change Brings Uncertain Future." *Pacific Northwest National Laboratory*, 21 Aug. 2024.

[8] *see*, for instance, Mize, Jeffrey. "Two Tribes Want Three Columbia River Dams Removed." *The Columbian,* 14 Oct. 2019.

salmon to the tune of one billion dollars.[9] Tension between environmental infrastructure development for some and justice for others is not a unique feature of the dams of the Columbia, and is instead visible in energy infrastructure and geoengineering investments around the world. Such clashes often trace back to a project's origins and intentions, prompting questions like: what did orchestrating figures perceive the benefits of dam building to be? For whom? What do their intellectual origins reveal about technological ambitions for managing nature in the early American West? And what can such lessons teach us about environmental infrastructure development today?

As the first major hydroelectric dam constructed on the Columbia, the Bonneville Dam provides a useful case study to examine the rise of hydropower in the region. Using three distinct voices—President Franklin Roosevelt in 1937, Woody Guthrie in 1941, and Chief Johnny Jackson in 1999—we can begin to make sense of such questions. All three come from different backgrounds. There is Roosevelt, the institutional power, a well-educated politician; Guthrie, the rambling counterculture figure who sang about the common man; and Jackson, a Cascades Indians Chief and fishing rights activist—and yet, all three illuminate the Bonneville. As this article will show, the Bonneville was a product of New-Deal-inspired dam building. Guthrie and Roosevelt leveraged the central and high plains climate insecurity of the Dust Bowl to justify the Bonneville and federal dam projects in the Pacific Northwest, while employing clear images of the white settler American who would benefit. Their omission of the impact of the dam on the Native Americans of the Columbia is complicated in the light of Chief Jackson's retelling of the creation of the Bonneville and the destruction it has brought his community.[10] Analysing these perspectives together reveals how ideas about the Dust Bowl and American identity transformed the physical landscape of the Columbia River Basin.

In the ensuing pages, the article argues that Roosevelt and Guthrie used Dust Bowl narratives to frame hydropower as a guarantor of white settler environmental security, obscuring the dispossession and ecological harm experienced by Native communities. It begins with a brief overview of relevant research within the fields of Science and Technology Studies (STS) and environmental history before clarifying its methodological approach. Next, it turns to the writings and recordings of Roosevelt, Guthrie, and Jackson to gain insights into the discursive practices that shaped the Bonneville, adding clarifying legal analysis from researcher Roberta Ulrich. The article concludes by connecting these historical arguments to present-day debates surrounding energy, climate governance, and infrastructure development.

II. **Literature Review**

Building from Jasanoff and Kim's foundational concept of "sociotechnical imaginaries", this paper contends that Roosevelt and Guthrie's imagined dam prosperity can reveal the cultural frameworks that underpinned hydropower and infrastructure investment in the Northwest. Jasanoff and Kim define sociotechnical imaginaries as "[c]ollectively held, institutionally stabilized, and publicly performed visions of desirable futures, animated by shared understandings of forms of social life and social order attainable through, and supportive of, advances in science and technology".[11] In doing so, it joins a growing body of scholarship that make sense of the form, function, and future of renewable

[9] Yachnin, Jennifer. "White House Pledges $1B to Restore Pacific Northwest Salmon, Steelhead." *Politico*, 14 Dec. 2023.

[10] Keeping with existing literature in the field and guidance from the National Museum of the American Indian, I use the terms Native American and Indigenous when referring to various Native peoples in the Columbia River region. Whenever possible, I attempt to use the specific names of individual tribes. *see* "Teaching & Learning about Native Americans." *National Museum of the American Indian*.

[11] Jasanoff, Sheila, and Sang-Hyun Kim,. *Dreamscapes of Modernity: Sociotechnical Imaginaries and the Fabrication of Power*. University of Chicago Press, 2015, at 4.

energy and geoengineering investment by centring its imagined impacts and assumed social contexts.[12] The value of this task is summarised by Jasanoff thus: the "ways in which we know and represent the world (both nature and society) are inseparable from the ways in which we choose to live in it".[13] Scholars have conducted similar investigations on different infrastructural projects at different times. For instance, O'Malley examines how oil pipeline expansion debates reflect "sociotechnical controversies over desirable sociotechnical futures", examining what visions it reflects "about those living within these borders".[14] This critical lens thus puts the Bonneville in conversation with modern stories of gas and pipeline construction, renewable energy initiatives, and other projects that derive form and function from their political and geopolitical contexts. This article thus produces new empirical evidence to unpack a historic example of infrastructure investment through this critical approach.

