IAM COMPACT

Expanding Integrated Assessment Modelling:
Comprehensive and Comprehensible Science
for Sustainable, Co-Created Climate Action

D5.4 – Modelling out-of-ordinary extremes

WP5 – Expanding – Resilient, inclusive, and sustainable recovery and development

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Responsible Author	Alaa Al Khourdajie		**Email**	a.alkhourdajie@imperial.ac.uk
	Imperial		**Phone**	+44 (0)20 7589 5111
Contributors	Panagiotis Fragkos, Eleftheria Zisarou [E3M]; Dirk-Jan van de Ven [BC3]; Lorenzo Rinaldi [POLIMI]; Adam Hawkes, Shivika Mittal [Imperial]; Jaime Nieto Vega [UVa]			
Reviewer(s)	Rasmus Magni Johannsen [AAU], Alexandros Nikas [NTUA], Vassilis Stavrakas [UPRC], Georg Holtz [WI]			
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EC Summary Requirements

1. Changes with respect to the DoA

No changes with respect to the work described in the DoA.

2. Dissemination and uptake

This report offers guidance for consortium partners on how to assess the impact of extremes on emission reduction pathways. It also serves as a resource for entities outside the consortium, illustrating how data related to the study of extreme events in the context of integrated assessment models (IAMs) and resilience pathways could be framed and addressed.

3. Short summary of results (<250 words)

The task aims to enhance the scenario analyses in WP4 by exploring a broad spectrum of uncertainties, including extreme environmental, technological, policy, and societal shifts. It focuses on resilient pathways and technologies in both national and global contexts, under extreme conditions. The urgency of addressing climate change underscores the importance of integrated assessment models (IAMs) in decision-making, especially in energy. IAMs, however, struggle with the complexities of real-world systems and extreme events like sudden technological or policy changes and natural disasters. This study addresses these challenges by examining critical questions across dimensions, defining extremes, understanding geographical differences, identifying system vulnerabilities, assessing model adaptability, and integrating new frameworks and technologies, aiming to improve IAMs' response to extreme events in the energy sector.

The literature review discusses IAMs' role in capturing extreme events, their types, impacts, and the need for IAMs to incorporate such conditions beyond conventional models. It categorises extremes, explores their origins and impacts, and proposes a scenario framework and narratives informed by recent studies and the NGFS scenario approach. This framework considers climate and socio-economic tipping points through transformational response and resilience, presenting four narratives: Business as Usual, Unadaptive Transformation, Effective Transformation, and Incremental Resilience.

Expert interviews explore how technologies and measures can enhance resilience in transformation pathways during extreme events and identify feasible mitigation trajectories. Key themes from the interviews highlight the distinction between risk and uncertainty, technological impacts, abrupt policy changes, regional differences, vulnerabilities, and challenges in adapting IAMs. The interviews underscore the need for adaptable strategies, robust modelling, and interdisciplinary collaboration.

4. Evidence of accomplishment

This report.

Preface

IAM COMPACT supports the assessment of global climate goals, progress, and feasibility space, and the design of the next round of Nationally Determined Contributions (NDCs) and policy planning beyond 2030 for major emitters and non-high-income countries. It uses a diverse ensemble of models, tools, and insights from social and political sciences and operations research, integrating bodies of knowledge to co-create the research process and enhance transparency, robustness, and policy relevance. It explores the role of structural changes in major emitting sectors and of political, behaviour, and social aspects in mitigation, quantifies factors promoting or hindering climate neutrality, and accounts for extreme scenarios, to deliver a range of global and national pathways that are environmentally effective, viable, feasible, and desirable. In doing so, it fully accounts for COVID-19 impacts and recovery strategies and aligns climate action with broader sustainability goals, while developing technical capacity and promoting ownership in non-high-income countries.

NTUA – National Technical University of Athens	EL
Aalto – Aalto Korkeakoulusaatio SR	FI
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BC3 – Asociacion BC3 Basque Centre for Climate Change – Klima Aldaketa Ikergai	ES
Bruegel – Bruegel AISBL	BE
CARTIF – Fundacion CARTIF	ES
CICERO – Cicero Senter for Klimaforskning Stiftelse	NO
E3M – E3-Modelling AE	EL
KTH – Kungliga Tekniska Hoegskolan	SE
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Executive Summary

This task aims to complement the scenario analyses of WP4 by addressing a wide range of uncertainties, such as extreme environmental, technological, policy, and societal changes. It incorporates both national and global modelling approaches, aiming to pinpoint resilient pathways and technologies that hold under extreme conditions.

The increasing urgency to address climate change has elevated the significance of integrated assessment models (IAMs) in policy- and decision-making. However, IAMs often exhibit limitations in accounting for the complexities inherent in real-world systems, especially when faced with 'extreme events', like technological breakthroughs, abrupt policy changes, and natural disasters. This study seeks to delve into these complexities by posing critical questions across different dimensions, defining extremes, understanding geographical nuances, identifying system vulnerabilities, examining the adaptability of existing models, and exploring the integration of new frameworks and technologies. In doing so, it aims to identify gaps in current methodologies and propose new avenues for making IAMs more responsive to the challenges posed by extreme events in the energy sector.

This literature review explores the role of IAMs in capturing extreme events, delving into various types and impacts of these extremes, such as climate change extremes, societal and geopolitical changes, technological breakthroughs, and economic and financial risks. The discussion raises the case for the need for IAMs to better incorporate these extreme conditions, which are often overlooked in conventional models focused on averages or likely outcomes. The review categorises these extremes, discussing their origins and impacts, and proposes a scenario framework and narratives for IAMs to capture a wider array of uncertainties and risks. The scenario framework, informed by van Ginkel et al. (2020) and the NGFS approach, conceptualises the interaction between climate change tipping points and socio-economic tipping points (SETPs) through two dimensions: transformational response and resilience to socio-economic impact. It presents four narratives: Business as Usual (low transformational response and resilience), Ineffective Transformation (high transformational response but low resilience), Effective Transformation (high in both dimensions), and Incremental Resilience (low transformational response but high resilience). The review also highlights the interconnectedness of risks and the necessity for systematic risk assessments, and it suggests methodological innovations for IAMs to better account for these complex challenges.

The expert interviews focused on understanding how technologies and measures can enhance resilience in transformation pathways during extreme events, and on identifying feasible mitigation trajectories. The interviews covered various topics, including defining extremes in energy systems, geographical differences in addressing extreme events, vulnerabilities in energy systems, model adaptability to extreme variables, integration of SETPs framework into integrated assessment modelling, technological impacts on climate mitigation strategies, and capturing the effects of economic and geopolitical factors in IAMs. Key themes emerged from the interviews, such as the differentiation between risk and uncertainty in defining extremes, the impact of technological breakthroughs or failures on energy systems, the significance of abrupt policy changes, regional specificities in addressing extreme events, vulnerabilities in energy systems, and challenges in adapting IAMs to extreme variables. Overall, the interviews provided comprehensive insights into various dimensions of extreme events and their implications for energy systems and IAMs, highlighting the need for adaptable strategies, robust modelling approaches, and interdisciplinary collaboration.

The EU's ambitious decarbonisation goals aim to propel the region towards a sustainable and low-carbon future. However, limitations in key technologies such as Carbon Capture and Storage (CCS), biomass utilisation, and renewable energy sources (RES) could introduce significant challenges to achieving these goals. By employing PROMETHEUS, GCAM, and TIAM, we examine the impact of technology limitations on various aspects of the EU's decarbonisation efforts. Our analysis showed that technology constraints significantly influence CO_2 emissions, primary energy consumption and the composition of the electricity generation mix within the EU. The findings underscore the intricate relationship between technology limitations and the EU's ability to meet its decarbonisation targets.

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1 Introduction

This report documents the work of the IAM COMPACT project in the context of its Task 5.3 ('*Expanding the Comfort Zone – Out of Ordinary Extremes*'), which aims to complement the scenario analyses within the project's modelling component (WP4), by addressing a wide range of uncertainties, such as extreme environmental, technological, policy, and societal changes. This task qualitatively surveys the literature to identify salient issues that can be represented in models, before using expert interviews to understand which technologies or measures may add resilience to transformation pathways in the face of extreme events, as well as identifying what mitigation pathways may result from extreme circumstances. It also incorporates quantitative findings from both national and global modelling approaches, to eventually develop quantified narratives on the range of extremes, implications for pathways, and technologies or measures likely to be most resilient across these pathways. The outcomes of this flow of activities within the first cycle of the IAM COMPACT Policy Response Mechanism (PRM) are documented in this report, D5.4 (February 2024).

In detail, the scope of this report includes an early definition of extremes; factors under consideration include sudden technology breakthroughs or failures, abrupt policy changes, swift structural alterations, global crises, and other unforeseeable events of significant scale. These may also encompass financial and investment risks like those in power markets, as well as social acceptance, resource availability, and geopolitical factors. The report then identifies vulnerabilities, in the form of key bottlenecks and susceptibilities in the system, before eventually investigating and demonstrating how existing models and scenarios can be adapted to account for these extremes. This definition of extremes, vulnerability identification, and model adaptability and investigation is carried out at both the global and the regional levels (see Section 3).

A first component relevant to this task and deliverable consisted of a multi-model scenario exercise carried out early in the project with regards to the 2022 energy-supply crisis, aiming to understand the trade-offs between different strategies for the EU to overcome the energy crisis, fuelled by the Russia-Ukraine war and the policy and energy-supply decision-making in response to it. Due to the timing of this exercise (at the onset of the IAM COMPACT project), which was selected to provide quick, relevant, and meaningful input to EU policy processes, this component was instead carried out in the context of Task 4.3 ('Global and national/regional mitigation analysis') and documented in the associated report D4.5 ('Global and national/regional mitigation analysis').

A second objective of this deliverable is to incorporate the questions coming from the Policy Steering Groups and associated scenario elements from the Core Working Group on 'Global Effects' into modelling work (see deliverable D4.5 for more information on the questions across groups and their grouping into Studies), as part of Study 3 of the 1st PRM cycle, led by E3M. This report documents preliminary results, which will be refined after stakeholder consultation/feedback and potential reruns, leading to a dedicated policy brief.

Critically, the deliverable reflects the findings of a literature review (conducted in Sep-Nov 2023), which was carried out to identify salient issues related to extraordinary extremes that can (or cannot) be represented in models. This review was then complemented by a series of expert interviews (conducted in Dec 2023 - Feb 2024), which aimed to help understand which technologies or measures may add resilience to transformation pathways in the face of extreme events, as well as identify what mitigation pathways may result from extreme circumstances. This process led to quantified narratives and a complete scenario framework on the range of extremes, implications for pathways, and technologies or measures likely to be most resilient across extreme pathways (designed in February 2024). Eventually, the range of resulting scenarios will be developed and translated into modelled pathways, to identify what mitigation pathways may result from extreme circumstances; the latter step will be carried out in the context of the 2nd PRM cycle (ending in July 2025 and documented in D5.5).

The report is structured around key research questions, indicatively such as:

- What are the supply-chain implications and constraints of ramping up the deployment of key technologies?
- How resilient are transition pathways if certain technologies become unavailable?
- What is the resilience or vulnerability to geopolitical events of different energy system configurations? For example, what are the energy-system implications of the Russia-Ukraine conflict and respective policy responses, and how should the EU adapt its net-zero trajectory to the resulting energy crisis?
- What are the impacts of a decoupling/multipolar world on clean energy technology supply chains?

2 Literature review

2.1 Introduction

Extreme events and tipping point conditions include a wide range of phenomena, from extreme climate events, abrupt structural socioeconomic changes, unforeseen environmental and geopolitical crises, to sudden technological breakthroughs and swift policy shifts. Such extremes can be categorised based on their origins, such as technological, environmental, societal, or policy-related, and their impacts, be it short-term shocks or long-term transformations (Seneviratne et al., 2021; O'Neill et al., 2022).

