Future of Integrated Assessment Models: Pathways Towards Carbon Neutrality for Climate, Environment, Health and Socio-economic Co-benefits

852. WE-Heraeus-Seminar

20 - 24 April 2026

at the Physikzentrum Bad Honnef, Germany

WILHELM UND ELSE
HERAEUS-STIFTUNG

Introduction

The Wilhelm und Else Heraeus-Stiftung is a private foundation that supports research and education in science with an emphasis on physics. It is recognized as Germany's most important private institution funding physics. Some of the activities of the foundation are carried out in close cooperation with the German Physical Society (Deutsche Physikalische Gesellschaft). For detailed information see https://www.we-heraeus-stiftung.de

Aims and scope of the 852. WE-Heraeus-Seminar:

Integrated Assessment Models (IAMs) are essential tools for exploring pathways to carbon neutrality and designing effective policies. By addressing the intersections of climate, environment, health, and socio-economic co-benefits, the seminar aims to foster an interdisciplinary exchange of knowledge concerning three critical themes:

A. Challenges in Linking Earth System and Socio-Economic Models: Integrating physical and socio-economic processes is crucial for holistic climate policymaking. Discussions will cover strategies to harmonize temporal and spatial scales and incorporate socio-economic feedback into Earth system models.

B. Dynamic System Modeling Approaches: Exploring advanced methods for capturing non-linear dynamics, feedback loops, and time delays, as well as impacts of Extreme Events and Tipping Points. Emphasis will be on overcoming computational barriers and enhancing the usability of models for policymakers.

C. Pathways Towards Carbon Neutrality: Identifying existing barriers and potential improvements impacting IAMs ability to inform actionable decarbonization pathways. Critical aspects concerning the balance of climate goals with economic development and social equity, as well as the impact of policy integration and technological innovations, will be addressed.

A fruitful interplay between leading experts, early-career researchers, and doctoral students will contribute through lectures, poster presentations, and collaborative discussions to a greater understanding of the IAMs future and role of the latter in the decarbonization process.

Introduction

Scientific Organizers:

Prof. Dr. Yafang Cheng — Aerosol Chemistry Department
Max Planck Institute for Chemistry, Germany

Prof. Dr. Klaus Hubacek — Energy and Sustainability Research Institute Groningen (ESRIG), Faculty of Science and Engineering
University of Groningen, Netherlands

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Introduction

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Registration:

Nadine Mock(WE Heraeus Foundation)
at the Physikzentrum, reception office
Monday (16:00 h – 21:00 h) and Tuesday morning

Program

Program

Monday, 20 April 2026

16:00 - 21:00	Registration
17:30 - 19:00	Ice breaking drink
19:00 - 20:15	*BUFFET SUPPER and informal get-together*

Program

Tuesday, 21 April 2026

07:30 – 08:30	*BREAKFAST*	
08:30 - 09:00	Scientific Organizers	**Opening talk**
09:00 - 09:15	Scientific Organizers	**Video "About the Wilhelm and Else Heraeus Foundation"**
09:15 - 10:00	**SESSION A1** Paul E. Brockway	**The missing link: how and why IAMs should better include energy's role in economic growth**
10:00 - 10:45	**SESSION A1** Chao Li	**Plausible climate futures depend on better integration of social and natural systems**
10:45 - 11:15	*CONFERENCE PHOTO (in front of the main entrance) & COFFEE BREAK*	
11:15 - 12:00	**SESSION A2** Sarah Cornell	**"We're all part of the system": Dealing with diversities in the global (-ising) models that shape planetary power systems.**
12:00 - 12:45	**SESSION A2** Hans Kremers	**Confronting the climate change related sciences with the 'Dismal Science': A personal 'integrated assessment'**
12:45 - 14:00	*LUNCH*	
14:00 - 14:45	**SESSION A3** Konstanty Ramotowski-Kula	**Integration of social sciences and humanities in Swiss energy modelling: situating the context of research practices**
14:45 - 15:30	**SESSION A3** Aleksandra Wagner	**A Human in the Loop. Social Sciences as Catalysts for Reflexive Modeling**
15:30 - 16:15	Chris Foulds	**Making and disputing models: A Critical Social Scientist's provocation on how people and societies are accounted for in energy model outcomes and processes**

Program

Tuesday, 21 April 2026

16:15 - 16:45	*COFFEE BREAK*
16:45 -18:30	**Poster madness session**
19:00	*Dinner*

Program

Wednesday, 22 April 2026

07:30 - 08:30	*BREAKFAST*	
08:30 - 09:15	**SESSION B1** Matteo Pedercini	**System Dynamics modeling for integrated assessment: challenges and opportunities**
09:15 - 10:00	**SESSION B1** Franco Ruzzenenti	**Complexity is the substance of evolution; how can our models neglect it?**
10:00 - 10:45	**SESSION B1** Antonios Katris	**Exploring the economy-wide implications of nascent sector activity using national CGE models: The example of CO2 transport and storage**
10:45 - 11:15	*COFFEE BREAK*	
11:15 - 12:00	**SESSION B2** Jaime Nieto	**Exploring the techno-economic and biophysical limits of the energy transition: an Integrated Assessment Model analysis**
12:00 - 12:45	**SESSION B2** Wided Medjroubi	**Optimization and Techno Economic Analysis of Energy Systems**
12:45 - 14:00	*LUNCH*	
14:00 - 18:00	EXCURSION	
19:00	*DINNER*	

Program

Thursday, 23 April 2026

07:30 – 08:30	*BREAKFAST*	
08:30 - 09:15	**SESSION C1** Jianmin Ma	**The 21st Century Climate Response to China's Clean Air Action and Carbon Neutrality Targets**
09:15 - 10:00	**SESSION C1** Wenjun Meng	**Energy Price Volatility and the Costs and Benefits of the EU Energy Transition: Integrated Assessment Modeling for Carbon Neutrality Pathways**
10:00 - 10:45	**SESSION C1** Jing Meng	**Plant-Level Technology Pathways for Cost-Effective Industrial Decarbonization**
10:45 - 11:15	*COFFEE BREAK*	
11:15 - 12:00	**SESSION C2** Cristina Sarasa	**Greening Global Value Chains in Transition: Energy Technologies, Industrial Transformation, and modified Lifestyles**
12:00 - 12:45	**SESSION C2** Yolanda Bravo	**Policy assessment for electromobility transition: research insights from a dynamic EV-aware CGE approach**
12:45 - 14:00	*LUNCH*	
14:00 - 14:45	**SESSION C3** Prajal Pradhan	**A threefold approach for the acceleration of Sustainable Development Goals and beyond**
14:45 - 15:30	**SESSION C3** Jos Lelieveld	**Air quality, climate change, and health**
15:30 - 16:15	**SESSION C3** Miguel Menendez	**Economic and environmental impacts of e-fuels in Spain: Replacement of fossil fuels by DME**

Program

Thursday, 23 April 2026

16:15 - 16:45	*COFFEE BREAK*
16:45 -18:30	**Roundtable sessions (Three parallel sessions)**
19:00	*HERAEUS DINNER*

Program

Friday, 24 April 2026

07:30 - 08:30	*BREAKFAST*	
08:30 - 09:15	**SESSION C4** Detlef van Vuuren	**Broadening Climate Mitigation Pathways in an Era of Overshoot and Global Constraints.**
09:15 - 10:00	**SESSION C4** Paraskevi Karka	**Identifying optimal circular economy pathways: Linking prospective sustainability assessment with Integrated Assessment Model scenarios**
10:00 - 10:45	**SESSION C4** Keywan Riahi	**New ScenarioMIP Pathways and Insights from the Scenario Compass Initiative: What the Latest Global Emissions Scenarios Tell Us**
10:45 - 11:00	*COFFEE BREAK*	
11:00 - 12:00	**Joint panel discussion**	
12:00 - 12:45	Scientific Organizers	**Closing remarks and poster awards**
12:45 - 14:00	*LUNCH*	

End of the seminar and departure

Posters

Posters

Noam Abadi	**Energy pathway diversity and the energy transition**
Lunanga Ananie	**From Fragile Cities to Carbon-Neutral Pathways: Integrating Climate, Health, and WASH Co-benefits in Bukavu, Democratic Republic of Congo**
Michael Chilinski	**Miniature Sensors In Profiling of Atmospheric Aerosols in Troposphere**
Yizhi Deng	**Needs for More Integrated, Inclusive, and Policy-Relevant Modeling of Food System Transitions: Insights from a Systematic Review**
Alvaro Garcia Riazuelo	**The role of technological trajectories in global sustainable growth**
Jinling He	**Adjoint Optimization of Ozone and PM2.5 Mitigation Pathways in China with Updated Chemical Mechanisms**
Ke Jiang	**Biomass Energy and Climate: Reassessing the Past and Modeling Future Feedbacks**
Peijin Jiang	**Climate Mitigation Scenario Generation with Large Language Models**
Teun Kluck	**System dynamics modeling of Dutch policy scenarios within planetary boundaries**
Gang Liu	**Wetland Methane Feedbacks Make the Paris Agreement Goals More Difficult to Achieve**
Qiming Liu	**Vertical Profile Corrections Explain Satellite–Inventory Ammonia Discrepancies and Reveal Concentrated Agricultural Sources in China.**
Tiancheng Luan	**Quantifying the Real Heat-Related Mortality Risk: The Mitigating Role of Air Conditioning and Its Global Regional Variations**

Posters

Ruikang Ma	**Towards Understanding Marine New Particle Formation: Progress and Challenges**
Zelin Mai	**Development of a Multi-Species Hybrid Inversion Framework for Anthropogenic Emission inversion: An Online Adaptive Regularization Strategy within CMAQ-Adjoint**
Cristina Margalejo	**Integrating Household Consumption into Sustainability Pathways: Evidence from the European Union**
Marcin Mielewczyk	**Discussing with future generations: how can we predict their behavior, and could they bear the burden of future climate policies?**
Shuyu Ouyang	**From China's 2035 NDC Targets to Near-Term Power-System Pathways: Renewable Penetration, Electrification, and CCS Reliance**
Hannah Prawitz	**Towards modelling the Anthropocene: A systematic review of World-Earth models**
Sabin Roman	**Modelling the collapse of complex societies**
Arkadiusz Szlaga	**Designing Stakeholder Scoping Workshops for Integrated Assessment Modelling**
Pedro Trus Mendes	**Invisible Intermediaries: Sustainability Discourse and the Reproduction of Power in Transnational Soy Supply Chains**
Dong Xie	**Impacts of Rural–Urban Population Migration on Air Pollution Exposure and Premature Mortality in China Since 1949**
Junpeng Xu	**Synergistic Effects of Transport and Subsidence on Extreme Ozone Pollution Induced by Sequential Typhoons in the Greater Bay Area**

Posters

Linghan Zeng	**Impacts of Sustainable Aviation Fuels on Emissions and Contrail Properties in Micro Turbojet Experiments**
Jingyu Zhang	**Unveiling Hidden Costs in Agrifood Systems: A Systematic Review of True Cost Accounting**
Wenxiao Zhang	**Environmental and health impacts related to cross-region air pollution in China**
Yuxuan Zhang	**Black Carbon in the Marine Atmosphere: Concentration and Mixing State From Coastal to Remote Atlantic Regions**
Xucheng Zhao	**Balancing Provincial Burden-sharing Capacity in China's Carbon Neutrality Pathway: Trade-offs Among Economic Burden, Pollutant Emissions, and Provincial Equity.**

Abstracts of Talks

(in alphabetical order)

Policy assessment for electromobility transition: Research insights from a dynamic EV-aware CGE approach

Yolanda Bravo[1], Rosa Duarte[1], Cristina Sarasa[1]

[1]Economics and Business School, University of Zaragoza, Zaragoza, Spain

The automotive industry is undergoing a profound transformation due to the electrification of vehicle fleets. This transition entails technological shifts across productive sectors, changes in demand, and adjustments in fiscal policy, all of which have significant economic and social impacts. Given the fact that the automotive industry can be an important actor for certain regions and countries, it is relevant to assess the potential economic, social and environmental impacts. Spain is the second largest producer of automotive components and vehicles in the European region, only preceded by Germany. In order to evaluate the implications of the transition for the Spanish economy, a dynamic Computable General Equilibrium (CGE) model is developed to address electric vehicles transition. The evolution of the car fleet up to 2050 has been integrated. The introduction and massive implementation of electric vehicles are being imposed by regulations, the offer of automotive companies and local constraints for circulation of vehicles. The EV-aware CGE model evaluates the socio-economics impacts across various scenarios projected up to 2050.