This study contributes to what Fladvad has called an "infrastructural turn in the social sciences".[15] Rather than treating the dam as a neutral entity, it acknowledges that "dams, roads and bridges and energy technologies ... are imbued with power relations and normative orders, as well as social meanings and imaginaries of the future".[16] While documenting both potentials and pitfalls of this early infrastructure investment, this article reflects the increasing acknowledgment of the potential of infrastructure to shape sociotechnological futures and effect ecological change.[17] Prior scholars have written on the ways in which infrastructure can organise people and land to benefit settler colonial states' control.[18] This article extends those insights by applying this framework to a case in the early 20th century.

Lastly, this paper builds on histories of environmental colonialism that study how settler anxieties about the climate have inspired large-scale utopian projects. Lehmann's *Desert Edens: Colonial Climate Engineering in the Age of Anxiety* is of particular relevance. Lehmann traces how European explorers, planners, and colonial officials attempted to remake the Sahara into productive farmland, harnessing "technological advances and colonial fears" for "utopian geoengineering projects".[19] By examining the Pacific Northwest, this study adds evidence of how climate anxiety and settler colonialism worked in tandem to produce imagined dam-brought utopias. Meaningfully addressing climate change and climate-focused infrastructure will undoubtedly need to depart from an understanding of its origins. Following Lehmann's lead, this article aims to place an early instance of green infrastructure development within its milieu to examine how the intellectual tracks which it carved steer modern environmental decision.

III. **Methodological Reflection**

To approach the origins of hydropower in the Pacific Northwest, this article focuses on the

[12] *see*, for instance, Rudek, Tadeusz Józef. "Capturing the Invisible: Sociotechnical Imaginaries of Energy." *Science and Public Policy*, vol. 49, no. 2, 2022, pp. 219-245.
[13] Jasanoff, Sheila. *States of Knowledge: The Co-Production of Science and Social Order.* Routledge, 2004, at 2. Jasanoff uses this phrase in defining the term "co-production". More remains to be said regarding the co-production of a "managed" Pacific Northwest, but that is outside the scope of this article.
[14] O'Malley, Alana. *Workers in Canada's Energy Future: Sociotechnical Imaginaries, Settler-Colonialism, and the Coastal Gaslink Pipeline*. Ph.D. Dissertation, University of Ottawa, 2023, at 7.
[15] Fladvad, Benno. "Infrastructuring Environmental (In)Justice: Green Hydrogen, Indigenous Sovereignty and the Political Geographies of Energy Technologies." *Geographica Helvetica*, vol. 78, no. 4, 2023, p. 493.
[16] ibid.
[17] *see*, for instance, Degens, Philipp, et al. "Analyzing Infrastructures in the Anthropocene." *Historical Social Research,* vol. 47, no. 4, 2022, pp. 7-28.
[18] Some recent research on infrastructure highlights its potential for harm. *see*, e.g., Spice, Anne. "Fighting Invasive Infrastructures: Indigenous Relations against Pipelines." *Environment and Society*, vol. 9, 2018, pp. 40-56.
[19] Lehmann, Phillip. *Desert Edens: Colonial Climate Engineering in the Age of Anxiety*. Princeton University Press, 2022. For more on the history of geoengineering, *see* Lagercrantz, Oona. "Turning Deserts into Paradises: Geoengineering in Science, Practice, and Fiction in the 19th and Early 20th Centuries." *Cambridge Journal of Climate Research*, vol. 1, no. 2, 2024, pp. 237-244.

intellectual roots and intended impacts of dam construction, comparing it with its real impact on Native American communities. It draws on digital archives, choosing key sources based on their reach and public-facing nature. Roosevelt's speeches at the Bonneville Dam offer insight into the institutional, national perspective, and Guthrie's songs reveal information about the dam's appeal for both the Bonneville Power Administration and the folk movement. These documents represent some of the only ways in which Americans outside of the Northwest heard about and understood the Bonneville and federal dam-building in the 1930s and 1940s. They are thus used as representative pieces of dominant discourse. Roosevelt's political speeches and Guthrie's folk songs help the investigation "gain insight into broad processes of collective formation in relation to sociotechnical imaginaries".[20] Their work is supplemented with contemporary newspaper reports, government reports, and regionally focused secondary sources for additional context of how such topics were treated.

To account for the lack of Native American consideration in Roosevelt and Guthrie's work and in other widely disseminated media of the 1930s and 1940s, I read into the silences in these documents. I make note of intentional omissions and elisions of Native American presence, participation, and protest. I supplement my analysis with the oral history of Chief Jackson and the legal scholarship of Roberta Ulrich. Jackson's publicly accessible oral history provides a glimpse of the crucial Native perspective on issues like land use rights, salmon sustainability, and environmental change.