In the context of integrated assessment models (IAMs), the analysis of extreme conditions has gained increasing importance. The literature increasingly acknowledges that conventional models, primarily tailored to assess averages or likely outcomes, often neglect the significance of extremes, and hence inadequately account for their impacts (Koasidis et al., 2023; Grubb et al., 2022).

In this section, we aim to delve into the various types of extremes, assess their relevance for IAMs, and explore how these models can better integrate them. We also propose a scenario framework and narratives that IAMs are able to explore, thereby enhancing their capability to capture a fuller array of uncertainties and risks.

2.2 Out-of-ordinary Extremes

We structure our review by categorising the relevant extreme events and tipping point conditions that may occur into domains, presented below.

2.2.1 Climate change extremes

In assessing climate change extremes, we rely on two principal definitions outlined by the IPCC WGI AR6 report. First is the concept of 'climate change risk', which encompasses the potential for adverse impacts on human or ecological systems due to climate change as well as human responses to it (climate action). Second is 'climatic impact-drivers' (CIDs), which are physical climate conditions, such as means, events, and extremes, that directly affect human or ecological systems (Ruane et al., 2022), regardless of whether their impacts are harmful or beneficial or can be quantified using various sector-specific indices. The framework of climate change risk integrates climatic impact-drivers and also considers low-likelihood but high-impact outcomes (IPCC, 2021).

The frequency and intensity of hot extremes are projected to escalate, while occurrences of cold extremes are expected to diminish, at both global and continental levels, as well as in the vast majority of populated regions, in response to rising levels of global warming. Such trends are projected to persist, even if global warming is stabilised at a 1.5°C threshold (Seneviratne et al., 2021). The extremes considered include temperature extremes, heavy precipitation and pluvial floods, river floods, droughts, storms (including tropical cyclones), as well as compound events (multivariate and concurrent extremes). This also includes low-likelihood, high-impact scenarios that would result in drastic regional shifts in precipitation patterns, greater sea-level rises due to ice sheet collapse, and even abrupt changes in ocean circulations like the Atlantic Meridional Overturning Circulation (AMOC) (van Westen et al., 2024). The probability of these outcomes increases with higher levels of global warming, and more so if the realised climate sensitivity is at the higher end of current estimates. Additionally, the occurrence of rare and compound extreme events is likely to become more frequent, introducing events unprecedented in the observational record. These low-likelihood, high-impact scenarios could also be influenced by external factors such as large volcanic eruptions; several such eruptions in the 21st century would significantly alter climate trajectories from SSP-based Earth system model projections (IPCC, 2021, Lenton, 2011).

Current climate system responses are generally proportional to recent temperature changes, but some components like deep ocean circulation and ice sheets are slow to react and already exhibit irreversible changes due to past emissions. The paleoclimate record suggests the existence of tipping elements that can suddenly shift the system's sensitivity to changes. While evidence for abrupt global changes is limited, regional scales could experience abrupt shifts, tipping points, and even reversals, with potentially severe local impacts like extreme weather and increased droughts (Lenton et al., 2019; Milkoreit et al., 2018). Once crossed, these tipping points may be irreversible even if conditions revert to pre-threshold levels (IPCC, 2021). This aspect is particularly relevant to the discussion around temporary overshoot trajectories, where a certain temperature goal is exceeded for up to a few decades (Reisinger and Geden, 2023).

Compound interactions between multiple extremes, such as extreme marine heat waves and extreme ocean acidity, can have larger impacts on marine ecosystems than individual extremes. Vulnerabilities such as low income, food insecurity, and limited access to institutional resources and finance negatively affect responses to compound climate events, requiring current decision- and policymaking directions to move toward compound-risk management strategies (Kemp et al., 2022; Thaler et al., 2023; Simpson et al., 2021 and 2023; Hao et al., 2022, Zscheischler et al., 2018, Gaupp et al., 2019).

Risks emerging from extreme and tipping point events are closely interconnected, underscoring the need for a systematic risk assessment approach (Ringsmuth, 2022). Lamperti et al. (2021) identifies nine capacities of the planet, such as limits on atmospheric GHG concentrations, biodiversity loss rate, surface water consumption, and cropland conversion, emphasising the need to investigate these boundaries. Richardson et al. (2023) provide an update within the 'planetary boundaries' framework, revealing a heightened state of risk, with six out of nine boundaries already breached. These boundaries serve as key control variables for maintaining planetary stability and are now largely transgressed, taking Earth beyond a 'safe operating space' for humans.

2.2.2 Societal and geopolitical extremes and tipping points

Due to, or in response to, climate extremes and tipping points (or to perceptions thereof), socio-economic tipping points may also emerge, following associated abrupt changes in a socio-economic system, which may push it into a new and fundamentally different state. This is due to the nature of the interconnected crises—geopolitical conflicts, energy security, economic recessions, pandemics, climate change, and migration (O'Neill et al., 2022; Blondeel et al. 2024). In this context, climate change in particular could act as a 'risk multiplier', intensifying existing issues such as resource scarcity, risks to human security, and political instability (Scheffran, 2023; Juhola et al., 2022). Scheffran (2023) also discusses associated aspects of disruptions to critical infrastructure, intensification of the water-energy-food nexus and economic crises.

The collapse of winter sports tourism, farmland abandonment, and sea-level rise-induced migration are some examples of socio-economic tipping points (SETPs) that can be triggered by climate tipping points (van Ginkel et al., 2020). Kemp et al. (2023) emphasise the urgency of re-evaluating climate-induced impacts and societal fragility, advocating for integrated risk assessments that factor in systemic vulnerabilities and cascading risks. van Ginkel et al. (2020) propose a two-dimensional framing for exploring SETPs: *transformational response*, which refers to a significant change in the way societies and systems respond to climate change impacts, and *socio-economic impact*, which refers to the consequences of climate change on social and economic systems. Here, we adopt and adapt this framework to develop a narrative of the scenario space, which we then explore in our modelling exercise.

2.2.3 Technological extremes and breakthroughs

In this subsection, we look into a broad range of technologies and their role in combating or exacerbating climate change, from abrupt technological innovations such as green hydrogen and AI-assisted Earth System Modelling, to the cascading impacts of extreme climate events on global systems like agriculture, energy, and manufacturing.

Some energy supply technologies have gained significant attention and investment for their potential to mitigate the current energy crisis and reduce reliance on fossil fuels. One prime example, particularly in Europe, is green hydrogen (Zeyen et al., 2023). However, feasibility analyses indicate that, even if electrolysis capacity grows as fast as wind and solar power have done in the past decade, large-scale deployment of green hydrogen faces a high risk of short-term scarcity and long-term supply uncertainty, threatening its role in large-scale mitigation efforts (Odenweller, et al., 2022).

Other technologies regarded as breakthrough technologies feature considerable risks. Research on aerosol-based solar radiation modification (SRM) indicates that this technology could mitigate some climate change effects but with significant drawbacks: while it could partially offset greenhouse gases (GHGs), SRM introduces regional climate changes and does not stop rising atmospheric CO2 or ocean acidification. Rapid implementation or termination could lead to abrupt climate shifts. A cautious strategy that phases out SRM while reducing emissions could mitigate these risks, coupled with carbon dioxide removal (CDR) mechanisms (IPCC, 2021). Understanding climate risks can effectively inform last-resort interventions, such as SRM, which carry their own set of risks (Kemp et al., 2022).

Nijsse et al. (2023) suggest that a positive tipping point for global solar energy deployment may have been reached due to existing technological and economic trajectories. Solar energy is poised to become the dominant source of electricity globally, even without additional climate policies. However, uncertainties remain, including grid stability in a renewable energy-heavy system, financial availability in developing economies, and supply chain capacity (Clarke, 2022). Furthermore, adverse events may inadvertently be triggered even by positive tipping points such as political resistance, especially in regions negatively affected by the decline of fossil fuels (e.g., coal-dependent regions).

Surveying 260 climate and energy experts worldwide, Perdana et al. (2023) assessed 27 low-carbon innovations against their mitigation potential, expected (at-scale) maturity timing, and risk of diffusion delay. The authors identify next-generation energy storage, alternative building materials, iron-ore electrolysis, and hydrogen in steelmaking as top priorities, whereas other well-known promising technologies (e.g., nuclear fusion and direct air capture) could face critical delays that would render mitigation pathways largely counting on them unrealistic. In the same study, experts displayed greater consensus regarding the promise lying in non-technological innovations like lifestyle changes and alternative economic/business/societal models, acknowledging of course the limitations to their potentials.

Sectoral impacts of climate extreme events and tipping points, including agriculture, energy, and manufacturing, expose the potential of cascading impacts, especially when viewed through the lens of interconnected global systems. As they become more frequent, these disruptions cascade through the interconnected systems, compounding vulnerabilities and posing intricate challenges for policymakers and stakeholders. In the case of manufacturing, for instance, the supply chain network is increasingly susceptible to disruptions from various sources, including extreme weather events and political instability as exacerbated by climate change (Elimbi Moudio et al., 2022). In the case of energy systems, extreme events can disrupt the supply chains for fossil fuels and interfere with power generation capabilities (Clarke et al., 2022). Solar storms, on the other hand, can impact electrical grids and satellite communications, while severe heat or cold waves can create high demand imbalances. These events can lead to an array of issues including, but not limited to, power outages, increased costs, and grid failures.

Finally, the role of Artificial Intelligence (AI) is increasingly being explored to combat global climate change, including to improve and expand current understanding of climate change as well as to address various climate change risks more effectively, such as by anticipating extreme weather like heavy rain damage and climate adaptation (Cowls, et al., 2023; Cheong et al., 2022). Recently, the role of AI in supplementing or replacing traditional modelling tasks in Earth System Models (ESMs) has been examined. The inclusion of AI, particularly deep neural networks, offers the promise of addressing some of climate science's most significant challenges. These AI tools aim to improve the accuracy and efficiency of various applications, such as numerical weather prediction. The surge in Earth system observational data and computational resources is facilitating the integration of AI, particularly machine learning, to overcome existing limitations in ESMs. The future trajectory indicates a methodological transformation into what is termed as "Neural Earth System Modelling" (NESYM) (Irrgang et al., 2021). Nonetheless, AI research faces ethical challenges related to transparency and reproducibility, which can hinder the verification and reproduction of results (Cowls, et al., 2023). Furthermore, the carbon footprint of AI research itself can be substantial, requiring a careful balance between the GHG emissions it generates, on the one hand, and the energy efficiency gains it offers, on the other (Nordgren et al., 2022).

2.2.4 Economic and financial risks

The relationship between climate tipping points and economic impacts is underexplored in the climate change economic literature. Various contributions in the economics literature show that the probability of incurring significant damage costs outweighs that of elevated mitigation expenditures (van der Wijst et al., 2021; van Vuuren et al., 2020; Emmerling et al., 2019). Importantly, while these studies examined the uncertainty stemming from the broad spectrum of key parameter values, they do not encompass stochastic uncertainty, particularly the randomness that could arise from tipping points in the climate system, as well as socio-economic tipping points.

Caldecott (2022) advocates for a new metric called dated mitigation value (tCO2edmv) to evaluate climate mitigation strategies against a potential biosphere tipping point (BTP). The metric is designed to quantify the time-sensitive value of GHG emissions reductions. Using this metric, the author found significant differences in cost-effectiveness and mitigation impact across projects like 'avoided deforestation', 'renewable energy', and 'capacity building', and argues for selecting mitigation projects based on their potential not only to deliver immediate and substantial GHG reductions but also co-benefits such as biodiversity conservation.