JEL codes: O14, O25, O33
Keywords: electric vehicles; electrification; computational general equilibrium model; mobility scenarios; economic impact

The missing link: how and why IAMs should better include energy's role in economic growth

P Brockway[1], E. Aramendia[1], T. Domingos[2], M.K.Heun[1,3,4], J.Nieto[1,5], J. Santos[2]

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[b] *Instituto Superior Técnico, Universidade de Lisboa, Portugal.*

[c] *Calvin University, Grand Rapids, MI 49546, USA;*

[d] *School of Public Leadership, Stellenbosch University;*

[e] *Department of Applied Economics, University of Valladolid, Spain.*

Context: IAMs are a foundational modelling tool, used within the IPCC process to set out pathways for climate change mitigation (CCM) to meet Paris-type greenhouse gas (GHG) emissions reductions for a net zero future. Three key CCM levers are used in IAMs: decarbonisation of energy supply (mainly, renewables), energy demand reduction (EDR) via mainly energy efficiency, and carbon sequestration (mainly CCS).

The issue: EDR is heavily relied upon in global IAMs, which typically project emissions pathways that both (a) feature (efficiency-driven) lower-than-baseline energy use in the future whilst (b) maintaining continued economic growth. However, this unprecedented extent of energy-GDP decoupling has never happened before [1]. IAMs allow such decoupling via lack of links of energy to economic growth and missing energy rebound channels. All of this matters, because achieving a Net Zero future requires both an energy-supply and an energy-use transition. If energy and efficiency play a key role in economic growth, then we may be overestimating the effect of EDR measures and underestimating the future roles needed of renewables and carbon sequestration.

This talk: We set out the last decade of key insights into energy and economic growth from the Exergy Economics community, building on the foundational work of Bob Ayres and others. We (a) present the primary-final-useful (PFU) energy conversion chain and (b) show how historical final-to-useful energy efficiency gains [2] are a key factor in economic growth [3, 4] that explains total factor productivity (TFP) growth in production functions [5]. We also showcase how inclusion of final-touseful energy conversion for electrified end uses allows new insights into net energy analysis [6] and sociomacroeconomic impacts [7]. Finally, we provide links to the country-level PFU (CL-PFU) energy and exergy database [8] that we have constructed for over 150 countries, since 1960.

References

[1] Brockway P. E., et al. (2021) *Renew Sustain Energy Rev* 141, 110781;

[2] Brockway P., et al. (2015) *Appl Energy* 155 pp.892–903;

[3] Sakai, M., et al. (2019) *Energies* 12, 110;
[4] Heun, M.K., et al. (2019) *Applied Energy* 251, pp.124;
[5] Santos et al. (2021) *Energy Econ*. 101 105407;
[6] Aramendia, E., et al. *Nature Energy* (2024) doi:10.1038/s41560-024-01518-6;
[7] Nieto, J., et al. *Appl Energy* (2024). doi:10.1016/j.apenergy.2024.123367
[8] Brockway, P.E., et al. (2024). '*Env Res: Energy'* 1, 025005.

"We're all part of the system": Dealing with diversities in the global (-ising) models that shape planetary power systems

S.E. Cornell[1]

[1] *University of Gävle, Gävle, Sweden, and Centre for Global Sustainability, University of Oslo, Oslo, Norway*

The prime purpose of integrated assessment models is to combine relevant knowledge about techno-environmental and socioeconomic systems in ways that yield quantitative information for use in decision-making contexts. By design, IAMs are rooted in a reductionist philosophical tradition – and I do not mean this in a derogatory way! – where the largely linear treatments of cause-effect relationships allow modelers and model users to make meaningful statements about possible pathways and associated uncertainties. And by design, IAMs influence the world's systems of power, informing the complex interactions of regulation, markets, social norms, the developments of infrastructures of various kinds, and many interventions in the immensely diverse biocultural systems of the living world.

As IAMs become more comprehensive in their content and scope, and as demand for IAM applications arises in more arenas of power and global governance, attention turns (as it should, in my view) to vitally important aspects that are outside of "the system" that the quantitative models integrate. Scenario narratives have long been used as a way to add back qualitative substance, countering some of the necessary reductiveness of IAM analysis. And yet they also embed simplifying assumptions and often-hegemonic worldviews.

In this talk I will reflect on the challenges of dealing with social and ecological diversities, with reference to IAM-related initiatives that I have been involved in and with attention to the arenas of power that have taken up some messages from our work. We – modelers, model users, and those involved in IAM-using engagement processes – have rich experiences to learn from. More dialogue is especially useful for those of us whose work bridges from the IAM community to other (global) modelling contexts (biodiversity destruction, material sufficiency etc), and who are concerned about the selective deployment of IAM quantities without their associated qualities.

Making and disputing models: A Critical Social Scientist's provocation on how people and societies are accounted for in energy model outcomes and processes

Chris Foulds[1]

[1]*Global Sustainability Institute, Anglia Ruskin University, East Road, Cambridge, UK*

Energy models routinely inform major decisions about Europe's low-carbon future. Yet despite their sophistication, these predominantly STEM-driven (Science, Technology, Engineering, Mathematics) tools often struggle to capture the messy, dynamic and emergent realities of the societies they aim to serve. Inspired by extensive work on Social Sciences and Humanities (SSH) integration in energy projects – via e.g. coordination of SHAPE ENERGY, Energy-SHIFTS and SSH CENTRE – this presentation reflects critically on how people, social processes and political contexts are (and are not) represented within modelling practices and outputs. These reflections build on empirical research into interdisciplinary energy research cultures, which shows how institutional structures, epistemic norms and power relations shape the roles SSH researchers play, including how more critical or interpretive perspectives are too often marginalised. [1]

I speak not as a modeller but as a Social Scientist who has collaborated with modellers, and who has interviewed both energy modellers and the policymakers who rely on (and fund) their models. This research demonstrates that energy models and their assumptions are far from neutral: political dynamics shape modelling choices, and policymaking environments influence what evidence becomes seen as credible. Although models are often treated as objective tools, policymakers rarely engage deeply with the interpretive choices embedded in them, revealing a striking asymmetry between model production and model use. [2, 3]

These insights collectively prompt a series of provocations for workshop participants, including: how do current modelling approaches 'account for' people and social change – and what falls through the gaps? Whose expectations – from policymakers to modellers to SSH scholars – shape what modelling evidence is expected to deliver? How has the same modelling evidence been used to support divergent political or policy agendas? What are the consequences of treating models as neutral and objective, rather than as socially and politically situated? And might more attention to modelling *processes* – rather than only outputs – allow for richer reflexivity, more inclusive epistemic practices and greater openness about uncertainty, interpretation and judgement?

Rather than offering definitive answers, this presentation seeks to open space for interdisciplinary dialogue. Many workshop participants will, of course, have their own

experiences of navigating modelling-policy interfaces, interdisciplinary tensions, or the challenges of representing society within formal analytical tools.

References

[1] Silvast, A., Foulds, C., 2022. *Sociology of interdisciplinarity: The dynamics of energy research*. Cham: Palgrave Macmillan.

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Identifying optimal circular economy pathways: Linking prospective sustainability assessment with Integrated Assessment Model scenarios

Safdar Abbas[1], Paraskevi Karka[2], Stavros Papadokonstantakis[1]

[1]TU Wien, Institute of Chemical, Environmental and Bioscience Engineering, Vienna, Austria
[2]University of Groningen, Faculty of Science and Engineering, Engineering and Technology Institute Groningen (ENTEG), Groningen, The Netherlands

Advanced biofuels are increasingly recognized for their potential to reduce emissions in sectors reliant on liquid fuels, and contribute to the European Union's carbon neutrality targets.
This study explores sewage sludge valorization within a circular economy framework for the production of renewable fuels via Hydrothermal Liquefaction (HTL). HTL is an emerging conversion technology with strong environmental and economic potential, influenced by process design choices (foreground system) and the performance of the supporting background system that provides materials and energy.
A prospective sustainability assessment framework is employed to develop future scenarios, combining prospective life cycle assessment (pLCA) and techno-economic analysis (pTEA). Integrated Assessment Model (IAM) scenarios are used to model the evolution of background systems in the pLCA and formulate the set of the background scenarios, while technological learning is incorporated in the pTEA to assess cost reductions from early-stage to mature deployment. Background scenarios are derived from the IAMs using the REMIND model, under the Shared Socioeconomic Pathway SSP2, to represent transformations in the energy–economy–climate system across different climate targets for 2030–2050. The alternative foreground design options are combined with the future background scenarios under an optimization-based approach to assess trade-offs between emissions, costs, and resource use under multiple future scenarios.
Overall, the study demonstrates how combining IAM-based scenarios with prospective sustainability assessment supports the identification of efficient circular economy pathways, contributing to more informed strategies towards carbon neutrality.

References

[1] Abbas S, Karka P, Papadokonstantakis S. Optimization of prospective circular economy in sewage sludge to biofuel production pathways via hydrothermal liquefaction using P-graph. Systems and Control Transactions 4:2000-2006 (2025)

[2] L. Baumstark et al., "REMIND2.1: transformation and innovation dynamics of the energy-economic system within climate and sustainability limits," Geosci Model Dev, vol. 14, no. 10, pp. 6571-6603, 2021

Exploring the economy-wide implications of nascent sector activity using national CGE models: The example of CO_2 transport and storage

K. Turner[1], A. Katris[1], C. Calvillo[1] and J. Race[2]

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[2] Department of Naval Architecture, Ocean and Marine Engineering, University of Strathclyde, Glasgow, United Kingdom

The UK Climate Change Committee (CCC) views carbon capture utilisation and storage (CCUS) as essential for the UK to achieve its net zero objectives. Although, capturing CO_2 involves additional capital requirements and processes added to the production structure of existing industries/sectors, transportation and storage (T&S) of captured CO_2 constitutes a new economic activity. As economy-wide models typically rely on historical data, considering a nascent T&S sector introduces challenges around modelling the sector's upstream supply chain structure, representing its labour and capital requirements, capturing the potential users of T&S services and ultimately reflecting the value of the activity and the value-added that this nascent sector might generate. It is therefore challenging to assess the economy-wide and socio-economic implications of a T&S sector to the economy (here focusing on the UK economy).