IV. **Argument**

A. *Roosevelt*

The Pacific Northwest, which possessed 40% of the nation's potential hydroelectricity, played a prominent role in the early history of hydropower. In 1889, the first long-distance transmission of electric energy in the United States occurred when the Willamette Falls Electric Company transmitted electricity from its station at Oregon Falls to Portland, Oregon, 14 miles away. As cities in the Northwest soon adopted electric power grids—McMinnville led the way with its 1889 city light system—rural lands near the Columbia lagged behind.[21]

Demand for electricity and optimism about its potential to positively transform American society skyrocketed over the ensuing decades, drawing federal attention to the enormous potential of the Columbia River. In 1932, shortly before Roosevelt's election as president, the Army Corps of Engineers published its 308 Report, analysing the river basin as an integrated system. The engineers set forth a plan for the Columbia involving ten multi-purpose dams, beginning at Grand Coulee in Washington and ending at what would become Bonneville Dam. Alongside the generation of public power, engineers highlighted the benefits of flood control, irrigation, and navigable waterway that the dams would bring.[22]

Although national momentum gathered behind hydropower, it was not until the shock of the Great Depression and the election of President Roosevelt that dam building took on an entirely new scale and rapidity—both nationally and in the Pacific Northwest. The economic downturn of the Great Depression left millions out of work, hitting hard in the logging- and mining-dependent states of Washington, Oregon, and Idaho. By 1933, half as many people were working in the Pacific Northwest as had been in 1926.[23] Roosevelt's New Deal programs that targeted poor and unemployment relief and economic recovery through government spending provided a strong foundation for support of dam building. In the words of historian Carl Bauer, "President Roosevelt's New Deal marked the

[20] O'Malley (n 14) *supra* at 15.
[21] Spring, Vera. *Power and the Pacific Northwest: A History of the Bonneville Power Administration.* US Department of the Interior, 1976, at 4-6.
[22] Kramer, George. *Corridors of Power: The Bonneville Power Administration Transmission Network Historic Context Statement,* Kramer & Company, 2010, at 15.
[23] "The Great Depression and the New Deal." *The National Archives,* 15 Aug. 2016.

entrance of hydropower to a leading role in river development."[24] Most important for dam building was Roosevelt's creation of the Public Works Administration (PWA) in 1933, which set forth a large-scale construction agency for public works.[25] The PWA exemplified the collectivist notion of government investment to break free from economic depression: creating the infrastructure necessary for a thriving economy would jumpstart the creation of that economy.

Damming the Pacific Northwest, as laid out in the 308 Report, likely appeared as the perfect PWA project for both administrators and many Depression-affected locals. Building a major dam required thousands of workers contracted for years at a time. Until this point, the difficulty of the work and scale of employment had been intimidating enough to prevent any prior construction.[26] Dams also returned desirable public goods: cheap electricity, increased commerce, and irrigation. Such a scheme appealed greatly to the impoverished Northwest; perhaps unsurprisingly, the development of the Columbia through government investment was a key part of Roosevelt's 1932 election platform. Speaking in Portland on his campaign trail, Roosevelt focused greatly on the "the vast possibilities of power development on the Columbia River".[27] Roosevelt promised the crowd, in "definite and certain terms, that the next great hydro-electric development to be undertaken by the Federal Government must be that on the Columbia River".[28] To a region filled with unemployed individuals, the prospect of guaranteed employment through dam development would have appeared essential. When Roosevelt returned in 1934 after construction had commenced, he also focused on the economic promises of the dam, explaining that he viewed "the Columbia River as one of the greatest assets not only of the Northwest, but of the whole United States", which could unleash power for the whole region.[29]

By 1937, construction on the Bonneville had been underway for four years and Roosevelt's promise had begun to materialise in earnest—realised with new significance for regional spatial identity politics against the backdrop of the Dust Bowl. When the Bonneville Dam neared completion in fall of 1937, Roosevelt returned to the site to dedicate the dam's spillway. There, he hit the switch to start the two hydroelectric generators of the dam.[30] Addressing an assembled crowd and a tuned-in radio audience, Roosevelt offered a new justification for the creation of the Bonneville Dam, characterising the dam as the antidote to the policy failures of the environmental havoc of the Plains. Roosevelt referenced the well-known and ongoing drought and dust storms of the Plains which had begun roughly six years prior, an event now referred to as the Dust Bowl. He argued that such devastation sprung from management neglect—one that the nation could learn from. He noted that, if we had "known as much and acted as effectively twenty and thirty and forty years ago as we do today in the development of the use of land", the "abandonment of thousands and thousands of farms in portions of ten states would have been preventable".[31] Roosevelt singled out an array of environmental management techniques as retroactive solutions, contending that avoiding vast ploughing, applying "stricter regulations to prevent over-grazing", checking soil erosion, protecting forests, and controlling fires might have left the region