On a more localised economic assessment, Oughton et al. (2017), examine the economic impact of extreme space weather on U.S. electricity transmission infrastructure, presenting two scenarios: a temporary blackout and a prolonged event. The study emphasises that direct economic losses from electrical disruption constitute only 49% of the total potential macroeconomic cost, highlighting the importance of considering indirect supply chain costs, and calls for future economic assessments to account for multi-day, multiregional events.

The financial risks associated with climate change are not adequately accounted for in current investment and policy decisions; traditional economic and financial risk models feature inadequacies in capturing the complexities of climate risks, which could lead to poorly designed climate policies (Monasterolo, 2020). Many investments are still directed towards carbon-intensive activities, making them vulnerable to devaluation. Furthermore, the financial market does not correctly price in climate-related risks, adding to financial instability. Among the significant recommendations of the Network for Greening the Financial System (NGFS), which was established in 2017 by a consortium of central banks and financial regulators with the principal objective of aiding investors in assessing climate-related risks within their portfolios, was the introduction of climate stress tests to evaluate financial stability implications of climate risks (NGFS, 2019). To that end, a framework connecting climate risks to the finance sectors has emerged, categorising climate risks into (a) physical risks, which include damages to assets due to climate events, and (b) transition risks, which come from (sudden) changes in climate policy or regulation. The framework also provides an overview of the channels through which these risks are transmitted, including policy shifts and investor sentiments (NGFS, 2019).

Evidence shows that the valuation of energy companies by financial markets has consistently underestimated physical climate risks (Griffin, 2020). Investors and asset managers have been slow to integrate these risks due to limited past data and the absence of long-term climate risk predictions. Although services are emerging to fill this data gap, markets still do not fully account for climate risks. Stringent climate policies and potential litigation further contribute to future financial (transition) risks for energy companies (Gundlach, 2020). Griffin (2020) highlights that energy companies have more exposure to climate risks due to their locations and infrastructure. These risks are yet to be fully priced in by the market, and any legal rulings against these firms could set off a wave of new litigations and requirements for more stringent disclosures, which could have a negative impact on stock prices (Gundlach, 2020).

Large financial crises and collapses in international finance and trade can also have significant impacts on both climate mitigation and climate adaptation (Jalles et al. 2023). These events can lead to a short-term deterioration

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in a country's resilience to climate change, particularly in developing economies (Phan et al. 2023). Additionally, financial frictions, such as heightened borrowing costs, can hinder post-disaster recovery. The destruction of capital stocks and jumps in risk premia resulting from rare large disasters can disrupt financial sectors and have negative feedback effects on the macroeconomy (Mittnik et al. 2020). Therefore, any event that causes a collapse in critical supply chains or loss of confidence in a major currency, like the US dollar, could have a significant impact on climate change adaptation and mitigation efforts. It is crucial to consider the link between financial crises and climate change when formulating policies for both mitigation and adaptation.

2.2.5 Interacting risks, and risk assessments

Westra et al. (2023) argue that traditional top-down risk assessments have limitations rooted in systemic complexities such as uncertainty, ambiguity, and complex causal pathways. Such methods are still heavily guided by government legislation and industry guidelines and primarily focus on hazard components, often ignoring social and economic landscapes that also contribute to risk. Bottom-up risk assessments are emerging as a more nuanced approach to understanding climate risk. They offer a greater focus on exposure, vulnerability, and intricate interactions between climatic and socio-economic factors. The bottom-up approach provides room for integrating diverse lines of evidence, interdisciplinary knowledge, and qualitative information, thus offering a more complex but realistic modelling of risks. In their work, Westra et al. suggest that methodological innovations in scenario planning and the integration of diverse lines of evidence and expertise into the risk assessment process are necessary.

2.2.6 Role of Integrated Assessment Models and Scenarios Analysis

We now turn to the potential role of IAMs in capturing such extreme events and their impacts. We also present a scenario framework matrix that serves to explore the intricacies of climate-related extremes and tipping points, and their socio-economic impacts. This framework is a novel contribution of this section and is presented as a guidance for IAM-based studies to design scenario protocols that aim to capture such extreme events and analyse their impacts.

2.2.7 Integrated assessment and energy systems modelling

In assessing climate change mitigation, particularly in energy system planning but also in other end-use sectors, there is a strong reliance on least-cost approaches (IPCC, 2022, Annex III). Gambhir and Lempert (2023) argue that, while the least-cost method has intuitive appeal, computational ease, and alignment with policy expectations, these factors have overshadowed the essential shift towards least-risk planning; they thus suggest that incorporating other models and methodologies to create more comprehensive and nuanced scenario databases may help enhance and capture complexities that least-cost models typically overlook.

Otto et al. (2020) discuss how current IAMs inadequately account for the nonlinear impacts of extreme weather events on energy systems and the macroeconomy. Traditional models focus on average changes in climate variables and employ coarse temporal resolutions that cannot capture the complexities arising from extreme events. They also assume optimal recoveries and neglect cascading effects, leading to an underestimation of the socioeconomic impacts. Otto et al., thus, advocate for the development of event-based economic models that are empirically constrained and use high-resolution biophysical impact projections, thereby better accounting for direct, indirect, and long-term consequences of extreme events on energy systems and the economy.

Similarly, current energy models have limitations in accounting for extreme events like wars, weather, technological innovations, and social changes. These models usually have long-term time horizons and limited temporal and spatial resolutions, making it challenging to consider transient events and sudden shifts (McCollum et al., 2020). They are often constrained by computational limits and are designed to be realistic based on current scientific understanding, which may limit their ability to explore out-of-the-ordinary scenarios. McCollum et al. (2020) argue that modellers should be more imaginative in the scenario-building process, considering a broader range of assumptions and boundary conditions, to better account for these extreme events and their long-lasting impacts.

Gambhir et al. (2022) draw on the NGFS risk framework (discussed in Section 2.2.4) and employ a framework to assess both physical and transition climate risks under various temperature scenarios. In this framework, physical risks are assessed using seven hazard indicators, such as heatwaves, droughts, and flooding, calculated at a granular level and then averaged to the regional scale. These metrics distinguish between acute (extreme events) and chronic risks (long-term changes, like crop yield duration). Transition risks, on the other hand, are analysed using IAMs and various proposed low-carbon transition indicators. The metrics are normalised relative to a 2°C central scenario for 2050 (physical risks) and 2030 (transition risks). The research finds that physical risk metrics show a non-linear relationship with temperature, highlighting the complexity of risk assessment, particularly for agricultural indicators and heatwaves, while transition risks also vary significantly depending on the scenario, even when targeted for the same temperature limit. The study emphasises that no set low-carbon transition pathway exists for each region, indicating varying degrees of risk, and therefore argues that both the type of physical risks and the dynamics of the transition risks are scenario-dependent and must be considered for comprehensive risk assessment.

Quantitative mitigation scenarios are usually compiled into databases (Byers et al., 2022), aiding data storage and archival, and the assessment itself. Approaches for such processes should accommodate alternative modelling frameworks to those of IAMs, allowing to expand the paradigm within which climate mitigation scenarios are assessed (Peters et al., 2023). Finally, there must be increasing emphasis on methodological advancements including advanced statistical methods, such as classification and regression trees, principal component analysis, and machine learning techniques (Gambhir and Lempert, 2023; Guivarch et al., 2022), as these could enable the extraction of nuanced insights from large datasets, thereby highlighting vulnerabilities and opportunities in various scenarios (at least to the extent that those vulnerabilities and opportunities are reflected in the included models).

2.2.8 Capturing climate extremes into integrated assessment and energy systems models

Clarke et al. (2022) highlight three primary areas through which climate change significantly impacts the energy system: supply, consumption, and infrastructure. Future low-carbon energy systems will be more weather-dependent, due to the intermittent nature of technologies like hydro, wind, and solar, all being susceptible to climate change. While global impacts should not compromise mitigation efforts, regional effects can be significant. For example, climate change could affect the bioenergy potential, which remains uncertain due to factors such as water availability and crop responses (Staffell and Pfenninger, 2018). Furthermore, there is increased risk of thermal power plant shutdowns during droughts, due to cooling water scarcity. Carbon Capture and Storage (CCS) technologies could exacerbate this problem due to their additional cooling water needs (Clarke et al., 2022). In terms of consumption, climate change is also expected to reduce heating demand but increase cooling demand. Peak load of heating and cooling may also increase disproportionately compared to overall energy consumption, with variability in these trends is expected to be region-specific (Yalew et al. 2020; van Ruijven 2019). As for infrastructure, vulnerabilities in electricity systems may arise due to changing climate conditions. Extreme weather events like heat waves could reduce transmission and distribution capacity, risking blackouts and brownouts (Auffhammer et al., 2017).

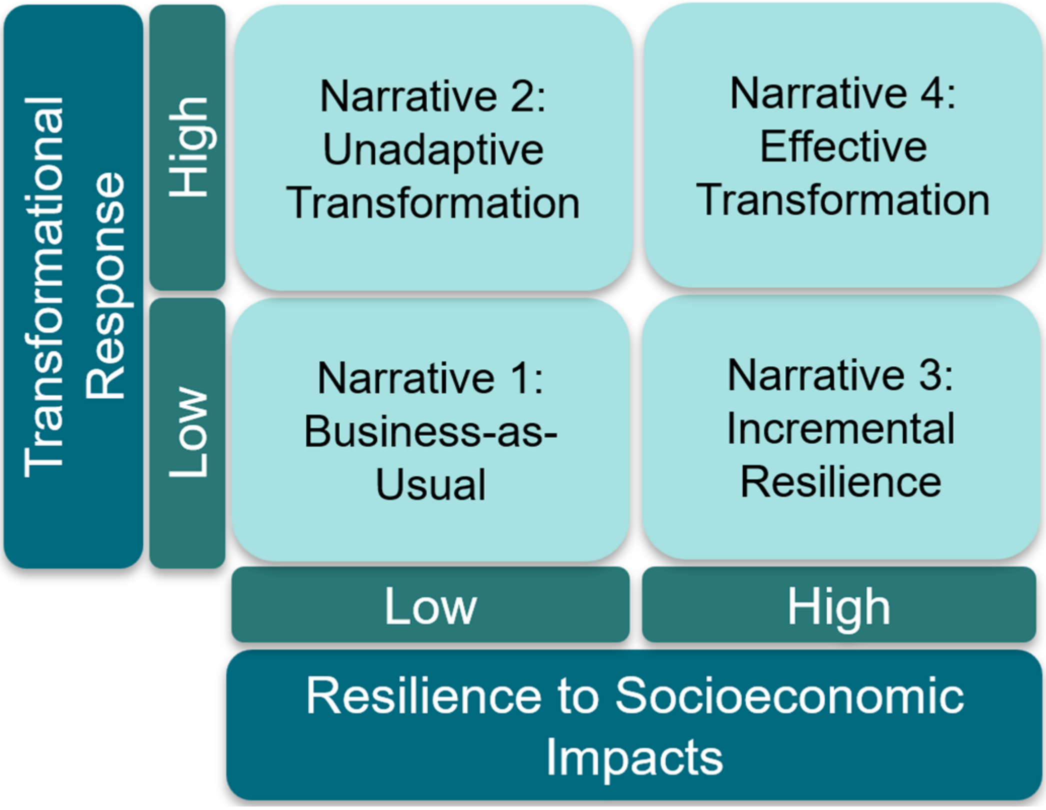
2.3 Scenarios Framework

As mentioned above, van Ginkel et al. (2020) **proposed two dimensions to explore how climate change tipping points can result into socio-economic tipping points (SETPs)**. These dimensions are:

- **transformational response**, which refers to a significant change in the way societies and systems transition in preparation for, or in response to, climate change impacts,

- and **resilience to socio-economic impact**, *which refers to the resilience to consequences of climate change on social and economic systems.*

Building on these two dimensions proposed by van Ginkel et al. (2020) and following the adopted scenario framework by NGFS, we can design the following scenario framework matrix that serves to explore the intricacies of climate-related extremes and tipping points, and their socio-economic impacts. This approach is particularly valuable as it integrates the broader socio-economic effects, hence offering a more comprehensive view than traditional models.