CEP has conducted extensive work on the economy-wide impacts of developing and operating a nascent T&S sector, along with the implications of who pays for the T&S services [1] and the role of labour market constraints in determining the economy-wide outcomes [2]. This presentation will reflect on the lessons learned on how a nascent sector can be introduced in a computable general equilibrium (CGE) model through the use of appropriate proxies and how bottom-up engineering analyses [3] can be used to inform relevant modelling scenarios. We will discuss the necessary steps to validate the proxy choices, the adjustments required in the underlying social accounting matrices (SAM) and the strengths and limitations of this approach. We will also discuss the approach taken to model 'who pays' for T&S services, how the labour market constraints have been captured and what are the main insights from the applied work exploring different 'who pays' approaches and levels of labour market constraints.

References

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Confronting the climate change related sciences with the 'Dismal Science': a personal 'integrated assessment'

Hans Kremers[1]

[1]*Department of Economic Analysis, University of Zaragoza, Spain*

The PANTHEON project introduces “decarbonization roadmaps to help the EU and China achieve carbon neutrality while considering socio-economic and environmental impacts”. In order to successfully develop such roadmaps, models from several climate change related scientific areas have to be integrated into one framework. The PANTHEON project attempts to combine the WILIAM integrated assessment model with a so-called ‘computable general equilibrium’ model.

Computable general equilibrium models are mainly applied at large economic institutes such as the EU, to assess the economic and environmental impact of climate change or decarbonization policy measures in an economy, by comparing the available policy alternatives with respect to their net (welfare) costs. A significant advantage of applying computable general equilibrium models is the possibility to quantify direct and indirect impacts of policies. Economists build and apply their models traditionally very differently than the other sciences involved in integrated assessment frameworks. Economic models are mainly theoretical models. In particular, computable general equilibrium models. It does not describe a real-world economy at all. The model is based on a particular general equilibrium model founded in microeconomic theory. The Arrow-Debreu general equilibrium model provides an economy that satisfies the *two theorems of welfare*, i.e. each market equilibrium is (Pareto) *efficient*, and every efficient market allocation can be obtained by a suitable reallocation of resources, under well-known assumptions. As such, the computable general equilibrium model provides a net (welfare) cost efficient *benchmark* equilibrium against which the (counterfactual) equilibria associated with the implementation of (climate change or decarbonization) policies can be compared with respect to their (opportunity) *costs*. The important role of applying the computable general equilibrium model to any policy impact analysis lies in the provision of a net welfare cost efficient benchmark equilibrium.

In this short lecture, I would like to take the opportunity to make you at least aware of some of the issues, misunderstandings, etc. involved when including economic models, in particular computable general equilibrium models, in such integrated assessment frameworks.

Air quality, climate change, and health

Jos Lelieveld[1]

[1]*Max Planck Institute for Chemistry, Mainz, Germany*

Air pollution, mainly caused by fossil fuel use and industrial activities, includes particulate matter and oxidant gases that pose serious health risks. Short-term exposure can irritate the respiratory system and worsen asthma, while long-term exposure is linked to chronic conditions like cardiovascular disease, COPD, and lung cancer. Globally, air pollution leads to millions of early deaths each year. Measures such as setting air quality standards, expanding renewable energy, reducing greenhouse gas emissions, and promoting electric transportation improve air quality and extend life expectancy. It may seem a dilemma: particulate matter can cool the climate by scattering sunlight and brightening clouds, and reducing it to improve air quality can accelerate warming in the short term. However, cleaner air is crucial for human and planetary health, providing co-benefits for public well-being and long-term climate stability.

Plausible climate futures depend on better integration of social and natural systems

Chao Li[1], Lennart Ramme[2], and EU-WorldTrans Consortium

[1]Max Planck Institute for Meteorology, Hamburg, Germany

Plausible climate futures require understanding the co-evolution of human and natural systems. I will first outline the physical basis of anthropogenic warming and why rapid emissions cuts together with carbon removal are essential for mitigation. I then review how future pathways are commonly built with integrated assessment models (IAMs) and Earth system models (ESMs), and why using them separately misses crucial two-way feedbacks between society and climate. To address this, I present FRIDA v2.1, a fully coupled framework that links socioeconomic dynamics with the physical climate system, and the Hamburg Climate Futures Outlook, which evaluates the plausibility of scenarios under real-world social, technological, and institutional constraints. I will also introduce FRISIA, a process-based model of global sea level rise (SLR) impacts and adaptation that can be coupled to FRIDA. Unlike costoptimization approaches, FRISIA prescribes alternative adaptation pathways (e.g., coastal protection, planned retreat) and resolves socioeconomic feedbacks—for example, when limited finance reduces protection, storm damages slow growth and further constrain protection. In a scenario with ~0.8 m SLR by 2100 (≈1% per-year acceleration), FRISIA–FRIDA yields global GDP losses of 1.5–6.2% without adaptation and 0.5–3.2% with adaptation. Accounting for feedbacks shows damages may peak in the first half of the 22nd century and then decline as vulnerable assets lose value and investment shifts away from high-risk zones, though residual and uneven losses remain and delays in protection matter.Together, these results show how coupling social and natural systems improves the plausibility and usefulness of climate scenarios, from mitigation pathways to SLR adaptation. FRIDA and FRISIA are open source and under active development.

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The 21st Century Climate Response to China's Clean Air Action and Carbon Neutrality Targets

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China's clean air action (CAA) has significantly reduced air pollution and human risk, cutting sulfur dioxide emissions and the cooling effect of sulfate aerosol (SO_4) by 90% since 2007. However, the extent to which the CAA and the emission reductions of SO_2 and other scattering aerosols could affect climate and the country's carbon targets remains unclear. Here we use Earth system model simulations and radiative forcing decomposition to quantify how changes in sulfate and other short-lived climate forcers have altered the regional climate trajectory. We find that the CAA has reduced SO_4 cooling by a factor of approximately six in 2020 relative to a counterfactual scenario without the CAA, contributing to in a 0.08^{o}C increase in surface temperature over 1990-2020. A transition from cooling to warming trends occurred in 2007, and would have been postponed to 2013 in the absence of CAA. We construct an adjusted CO_2 emission metric that accounts for the co-evolution of sulfate cooling and greenhouse-gas (GHG) warming. This framework reveals that the diminished sulfate cooling substantially amplifies the climate impact of CO_2 emissions, but that simultaneous reductions in black carbon and other short-lived forcers help moderate the overall warming effect. Our results show that that co-management of aerosols and GHG is essential for achieving China's carbon neutrality targets.

Optimization and Techno Economic Analysis of Energy Systems

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The global energy system faces the dual imperative of decarbonization and operational reliability, requiring accelerated renewable integration and sector coupling. Energy system modeling plays a central role in identifying robust transition pathways by enabling systematic evaluation of future energy scenarios. By combining techno economic analysis with optimization methods, energy system models can assess trade offs between emissions reduction, system cost, and supply reliability.

Optimization of energy systems serves as a core methodology for the design and operation of complex multi carrier energy infrastructures under technical and economic constraints. Techno economic analysis links technical system performance with cost and economic metrics to support rational and transparent decision making. Key challenges include increasing model complexity, data uncertainty, temporal and spatial resolution requirements, computational scalability, and limited representation of social dimensions. Methodological and computational solutions can improve the robustness and tractability of energy system models.

Economic and environmental impacts of e-fuels in Spain: Replacement of fossil fuels by DME

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Dimethyl Ether (DME) stands out as a promising substitute for diesel and liquefied petroleum gas (LPG) and may be produced from CO_2 and green hydrogen, which makes DME one of the most interesting e-fuels. This study focuses on the introduction of a new DME production sector into the Spanish economy, aimed at partially replacing the current refining sector. An advanced technology, such as a membrane reactor [1] or a sorption-enhanced reactor [2] is considered for DME production, which allows higher yield to DME in the reactor. The analysis employs a customized input-output model in which a new DME-producing sector is incorporated, following previous developments [3]. The model includes detailed economic components such as capital expenditures (CAPEX), operating costs (OPEX), labor costs, and production volumes, assuming a plant capacity of 100 kilotons of DME per year. Other aspects, such as water consumption or by-products valorization, are also considered. The environmental analysis reveals potential reductions in environmental impacts, with embodied emissions of CO_2 decreasing by 0.23% compared with the benchmark year in 2021, along with SO_x, CH_4 and NO_x emissions being reduced by 0.29 %, 0.24%, and 0.08% respectively, , as a result of replacing 0.37% of the petrol refinery sector with DME production. Overall, the results demonstrate that DME, produced from renewable electricity, offers a viable path toward industrial decarbonization. The methodology provides a policy-relevant framework for integrating synthetic fuels into national economies through sectoral restructuring and input-output analysis.

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Plant-Level Technology Pathways for Cost-Effective Industrial Decarbonization

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To effectively decarbonize heavy industry, climate policy must move beyond broad national targets and address the complex economic realities of individual industrial plants. Overlooking vast plant-level heterogeneity leads to inefficient, costly transition strategies. This presentation introduces a powerful bottom-up modeling framework that overcomes this barrier by engineering least-cost, technologically feasible decarbonization pathways for thousands of facilities across the globe. By integrating granular plant-level data with dynamic techno-economic forecasts, our research constructs an actionable blueprint for a smarter industrial transition. This plant-specific approach allows policymakers to target interventions effectively, minimize economic costs, and demonstrate that achieving ambitious climate goals can be aligned with industrial competitiveness.

Energy Price Volatility and the Costs and Benefits of the EU Energy Transition: Integrated Assessment Modeling for Carbon Neutrality Pathways

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Energy markets have entered a period of heightened uncertainty, and fossil fuel price volatility increasingly shapes the costs and benefits of the energy transition and the feasibility of carbon neutrality pathways. We introduce a comprehensive framework integrating the advanced Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) model with a newly developed system dynamic WILIAM ("Within limits") Integrated Assessment Model to quantify how energy price influence the cost-effectiveness of EU energy transition pathways. We find that rising energy prices substantially influence the cost-effectiveness of accelerated EU energy transitions. Under current high energy price levels, the benefits from achieving energy targets earlier could outweigh the additional costs. Our results indicate that explicitly representing energy price volatility and linking energy system with environment-climate-health impacts is essential for robust, decision-relevant carbon-neutrality assessments.

Exploring the techno-economic and biophysical limits of the energy transition: an Integrated Assessment Model analysis

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The *Within Limits Integrated Assessment Model* (WILIAM) is an Integrated Assessment Model developed under the EU H2020 LOCOMOTION project to explore sustainable decarbonisation pathways while accounting for biophysical constraints [1]. The model brings together the synergies of combining two key methodologies: system dynamics and input-output analysis, similarly to its twin model, MEDEAS [2], [3]. Unlike optimisation-based IAMs assuming unlimited technological progress, WILIAM integrates eight interlinked modules — demography, economy, finance, energy, materials, land and water, climate, and society — to represent feedbacks and resource limits across socio-environmental systems.

A core innovation of WILIAM is its explicit modelling of resource, energy, and ecological boundaries: renewable potentials, energy return on investment (EROI), land competition, and material availability. This allows the model to evaluate not only how emissions can be reduced, but also whether such transitions remain physically and ecologically feasible. Considering that, we analyse decarbonisation pathways under different constraints: economic, biophysical and technical. First, by integrating WILIAM with a Techno-Economic (TEC) database within the HORIZON project PANTHEON, we harmonise energy technology cost assumptions and limit the growth in additional capacity in the WILIAM Energy module [4], considering its costs. Second, we assume renewables' maximum potentials that effectively limit the total installed capacity in a territory, given several biophysical constraints [5], [6], [7]. Third, we capture the technical limit posed by the intermittency of solar and wind power: as variable renewables expand, curtailment and declining capacity factors emerge unless system flexibility (e.g., storage, sector coupling, demand response) also grows, thereby constraining further deployment and shaping feasible decarbonisation pathways [8], [9].