[24] Bauer, Carl. "The Long View of the Water / Energy Nexus: Hydropower's First Century in the U.S.A." *Natural Resources Journal*, vol. 60, no. 2, 2020, p. 176.
[25] Smith, Jason Scott. *Building New Deal Liberalism: The Political Economy of Public Works, 1933-1956*. Cambridge University Press, 2006, at 94.
[26] Spring (n 20) *supra* at 12.
[27] Roosevelt, Franklin Delano. "A Campaign Address on Public Utilities and Development of Hydro-Electric Power, Portland, Oregon, 21 September 1932." *American Presidency Project*.
[28] ibid.
[29] "Roosevelt Pledges Control of Power for Whole People." *The New York Times,* 4 Aug. 1934.
[30] Vandy, Greg, and Daniel Person. *26 Songs in 30 Days: Woody Guthrie's Columbia River Songs and the Planned Promised Land in the Pacific Northwest*. Sasquatch Books, 2016, at 147.
[31] Roosevelt, Franklin Delano. "Speech of the President, Bonneville Dam September 28, 1937." *The National Archives*, Speech File, 1081, at 2.

unblemished.[32] Viewed in the context of admitted absence and failure of environmental management in the Plains, the plan to rework the hydrology of the Northwest to deliver more water to the agricultural fields of Oregon, Washington, and Idaho become a preventative step against future environmental disaster and the guarantor of climate security.

Roosevelt posited the dam as an answer to larger current environmental anxieties; people across the nation noticed the problems of the Depression intensified by the dissipation of natural resources. As historian Wesley Arden Dick recounts, individuals saw "floods, drought, dust storms, and erosion ... jeopardizing the organic stability of the United States".[33] And yet, by juxtaposing the situations in the Plains and the Northwest, Roosevelt characterised the Bonneville as a healing instrument that "[could establish] a rapprochement with nature".[34] It was in the untarnished lands of Oregon and Washington that dam construction could act upon the lessons of the Dust Bowl—setting up the region as a permanently stable lush idyll a world apart from the environmental disasters of the Plains.

But Roosevelt defined the future of the Northwest not only against the physical characteristics of the dry Plains, but against its human characteristics as well. Residents of the Pacific Northwest encountered the impacts of the Dust Bowl primarily through the waves of new migrants it sent west from the Midwestern Plains.[35] Between 1930 and 1940, about 3.5 million people moved out of the Plains, with over two-thirds departing after 1935.[36] The vast majority of these migrants headed to Washington, Oregon, and California.[37] These migrations peaked in Oregon not long before Roosevelt spoke.[38] Oregonian and Washingtonians viewed these migrants with apprehension—one economist explained that "many farmers in Oregon and Washington have been hesitant to welcome these new families who, they believe, will add to existing problems of relief and unemployment".[39] Roosevelt acknowledged this reality in his Bonneville speech, trading in Northwesterners' contemporary anxieties about their own environmental futures. He claimed the scientific knowledge that the government now had could prevent environmental degradation and any repeat of "the migration of thousands of destitute families from [the Midwest] into the States of Washington and Oregon and California".[40] While the migrants of the Dust Bowl had already fallen victim to poor environmental management, and were then struggling to find safe living conditions, Roosevelt reassured the residents of the Pacific Northwest that they need never fear of being forced to leave their homes.[41] The dam would serve as a technological solution to environmental problems, guaranteeing both security and environmental stability in the face of the uncertainty and disruption of the Dust Bowl.[42]

Such a focus on the impacts of the Dust Bowl also hints that the central characters in Roosevelt's narrative were Americans of European descent: omitting Native Americans. White Americans could likely see themselves in the "Oakies" of the Dust Bowl and thus needed reassurance that they were not bound to that same fate. Throughout the speech, Roosevelt catered his words to a very specific "American" audience, relating his focus on the

[32] ibid.
[33] Dick, Wesley Arden. "When Dans Weren't Damned: The Public Power Crusade and Visions of the Good Life in the Pacific Northwest in the 1930s." *Environmental Review*, vol. 13, no. 3-4, 1989, pp. 113-153.
[34] ibid.
[35] Hoffman, Charles. "Drought and Depression Migration into Oregon, 1930 to 1936." *Monthly Labor Review*, vol. 46, no. 1, 1938, p. 28.
[36] Worcester, Donald. *Dust Bowl: The Southern Plains in the 1930s*. Oxford University Press, 1979, at 49.
[37] ibid at 50. In the 1930s, two out of five migrants across state lines were heading to California.
[38] Hoffman (n 35) *supra* at 28. Hoffman's data, while incomplete, shows migration to rural Oregon tapering off in 1936.
[39] ibid at 27.
[40] Roosevelt (n 31) *supra* at 2.
[41] Ibid.
[42] Roosevelt was not alone in this view; social theorist Stuart Chase echoed it in 1938: "[t]he chief purpose of the great dams is to restore equilibrium". Dick (n 35) *supra* at 132.