The scenario matrix differentiates between resilience and transformation through the two key dimensions of transformational response and socio-economic impact. The combination of these two dimensions yields scenarios that express varying levels of both resilience and transformation:

- **Narrative 1 Business as Usual: (Low Transformational Response, Low Resilience to Socio-Economic Impacts):** The society does not make significant changes in its approach to climate change (both mitigation and adaptation), and hence the socio-economic impact of any extreme events is high, due to low resilience.
- **Narrative 2 Unadaptive Transformation: (High Transformational Response, Low Resilience to Socio-Economic Impacts):** Significant transformations to mitigate climate change are undertaken; however, their focus is too narrow, rendering them unadaptive to additional external factors that may hinder their implementation. An example of such external factors can be supply-chain shocks.
- **Narrative 3 Incremental Resilience: (Low Transformational Response, High Resilience to Socio-Economic Impacts):** The society does not make significant changes in its approach to climate change, yet a high level of resilience to its socio-economic impacts remains. This narrative reflects a situation of expanding current capacities rather than adopting new technologies or methods. It illustrates resilience achieved through incremental improvements and expansion of existing capacity, as opposed to transformative or efficiency-driven changes. An example of such narrative is expanding healthcare capacity like hospital beds and staff to deal with heat-related illnesses rather than implementing systems

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to monitor and warn vulnerable populations.

- **Narrative 4 Effective Transformation: (High Transformational Response, High Resilience to Socio-Economic Impacts):** This is the ideal resilient scenario, where significant transformations are made, taking into account external factors' shocks. As a result, resilience to the socio-economic impact of climate change is high.

3 Expert Interviews

By conducting expert interviews, we have aimed to elicit valuable insights into the technologies and measures that can enhance the resilience of transformation pathways during extreme events. The experts interviewed for this study were identified through a scoping key organisations and research institutions working on climate change resilience and mitigation globally. We engaged experts from diverse backgrounds, including climate research, energy and environmental policy from leading universities and national laboratories. The insights shared reflect both academic research and applied knowledge from advising governments and industry on managing climate risks and transitions.

Our findings, discussed in the sub-sections below, have indeed highlighted the significance of adaptable strategies and outlined feasible mitigation trajectories in response to extreme circumstances. The discussions with the engaged experts have effectively mapped out resilience-building mechanisms and the resultant mitigation options, offering a clear direction for future planning and policy formulation. Below we present the interview questions and analysis of responses.

3.1 Overview of the purpose of the interview

The increasing urgency to address climate change has elevated the significance of IAMs in policy- and decision-making, particularly in the energy sector. However, IAMs often exhibit limitations in accounting for the complexities inherent in real-world systems, especially when faced with ‘extreme events’, like technological breakthroughs, abrupt policy changes, and natural disasters (see also Section2.2.6). This study seeks to delve into these complexities by posing critical questions across different dimensions, defining extremes, understanding geographical nuances, identifying system vulnerabilities, examining the adaptability of existing models, and exploring the integration of new frameworks and technologies. In doing so, it aims to identify gaps in current methodologies and propose new avenues for making IAMs more responsive to the challenges posed by extreme events in the energy sector.

3.2 Interview questions

We structure the interview questions in terms of topic, as well as the domains used above to categorise the relevant extreme events and tipping point conditions that may occur.

Defining Extremes

1. How would you frame ‘extreme events’ with respect to the terms ‘risk’ and ‘uncertainty’?
2. How would you define ‘extreme events’ in the context of energy systems? Could you provide examples of sudden technology breakthroughs or failures that qualify as ‘extreme’?
3. In your experience, how could abrupt policy changes impact energy systems? Can you describe a case where this has had a notable effect?

Geographical Coverage

4. How do the challenges and opportunities for addressing extreme events differ between the EU and other regions?
5. Are there region-specific factors in the EU, or beyond, that significantly influence the impact of extreme events on energy systems?

Vulnerabilities

6. What are the key bottlenecks you have identified in energy systems, when confronted with extreme events?
7. Can you describe a scenario where social acceptance became a significant ('extreme' even) vulnerability for energy system configuration?

Model Adaptability

8. What are the shortcomings in current IAMs in adapting to extreme variables, like geopolitical crises or global pandemics, and how can these frameworks be extended to more effectively capture such events, especially in the energy sector?
9. Given the increased frequency of low-likelihood but high-impact climate events, such as drastic shifts in regional precipitation or sea-level rises, how do existing models adapt to these new risk parameters?
10. What methods can be developed to more comprehensively integrate regional effects into global IAMs, particularly given that future low-carbon electricity systems will be based on technologies like hydro, wind, and solar which are weather-dependent and therefore vulnerable to regional climate impacts?
11. How can these methods be validated to ensure they are robust across a range of scenarios?

Integrating the SETPs framework into IAMs analysis

12. How could IAMs incorporate socio-economic tipping points (SETPs) triggered by climate extremes, such as the collapse of winter sports tourism, sea-level rise-induced migration, massive societal disobedience, etc.?

Technology

13. How can IAMs be enhanced to incorporate the impact of breakthrough technologies like green hydrogen, or nuclear fusion, on climate mitigation strategies, and what alternative routes should be prioritised in case of failure of other technologies like bioenergy with carbon capture and storage (BECCS)?
14. What is the role of AI in enhancing the robustness of IAMs, particularly in capturing the nonlinear impacts and cascading effects of extreme events on interconnected global systems such as energy, agriculture, and manufacturing? (noting an already applications of AI-assisted Earth System Modelling)

Economy and Financial System

15. Considering the interconnectedness of global financial systems, how would extreme economic events, such as hyperinflation or a global financial crisis, affect the robustness and reliability of IAMs? What modelling adaptations would be necessary to effectively capture the impacts of these economic extremes on energy systems and climate change mitigation strategies?
16. In the context of rapid technological advancements and changing market dynamics, how can IAMs be adapted to model the impact of sudden economic shifts, like the rise of green finance or a significant drop

in fossil fuel investments, on energy systems and climate policy? Can you provide an example where economic extremes have had a substantial impact on energy systems?

Geopolitical Factors

17. How can IAMs be modified or enhanced to better model the impact of geopolitical extremes, such as major conflicts or significant shifts in global power dynamics, on energy systems and climate policies? What are some of the challenges in predicting and integrating these geopolitical factors into current models?
18. In light of recent global events, such as trade wars or geopolitical tensions, how important is it to incorporate geopolitical risk assessment into IAMs? Can you describe a scenario where geopolitical extremes significantly altered the trajectory of energy systems or climate action plans?

3.3 Summary of interviews' responses

Here we summarise the experts' responses to the questions following the same structure of the survey in terms of topics, as well as the domains.

3.3.1 Defining Extremes

Considering the definition of extremes, and the distinction between risk and uncertainty, Expert 1 distinguishes between 'risk', which often carries a negative connotation implying a desire to avoid, and 'uncertainty', which is seen as an inherent aspect of various scenarios. This differentiation is crucial in understanding and characterising the nature of extremes within energy systems, where risk typically implies a deviation from an ideal state (depending on what is ideal) often negatively impacting these systems. In terms of examples, they highlight the gradual yet significant progress in electric vehicle batteries and solar PV technology, emphasising that these are not 'extreme' breakthroughs but results of decades-long developments. They note that real 'extreme' changes often originate in fundamental science discoveries, like new materials, which eventually permeate technology and engineering. Regarding failures, they anticipate potential catastrophic events in new technologies, such as CO2 capture facilities, which could setback their adoption significantly and impact emission reductions plans. They also discuss the Inflation Reduction Act (IRA) as a breakthrough in policy, not due to its suddenness but because of its long-term cumulative effect. The respondent added

"It will gradually transform the U.S. energy system and societal attitudes towards climate change and energy transition, reflecting its potential to create lasting change that transcends political shifts.

Expert 2 explains the notion of 'extreme events' as statistical anomalies within a predetermined distribution, highlighting the significance of their frequency and intensity. These distributions are dynamic by nature and can shift over time. They emphasise the value of examining specific characteristics within high percentile ranges of these extreme events for deeper insights. They discuss the concept of 'response functions', correlating the extreme events to various outcomes in socio-economic and health domains to understand their non-linear characteristics. Specifically in energy systems, they cite power outages as an example, including the impact of temperature extremes. Additionally, they note the complexities in assessing energy system impacts due to different energy types and potential supply chain disruptions. They also note the significant and immediate impact of abrupt policy changes in response to unforeseen events, such as wars or pandemics, on energy systems.

Expert 3 views 'extremes' in energy systems as encompassing a broad range of shocks, including climatic, technological, and geopolitical events. They suggest a shift from a narrow biophysical perspective to a broader interpretation that includes various types of shocks, some of which may have prolonged impacts. In discussing technological breakthroughs or failures, they point out the potential of technologies like CDR to cause significant shifts, either positive or negative, in energy systems. They express caution towards over-reliance on future technological solutions, advocating for immediate action to address current challenges.

Expert 4's perspective on extreme events in the context of risk and uncertainty involves framing them as unintended side effects, aligning with the definitions offered by the Society for Risk Analysis. Risk represents these unintended consequences, while uncertainty pertains to unknown factors in future planning. When defining extreme events within energy systems, they adopt a socio-technical approach, acknowledging their multifaceted nature. These events can encompass technical breakthroughs, like LED lights or shale gas, which revolutionise energy markets, or negative failures such as Fukushima or Deepwater Horizon disasters that shock the system. Moreover, extreme events extend beyond the technical realm, encompassing political, social, and environmental dimensions. They highlight that abrupt policy changes can exert substantial impacts on energy systems, citing historical instances where policies like the Clean Air Act or German feed-in tariffs have rapidly transformed energy landscapes, emphasising the importance of policy-driven transformations in energy systems.

Expert 5 conceptualises 'risk' in a probabilistic manner, potentially represented by a Gaussian distribution or a distribution with fatter tails. An 'extreme event' in this context lies at the tail end of such a distribution, though the exact percentile or standard deviation may vary. Contrasting this with 'uncertainty', they refer to the Frank Knight distinction, where 'uncertainty' is less about measurable risk and more about the truly unknowable events that are infrequent, yet impactful.

In the context of energy systems, Expert 5 identifies 'extreme events' as significant, unforeseen developments, exemplified by the drastic reduction in solar and battery costs, and contemplates scenarios such as an abrupt end to fossil fuel extraction. One example they provide is the impacts of sudden policy shifts, citing the post-1970s oil crisis energy policies that prompted specific technological advancements, albeit without substantially reducing fossil fuel reliance. They also note the European Emissions Trading Scheme (ETS) as a pivotal policy influencing shifts towards gas and local electricity, emphasising that many seemingly abrupt policy changes are often outcomes of prolonged planning, thus actual abrupt shifts are rarer than perceived.

3.3.2 Geographical Coverage

In addressing the impact of extreme events on energy systems, Expert 1 identifies the European Union's unique vulnerability due to its reliance on Russian gas and imports, including critical energy resources and consumer goods. This dependency, coupled with the EU's limited natural resource base, notably in critical minerals for energy technologies, heightens its susceptibility to supply shocks. Additionally, shifting political dynamics within the EU, particularly towards right-wing ideologies, could significantly influence energy and climate policies towards less decarbonisation efforts.

Expert 2 emphasises the advanced capabilities of the EU in monitoring and analysing extreme events through comprehensive weather data systems. This enables effective assessment of environmental conditions affecting businesses and economies. In contrast, they note the challenges faced by less developed regions due to limited data infrastructure. They also highlight the importance of satellite-based global monitoring systems that provide uniform data beyond political and economic borders, crucial for understanding and managing extreme events worldwide.