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System Dynamics modeling for integrated assessment: challenges and opportunities

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Over the last twenty years, system dynamics (SD) modeling has gradually emerged as a useful complement to other common modeling methods for integrated assessment. SD modeling facilitates multidisciplinary approaches, supporting the integration of analytical frameworks of economic, environmental, and social nature. The solution via numeric simulation also allows for a step-by-step analysis of the dynamics involved with different development pathways, which essential to design effective long-term strategies. Also, SD models can represent feedback-rich and non-linear systems, relevant to capture policy amplification or resistance (rebound effects) in ex-ante assessments. Despite these important advantages, SD modeling is not yet effectively included in most integrated assessments. Three orders of factors seem to pose a particular challenge towards coupling SD models with other tools used for integrated assessment: the harmonization of time, granularity, and of their central hypotheses about economic behavior. First, the simulation paradigm of SD models is not directly compatible with static or optimization approaches. This implies that hard coupling is especially challenging and might require iterative solutions that lead to losing some of the advantages of the feedback-rich approach. Second, to allow for reasonable simulation speed and interpretability, SD models tend to adopt a higher level of aggregation than traditional economic models or spatially defined environmental models. Consequently, some finer level dynamics might be lost in such a coupling. Third, SD models for IA often use economic formulations that depart from traditional CGE frameworks. This often happens because of the enhanced flexibility that SD modeling provides when representing agents' behavior, but it undermines comparability and replicability of results with other tools. While recent software development is facilitating communication between different modeling paradigms, a substantial research gap remains towards addressing these challenges and thus fully harvesting the capabilities of SD modeling for integrated assessment.

A threefold approach for the acceleration of Sustainable Development Goals and beyond

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Countries are not on track to meet the 2030 Agenda for Sustainable Development that calls for transformative changes to shift the world onto a sustainable and resilient path. The 2030 Agenda comprises 17 Sustainable Development Goals (SDGs) and 169 targets to be achieved by 2030, balancing the three sustainability dimensions—social, economic, and environmental. So far, SDGs have had a limited transformative impact due to their selective implementation, which overlooks their complex interactions. SDGs interact positively (i.e., synergies) or negatively (i.e., trade-offs) depending on context- and location-specific mechanisms. Failing to meet SDGs will negatively affect the lives of billions of people and worsen socioeconomic and environmental crises. Therefore, the next few years are crucial for accelerating SDG progress and for adopting a post-2030 Agenda or a follow-up to the SDGs. I propose three research avenues, grounded in a threefold scientific approach, to address these urgent needs (Fig. 1).

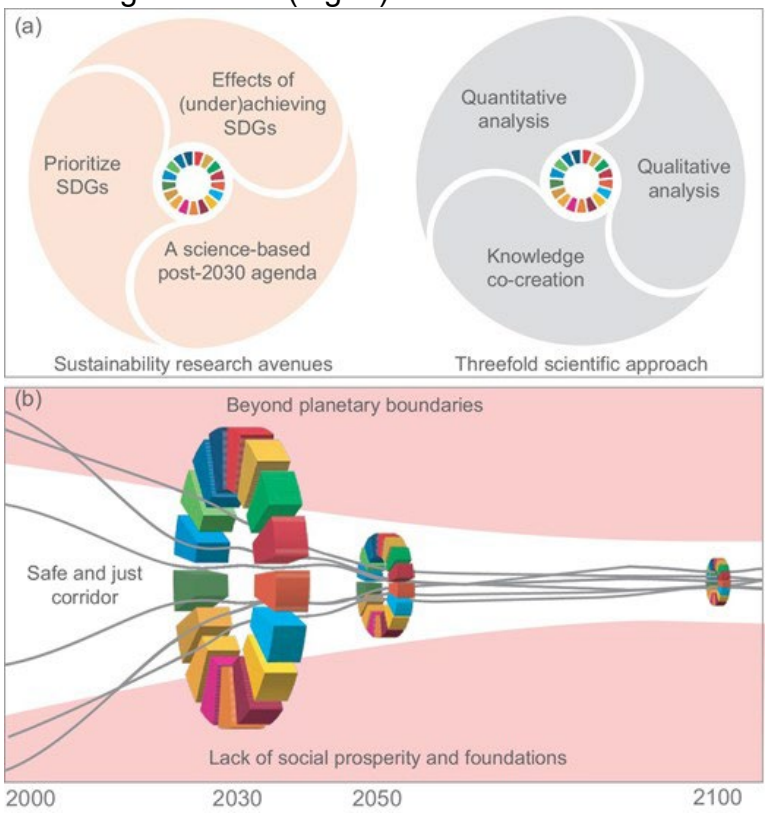

Figure 1. A conceptual framework for ensuring sustainability beyond achieving Sustainable Development Goals. (a) The threefold scientific approach (left) combines three methods. (b) Sustainability requires building social prosperity and foundations without transgressing planetary boundaries (the red areas). Grey lines illustrate sustainable development pathways for various countries, highlighting the need for transformative change. [1]

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Integration of social sciences and humanities in Swiss energy modelling: situating the context of research practices

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The energy transition in Europe is haunted by the mounting political contestation, public unease and geopolitical instability. For decades, techno-economic modelling has been a primary interface between energy scientists, experts and policymakers. Modelling presents a convenient, adaptable and constantly advanced way of dealing with uncertainty and change within the energy systems. Yet, it remains deeply sensitive to shifting contextual factors of research, which affect accuracy of what models represent, but no less importantly, how models are being made and legitimized.

Recent push from European funders and policymakers to support research focused on crossing disciplinary boundaries and engaging societal actors has become one of the proposed responses to the troubled landscape of energy transition. This attempt inevitably surfaces the problem of integration in the knowledge production process and calls for in-depth understanding of the practices, challenges and contexts that diverse research teams face.

In this presentation, I argue that reflexive social sciences and humanities offer an essential epistemic counterweight to the techno-economic modelling that sensitise energy research to power, context and legitimacy. Drawing on my ethnographic research within a major Swiss energy-modelling consortium I examine how knowledge hierarchies, institutional environments, and research cultures shape attempts at integration. Using insights from my qualitative, hands-on approach to study Swiss energy research, I show what practices researchers share in collaborations and what discourses impact their understanding of integration.

Building on these findings, I outline a set of recommendations for facilitating meaningful and reflexive SSH integration in large energy modelling research projects, alongside a framework for interpreting the context-based dimensions of integration and broader perspective on the relation between energy science and energy transition policy. The talk invites researchers across disciplinary boundaries to reconsider how energy knowledge is constructed and what forms of expertise are needed for a socially and epistemically robust energy transition.

New ScenarioMIP Pathways and Insights from the Scenario Compass Initiative: What the Latest Global Emissions Scenarios Tell Us

K.Riahi, et al., 2026

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Global emissions scenarios form a critical evidence base for climate policy, informing assessments of mitigation pathways, transition risks, and the feasibility of long-term climate targets. In this seminar, I will present recent advances in the global scenario landscape, focusing on the newly developed scenarios for the next phase of ScenarioMIP and on emerging insights from the Scenario Compass Initiative (SCI), a new community-driven process designed to provide continuously updated and policy-relevant scenario information.

The first part of the talk introduces the new ScenarioMIP scenarios, developed by an international modelling community to support the next generation of climate model intercomparison, impact, and risk analyses. These scenarios provide an updated and internally consistent set of global emissions pathways across a wide range of climate targets and socioeconomic assumptions.

The second part of the seminar draws on the rapidly expanding community scenario ensemble, including several hundred global emissions scenarios that the SCI collected since the IPCC Sixth Assessment Report. Using this broader and more up-to-date evidence base, I will highlight what recent scenarios imply for near-term emissions reductions, the timing of net-zero CO_2 and greenhouse gas emissions, and the evolving feasibility space of mitigation pathways. The results illustrate how recent real-world developments have shifted key benchmarks compared to earlier assessments, with important implications for policy ambition and implementation.

Together, the ScenarioMIP and SCI efforts represent a major step forward in aligning scenario development with the needs of decision-makers. These processes are expected to provide a central quantitative input into the next assessment cycle of the Intergovernmental Panel on Climate Change (AR7), supporting more timely, transparent, and policy-relevant climate assessments.

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Complexity is the substance of evolution; how can our models neglect it?

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Like a ghost hoovering in the rooms of an old castle, frightening the guests' nights, complexity haunts our predictive endeavors and the unscathed, though unintended, will to morph reality into a mechanical system while modelling it as such.

While our attempts to embrace complexity though more complicated models –and computational power, often fall short in achieving better predictability, recent evolution of algorithm complexity (like AI and ML) has led to a new formidable ability to forecast events, often a detriment of explanation. The conundrum of complexity cannot be solved only iteratively and empirically because it is not just about predictions, nor it can be solved only by adding *more elements to the same paradigm*, because it is not just about sophistication.

A model is like a metaphor and needs to preserve both the sematic (explanation) and the syntactic (prediction) elements.

Most existing system dynamics models rely on fixed network topologies, which limits their ability to represent structural change . This research aims to apply the maximum caliber theory to develop a next-generation system dynamics model which considers changes in topology. We first apply Maximum Caliber to backcast historical energy technology trajectories on a fixed network, validating the framework using empirical data from Europe. Building on this validation, we then extend the model to allow endogenous structural changes in the energy network and analyze the coupled dynamics between node dynamics and network topology.

This approach aims to improve the modeling of energy transition pathways and system resilience under uncertainty

Greening Global Value Chains in Transition: Energy Technologies, Industrial Transformation, and modified Lifestyles

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Technological development and structural diffusion of cleaner technologies are fundamental to achieving deep decarbonisation and mitigating the impacts of climate change. This work presents a modelling approach to assess technologies' decarbonization contribution and anticipates economic, social and environmental outcomes of this dynamic and complex process. The main objective is twofold. First, to evaluate the socioeconomic and environmental impacts of current lifestyles of EU and Chinese households linked to the characteristics of households by gender of the main earner, as well as other structural characteristics such as income. Second, to increase the understanding of the socioeconomic and environmental implications decarbonization efforts through the implementation of new technologies to contribute to decarbonization in energy and industrial sectors in MRIO models. In particular, we present a novel approach to implement new technologies into Multi-Regional Input-Output models (MRIO). This approach allows to simulate the gradual adoption of new technologies (based on logistic ttrajectories of technology), and to evaluate then the long-term effects in a context of economic growth as well as the implications of technological changes in new and old technologies. To address this, a MultiRegional Input-Output model (MRIO) with high country and sector detail is developed and extended on the final demand side socially through the consumption of households for different income groups and by gender, based on the most detailed global consumption database; and on the production side both socially through employment data by gender, sector and occupation; and environmentally, with regional detail to evaluate local to global impacts.

Broadening Climate Mitigation Pathways in an Era of Overshoot and Global Constraints.