Columbia to "the future of the United States".[43] He himself was part of this vision of an American identity, referring to "our children".[44] The promises of increased economic activity, irrigation, and electricity focused on a uniform American, and he touted those benefits to those who were thousands of miles away.[45] Not once did Roosevelt acknowledge the diversity of peoples that called the region and the Columbia River home—the Chinook, Wanapum, Nez Perce, Yakama, Umatilla, Warm Springs, Cowlitz, and Grand Ronde; he made no explicit mention of their existence or their uniqueness. Instead, he targeted his appeal to those who could identify with a homogenous American identity, addressing only the concerns of the white populace. These absences indicate that speechwriters and the President considered Americans of European descent as important enough to make it into a President's speech—Native Americans, by contrast, were not.

Roosevelt also omitted any discussion of the impact of the dam on salmon populations, further relegating concerns of Indigenous populations. Many Native American tribes depended on the fisheries of the Columbia as the guarantor of their own survival. The abundant salmon, steelhead, and sturgeon of the river had served as a consistent source of food and trade for generations.[46] Moreover, the waters and the salmon held an important role in spiritual practice. Columbia River Basin tribes believed that their souls were connected to the natural world and all of its inhabitants, with special reverence for salmon, which held a central cultural role.[47] While it is unclear whether Roosevelt understood the full impact that this dam project would have on fisheries, it was clear that the Bonneville threated salmon runs and would submerge Native American fishing spots.[48] The April before his speech, the New York Times ran a story titled "Fear Bonneville May Doom Salmon", recounting the worries of men in the salmon industry regarding their likely future catches. The article devoted two brief sentences to note that "[a]mong those skeptical of the dam are the Indians" as they "insist ... that the white man will now destroy their fishing grounds".[49] Moreover, just weeks before Roosevelt came to visit the dam, Native Americans were working with the Bureau of Indian Affairs (BIA) to document the dam's damage for compensation claims. As scholar Roberta Ulrich reveals, a dozen tribal elders travelled in a Corps of Engineers boat from the nearby town of the Dalles to the dam, pointing out traditional fishing sites to the BIA officials that accompanied them. BIA officials took photographs of each site, to be joined by a second of the same site the next year after the sites had been flooded by the dam's reservoir.[50] The imminent loss of fishing sites was thus apparent to those on the ground. By characterising the Bonneville as the key to environmental safety and prosperity for nearby residents—and omitting any mention of loss—Roosevelt rejected the river and its fish as sources of that same safety and prosperity for generations of Columbia River Native Americans. In this, it becomes clear who stood to benefit from the dam in Roosevelt's eyes: it was not those that relied on the waters and salmon of the Columbia for millennia, but rather the population that has settled in the basin in the past 200 years.

B. *Guthrie*

Four years later, another iconic American voice joined Roosevelt to promote the

[43] Roosevelt (n 31) *supra* at 3.
[44] ibid at 11.
[45] ibid at 10.
[46] Beckham, Stephen. *An Interior Empire: A Historical Overview of the Columbia River Basin*. Eastside Ecosystem Management, 1995, at 2. Salmon were a main source of sustenance and income. For example, one fisherman, John Polk, estimated "the value of the fish he caught to feed his family of six was $300 per year. He also sold and traded about $900 worth of fish for whatever else his family needed ... Meagre as Polk's income sounds ... he and the other river people considered that the river provided a good living before Bonneville Dam was built": Ulrich, Roberta. "Empty Promises, Empty Nets." *Oregon Historical Quarterly,* vol. 100, no. 2, 1999, p. 137.
[47] "We Are All Salmon People." *Columbia River Inter-Tribal Fish Commission*, 2021.
[48] Ulrich (n 46) *supra* at 136.
[49] "Fear Bonneville May Doom Salmon: Fishermen Threaten Suit Over Baneful Effects of Big Hydroelectric Dam." *The New York Times,* 18 Apr. 1937.
[50] Ulrich, Roberta. *Empty Nets: Indians, Dams and the Columbia River*. Oregon State University, 1991, at 21.

Columbia dam—elaborating on a settlor Northwestern identity in opposition to the Plains. Guthrie differed from Roosevelt in many facets. When he was hired by the Bonneville Power Administration (BPA) to write songs about the Bonneville, he was 28 years old, a father of three, and an itinerant left-wing songwriter.[51] As opposed to the presidential position of Roosevelt, Guthrie had a reputation for going against the grain, and was coming off a recent stint as a columnist in Los Angeles for the communist newspaper, *People's World*.[52] Desperately in need of a job, Guthrie was connected to the BPA by his friend, Allen Lomax, who was the head of the Archive of Folk Song at the Library of Congress. The BPA had been looking to produce a second documentary on the benefits of the Bonneville as well as the Grand Coulee dam, which had opened that year. The BPA ended up hiring Guthrie for 30 days, paying him a rate of ten dollars per song.[53]

Guthrie, an otherwise anti-establishment dissident, viewed the dam project optimistically. As music critic Paul de Barros writes, "Guthrie saw the Grand Coulee project as a Rooseveltian populist endeavour that would not only bring electric power to the people ... but also irrigate a gigantic 'pasture of plenty' east of the Cascades, which could accommodate the Dust Bowl refugees".[54] Over the course of his month of employment, Guthrie wrote 26 songs which, when viewed as Guthrie's own songs, offer insight into the ways Guthrie himself perceived the Northwest and the dam building project—and as government-endorsed propaganda, offer insight into the ways in which the BPA justified the Bonneville.