In discussing the impact of extreme events on different regions, Expert 3 highlights that such events tend to manifest globally through price changes, notably in food systems. This global transmission of shocks, while diluting their local impact, disproportionately affects the poorest in society, regardless of their geographical location. The poorest regions, such as Sub-Saharan Africa, suffer more significantly from these shocks due to their higher vulnerability and lower capacity to cope. They suggest that, while globalised systems help in risk distribution, they do so inequitably.

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In discussing the challenges and opportunities related to extreme events in the EU compared to other regions, Expert 4 emphasises three key factors that set the EU apart. First, the EU benefits from high-quality and accessible data, enabling better modelling and understanding of extreme events. Second, the EU displays strong focus on equity, justice, and just transitions, as in the European Green Deal. Third, Europe's affluence and resilience provide resources to invest in climate protection and novel technologies such as CCS, making it a leader in both climate mitigation and adaptation. However, they acknowledge variations within Europe and highlight climate refugees as an important extraterritorial factor that could significantly impact EU policies.

In terms of geographical differences in addressing extreme events, Expert 5 contrasts the energy systems of the EU with other regions. The EU, as an energy importer, is more vulnerable to shocks in energy trade, especially in fuels like gas and bioenergy. This contrasts with regions like the United States, which has been self-reliant due to shale gas but is now facing shifts, and Latin American countries like Brazil, which are energy exporters with a diversified energy mix. They highlight the EU's strengths in good governance, wealth, commitment to decarbonisation, and advancements in energy efficiency, making it both a recipient and a participant in managing extreme events. Additionally, they point out the EU's dependency on external technology and trade networks, particularly in relation to battery production and the influence of global geopolitical dynamics, as evidenced by recent developments involving China and Russia.

3.3.3 Vulnerabilities

Expert 1 identifies the 'Not In My Backyard' (NIMBYism) attitude as a key bottleneck in energy systems during extreme events, noting that while social acceptance issues—especially regarding renewable energy infrastructure—may not always escalate to 'extreme' scenarios, they represent significant, albeit gradual, challenges to energy system configuration and evolution.

Expert 2 identifies infrastructure resilience as a critical bottleneck in energy systems facing extreme events. One example could be wildfire risk linked to above-ground energy lines and the extensive time and financial investment required to transition to underground systems. They point out the vulnerability of energy operations in hurricane-prone areas and the dependence of nuclear facilities on potentially jeopardised water sources. On social acceptance as a vulnerability, they mention the challenge of habituation, where people may become accustomed to 'normal' and underestimate abnormal situations. They suggest a need for greater understanding of public adaptation to these outlier events.

Expert 3 highlights that vulnerabilities in food systems, when confronted with shocks or extreme events, often manifest due to international trade. This global interconnectedness, while distributing risk and diluting localised impacts, disproportionately affects the poorest globally, especially in regions like Sub-Saharan Africa. Additionally, they point out that shifts in social acceptance, such as a widespread move towards veganism or controversies surrounding Genetically Modified Organisms (GMOs), could dramatically impact food systems. They also mention emerging technologies like cellular agriculture, acknowledging their potential transformative effects, yet caution about their unproven nature and possible unintended consequences.

Expert 4 identifies supply chain issues and the scarcity of critical minerals as primary bottlenecks in energy systems when faced with extreme events. They highlight the systemic nature of these challenges. The COVID-19 pandemic highlighted these vulnerabilities. They also point out the importance of transportation routes like the Panama and Suez Canals in the global energy trade, with blockages causing significant ripple effects. On social acceptance, they cite examples from Germany, Austria, and the US where social opposition and misinformation campaigns have significantly impacted energy projects, particularly in the case of carbon and hydrogen pipelines and offshore wind farms.

On bottlenecks in energy systems amid extreme events, Expert 5 emphasises that they can be both infrastructural and societal. They identify the challenges in integrating high levels of renewable energy due to existing market structures, which are tailored for marginal cost generators and lack incentives for renewable integration and storage. This results in inadequate physical infrastructure, notably in storage capacity, thus impeding the effective deployment of renewables. They also highlight social acceptance as a pivotal vulnerability, particularly in the context of electric vehicles. Public apprehension, fuelled by negative press from vested interests and the challenges of adopting new technologies, acts as a significant barrier. This is compounded by infrastructural deficits like insufficient charging facilities.

3.3.4 Model Adaptability

In discussing model adaptability to extreme events, Expert 1 emphasises the challenges and opportunities in improving IAMs, particularly regarding granularity in temporal, geographic, and governance aspects. They identify the need for increased resolution in these models to effectively capture geopolitical crises and climate events. They suggest the potential of coupling IAMs with sector-specific models for enhanced precision, especially in scenarios involving low-likelihood but high-impact climate events. They also highlight the importance of integrating regional effects into global IAMs, considering the weather-dependency of future low-carbon electricity systems. Regarding validation, they acknowledge the inherent challenges in IAMs due to their dealings with social and geophysical systems, advocating for a mix of quantitative and qualitative validation methods, including stakeholder engagement. Lastly, they propose exploring agent-based models and recursive dynamic approaches to better represent the drivers and effects of extreme events in energy systems.

Expert 2 highlights the reliance of these models on historical data and the challenge of adapting to changes in historical conditions. They suggest enhancing models by predicting input variables and incorporating machine learning to continuously update these inputs, thus improving predictions. For integrating regional effects into global models, they recommend a multi-layered approach using detailed geospatial and economic data to capture regional nuances. They emphasise the importance of validating these models through methods like placebo test and replication in different regions, ensuring robustness and reliability in capturing the complexities of extreme events.

Expert 3 discusses the adaptability challenges faced by current IAMs primarily due to their inherent equilibrium-based framework and long-term focus. Limitations become particularly apparent when IAMs are confronted with extreme variables, such as geopolitical crises and pandemics, which hinder their ability to accurately capture the dynamics of non-equilibrium extreme events with shorter timeframes. Furthermore, these models have intricate complexity and inertia which pose significant barriers to addressing new risk parameters. They also highlight the uncertainties surrounding the integration of regional effects into global IAMs and the persistent challenges of validating models across a range of scenarios, due to data constraints. They highlight the pressing need for more adaptable modelling approaches and nuanced conceptualisation of extreme events to accurately represent their complexities and implications.

Expert 4 believes that current IAMs face substantial challenges in adapting to extreme variables like geopolitical crises or pandemics. They view IAMs as tools of persuasion rather than definitive truth-finders, noting their limitations in predicting political events. While suggesting the improbability of accurately forecasting geopolitical events, they advocate for the capability of IAMs to map impacts of such events post-occurrence. They recommend coupling IAMs with political science research for better adaptability.

Expert 5 critiques the adaptability of current IAMs in the energy sector, identifying their shortcomings in addressing extreme variables such as geopolitical crises and global pandemics. They highlight a lack of technical granularity and an inadequate representation of technological breakthroughs, which leads to shortcomings in system configuration and energy efficiency solutions. Further, they note the inadequate representation of regional disaggregation, spatial configurations, and the social dimensions of energy systems in these models. Expert 5 suggests that IAMs need to incorporate more relevant assumptions about technology performance in varied environmental conditions, such as considering the impact of wildfires on solar insulation efficiency. To enhance the integration of regional effects into global IAMs, they advocate for a shift towards 'no regret' frameworks,

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focusing on resilience and identifying strategies least vulnerable to uncertainty. Validating these methods, they propose, should focus on the sensibility of the strategic advice derived, rather than on the methods themselves.

3.3.5 Integrating the SETPs framework into IAMs analysis

Considering the dimensions of the framework above, Expert 1 frames the idea as a transformational response that entails a shift from one equilibrium to another, thereby realigning the system's steady state in anticipation of, or in response to, a climate shock, in order to ensure that the system remains resilient within this new state of equilibrium. As for the narratives, the respondent helped conceptualise the 3rd narrative 'Incremental Resilience' with an example from the state of Texas that illustrates a scenario where, following a severe winter storm, the state focused on expanding its existing fossil fuel-based power infrastructure to increase capacity, a response that enhances resilience without fundamentally transforming the system.

Expert 2 contemplates the incorporation of non-linearity in models to capture extreme responses, as a good approach for incorporating SETPs framework into models' analyses. They suggest that models could differentiate between moderate and severe responses based on thresholds within the distribution, such as transitioning from a P95 to a P99 scenario.

"This approach would allow models to distinguish between manageable negative ranges and those that result in significantly adverse outcomes."

Expert 2 highlights the potential of identifying clear breaks in response curves. This could signal points where systems break down, leading to cascading failures. Such modelling could effectively capture the dynamics of SETPs, particularly in scenarios involving extremes.

On incorporating SETPs within IAMs exercises, Expert 3 thinks this presents a notable challenge. While IAMs are adept at simulating and assessing climate-related impacts, their ability to anticipate and integrate SETPs triggered by climate extremes, such as the collapse of winter sports tourism or sea-level rise-induced migration, remains limited. This limitation stems from their inability to capture the rapid and non-equilibrium dynamics associated with extreme events.

Addressing the incorporation of SETPs framework in IAMs, Expert 4 stresses the complexity of predicting events like mass migration due to climate change. They suggest that acknowledging the limitations of IAMs in projecting socio-political changes is crucial, while focusing on post-event impact modelling. They advocate for a multidisciplinary approach, incorporating inputs from diverse fields such as social sciences to enhance the comprehensiveness of IAMs.

Technology

Expert 1 suggests that, for technologies like green hydrogen or nuclear fusion, IAMs could conventionally model their techno-economic aspects. However, they propose a more holistic approach, involving the modelling of the global energy technology supply system's dynamics, encompassing capital, labour, materials, and sub-components. This method captures the emergent properties critical for the fruition of such technologies. They also note that, while AI's current use in IAMs is largely limited to data preparation, there is potential for expanding its role to cover technological, environmental, and socio-economic dimensions.

Expert 2 highlights the necessity for IAMs to experiment with assumptions based on past behaviour and similar innovations to predict the impact of new technologies. Regarding the role of AI in enhancing IAMs, they emphasise its importance in managing large datasets and identifying patterns, outliers, and relationships, which are crucial in capturing nonlinear impacts and cascading events in interconnected systems.

Expert 3 posits that the enhancement of IAMs to accommodate the impacts of groundbreaking technologies like green hydrogen or nuclear fusion is a complex task. It is essential to recognise that not all technological advancements have the same characteristics or requirements. For instance, while green hydrogen may not necessarily require a fundamental technological breakthrough, it faces challenges related to scaling, cost

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reduction, and establishing use cases. In contrast, nuclear fusion represents a more speculative and disruptive technology that could indeed transform the energy landscape if proven feasible. IAMs should adopt a flexible approach to scenario development that integrates these technologies. As for the role of AI, they add that it can facilitate parameterisation and model tuning, addressing challenges associated with complex processes and empirical relationships. Additionally, AI can contribute to downscaling techniques, providing finer-grained regional information within global models.

Expert 4 discusses the challenges of integrating breakthrough technologies like green hydrogen into IAMs, such as uptake rates and costs projections. They emphasise the importance of considering supply chain resilience and societal acceptance in the integration process.

Expert 5 discusses the enhancement of IAMs to incorporate breakthrough technologies like green hydrogen and nuclear fusion, emphasising the importance of credible forecasting for key parameters such as energy input, capital costs, and efficiency. They suggest that in the event of failure of technologies like BECCS, alternatives such as accelerated deployment of renewables, electric vehicles, heat pumps, and other CDR strategies should be prioritised. Regarding the role of AI in IAMs, they see potential in using AI to analyse historical data, to better understand technological trends and interactions. This approach could improve model robustness by identifying economically and physically implausible scenarios, considering factors like finance availability, system size, technological development, and workforce skills.