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The window to achieve the goals of the Paris Agreement is rapidly narrowing. By now, it is only possible to achieve the goals after a temporary overshoot while geopolitical tensions and shifting priorities create additional headwinds. There is a growing need to broaden our understanding of climate mitigation pathways. This presentation discusses some of the options of expanding the mitigation portfolio, addressing the implications of overshoot, and strengthening linkages with wider sustainable development objectives. Regarding the latter: climate change cannot be considered in isolation: it intersects with pressures on multiple planetary boundaries and persistent inequalities in access to resources. Integrating these dimensions is essential for developing robust and equitable strategies

A Human in the Loop. Social Sciences as Catalysts for Reflexive Modeling

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Integrated Assessment Models (IAMs) are widely used to explore pathways for climate and sustainability transitions by linking social, economic, and environmental dynamics. While IAMs generate technically feasible scenarios, they often leave implicit the human, institutional, and societal factors that determine which futures can actually materialize. This contribution introduces a *human-in-the-loop* perspective, positioning humans not only as users of model outputs but as integral participants in shaping, interpreting, and constraining modeled futures. By coupling this perspective with a potentiality–actuality lens, the approach highlights the gap between what is theoretically possible and what is socially, politically, and institutionally realizable. Embedding human judgment, agency, and social constraints into IAM processes enhances reflexivity, helping models move beyond purely technical projections toward tools that support deliberation, learning, and context-sensitive sustainability transitions.

Abstracts of Posters

(in alphabetical order)

Energy pathway diversity and the energy transition

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The integration of renewable energy forms into existing energy infrastructure presents one of the central challenges of the contemporary energy transition. Understanding this process requires attention not only to the introduction of new energy sources, but also to the paths through which energy is transformed and consumed across different activities. Here we apply techniques from network science — specifically, random walkers on weighted directed networks — to analyse the energy systems of 29 European countries over the period 1992–2021, using the JRC-ENERNET database. We decompose energy flows into effective transformation paths, capturing the proportion of energy introduced in one carrier form that ultimately exits the system in another, and quantify the heterogeneity of these paths using the Herfindahl-Hirschman Index. Across countries and levels of resolution — from individual activities to activity groups and entire national systems — we find a strikingly consistent parabolic trajectory: as the share of non-renewable energy declines, system heterogeneity initially increases, peaks near a common threshold, and subsequently decreases as non-renewables are phased out. Only Iceland has crossed this threshold, consistent with its relatively small and stable energy network. Furthermore, we demonstrate that greater heterogeneity is associated with larger annual fluctuations in the non-renewable share, establishing a direct link between systemic complexity and the pace and stability of the transition. These findings suggest that diversification of energy pathways — rather than vertical scaling of individual technologies — may serve as a key lever for accelerating and stabilising the European energy transition.

From fragile cities to carbon-neutral pathways: integrating climate, health, and wash co-benefits in Bukavu, democratic republic of Congo

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Rapid urbanization in fragile contexts presents complex and interconnected challenges for climate resilience, public health, and sustainable water and sanitation systems. In Bukavu, Democratic Republic of the Congo, these challenges are exacerbated by limited infrastructure, environmental degradation, and socio-economic vulnerability. This study explores integrated pathways toward carbon neutrality by examining the co-benefits of aligning climate action with health outcomes and Water, Sanitation, and Hygiene (WASH) interventions.

Drawing on programmatic experience from Fondation Anansoft, this paper highlights how localized, community-driven approaches can simultaneously reduce greenhouse gas emissions, improve public health, and enhance access to sustainable WASH services. The analysis focuses on key interventions, including nature-based solutions, decentralized sanitation systems, and the integration of clean energy solutions in underserved urban communities.

The findings demonstrate that cross-sectoral strategies can effectively address both climate mitigation and adaptation while generating measurable health co-benefits, such as reduced incidence of waterborne diseases and improved environmental conditions. Furthermore, the study emphasizes the critical role of governance, stakeholder engagement, and policy coherence in scaling these solutions within fragile urban environments.

By positioning Bukavu as a case study, this research contributes to ongoing discussions on inclusive and context-sensitive climate pathways in Sub-Saharan Africa. It advocates for integrated frameworks that bridge climate, health, and WASH sectors to accelerate progress toward carbon-neutral, resilient, and healthy cities.

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Miniature Sensors In Profiling of Atmospheric Aerosols in Troposphere

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Aerosols influence the climate (through direct and indirect effects), human health (via smog formation), and the economy (by affecting photovoltaic energy production and primary productivity) [1,2,3]. They can be measured in situ—typically at the surface—or remotely, either as integrated columnar loads (aerosol optical depth) or in vertically resolved profiles from LIDARs (ground or satellite).

Ground-based observations are conducted using high-precision instruments within operational networks and increasingly with low-cost sensors in community-based projects. For reliable radiative transfer and aerosol transport modeling, detailed knowledge of vertical aerosol distribution is needed, not just surface concentrations [4]. However, vertically resolved data remain limited due to the high costs of measurement infrastructure and the challenges of inverse remote sensing methods. This scarcity is especially problematic during extreme events, when the absence of vertical profiles can impair timely societal responses.

To address this limitation, we propose the use of aerosol microsensors—commonly applied in surface measurements—mounted on sounding platforms capable of sampling across different tropospheric layers. Owing to their small size, low weight, and low cost, these sensors can be deployed in modular systems installed on tall static structures (towers, skyscrapers [5]) or mobile platforms (drones [6], meteorological balloons [7]). They support both continuous monitoring in remote regions and rapid deployment during extreme events such as wildfires or volcanic eruptions. Our poster presents results from several vertical profiling campaigns, including recent measurements from the summer of 2025. These studies demonstrate the feasibility and advantages of the MICE (Microsensors In Challenging Environments) approach for expanding access to vertical aerosol data, which could be used for integrated modelling.

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Needs for More Integrated, Inclusive, and Policy-Relevant Modeling of Food System Transitions: Insights from a Systematic Review

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Food systems underpin human nutrition and livelihoods but are currently on unsustainable trajectories, failing to ensure global food security while exerting substantial environmental pressures. Transitioning towards sustainable food systems therefore requires robust, integrated modeling frameworks to assess trade-offs, impacts, and pathways for change. Here, we conduct a systematic review of food system modeling studies and synthesize more than 850 sustainability indicators from 150 publications. We show that indicator use is highly fragmented across the reviewed literature: of the more than 850 indicators identified, 436 are unique, with limited convergence in definitions, metrics, or reporting practices. This lack of standardization substantially constrains comparability across models, scenarios, and regions, hindering cumulative knowledge building and cross-study synthesis. We further find that around one-third of studies apply model coupling or integrated assessment frameworks, yet such approaches remain unevenly adopted across spatial scales and transition strategies. Our findings highlight the need for harmonized, transparent, and policy-relevant indicator frameworks to enable systematic and comparable assessment of food system transition outcomes.

The role of technological trajectories in global sustainable growth

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Technology plays a key role in achieving sustainable growth by enabling the development of less polluting production processes, as highlighted in the existing literature. Consequently, an analysis of technological evolution at the global level is useful for identifying key areas for improvement and understanding technological differences across countries. In this context, this study first examines the evolution of several technological indicators computed using a Multiregional Input–Output (MRIO) framework. Second, it simulates the potential impact on global emissions if developing economies were to operate with the technologies of more advanced economies through counterfactual scenarios.

Technology is proxied using a set of indicators, including backward and forward linkages; the standard deviation of the columns of the technical coefficients matrix (Matrix A) as a measure of specialization; the share of intermediate inputs and value added relative to output; the share of domestic inputs relative to total inputs; the share of labour compensation relative to value added; and the share of intermediate inputs sourced from similar countries. After analyzing the technological evolution across countries, a Synthetic Control Method [1] is applied to assess how emissions would have evolved if less developed countries had adopted more advanced technologies.

Regarding the data, the analysis relies on the GLORIA database [2], which provides information for the period 1990–2030 and is disaggregated into 164 countries and 120 sectors. The study focuses on key sectors for the sustainable transition, particularly iron and steel, energy, electricity (renewable and non-renewable), cement and plaster products, transport equipment, and chemical sectors. Preliminary results reveal significant differences across countries and sectors, with clear patterns distinguishing developed and developing regions.

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Adjoint Optimization of Ozone and $PM_{2.5}$ Mitigation Pathways in China with Updated Chemical Mechanisms

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This study presents the development of an upgraded CMAQ-Adjoint modeling framework that integrates a state-of-the-art chemical mechanism with comprehensive re-derivation of sensitivity coefficients specifically tailored for the Chinese atmospheric environment. The enhanced system generates high-resolution, grid-scale sensitivities of ground-level ozone and fine particulate matter ($PM_{2.5}$) to nitrogen oxides (NO_x) and volatile organic compound (VOC) emissions across all major economic sectors, including power generation, industry, transportation, residential, and agriculture. These atmospheric response matrices, which capture the nonlinear photochemical interactions and regional transport patterns characteristic of China's complex emission landscape, are systematically coupled with sector-specific marginal abatement cost curves derived from bottom-up technology assessment and econometric analysis. This integration enables the identification and prioritization of cost-effective joint ozone–$PM_{2.5}$ control pathways that account for both atmospheric effectiveness and economic feasibility. We further present the methodological framework for integrating atmospheric and economic data, including the treatment of sectoral interdependencies, temporal dynamics of emission reductions, and uncertainty propagation across coupled modeling systems. Finally, we discuss the broader implications of mechanism-level refinements for advancing system-dynamics approaches in air quality management, particularly regarding the representation of chemical feedbacks, the characterization of multi-pollutant responses, and the support of adaptive policy design under changing emission scenarios and climate conditions. This study is ongoing.

Biomass Energy and Climate: Reassessing the Past and Modeling Future Feedbacks

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Conventional wisdom often treats biomass energy as inherently carbon-neutral, assuming that emissions from combustion are offset by regrowth. This assumption, however, may overlook significant historical climate forcing from traditional biomass use, as its harvesting can drive land-use changes and associated carbon losses from ecosystems. This study re-evaluates the climate impact of past biomass energy systems by quantifying these indirect emissions, challenging the simplistic carbon-neutral narrative. Furthermore, while integrated assessment models (IAMs) project large-scale bioenergy deployment as a cornerstone of future climate mitigation, they frequently operate under static climatic and biophysical conditions. This work advances the modeling of bioenergy within IAM frameworks by explicitly integrating dynamic climate-biosphere feedbacks. We analyze how climate change-induced shifts in temperature and and CO_2 fertilization affect bioenergy crop yields, and how these altered yields in turn influence long-term mitigation pathways and land-use dynamics. Our findings reveal that overlooking these bidirectional interactions can lead to significant biases, potentially overestimating the mitigation efficacy of bioenergy and underestimating its pressure on land resources. By bridging historical reassessment and forward-looking model development, this research provides a more nuanced and systemic understanding of biomass energy's role in the climate system, which is critical for designing robust and sustainable climate policies.

Climate Mitigation Scenario Generation with Large Language Models

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IAM scenario coverage is limited by structural biases and high computational costs, alongside restricted code access and model complexity. Recent advances in generative AI offer new opportunities by enabling the efficient generation of large ensembles of synthetic mitigation pathways from high-dimensional scenario data. Early studies employing deep generative models, such as variational autoencoders (VAE), have demonstrated the ability to reproduce key statistical characteristics of IAM outputs derived from IPCC AR6 scenarios at substantially reduced computational cost (Li et al., 2025). However, the existing approaches emphasize reproducing marginal distributions and correlations, while neglecting the uneven representation of models across scenario categories. Consequently, whether generative approaches can genuinely expand the policy-relevant scenario space beyond existing IAM outputs, and how such synthetic scenarios should be applied in practice, remains an open question.