In many ways, Guthrie echoed Roosevelt's efforts to contrast the Pacific Northwest with the Plains. However, he repeatedly credited dams with establishing the Northwest as a safe haven for Dust Bowl migrants, not just Pacific Northwesterners. In "Pastures of Plenty", Guthrie established this argument, describing the struggles of Plains migrants: "it's a mighty hard row that my poor hands have hoed / My poor feet have travelled a hot dusty road / Out of your Dust Bowl and Westward we rolled".[55] When the Midwestern Plains failed, the characters of Guthrie's lyrics turned their hopes to the West. In subsequent verses, Guthrie characterised the Northwest as a solace for migrants made possible through the irrigation of dams, writing, "Green pastures of plenty from dry desert ground / From the Grand Coulee Dam where the waters run down".[56] Undoubtedly influenced by his childhood in Oklahoma and dust-stricken rural Texas as well as time spent traveling with migrants in the spring of 1938, Guthrie spoke on behalf of suffering migrants.[57] Unlike Roosevelt, who had tailored his speech to a largely Pacific Northwest audience, Guthrie opened up his scope, including migrants as a core stakeholder group.

Like Roosevelt, Guthrie also linked the damming of the Columbia to the tale of white Americans. In "Oregon Trail", Guthrie reinvented the narrative of the Oregon Trail to represent the Dust Bowl migration, once again setting up the devastation of the plains: "I been a grubbin' on a little farm on the flat and windy plains / I been a list'nin to the hungry cattle bawl".[58] And again, Western migration was the solution for his protagonist: "I'm gonna hit that western road / I'm gonna hit that Oregon Trail this comin' fall".[59] In calling

[51] Carriker, Robert. "Ten Dollars a Song: Woody Guthrie Sells His Talent to the Bonneville Power Administration." *Columbia Magazine*, vol. 15, no. 1, 2001, p. 34.
[52] Briley, Ronald. "'Woody Sez': Woody Guthrie, the 'People's Daily World,' and Indigenous Radicalism." *California History*, vol. 84, no. 1, 2006, p. 30.
[53] Carriker (n 51) *supra* at 32.
[54] de Barros, Paul. "26 Songs in 30 Days: How Woody Guthrie Wrote Those Great Songs—For $266." *The Seattle Times,* 11 Apr. 2016.
[55] Guthrie, Woody. "Pastures of Plenty." Moe Asch, 1941, *Rounder Records,* 16, 1987.
[56] ibid.
[57] Carriker (n 51) *supra* at 33.
[58] Guthrie, Woody. "Oregon Trail." Moe Asch, 1941, *Rounder Records,* 1, 1987.
[59] ibid.

upon the historic Oregon Trail, which had sent hundreds of thousands of settlers to the West in the mid-19th century, Guthrie connected the draw of the dam for migrants to settler history. Dams were the successor to earlier land grants that had attracted settlers; it was the lush productive land of hydropower that would entice migrants. Those who travelled on the trail were the same Americans of European ancestry that Roosevelt had appealed to four years prior; Native Americans had not participated in the Oregon Trail. Moreover, national press had depicted Native Americans as the primitive antagonist of settlers, suggesting that Oregon and Washington were blank slates open for settlement. Through Oregon Trail symbolism, Guthrie cast the Bonneville and the dam project as a draw for a white populace.

Guthrie joined in the erasure of Native American presence not only by glorifying settler narratives, but also by depicting Indigenous tribes as vanquished. "Roll on Columbia" highlights Guthrie's connection of settler victories over Native Americans to the modern victory of man over the Columbia itself. Guthrie wrote about the struggles of early settlers journeying to the Columbia: "year after year we had tedious trials, / Fighting the rapids at Cascades and Dalles. / The Injuns rest peaceful on Memaloose Isle".[60] The battle against the rapids of the pre-dammed river was one fought in tandem against Native Americans. Guthrie also used an implicit "we", extending Roosevelt's identification with a settler population, and thereby excluding Native Americans. Moreover, the first mention of Native Americans is to the dead: "Memaloose Isle" refers to one of what was once several islands in the Columbia where Chinook people lay their dead to rest.[61] Guthrie associated white settlement with Native American death. His reference to "peaceful rest" reads as ironic; the dam whose power he extolled in that very song submerged almost all Memaloose islands.[62]