Economy and Financial System

Expert 1 highlights the significance of capital availability for financing decarbonisation projects, especially in developing countries. They point out that economic extremes like hyperinflation and financial crises could further complicate the financing landscape, impacting the robustness and reliability of IAMs. They cite the example of green recovery packages during the COVID-19 pandemic to illustrate the necessity for IAMs to model individual years, thereby adequately representing rapid economic shifts and their impact on energy systems.

Expert 2 touches on the impact of extreme economic events on IAMs, underscoring the importance of continuously updating models with new data and trends. They suggest exploring and understanding correlations and mechanisms in economic events to adapt models accordingly. This exploration is vital for capturing the impacts of rapid technological advancements and market dynamics, like the rise of green finance or shifts in fossil fuel investments.

Expert 3 highlights that the interconnectedness of global financial systems introduces a significant dimension of complexity to IAMs when assessing the impacts of extreme economic events like global financial crises that go beyond the scope of standard scenarios. IAMs must prioritise comprehensive scenario development. These scenarios should encompass a wide spectrum of economic shocks and stress tests, including those triggered by geopolitical factors or shifts in market dynamics.

On the topic of economic and financial systems, Expert 4 highlights the impact of economic extremes on IAMs. They suggest that IAMs need to adapt to capture the effects of economic fluctuations, such as the rise of green finance or shifts in fossil fuel investments, on energy systems and climate policy.

Expert 5 emphasises the need for IAMs to effectively incorporate extreme economic events and rapid market changes, impacting energy systems and climate mitigation strategies. They suggest enhancing IAMs by adapting key parameters like cost of capital, investment constraints, and consumer discount rates to reflect economic extremes such as hyperinflation or global financial crises. This adaptation is crucial for realistically modelling the interplay between macroeconomic conditions and energy dynamics. Additionally, they propose using existing IAM frameworks to simulate the impact of sudden shifts like the rise of green finance or a decrease in fossil fuel investments, highlighting the importance of flexible modelling to accommodate variables like increased finance for decarbonisation or extreme negative financial shocks.

Geopolitical Factors

Expert 2 notes the challenges in integrating major conflicts and shifts in global power dynamics into IAMs. They advise looking into commercial operations already engaged in such detailed data analysis for insights and potential model enhancements.

Expert 3 says that, while some IAMs incorporate bilateral trade relationships and geopolitical factors to a certain extent, they often lack the capacity to fully anticipate and capture the rapid and non-equilibrium dynamics associated with geopolitical shocks. These events can lead to abrupt changes in energy systems and climate policies. To improve the modelling of geopolitical extremes, IAMs should focus on refining their scenario development methodologies. While IAMs have made strides in capturing the influence of geopolitical factors, ongoing challenges lie in predicting and quantifying the cascading effects of geopolitical events on global systems accurately. Incorporating robust geopolitical risk assessment into IAMs can help address these challenges.

Expert 4 notes the difficulty in modelling geopolitical extremes within IAMs. While predicting geopolitical changes is nearly impossible, they see value in IAMs mapping the impacts of such events on energy systems and climate policies post-occurrence. They advocate for integrating geopolitical risk assessment into IAMs and collaborating with political scientists to enhance their capability in this area.

Expert 5 emphasises the importance to modify IAMs for accurately capturing the impacts of geopolitical extremes, like major conflicts or shifts in global power dynamics, on energy systems and climate policies. They suggest incorporating scenarios such as international trade conflicts, protectionism, or significant fluctuations in fossil fuel costs in response to geopolitical events, which could lead to a shift towards renewable energy or affect the costs and integration of key technologies like solar panels and wind turbines. One of the primary challenges in this adaptation is the creation of plausible and specific geopolitical storylines, which require careful consideration and can be contentious. They highlight the historical precedent set by the oil embargoes of the 1970s, demonstrating how geopolitical events can significantly alter energy system trajectories.

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4 A quantitative case study: Geopolitics and global energy transition

4.1 How geopolitics shape global energy transition

The transition towards renewable energy sources and the pursuit of decarbonisation stands at the forefront of national and international environmental and climate initiatives. Moving deeper into this journey, it is important to acknowledge that the shift to cleaner energy solutions is not dependent only on technological advancements and the establishment of ambitious policy frameworks. Geopolitical factors play a pivotal role in shaping national and global decarbonisation pathways and low-emission strategies.

Geopolitical factors have always played an important role in shaping energy strategies, as observed in the recent energy crisis caused by the Russian invasion of Ukraine but also in previous energy supply disruptions. Energy security is a critical element of the European energy policy, as the EU has limited primary energy resources and is a large net importer of fossil fuels. Due to the high volatility of international energy prices and the increased geo-political tensions in several parts of the world, security of supply is a major objective of government energy policies. Energy security has several dimensions and is strongly related to policy issues related to energy system development, energy affordability, system resilience, climate change and environmental policies. As the EU currently imports more than half of its energy requirements and is highly vulnerable to supply disruptions as shown in the recent energy crisis, improving its security of energy supply is a cornerstone of the energy policy and the Energy Union Strategy.

Previous research has shown that ambitious decarbonisation policies would have positive impacts for EU's energy security triggered by reduced consumption and imports of fossil fuels combined with higher domestic production (renewable-based electricity, hydrogen and synthetic fuels) and lower energy consumption due to energy efficiency improvements. The EU's energy import dependency would decline massively in scenarios achieving climate neutrality by 2050, indicating clear benefits in terms of reduced exposure to energy imports. Decarbonisation strategies would also lead to higher diversification of energy supply, driven by the reduced dominance of fossil fuels and increased expansion of various renewable energy forms, thus improving the resilience of the decarbonised energy system and reducing the EU's exposure to fossil fuel imports with highly volatile prices.

On the other hand, a crucial facet of the energy transition is the escalating demand for critical minerals, necessary for the development of renewable energy infrastructure and clean energy technologies. The International Renewable Energy Agency's (IRENA) analysis (IRENA 2023), underscores the need for extensive reserves of critical minerals to achieve climate stabilisation. The criticality of these materials is dynamic and is dictated by economic shifts, geopolitical tensions, and technological advancements. Critical materials are today the focus of international dialogue and diplomacy. Their production and processing are highly concentrated geographically, posing challenges related to resource security and geopolitical dynamics. This concentration creates vulnerabilities and uncertainties for both consuming and producing countries that may affect the deployment, cost and sustainability of energy transition technologies and infrastructure. Strategies to diversify the supply and production chains for these materials are starting to emerge, reflecting multiple economic, political and social priorities and considerations.

The dependency risks and supply dynamics of critical materials fundamentally differ from those of fossil fuels, owing to their vastly different characteristics and patterns. As the current patterns of production and processing of critical materials is difficult to change in the coming years international cooperation and prudent policy choices are required to ensure that the energy transition advances at the necessary speed worldwide through adequate supply of critical materials needed for the manufacturing of clean energy technologies. Transparent markets with coherent standards and norms are required, while developing countries can advance their industrialisation strategies and capture greater economic value from their mineral wealth without constraining the global clean energy transition. Geopolitical factors introduce a layer of complexity to the critical material supply chain and influence the dynamics of extraction alongside production and trade. Current lists of critical materials are location-specific (Figure 1) which reflects the subtle differences of global power dynamics.

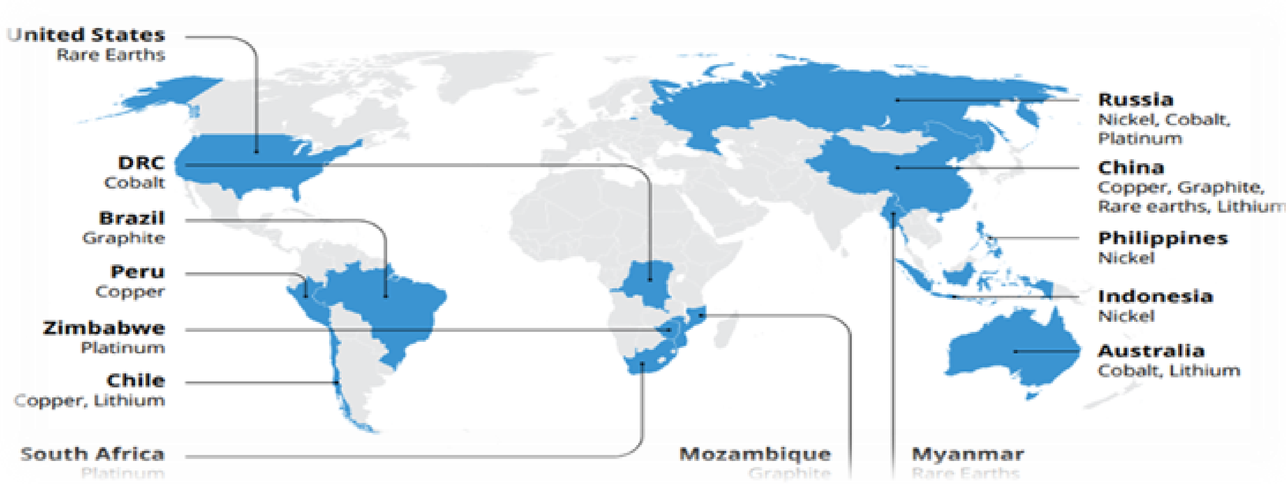

Figure 1: Top producers of energy transition minerals, Source: https://transparency.org.au/corruption-minerals-energy-transition-risk/

The concentration of mining activities in specific countries (Figure 2) including Australia, Chile, China, Democratic Republic of Congo, Indonesia, and South Africa, amplifies geopolitical considerations related to the clean energy transition. Notable, China's dominance in the processing stage of critical materials further accentuates the geopolitical dimension with implications for global supply chains of clean energy technologies, including solar PV and batteries.

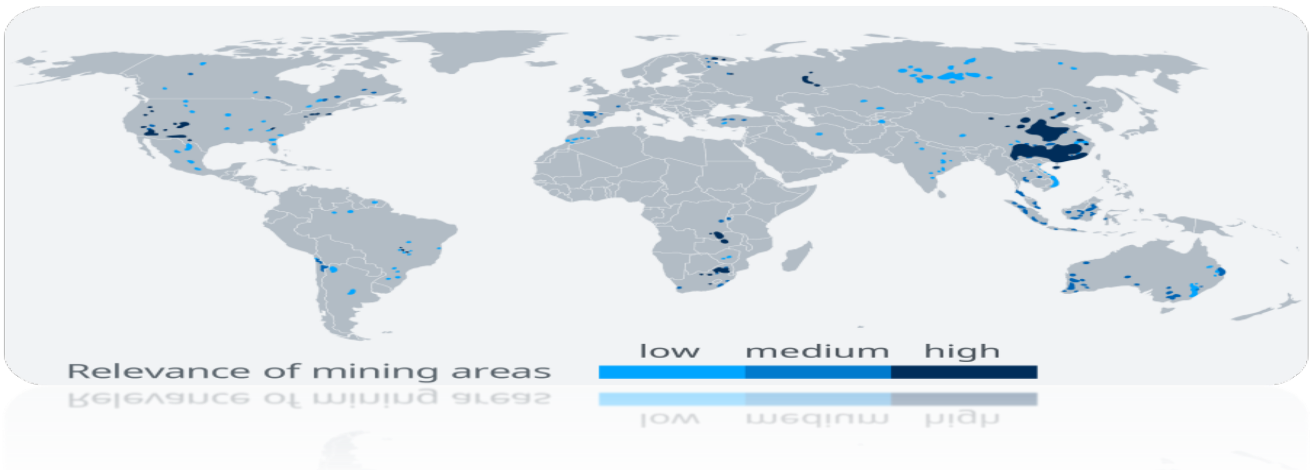

Figure 2: The most important mining areas of critical raw materials, Source: EU Commission, US geological survey, https://www.dw.com/en/how-chinas-mines-rule-the-market-of-critical-raw-materials/a-57148375

A pivotal concern arises from the shift from fossil fuel dependency to increased reliance on critical materials triggered by decarbonisation. While disruptions in critical material supply might not directly impact energy security, they can significantly hinder the speed and/or increase the cost of the energy transition. The interconnectedness of global supply chains, coupled with geopolitical risks such as external shocks, resource nationalism and market manipulation (Figure 3) emphasise the vulnerabilities inherent in the energy transition.