In this study, we propose an LLM-assisted framework for generating interpretable and policy-relevant synthetic energy system scenarios that explicitly addresses these limitations. Methodologically, for a given new region-model–policy scenario combination, we first employ retrieval-augmented generation (RAG) to identify semantically similar model–scenario pairs within the existing IPCC AR6 database. By jointly analyzing the distributions of scenario outputs, model fingerprints, and scenario narratives, the LLM leverages semantic understanding to infer and generate coherent new region-model–scenario combinations, expanding the IPCC AR6 IAM scenario database by a factor of five. We further benchmark this approach against conventional machine learning methods (e.g., VAE), and demonstrate that under multivariate settings with limited training data, prompt engineering can provide a more efficient and flexible alternative to training task-specific models. Our analysis focuses on the variables of the energy system. The resulting scenarios can be integrated into prospective LCA frameworks, enabling the assessment of product-level environmental impacts across a broader range of plausible future energy system pathways.

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System dynamics modeling of Dutch policy scenarios within planetary boundaries

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The Dutch economic trajectory is unsustainable across social, economic, and environmental dimensions and has already led to the exceeding of planetary boundaries[1]. The EU and Dutch governments have introduced policies and emission targets to mitigate their impact. However, current trends show that the Netherlands is not sufficiently lowering its contributions to exceeding planetary boundaries, and proposed policies may fall short[1]. Meanwhile, research argues that a drastic economic shift towards degrowth is necessary to get on track[2]. While integrated, model-based analysis is a powerful tool for assessing environmental and socio-economic impacts, its application to evaluate policy pathways designed to keep the Netherlands within planetary boundaries remains limited[1]. Our study analyses the effects of various policy pathways on sustainability dimensions using the iSDG model adapted to the Netherlands. The iSDG model is a national-level system dynamics model that includes environmental and socio-economic sectors[3]. When analyzing the effects of policies to reduce emissions, accounting for impacts on well-being and other socio-economic indicators is crucial[4]. Our study is the first to address this by considering indicators across all 17 SDGs for the Netherlands. We explore policies that change economic incentives, such as a carbon tax and investments in green energy. Additionally, we analyze a policy pathway involving direct emission reductions through structural interventions, such as limiting livestock numbers, reducing pesticide and chemical fertilizer use, and phasing out machinery dependent on fossil fuels. These measures aim to enforce emission targets by reshaping economic activities rather than relying on profit-oriented incentives. Preliminary findings suggest that drastic transformations are needed for the Netherlands to limit its contribution to exceeding planetary boundaries. Public investments in green practices, while aligned with the values of the Green Deal and the Dutch National Recovery and Resilience Plan, are insufficient and require substantial scaling up. Alternatively, enforcing emission reductions to the required levels results in limited trade-offs with socio-economic indicators and, combined with social reforms, could lead to a truly sustainable society.

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Wetland Methane Feedbacks Make the Paris Agreement Goals More Difficult to Achieve

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Human-induced climate change has increased global wetland methane (CH_4) emissions over the past decades, further amplifying global warming. However, this positive feedback has not been routinely accounted for in CMIP6 Earth System models (ESMs), leading to an underestimation of future warming and, consequently, an underestimation of the difficulty of achieving the Paris Agreement temperature stabilisation targets. We present a framework for coupling a reduced-complexity climate model and emulators with a process-based wetland emission model to evaluate expected wetland methane-climate feedbacks across a range of potential future climate change scenarios. We find that wetland CH_4 emissions are likely to cause an additional 0.07–0.12 ℃ of global warming by the year 2100, depending on the scenario. When wetland CH_4 climate feedbacks are considered, 22% of the anthropogenic scenarios aiming to limit global warming to 2 ℃ in IPCC AR6 WGIII will exceed this temperature threshold. Alternatively, due to wetland CH_4 feedbacks, stabilising global temperature at the 1.5 ℃ or 2 ℃ global warming levels implies that the remaining anthropogenic emission carbon budgets (RCBs) should be reduced by 6% and 3%, respectively. For scenarios in which global temperature stabilisation is eventually achieved after a period of warming overshoot through carbon dioxide removal (CDR), increased atmospheric CH_4 concentrations driven by wetland emissions could require an increase in cumulative CDR of at least 32% to offset the additional warming. Such sustained pressure from wetland methane-climate feedbacks in scenarios with temperature overshoot will be due to their high magnitude during the periods of high warming. Hence, our results highlight how earlier climate mitigation measures could enhance the likelihood of achieving the goals of the Paris Agreement, as this will lessen CH_4 release from wetlands

Vertical Profile Corrections Explain Satellite-Inventory Ammonia Discrepancies and Reveal Concentrated Agricultural Sources in China

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Persistent discrepancies between bottom-up inventories and satellite-based ammonia (NH_3) emission estimates have hindered effective air quality management and nitrogen deposition control policies. This study addresses this fundamental challenge by demonstrating that systematic biases in satellite vertical profile assumptions substantially explain long-standing discrepancies, with satellites typically reporting values one-third higher than inventories. We employed the IASI satellite NH_3 retrievals and replaced default vertical profiles with spatially and temporally resolved atmospheric profiles from CMAQ modeling. This correction reduced satellite-model discrepancies from 71% to 18%, effectively closing the NH_3 budget gap. Our hybrid inversion analysis reveals that baseline satellite retrievals overestimated China's growing season emissions by up to 43% due to systematic overestimation of near-surface NH_3 concentrations. Critically, our corrected estimates show that China's NH_3 emissions are more spatially concentrated than previously indicated, with the top 10% of high-emitting areas contributing 54-56% of national emissions. This concentration reflects agricultural intensification patterns inadequately captured by conventional bottom-up inventories, including the rapid growth of concentrated animal feeding operations. The improved emission characterization has important implications for integrated assessment models addressing climate-environment-health co-benefits. The more concentrated spatial pattern implies greater localized environmental burdens for $PM_{2.5}$ formation and nitrogen deposition, suggesting that targeted emission control policies in hotspot regions would yield disproportionate benefits for air quality improvement and ecosystem protection. This methodology provides a robust framework for enhancing satellite-based emission inventories that can support evidence-based policymaking for agricultural emission control, contributing to pathways towards environmental sustainability and

carbon neutrality goals.

Quantifying the Real Heat-Related Mortality Risk: The Mitigating Role of Air Conditioning and Its Global Regional Variations

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Most epidemiological models rely on ambient outdoor temperature to estimate heat-related mortality, overlooking the fact that humans spend approximately 90% of their time indoors. This reliance creates an "exposure misclassification" that underestimates the true health burden and obscures the crucial mitigating role of air conditioning (AC). To address this gap, this study aims to establish an exposure-response relationship that directly links actual personal heat exposure–specifically, indoor temperature adjusted for active cooling–to mortality risk. This approach allows for an accurate quantification of the underlying human vulnerability to heat and the protective effect of AC on a global scale.

To achieve this, we employed a novel, data-driven approach. We first generated a global dataset of AC-modified indoor heat exposure by combining gridded AC penetration rates–estimated via a machine learning model–with physical simulations of indoor temperature. This exposure dataset was then linked to daily mortality records for over 1,000 cities using Distributed Lag Non-linear Models (DLNMs) to estimate city-specific exposure-response functions. Finally, we employed multivariate meta-regression to extrapolate these city-specific estimates to a global scale.

Our analysis provides the first global quantification of the "real," physiology-based heat-mortality relationship, effectively decoupling it from the masking effect of air conditioning. The resulting risk function is steeper at high temperatures than estimates based on ambient data, revealing a greater underlying human thermal vulnerability. It simultaneously confirms the substantial, yet spatially heterogeneous, protective effect of AC. These refined risk parameters are therefore critical for accurately projecting future health burdens under climate change and for designing resilient, equitable adaptation policies that balance immediate health protection with the long-term imperative of carbon neutrality.

Towards Understanding Marine New Particle Formation: Progress and Challenges

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New particle formation (NPF) is a major global source of cloud condensation nuclei (CCN) and plays a central role in regulating cloud properties and Earth's radiative balance. In the remote marine boundary layer (MBL), however, the processes governing NPF remain poorly constrained. Progress has been made in identifying key precursors and photochemically driven pathways, yet current understanding is not sufficient to fully explain observed NPF events, and fundamental characteristics such as their frequency and vertical structure remain uncertain. This challenge remains a major source of uncertainty in the representation of aerosol–cloud interactions in Earth system models, thereby affecting climate projections and assessments based on integrated assessment models (IAMs). We will review the current understanding of marine NPF and discuss its key limitations and challenges, including the difficulty of disentangling competing chemical pathways and the limited observational constraints on precursor–particle relationships. We then present an approach that combines multi-year shipborne and aircraft observations with cloud-resolving modeling to investigate marine NPF across a range of atmospheric conditions. In particular, we explore how these observations can be used to better isolate the processes governing particle formation and their vertical structure. By integrating observational constraints with process-level modeling, this work aims to improve our understanding of marine aerosol sources and their connection to cloud-relevant particle populations. Advancing this understanding is essential for improving the representation of aerosol–cloud interactions in large-scale models, reducing uncertainty in radiative forcing, and strengthening the scientific basis for climate projections and pathways toward carbon neutrality.

Development of a Multi-Species Hybrid Inversion Framework for Anthropogenic Emission inversion: An Online Adaptive Regularization Strategy within CMAQ-Adjoint

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Accurate quantification of anthropogenic emission inventories is vital for assessing air quality and climate change, particularly in rapidly developing regions like China. While satellite-based top-down inversion is a standard constraint for bottom-up inventories, traditional methods struggle to balance computational efficiency (e.g., Mass Balance) with physical consistency (e.g., 4D-Var). Furthermore, reliance on single-species constraints neglects complex non-linear chemical couplings (e.g., SO_2-NH_3-Aerosol), causing aliasing errors. To address this, we developed a novel multi-species hybrid inversion framework based on the CMAQ-Adjoint model. This system integrates a mass balance-based initialization with a rigorous 4D-Var optimization loop, ensuring both rapid convergence and chemical consistency. By employing the Online Iterative-Adaptive Regularization Strategy (IARS) rather than fixed-parameter approaches, we dynamically optimize the regularization factor via the L-curve criterion at each iteration. Evaluations using Observing System Simulation Experiments (OSSEs) over China demonstrate that: (1) IARS significantly enhances stability, eliminating the convergence oscillation inherent in fixed-parameter schemes and achieving a Normalized Root Mean Square Error (NRMSE) < 30%; (2) joint multi-species inversion outperforms single-species approaches by leveraging thermodynamic coupling (specifically the sulfate-nitrate-ammonium equilibrium) to disentangle complex emission errors; and (3) the framework maintains robustness under spatially heterogeneous error scenarios, providing a reliable basis for future high-resolution applications.

Integrating Household Consumption into Sustainability Pathways: Evidence from the European Union

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The greater visibility and notoriety of the consequences of climate change on natural resources and the physical environment in which we live have prompted heightened citizen concern and a stronger commitment on the part of authorities to mitigate environmental degradation. This has led to the establishment of international commitments aimed at ensuring sustainable development and achieving carbon neutrality in Europe during the second half of the century, including the Paris Agreement and the Sustainable Development Goals (SDGs) of the 2030 Agenda.

Recent literature has emphasized the role of households as significant drivers of environmental impacts, identifying them as pivotal actors in environmental policy design, where shifts in demand contribute to reducing environmental footprints and fostering the development of sustainable and resilient economies.