Guthrie linked dam building to the American Indian wars of the late 19th century that occurred when Native Americans resisted the ethnic cleansing and incursion of white settlers. He commemorated the murder of "wild" Native Americans, writing, "Remember the trial when the battle was won, / The wild Indian warriors to the tall timber run, / We hung every Indian with smoke in his gun".[63] Circling back to the triumphant chorus once more ("your power is turning our darkness to dawn / roll on Columbia, roll on"), Guthrie wove the murder of Native Americans into the tale of the modern Bonneville's power and fortune, creating a continuous narrative that defined the dam as a project for the white settler victors he described.[64] "Roll on Columbia's" endorsement by the BPA highlights that such narratives were readily accepted by major institutions.[65] The fact that the only Native Americans listed in either of Guthrie's work are dead ultimately diminished the voices of the Native Americans who still lived in the Columbia region. Such lyrics and speeches painted Native American peoples as a feature of the past, not the present. Whether conscious or unconscious, such texts thus wrote Native American needs and desires out of the story of the Bonneville.

C. *Jackson*

Native Americans lived in the Columbia region as Guthrie and Roosevelt wrote—and their recollections, like those of Chief Johnny Jackson of the Cascade Band of the Yakama

[60] Guthrie, Woody. "Roll on Columbia." Moe Asch, 1941, *Rounder Records,* 5, 1987.
[61] "Memaloose Island." *Northwest Power and Conservation Council*. The name *Memaloose* comes from the Chinook word *memalust*, which means "to die".
[62] ibid. The dams of the Columbia disturbed all such burial sites. While a "Memaloose island" exists today in Memaloose State Park, it is submerged two thirds by water today compared to what explorers Lewis and Clark first noted.
[63] Guthrie (n 60) *supra.* This is likely a reference to the narrative that Sheridan hanged a Native American he "suspected of disloyalty, solely on the evidence that his gun was still hot": "Woody Guthrie and Sherman Alexie Narrate the Columbia." *Cascadia Chronicles,* 2012.
[64] Guthrie (n 60) *supra*. Most of Guthrie's verses detailing the Indian Wars have been removed from modern official lyrics. The Washington State official song version leaves out this section.
[65] Vandy & Person (n 30) *supra* at 182.

Tribe, offer an important counterpoint to the relentless dam optimism of Guthrie and Roosevelt. Jackson, who grew up along the Columbia River, recalled the process of dispossession at an oral history interview conducted in 1999. To Jackson, speaking about the Bonneville meant speaking of the theft of land from Native Americans. Jackson remarked that Underwood, Washington, where he had lived as a child during fishing season, "used to be a village" before the Bonneville, and the government "never paid for it".[66] Money was offered on paper, but never ultimately made it into the hands of his people; "[the government] paid [us] for Bonneville, fifty-thousand. But we've never seen it".[67] Roberta Ulrich provides clarity on the process Jackson described: the government acquired "flowage easements" from local residents—permission to flood the land—not title to riverside property, making it easier for them to pay little or no money to Native land owners.[68] By highlighting the injustice in the process of construction, Jackson complicates the narrative of the Bonneville as a guarantor of freedom and safety.

Furthermore, Jackson pointed to the broken promises of the federal government, which had sworn to replace the homes in villages it depopulated and razed—dwellings with significance far beyond economic terms. He noted that "[s]ome people lived here year round. They took [the homes] out and told them that they were going to replace them, and promised them a lot, which didn't happen".[69] Jackson's experience is representative of many other Native Americans in the region. 50 years later, the government had provided only five replacement fishing sites for those flooded by the Bonneville, equivalent to one-tenth of the land they had promised.[70] Jackson thus offers information about the Bonneville that would otherwise be obscured in the propagandist works of Roosevelt or Guthrie. Jackson's perspective casts the government as complicit in the exploitation of Native Americans and expropriation of their sites.

D. *Ulrich*

Roberta Ulrich's legal analysis can also help to piece back in Native voices to the narrative—highlighting that in the years between Roosevelt and Guthrie, Native Americans had actively resisted the federal government's theft of their property and ancestral fishing sites. Drawing from court briefs, Ulrich notes that in January 1939, Native Americans submitted their claim for damages from flooded spots, "listing twenty-three locations, each including at least several fishing sites". They addressed their claim to the officer in charge of Bonneville construction, Theron Weaver. They wrote: "[w]e have duly considered these losses at our tribal meetings" and "it is the opinion of our people that an effort should be made to have the United States Government, through your department, take steps to provide us with additional fishing sites and facilities".[71] Such evidence that Native Americans made their grievances known to authorities by demanding justice in court casts doubt on the notion that Roosevelt, the BPA, or even tangentially, Guthrie, were ignorant of the impact of the dam on Native Americans. While Jackson and Ulrich thus provide some clarity as to the role of the Bonneville in the dispossession of American peoples—acting as a counterpoint to the works of Roosevelt and Guthrie—these texts come over 60 years after the dam's creation, highlighting the dearth of contemporary Native American voices in the archive. It is clear that some Native Americans spoke out against the Bonneville, but little remains by way of primary sources. For instance, there are no contemporary reports or textual accounts written by Native Americans when they gathered at Kettle Falls in 1940 for their Ceremony of Tears, commemorating the