Figure 3: Key geopolitical risks to the supply of materials, Data Source: (IRENA 2023), Figure created by author.

Critical minerals play a pivotal role in the energy transition and serve as essential components for various clean energy technologies (Figure 4). Among the most crucial are rare earth elements (REEs), which are important to produce magnets for wind turbines and the motors of electric vehicles (EVs). Lithium, cobalt and nickel are vital for manufacturing high-performance batteries, essential for storing renewable energy and power electric vehicles (EVs). Cooper stands out as a fundamental material extensively used in electrical wiring, infrastructure, and renewable energy systems.

These minerals are indispensable for advancing the clean energy transition highlighting the intricate and interconnected nature of mineral dependencies in achieving a sustainable and low-carbon future.

Critical mineral needs for clean energy technologies

	Copper	Cobalt	Nickel	Lithium	REEs	Chromium	Zinc	PGMs	Aluminium
Solar PV	High	Low	Low	Low	Low	Low	Low	Low	High
Wind	High	Low	Moderate	Low	High	Moderate	High	Low	Moderate
Hydro	Moderate	Low	Low	Low	Low	Moderate	Moderate	Low	Moderate
CSP	Moderate	Low	Moderate	Low	Low	High	Moderate	Low	High
Bioenergy	High	Low	Low	Low	Low	Low	Moderate	Low	Moderate
Geothermal	Low	Low	High	Low	Low	High	Low	Low	Low
Nuclear	Moderate	Low	Moderate	Low	Low	Moderate	Low	Low	Low
Electricity networks	High	Low	Low	Low	Low	Low	Low	Low	High
EVs and battery storage	High	High	High	High	High	Low	Low	Low	High
Hydrogen	Low	Low	High	Low	Moderate	Low	Low	High	Moderate

Relative importance of minerals for a particular clean energy technology: High: ● Moderate: ● Low: ●

Figure 4: Critical mineral needs for clean energy technologies, Source: https://earthrights.org/blog/five-things-to-know-about-critical-minerals/

4.2 Literature review on geopolitics of energy transition

The intersection of geopolitics and decarbonisation pathways necessitates a comprehensive understanding of the dynamic relationship between geopolitical factors and the transition to clean energy to meet the Paris Agreement goals. Some of the gathered and analysed literature under this topic employed modeling approaches to analyze the geopolitical impacts on decarbonisation pathways.

For example, (Bazilian et al 2019) outline some geopolitical scenarios for the energy transition by 2030. Four different energy transition scenarios are presented alongside their effects on global geopolitics. The study extensively analyses mineral supply chains with a focus on geopolitical risks and recommend strategies to reduce bottlenecks using innovative recycling and substitution technologies.

The study of (Peng Wang et al 2022) addresses the overlooked interactions between climate targets, energy transitions and critical minerals. It introduced a Metal-Energy-Climate (MEC) nexus framework and applied to global energy transition scenarios under a carbon-neutral or below 1.5oC temperature target. Their methodology integrates metal production, energy and climate systems using six Integrated Assessment Models (IAMs) and six critical minerals. Climate scenarios adopt the RCP 1.9 target ensuring consistency with the Paris Agreement goals and involve six IAMs and six Shared Socioeconomic Pathways (SSPs). Mineral supply scenarios are linked to the SSPs and extend them by defining material related strategies for each SSP. Their key findings include a significant increase in the critical mineral demand due to ambitious mitigation efforts, challenges for solar and wind power due to specific mineral shortages and scalability issues. The study highlights the lack of attention in existing scenarios to mineral implications for a low carbon future and the insufficient consideration of mineral constraints along with mineral life cycle by IAMs.

Market power and geopolitical risks were investigated by Manberger and Johansson (Manberger et al 2019). Their study examined the geopolitical role of 14 critical materials used in solar and wind-energy industries, electric vehicles (EVs), batteries and fuel cells. Their findings suggest that the market power of major producers of critical materials remains below that of oil-exporting countries.

Valero et al (Valero et al 2018), proposed a methodology to identify possible bottlenecks in future demand of critical materials (2016-2050) concerning geological availability. Their focus is on global development of wind power, solar photovoltaics (PV), solar thermal power (CSP) and passenger EVs. Their goal is to provide insights into potential constraints in critical material availability within the context of energy transition.

The global forecasts of demand for critical materials differ based on climate policy assumptions and methodology to project future developments in production, processing and recycling technologies. Several studies focus on resource constraints within a single country or region (Blagoeva et al 2020) with limited coverage at the international level.

4.3 Impacts of technology constraints on mitigation pathways

There is a clear need for rapid and massive global emissions reductions to achieve the Paris Agreement goals, but an unclear landscape towards the specific pathway to meet this goal with a multitude of low-carbon technologies and mitigation options contributing to the overall decarbonisation goal. Clean energy technologies constitute the key pillars of the transition towards a sustainable and low carbon future. However, as the transition moves deeper into sectoral transformation challenges and barriers, its crucial to acknowledge the possibility of failure or limited uptake of certain clean energy technologies. This could be due to the commercial immaturity or the high cost of a certain technology (e.g. electrolysers, synthetic fuels) or due to limited social acceptance and political concerns (e.g. nuclear, CCS) or even due to trade-offs with broad sustainability goals (e.g. biomass) or other unforeseen external factors. The examination of technology failures and their impacts on mitigation pathways is crucial for robust, resilient, and realistic assessments of decarbonisation strategies.

Social unacceptance for example, can lead to resistance in the adoption of certain technologies (e.g. nuclear power or even wind turbines), while technical limitations (e.g. grid integration) could arise from inherent flaws or unexpected challenges during technology implementation, deployment and upscale. On the other hand, immature technologies may lack the necessary development or face unforeseen obstacles and increased costs that can make them economically unviable. Geopolitical events, resource constraints, technical failures, or other global disruptive events (e.g. COVID-19 outbreak, energy crisis) can contribute to such technology failures.

The literature confirms the importance of potential limitations/constraints of clean energy technologies in shaping realistic and resilient decarbonisation pathways at the national, regional and global level.

Researchers in (Climateworks 2023), employed a framework to categorise deployment levels of various energy technologies as 'Low', 'Medium' or 'High' with a specific focus on achieving the Paris Agreement temperature goals

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and net-zero carbon dioxide emissions by 2050. The technologies (Carbon Capture and Storage- CCS, Direct Air Capture- DAC, Nuclear, Renewable Energy, Bioenergy, Transport Electrification, Behavioural changes, Natural Carbon Dioxide Removal - CDR) were grouped based on their potential deployment levels to Low, Medium, High and the central scenario considers constraints in some technologies for specific groupings. The central scenario constrained bioenergy with CCS option (Carbon Capture and Storage), Low nuclear, High RE (Renewable energy), Low bioenergy, High electrification, and Low natural CDR (Carbon Dioxide Removal). The overarching modelling goal was to limit the global temperature rise to 1.5° C with limited overshoot in line with the Paris Agreement goals. The central scenario and most variants resulted in a global mean temperature rise of around 1.2° C by the end of the century, achieving a high probability of meeting the 1.5° C goal by 2100, but with temporary oveshoot during the century. The Zero-DAC scenario though, resulted in a somewhat higher temperature rise (1.3° C), but still considered compatible with the PA but with lower probability. The scenario assuming limited deployment of DAC/CCS led to just under 1.5° C temperature rise with an overshoot of about 0,1° C, representing a closer to 50% chance of meeting the 1.5° C target.

The study (Grant et al 2022) examined the role of Carbon Dioxide Removal (CDR) in low-carbon scenarios emphasising the potential impact on emissions reduction strategies. The research employs the TIAM-Grantham model to explore the relationship between CDR and emissions reduction in various scenarios aiming to achieve the Paris goals. The scenario sets that examined in this study were a) conventional decarbonisation pathways, b) stochastic scenarios considering uncertainty in CDR availability, and c) myopic scenarios introducing a degree of short-term decision making. The study concludes that CDR in conventional/deterministic scenarios can lead to higher fossil fuel consumption (and slower fossil phase out), reduced renewable energy investment, and limit necessary changes in the consumption patterns. The introduction of uncertainty in CDR availability constrains the intertemporal substitution between CDR and near-term mitigation, emphasising the need for more ambitious near-term climate policies. The research also identifies the risks of mitigation deterrence because its continuance could lead to temperature overshoot, with catastrophic consequences.

Another study (led by Riahi et al 2015) utilised nine global Integrated Assessment Models (IAMs) to develop climate stabilisation scenarios for the 21-century considering short- and long-term climate targets (scenario assumptions are presented in Table 1). Among others, the study assessed a scenario where the technology to capture and geologically store carbon dioxide (CCS) never becomes available. The absence of CCS technology impacts the potential implementation of more ambitious climate goals and the possibility to generate negative emissions when CCS is combined with bioenergy.

Table 1: Technology sensitivity cases that used in the developed scenarios of (Riahi et al 2015)

Technology cases	Description	Scenario name
Full technology	The full portfolio of technologies is available and may scale up successfully to meet the respective climate targets.	**"FullTech"**
Low demand and energy intensity	A combination of stringent efficiency measures and behavioural changes radically limits energy demand, leading to a doubling of the rate of energy intensity improvements compared to the past. The full portfolio of technologies is available on the supply side.	**"LowEI"**
No new nuclear	No new investments into nuclear power after 2020; existing plants are fully phased out over their lifetime.	**"NucOff"**
No CCS	The technology to capture and geologically store carbon dioxide (CCS) never becomes available. This impacts both the potential to implement lower emission options with fossil fuels and the possibility to generate "negative emissions" when combined with bioenergy.	**"NoCCS"**

Limited solar and wind	Limited contribution of solar and wind to 20% of total power generation, reflecting potential implementation barriers of variable renewable energy at high penetration rates.	**"LimSW"**
Limited biomass	Limited potential for biomass (maximum of 100 EJ/year), exploring strategies that would avoid large-scale expansion of bioenergy and thus avoid potential competition over land for food and fiber.	**"LimBio"**
Conventional solutions	Limited solar, wind and biomass potentials, leading to heavy reliance on conventional technologies such as fossil fuels in combination with CCS and/or nuclear.	**"Conv"**
Efficiency and renewables	A low demand case assuming "No CCS" and "no new nuclear", leading to heavy reliance on renewables and efficiency measures.	**"EERE"**

Another study (Oshiro eta la 2023) explored a Carbon Capture and Utilisation scenario as part of the climate policies and mitigation scenario assessments. In this scenario, hydrocarbon energy carriers are made available to energy demand sectors and offer advantages in increasing energy density and reducing dependence on fossil fuels and bioenergy. Their CCU scenario aims to avoid drastic changes in demand-side technology and infrastructure (like those posed e.g. by increased electrification) while minimising the reliance on carbon dioxide removal (CDR) and bioenergy options. However, this scenario presents challenges, including the need for significant transformations in energy supply, such as massive upscaling hydrogen generation and non-biomass renewable energy-supply. Despite moderate demand-side technological changes, the CCU scenario requires large scale deployment of Direct Air Capture (DAC) technology which poses significant challenges. It exhibits unique characteristics in terms of carbon flow, heavily relying on carbon released into the atmosphere. The study emphasises that CCU-oriented scenarios are economically viable under specific conditions and that their implications should be considered in climate policies, but noting increased mitigation costs compared to other scenarios, mainly due to synfuel production which is projected to remain relatively expensive by 2050.