Within this context, this research explores the environmental implications of household consumption patterns in the European Union by combining harmonised householdlevel microdata with environmentally extended multi-regional and multi-sectoral input–output frameworks. This integrated approach enables the analysis of how current consumption patterns translate into environmental pressures while explicitly accounting for heterogeneity across households.

In particular, the use of harmonised microdata allows a detailed characterization of households by income quintiles and gender-related characteristics, providing a more granular understanding of how environmental impacts are distributed across population groups. This level of disaggregation makes it possible to identify potential trade-offs between environmental sustainability and social equity.

Based on this empirical evidence, the study evaluates alternative consumption scenarios aligned with sustainability objectives. These scenarios assess potential changes in consumption behaviour across different household types and their contribution to reducing environmental footprints, thereby supporting a more targeted, fair and inclusive transition consistent with the Sustainable Development Goals.

Discussing with future generations: how can we predict their behavior, and could they bear the burden of future climate policies?

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The climate crisis has raised numerous questions about what kind of future awaits us as a society. To manage the impact of these changes on the environment and human communities, many significant social, political, and economic changes can be implemented. However, due to the longevity of the transition processes for implementing these policies, it is essential to consider the fairness of the transformation for current and future generations. Although the role of future generations in the green transformation has been noted, there is a lack of research on the procedural use of the category of future generations in the design and prediction of future human behaviour. Is it possible to gain insights into the values and worldview of future generations? If so, how can we give future generations a voice so they can speak for themselves?

The Imaginary Future Generations (IFG) method proposes creating imaginary groups that represent future generations (not yet born) and negotiate with representatives of the current generation regarding visions of the future and related decision-making processes. In this way, future generations could become one of the stakeholders in the deliberation process. The method thus bridges the gap between the need for intergenerational justice and supports the adoption of sustainable regional policies while ensuring acceptance and understanding among the currently living local societies.

In my poster, I'll show the results of the application of the IFG method in deliberation about green transformation policies (energy, housing, and transportation policies) in Poland, comparing visions of the future and the needs and goals expressed by the current and future generations during participatory workshops conducted in 2025 and 2026 in two municipalities. In the workshops, young adults envisioned their future and what they could and could not do in the context of the climate crisis. I analyze their statements qualitatively as a way to predict future human behavior.

From China's 2035 NDC Targets to Near-Term Power-System Pathways: Renewable Penetration, Electrification, and CCS Reliance

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China's 2035 nationally determined contribution (NDC) introduces absolute, economy-wide net greenhouse gas reduction targets and pairs them with headline energy-system indicators, including raising the non-fossil share of primary energy to 30% and expanding wind and solar installed capacity to about 3.6 TW by 2035. However, these targets do not uniquely determine the operational evolution of the power system or the degree to which the transition is driven by renewable build-out, end-use electrification, demand moderation, or end-of-pipe abatement.

This poster uses an integrated, scenario-based energy-system simulation to construct three archetypal net-zero pathways for China (2020–2060): (i) a clean-energy-led pathway (CE) with rapid electrification and deep renewable penetration; (ii) a technology-led pathway (TD) that preserves higher fossil shares while relying strongly on carbon capture and storage (CCS); and (iii) a demand-reduction-led pathway (DR) combining moderated energy-service demand with intermediate renewable and CCS deployment. Across pathways, near-term indicators already diverge: by 2030, the share of electricity in final energy rises to ~31% in CE versus ~26% in TD/DR, and renewables' share in power generation reaches ~58% (CE), ~51% (TD), and ~42% (DR). By mid-century and beyond, the pathways separate primarily along the renewable-vs-CCS axis: CE approaches an almost fully renewable power supply with only marginal CCS, whereas TD depends on sustained CCS scale-up, and DR sits between them.

To connect climate and health co-benefits within an IAM-compatible workflow, the poster further outlines a modular extension that maps pathway outputs (generation by fuel, CCS penetration, and electrification) to co-emissions (SO2, NOx, primary PM2.5) using technology-specific emission factors, and then to population exposure and mortality changes using reduced-form concentration-response tools. The contribution is a

transparent “NDC-to-pathway” mapping that clarifies which near-term power-system choices most affect long-run feasibility and co-benefits.

Towards Modelling the Anthropocene: A Systematic Review of World-Earth Models

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Since the onset of the Anthropocene, humans have significantly altered environmental processes. These alterations challenge existing modelling approaches due to the non-linear interactions and co-evolutionary dynamics between socio-economic and environmental processes. To capture those interactions, we require models that incorporate socio-economic, socio-cultural and environmental processes endogenously and couple them via process-based bidirectional feedback loops, moving beyond traditional economic cost-benefit analyses.

In this study, we provide a systematic overview of global studies that adopt this “World-Earth Modelling” approach. Starting with 21,999 entries sourced from the Web of Science and Scopus databases, we utilized novel, human supervised Large Language Model approach to support the screening process. With that, we are able to present a comprehensive overview of “World-Earth Modelling” approaches ranging from more traditional IAMs to novel methods of capturing co-evolutionary dynamics between environmental and socio-cultural processes such as social norms and learning. This allows us to identify research gaps and challenges and propose novel research directions.

Our findings reveal that most existing models focus on aggregated economic perspectives, thereby overlooking socio-cultural dynamics, the heterogeneity of actors and multi-scale dynamics. While many models focus on climate change, other environmental dimensions are overlooked. Nevertheless, existing models suggest that incorporating fully endogenous bidirectional feedback can help explore possible transformation pathways and produce more realistic and dynamic scenarios.

Modelling the collapse of complex societies

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Why do societies collapse? Some famous examples include Easter Island, the Maya, the Roman Empire, and the Chinese dynasties. Recent work has developed mathematical models for the collapse of these ancient societies [2, 4, 3] and the results point to a common narrative underlying their decline. The presentation will provide an overview of modelling long-term societal evolution and the potential for collapse. The general pattern, called the energy-complexity spiral [5], captures the feedback mechanisms that operate in different societies over the timescale of centuries, accounting for both long-term growth and eventual decline or collapse. The framework allows us to classify societies depending on the key activities and institutions they rely on: agriculture for Easter Island and the Lowland Classic Maya, the military and state bureaucracy for the Western Roman Empire and Imperial China, religious beliefs for the Egyptian Old Kingdom and the Greenland Norse, and trade activity for the East Mediterranean basin during the Bronze Age.

In the case of Easter Island and the Maya civilisation [2, 4], the collapse is driven by a critical transition that occurs when the rate of natural resource extraction passes beyond a critical value α_c, for which we present numerical and analytical results, see Fig. 1(a). For the Western Roman Empire we model the dynamics from 500 BCE to 500 CE, aiming to understand the interdependency of army size, conquered territory and the production and debasement of coins within the empire, see Fig. 1(b). We analyze the stability of the system and determine that it is neutrally stable. Based on this, we find that to prevent decline, the optimal policy was to stop debasement and reduce the army size and territory during the rule of Marcus Aurelius [3].

For the general case of an agrarian society we propose a simplified model of a socio-environmental system that accounts for population, resources, and wealth [1]. The model is generalized to multiple interacting systems, with chaotic dynamics emerging for small non-uniformities in the interaction matrix. In addition, we show that diffusion can stabilize networks of sustainable and unsustainable societies, and thus interconnection provides a way of increasing resilience in networked systems, see Fig. 1(c)–(d). Similar results have previously been found for Easter Island [2] in the case of two coupled societies but in a more restricted parameter range. The current results [1] generalize and strengthen the previous findings to multiple societies and larger parts of parameter space.

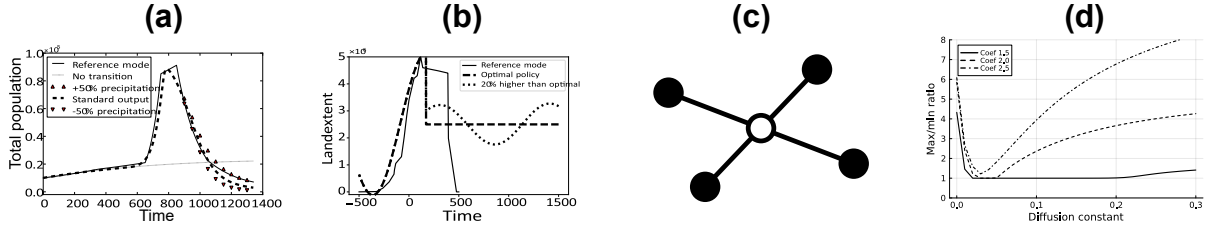

Figure 1: (a) The total population (solid line) of a region and the Maya model predictions when precipitation is: normal (dashed line), enhanced by 50% (triangles) and reduced by 50% (inverted triangles). (b) Comparing the territorial extent (solid lines) of the Roman Empire with policies that implement changes to prevent the decline (or collapse). Two policies are shown: one that changes the territory to prevent any oscillation, which we consider optimal (dashed lines) and another policy where stock values are 20% higher than the optimum (dotted lines). (c) The white nodes are systems with a sustainable harvesting rate below the critical harvesting rate α_c, while the black nodes have extraction rate equal to $Coef \times \alpha_c$. (d) The ratio of the maximum and minimum total population on the attractor for the networked systems on the left.

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Designing Stakeholder Scoping Workshops for Integrated Assessment Modelling

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Integrated Assessment Models (IAMs) play a central role in exploring pathways towards carbon neutrality, yet they necessarily rely on socio-economic assumptions, problem framings, and normative choices that are often implicit or weakly articulated. This contribution presents the design and implementation of stakeholder scoping workshops conducted within the Horizon Europe PANTHEON project as a methodological approach to engaging with these dimensions. The poster focuses on how EU and Chinese stakeholder perspectives on desirable post-decarbonisation futures, risks, priorities, and trade-offs were elicited through structured, participatory workshops. Rather than validating predefined scenarios, participants were invited to articulate their own visions of a post-transition world and to reflect on time horizons, enabling actions, and areas of disagreement. The contribution documents the workshop logic, recruitment strategy, and analytical framework, highlighting how qualitative and semi-quantitative inputs were organised in relation to Integrated Assessment Modelling. By presenting this approach, the poster contributes to ongoing discussions on how IAM-related research can engage with societal perspectives in a transparent and methodologically explicit way. It aims to provide a basis for exchange with other researchers on the role of stakeholder engagement, reflexivity, and problem framing in the development and interpretation of decarbonisation pathways and socio-economic co-benefits.

Invisible Intermediaries: Sustainability Discourse and the Reproduction of Power in Transnational Soy Supply Chains

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Sustainability transitions scholarship, particularly the Multi-Level Perspective (MLP), has been critiqued for undertheorising how power maintains regime stability. This study addresses this gap by examining how incumbent intermediary actors maintain regime dominance through the appropriation of sustainability governance. The analysis draws on eight ESG and sustainability reports from the four major transnational grain traders (ADM, Bunge, Cargill, and Louis Dreyfus Company, collectively the ABCD traders) operating in soy supply chains that connect Brazilian production regions to European consumption markets. Poland, which imports approximately 3.5 million metric tonnes of soyabean meal annually through ABCD-controlled channels, provides the destination market context.

The analysis reveals three convergent mechanisms of power operating through these texts. The traders define what sustainability means and how it is measured. Monitoring systems and traceability platforms discipline supply chain actors according to incumbent-defined standards. Compliance frameworks presented as technical and neutral structure market access, governing conduct through compliance architecture rather than through direct coercion. When these mechanisms converge, they produce structural exclusion. Actors who cannot meet compliance requirements are excluded by the governance architecture rather than by deliberate policy. These strategies converge across all four competing firms, indicating regime-level governance rather than individual corporate positioning.