[66] "Chief Johnny Jackson: Interview by Piper Hackett." *Radical Elders Program*, 28 Mar. 1999, at 1; Ulrich (n 45) *supra* at 142.
[67] ibid.
[68] Ulrich (n 46) *supra* at 136.
[69] Jackson (n 66) *supra* at 1.
[70] Ulrich (n 46) *supra* at 156.
[71] ibid at 145. For more on Native American resistance to fishing rights changes, *see* Ulrich (n 50) *supra*.

flooding of Kettle Falls in dam backwaters.[72] While government-sponsored propagandist sources have been catalogued and digitised, the voices of most Native American activists have not. Progress is being made; Roberta Ulrich interviewed Native Americans and pored over legal documents in the late 1990s, and Jackson was interviewed in 1999. However, more action is needed.

V. **Conclusion**

Roosevelt and Guthrie used the narrative of poor environmental management in the devastation of the Dust Bowl to support federal dam-building projects in the Pacific Northwest, equating large-scale engineering with stability, prosperity, and environmental control for a settler populace. Such narratives cast aside the desires of Indigenous peoples, either by omitting them completely or by depicting them as vanquished. Put differently, Roosevelt and Guthrie's ability to speak optimistically about the populist appeals of the dams relied on their exclusion of Native Americans as Northwesterners. The arguments by which the Bonneville was justified formed the intellectual foundation upon which the dam building fervour of the ensuing forty years would build. Disregard for Native American concerns and their exclusion continued in dam construction, treatment of fish, and fishing rights legislation. Moreover, this analysis demonstrates that looking only at the words of Roosevelt and Guthrie provides an incomplete view of the history of the Bonneville, eliding the fact that controversies around dams are as old as the projects themselves. Harnessing an array of primary sources offers richer insight into the ever-important history of the Bonneville. As debates about dams bubble up today, understanding the ways in which the dam was a product of its time—one that assuaged contemporary anxieties around the Dust Bowl and served a limited portion of Americans—allows for more nuanced consideration of the relevance of dams. Internationally, large-scale environmental infrastructure projects around the world continue to rely on similar narratives of prosperity through engineered landscapes. In 2024, the World Bank approved financing for the first of five "mega dams" in developing nations, returning to its role as a powerful hydropower backer after a ten-year freeze.[73] The World Bank-funded Rogun Hydropower Project in Tajikistan will be the world's tallest dam once completed in 2033. While its supporters claim it will promote economic productivity, support a clean energy future, and protect downstream areas from extreme flooding, critics point out that the dam will displace at least 50,000 people.[74] Desertification also remains a pressing concern motivating infrastructure development. Begun in 1978, China's Great Green Wall aims to create a barrier of forest approximately 4500 km long by 2050 to hold back the expansion of the Gobi Desert.[75] A similar project is underway around the Sahel.[76] Back in the United States, nine states have embraced cloud seeding technology as a mitigation instrument for increasing drought intensity and frequency.[77] As this in-depth reading of the Bonneville highlights, such projects can be viewed as technological responses to environmental anxieties. Developers make decisions based on established power structures, harnessing infrastructure to reconfigure the landscape and secure the futures of some at the cost of others. As governments continue to turn to large-scale infrastructure projects to confront ecological uncertainty, the Bonneville invites recognition that attempts to configure nature through technological infrastructure also have implications for the configuration of society.

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[72] Sprague, Holly. "Unjust Compensation: Grand Coulee Dam, Indian Claims, and the Colville Nation." University of Massachusetts Amherst Commonwealth Honors College Theses and Projects No. 11, 2011, pp. 39-40.

[73] "Why the World Bank Should Stop Funding New Dams." *Yale e360*, 20 Apr. 2023.

[74] "Rogun Hydropower Plant Project (HPP): FAQs." *World Bank*; "Why Development Banks Should Not Fund the Rogun Mega-Dam in Tajikistan." *The Coalition for Human Rights in Development*, 13 Mar. 2024.

[75] "China's Great Green Wall." *Royal Geographical Society*, 2015.

[76] "Great Green Wall Initiative (GGWI)." *United Nations Convention to Combat Desertification*.

[77]. *Cloud Seeding Technology: Assessing Effectiveness and Other Challenges.* United States Government Accountability Office, GAO-25-107328, Dec. 2024.


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