The analysis contributes to sustainability transitions scholarship by demonstrating empirically how intermediary actors deploy sustainability governance to reproduce rather than transform the conditions of their own dominance.

Title: Impacts of Rural–Urban Population Migration on Air Pollution Exposure and Premature Mortality in China Since 1949

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The urbanization-driven long-term population migration in China has fundamentally reshaped the human air environment and associated public health risks. In this study, we construct harmonized datasets for both factual migration and counterfactual no-migration scenarios spanning 73 years (1949–2021) to quantify changes in population exposure concentration, integrating both indoor and ambient $PM_{2.5}$, and the resulting premature mortality risks. By comparing factual outcomes with a no-migration scenario in which population redistribution is driven solely by natural growth, we isolate the net contribution of migration to exposure and health outcomes. Our results show that urbanization-driven migration reduced population-weighted $PM_{2.5}$ exposure concentration by 27.6 μg m^{-3} in 2019 and cumulatively prevented approximately one-fifth of the total premature mortality burden (16.2 million deaths) over the study period. These health benefits accumulated gradually over time, with an accelerated contribution during periods of rapid urban expansion and energy transition.

Spatially, all regions of China experienced reductions in population exposure, although the magnitude of benefits varied substantially. Northern regions exhibited larger exposure and health gains than southern regions, reflecting higher baseline pollution levels and stronger effects of fuel transitions. Indoor $PM_{2.5}$ concentrations, which dominated total population exposure throughout most of the study period, declined markedly due to the widespread adoption of cleaner household fuels and improved living conditions. Ambient $PM_{2.5}$ concentrations also decreased in most regions, except in Beijing and Urumqi, where persistent heating-related emissions combined with net population inflows offset exposure reductions.

Importantly, the benefits of migration extended beyond migrants themselves. Population redistribution reduced overall exposure risks for both migrants and non-migrant populations by altering population density patterns and accelerating energy structure changes. Overall, this study provides long-term, counterfactual evidence that urbanization-driven population migration has played a substantial role in improving air quality exposure and reducing public health risks in China, highlighting population redistribution as a critical but often overlooked determinant of environmental health outcomes.

Synergistic Effects of Transport and Subsidence on Extreme Ozone Pollution Induced by Sequential Typhoons in the Greater Bay Area

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Sequential tropical cyclones (TCs) are increasingly influencing regional air quality under a warming climate, yet their cumulative impacts and complex synergistic mechanisms remain underexplored compared to single TC events. In this study, we investigated a rare, long-duration ozone (O3) pollution episode in the Guangdong-Hong Kong-Macao Greater Bay Area (GBA) from 17 to 27 September 2025, driven by three sequential typhoons (MINA, RAGASA, and BUALOI). Using a chemical transport model with the integrated process rate analysis, we elucidated the spatiotemporal evolution of the episode and decoupled the physical-chemical drivers. The results show that the "relay effect" of the sequential typhoons prevented the re-establishment of clean marine airflows, sustaining northerly prevailing winds and strong synoptic subsidence for ten consecutive days. We identified a "Dynamic Transport-Thermal Compression" synergistic mechanism governing the pollution evolution. Dynamically, a "Typhoon-induced Conveyor Belt" driven by the tightened pressure gradient efficiently transported ozone-rich plumes from inland source regions to the coastal zone. Thermally, the peripheral downdrafts induced a severe "Lid Effect", particularly in the western coastal city of Zhuhai, where the Planetary Boundary Layer Height (PBLH) was compressed to below 500 m, acting as a physical amplifier for pollutant accumulation. Quantitative attribution via Integrated Process Rate (IPR) analysis revealed a distinct source-receptor decoupling: the inland region (e.g., Guangzhou) acted as a "Net Producer" dominated by in-situ photochemistry, while the coastal region (e.g., Hong Kong) functioned as a "Net Receiver" dominated by horizontal advection. Furthermore, the subsidence zone provided direct evidence of vertical ozone injection from an upper-level reservoir down to the surface. These findings suggest that strong, regionally coordinated strategies are essential for mitigation, particularly as such events recur more often under climate change. Crucially, this study quantifies the "climate penalty" often simplified in Integrated Assessment Models (IAMs), providing a physical basis to ensure that pathways towards carbon neutrality incorporate these resilient adaptation measures against extreme synoptic risks.

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Impacts of Sustainable Aviation Fuels on Emissions and Contrail Properties in Microturbine Experiments

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Sustainable aviation fuels (SAFs) are widely regarded as a key pathway for reducing the climate impacts of aviation, yet experimental constraints on their effects on engine emissions and contrail formation remain limited. Here we used a microturbine engine to investigate emission characteristics and contrail-relevant properties under different SAF blending ratios. The microturbine provides a stable and repeatable platform with precise control of operating conditions, enabling direct comparisons across fuels. A suite of measurements was performed, including particle size distributions, effective particle density, non-refractory chemical composition, and cloud condensation nuclei (CCN) activity. We find that SAF blending substantially alters exhaust particle properties, producing systematic changes in particle size distributions and composition relative to conventional jet fuel. These changes lead to measurable differences in CCN activity and cloud formation behavior in the chamber experiments. Our results suggest that fuel-dependent variations in particulate emissions play a key role in modulating contrail formation thresholds and cloud microphysical properties. This work provides experimental evidence linking SAF composition to contrail-relevant emissions and demonstrates the value of microturbine-based platforms as a scalable and cost-effective framework for studying non-CO_2 climate impacts of aviation fuels.

Unveiling Hidden Costs in Agrifood Systems: A Systematic Review of True Cost Accounting

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Background

Global agrifood systems generate substantial environmental, health, social, and economic externalities that remain largely invisible in market prices. True Cost Accounting (TCA) is an emerging framework to make these “hidden costs” visible and inform more sustainable food system decisions. However, studies on TCA remain fragmented across framework development, methodologies, and empirical applications.

Scope and approach

We conducted a systematic literature review to (i) trace the evolution of TCA, (ii) compare methodological practices, and (iii) synthesize empirical application patterns. Our review started with around 3{,}600 records for initial screening, narrowing to 53 papers on TCA related to agrifood systems.

Key findings and conclusions

We first consolidated dispersed TCA initiatives into an integrated three-phase timeline: conceptual framework (before 2019), operational guidelines (2020--2022), and mainstream applications (after 2021). Methodologically, we found four TCA steps that are unevenly developed across environmental, social, economic, and health dimensions. Integration approaches are typically hybrid, combining monetary and non-monetary elements, but remain weakly standardized. Empirical applications of TCA clustering at national and local scales focus on the production and consumption stages and most often integrate environmental outcomes with health or economic outcomes, while social equity and distributional aspects are seldom explicit. Our review highlights that TCA has the potential to transform agrifood systems by revealing hidden costs and promoting sustainable decision-making. However, doing so requires further research to standardize methodologies and embed TCA more directly into policy instruments.

Environmental and health impacts related to cross-region air pollution in China

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$PM_{2.5}$ (particulate matter suspended in the air with aerodynamic diameters less than 2.5 μm) is one of the crucial air pollutants in China. $PM_{2.5}$ could not only influence both outdoor and indoor air quality, but also has adverse impacts on human health. The motion of atmosphere leads to the atmospheric transport of air pollutants, therefore making $PM_{2.5}$ pollution a complex regional environmental problem. $PM_{2.5}$ concentrations in one place are not only contributed by local emissions, but also influenced by emissions in other places. Exploring the regional transport pattern of $PM_{2.5}$ and the related environmental and health impacts, on the one hand, helps with identifying the causes of $PM_{2.5}$ pollution, on the other hand, provides information for prevention and control of $PM_{2.5}$.

Based on a modeling framework considering both indoor and outdoor $PM_{2.5}$ exposure pathways, our results show that $PM_{2.5}$ regional transport caused by anthropogenic emissions in China mainly transports pollution from north to south. North region, central region, and east region, as important source regions, export $PM_{2.5}$ pollution to the receptor regions in their south directions. In 2019, 14.03% of anthropogenic $PM_{2.5}$-related premature deaths in China were attributed to regional transported $PM_{2.5}$. Our results also illustrate that, though $PM_{2.5}$ regional transport happens in ambient air, it finally influences human health mainly through indoor exposure pathway rather than outdoor pathway.

Black Carbon in the Marine Atmosphere: Concentration and Mixing State from Coastal to Remote Atlantic Regions

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Black carbon (BC) is a potent absorber of solar radiation and a significant driver of near-term climate warming. Maritime BC emissions influence radiation, cloud processes, and atmospheric dynamics over the oceans, linking climate impacts with air quality and human health. However, in-situ observations of BC over oceans remain scarce, and the role of the marine environment in shaping BC mixing state is poorly understood. Based on in-situ measurements from ten Atlantic Ocean cruises (1,120 measurement hours) aboard the S/Y Eugen Seibold, we present a comprehensive dataset of BC concentrations and mixing states across near-coastal and remote oceanic regions. Our analysis reveals previously unquantified marine pathways that enhance BC light absorption, providing insights into BC aging over the ocean. These findings have direct implications for carbon-neutrality strategies, as reducing BC emissions from shipping and other maritime activities can simultaneously mitigate climate warming, improve air quality, and deliver co-benefits for human health and socio-economic development. Incorporating such BC processes into climate and Earth system models is crucial for evaluating effective mitigation pathways and their broader environmental and societal benefits.

Balancing Provincial Burden-sharing Capacity in China's Carbon Neutrality Pathway: Trade-offs Among Economic Burden, Pollutant Emissions, and Provincial Equity

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Keeping global warming well below 2 ℃ requires rapid reductions in CO2 emissions. However, policy simulations in efficiency-oriented integrated assessment models (IAMs), such as pathways that minimize costs at each stage or over the entire planning horizon, often overlook pronounced heterogeneity across countries and regions in income levels, resource endowments, and fiscal capacities[1,2]. In China, where emissions are pledged to peak before 2030 and reach carbon neutrality before 2060 despite ongoing development needs, provincial governments are central to implementation, making it necessary to balance cost, feasibility, and equity. Decarbonization also yields air quality and health co-benefits, but mitigation pathways determine provincial responsibilities and technology choices that reshape the spatial distribution of air pollutant emissions.

To address key gaps in evaluating the fairness of provincial mitigation burden-sharing in China, we develop a capacity-guided carbon neutrality framework for China using GCAM-China, which represents provincial energy systems and technologies in detail. Under a national net-zero constraint, we operationalize the fair burden-sharing principle by constraining interprovincial differences in policy stringency, allowing mitigation burdens to shift from weak capacity provinces to high capacity ones. We quantify how alternative degrees of heterogeneity affect provincial mitigation costs, sectoral and technological portfolios, and air pollution co-benefits, ultimately linking mitigation cost, pollutant emissions, and burden fairness to clarify trade-offs. Results show that policy heterogeneity directly shapes the trade-offs between economic burden and air pollutant abatement, and can alter the sectors and technologies that drive emissions reductions. This capacity-guided design, combined with representations of technological transition and pollutant emissions, provides quantitative evidence for more implementable provincial carbon policies in China. It demonstrates that, along the carbon neutrality pathways, economic affordability, air quality co-benefits, and interprovincial equity can hardly be fully ensured within any single scenario, and thus require adequate consideration and explicit trade-offs. This also offers policy insights for other developing countries facing concurrent challenges of development, decarbonization, air quality improvement, and health protection.

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