Decarb America (Decarb America 2023) mention in their official site that they analyse seven distinct technology and policy pathways to reach net-zero. Among their developed pathways, they examine a scenario which assumes renewable energy constraints. This scenario achieves net-zero emissions by 2050 with constraints on the deployment of renewable electricity technologies to reflect technical and societal challenges. The renewable energy availability is reduced by 5% due to technical potential for onshore wind, compared to 25% in the "Net-Zero by 2050" scenario. Solar deployment is limited because of land availability, with no more than 0.5% of available land area in any region allowed to be used for utility-scale solar. This scenario also constrains offshore wind deployment to 25% of technical potential to reflect potential hurdles in terms of siting of supporting transmission infrastructure and avoiding encroachment on existing ocean uses.

Dekker et al 2023, presented an innovative framework to characterise energy model typology. Their aim is to reveal distinctive 'fingerprints' within scenario ensembles. The study identified five key dimensions and introduced 24 diagnostic indicators to provide a comprehensive insight into each model's behaviour. Applied to a series of "diagnostic" scenarios (Table 2) the framework provided a nuanced understanding cautioning against exclusive reliance on individual model results. The paper discusses the framework's flexibility for global applications positioning it as a valuable diagnostic tool. In the context of addressing technology constraints, the study contributes by addressing model behaviour in scenarios (Table 2) to explore how diverse models navigate challenges imposed by specific technological constraints on CCS options, biomass and nuclear power.

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Table 2: Description of the diagnostic scenarios

Scenario name	Carbon pricing	Additional assumptions
DIAG-NPI	National policies implemented	–
DIAG-C400-lin	Linear, equation (1)[1] (580 US$ t^{-1} CO_2 in 2050)	–
DIAG-C400-lin-LimBio	Identical to DIAG-C400-lin	Global primary modern bioenergy supply limited to 100 EJ, which is on the lower end of the range given in the Sixth Assessment Report by IPCC32. Maximum European primary biomass use is limited to 7 EJ, which is close to current use33. Biomass imports of Europe set to 0.
DIAG-C400-lin-LimCCS	Identical to DIAG-C400-lin	CCS (including BECCS and DACCS) limited to 2 Gt CO_2 per year globally. Max CCS use in Europe limited to 250 Mt CO_2 per year.
DIAG-C400-lin-LimNuclear	Identical to DIAG-C400-lin	Nuclear power limited to today's levels and no new constructions are allowed except capacity already under construction.
DIAG-C400-lin-HighVRE	Identical to DIAG-C400-lin	Set direct LCOE for offshore wind at €30 MWh^{-1}, onshore wind at €20 MWh^{-1} and solar PV at €10 MWh^{-1} by 2050. Linear interpolation from current prices.
DIAG-C400-lin-HighElectrification	Identical to DIAG-C400-lin	Provide emissions-free electricity for demand sectors at €30 MWh^{-1} (excluding transmission and distribution).
DIAG-C400-lin-H2	Identical to DIAG-C400-lin	Provide emissions-free hydrogen for demand sectors at €45 MWh^{-1} (excluding transmission and distribution).
DIAG-C400-lin-ResidualFossil	Identical to DIAG-C400-lin	Set fossil fuel primary energy prices at €70 GJ^{-1} (before carbon pricing).
DIAG-C400-lin-HighEff	Identical to DIAG-C400-lin	By means of a variety of lifestyle change or high efficiency options (models are free to choose), reach final energy values of 26 EJ in Europe in 2050 including bunkers and non-energy.

4.4 Impacts of technology constraints on mitigation pathways

This study assesses low-carbon transition pathways by incorporating disruptions from geopolitical events and technology failures as analysed in sections above. The study design involves implementing disruptions in existing IAM-COMPACT scenarios developed by global IAMs, focusing on supply chain constraints of specific clean energy technologies. The basic scenario used in the current study is the NDC-LTT scenario, assuming the imposition of Nationally Determined Contributions (NDCs) for 2030 and Long-Term targets (LTTs) for the longer-term developed in the IAM-COMPACT project. The NDC target reflects the level of short-term climate ambition (up to 2030),which most countries globally implement through law or policy, but with risks of falling short if dedication is not high enough and/or there are changes in the political landscape; The Long-term targets (LTT) level of longer-term ambition is significantly higher with many countries stated to fulfil their part in mitigating climate change, but in most cases not backed with an actual policy agenda and legislative policy measures.

The aim of this study is to answer research questions regarding the impact of supply-chain constraints on clean-energy technology ramp-up, susceptibility of system configurations to geopolitical disruptions and the resilience of transition pathways to technology unavailability.

4.4.1 Models

The study uses three well-established IAMs (GCAM, PROMETHEUS, TIAM) that have been widely used to assess the environmental, economic, and technology impacts of ambitious climate policies at national and global levels. A brief description of the three models is provided below, while detailed model descriptions can be found in the I^2AM PARIS platform[1].

The Global Change Assessment Model (GCAM) is a global integrated assessment model that represents both human and Earth system dynamics. It explores the behaviour and interactions between the energy system, agriculture and land use, the economy and climate. The role of GCAM is to bring multiple human and physical Earth systems together in one place to provide scientific insights that would not be available from the exploration of individual scientific research lines. The model components provide a faithful representation of the best current scientific understanding of underlying behaviour. GCAM allows users to explore what-if scenarios, quantifying the implications of possible future conditions. These outputs are not predictions of the future; they are a way of analysing the potential impacts of different assumptions about future conditions. GCAM reads in external "scenario assumptions" about key drivers (e.g., population, economic activity, technology, and policies) and then assesses the implications of these assumptions on key scientific or decision-relevant outcomes (e.g., commodity prices, energy use, land use, water use, emissions, and concentrations). It is used to explore and map the implications of uncertainty in key input assumptions and parameters into implied distributions of outputs, such as GHG emissions, energy use, energy prices, and trade patterns. Techniques include scenarios analysis, sensitivity analysis, and Monte Carlo simulations. GCAM has been used to produce scenarios for national and international assessments ranging from the very first IPCC scenarios through the present Shared Socioeconomic Pathways (SSPs) (Calvin et al., 2017).

PROMETHEUS is a global energy system model covering in detail the complex interactions between energy demand, supply and energy prices at the regional and global level. Its main objectives are: 1) Assess climate change mitigation pathways and low-emission development strategies for the medium and long-term 2) Analyse the energy system, economic and emission implications of a wide spectrum of energy and climate policy measures, differentiated by region and sector) 3) Explore the economics of fossil fuel production and quantify the impacts of climate policies on the evolution of global energy prices. The PROMETHEUS model provides detailed projections of energy demand, supply, power generation mix, energy-related carbon emissions, energy prices and investment to the future covering the global energy system. PROMETHEUS is a fully fledged energy demand and supply simulation model aiming at addressing energy system analysis, energy price projections, power generation planning and climate change mitigation policies. PROMETHEUS quantifies CO_2 emissions and incorporates environmentally oriented emission abatement technologies (like RES, electric vehicles, CCS, energy efficiency) and policy instruments. The latter includes both market-based instruments such as cap and trade systems with differential applications per region and sector specific policies and measures focusing on specific carbon emitting activities. Key characteristics of the model, that are particularly pertinent for performing the analysis of the implications of alternative climate abatement scenarios, include world supply/demand resolution for determining the prices of internationally traded fuels and technology dynamics mechanisms for simulating spill-over effects for technological improvements (increased uptake of a new technology in one part of the world leads to improvements through learning by experience which eventually benefits the energy systems in other parts of the World). PROMETHEUS is designed to provide medium- and long-term energy system projections and system restructuring up to 2050, both in the demand and the supply sides. The model produces analytical quantitative results in the form of detailed energy balances in the period 2015 to 2050 annually. The model can support impact assessment of specific energy and environment policies and measures, applied at regional and global level, including price signals, such as taxation, subsidies, technology and energy efficiency promoting policies, RES supporting policies, environmental policies and technology standards.

The TIMES Integrate Assessment Model, TIAM, is the multi-region, global version of TIMES, which combines an energy system representation of fifteen different regions with options to mitigate non-CO2 greenhouse gases as well as non-energy CO_2 mitigation options, such as afforestation in each of these regions. It uses emissions from these sources to calculate temperature changes using a simple climate module. As such, it can be used to explore a variety of questions on how to mitigate climate change through energy system and transformations, as well as reductions in non-energy CO_2 emissions and non-CO_2 emissions. TIMES is a modelling platform for local, national or multi-regional energy systems, which provides a technology-rich basis for estimating how energy system operations will evolve over a long-term, multiple-period time horizon (Loulou and Labriet, 2007). These energy system operations include the extraction of primary energy such as fossil fuels, the conversion of this primary energy into useful forms (such as electricity, hydrogen, solid heating fuels and liquid transport fuels), and the use of these fuels in a range of energy service applications (vehicular transport, building heating and cooling, and the powering of industrial manufacturing plants). In multi-region versions of the model, fuel trading between regions is also estimated. The TIMES framework is usually applied to the analysis of the entire energy sector but may also be applied to the detailed study of single sectors (e.g. the electricity and district heat sector). The framework can also be used to simulate the mitigation of non-CO_2 greenhouse gases, including methane (CH_4) and nitrous oxide (N_2O).

4.4.2 Scenarios

Under the NDC-LTT scenario, shared with other studies under the IAM-COMPACT project, this study introduces additional cases with clean technology limitations to explore their impacts on reaching the European climate targets for 2030 and 2050. These limitations are included in the scenarios and are presented in Table 3.

Specifically, the limited RES scenario (NDC-LTT-LimRES) envisions a world where geopolitical challenges and scarcity of essential critical materials hinder the widespread adoption and deployment of renewable energy and energy storage solutions as well as batteries and Electric vehicles. The constraints imposed on RES and battery technologies reflect a more challenging environment for transitioning to cleaner and sustainable energy systems, potentially impacting the achievement of climate and sustainability goals. This scenario is first quantified using the MARIO model (from POLIMI), coupling a self-consistent macro-economic framework with a tool capturing the linkages of clean energy technologies with the supply, demand and trade critical materials required. The MARIO model produced two contrasting scenarios; (1) one where there are no restrictions in the material supply and in the trade of clean energy technologies (so if cost-optimal the EU continues to import large PV quantities from China); and (2) one where trade import constraints are imposed among regions and each region should manufacture the required technologies, while the costs of critical materials increase due to import constraints reflecting geopolitical tensions. The MARIO model quantified the cost impacts of the scenarios on the clean energy technology costs (in particular for solar PV, wind turbines, batteries and electric vehicles) and the cost increases in the "constrained trade" scenario are then imposed on top of the cost assumptions of PROMETHEUS and GCAM models in the NDC-LTT context, increasing the transition cost and reducing the speed of clean energy technology uptake in the EU.

Other factors such as environmental considerations, resource availability, limit competition with food supply, and a shift in policy priorities are included in the limited biomass scenario (NDC-LTT-LimBio) which imply a significant impact on the energy mix that requires alternative sources to compensate for the reduced contribution of biomass to the overall energy supply. In particular, we use the assumptions from a recent high-level analysis (Dekker et al, 2023) where the biomass consumption in the EU27 is restricted to 5-6 EJ by 2050. The limited CCS scenario (NDC-LTT- LimCCS) envisions a future where the deployment of CCS technologies is constrained due to technological challenges, high costs and lack of social acceptance that reflects a deliberate policy decision to curtail the widespread adoption and utilisation of CCS technologies for capturing and storing carbon emissions. In particular, we restrict CCS deployment to 10-20MtCO2 by 2050 assuming that only the current list of pilot CCS projects will be materialised in EU countries. It is important to mention that in the series of NDC-LTT technology-constrained scenarios the same carbon prices (and other policy instruments) are used as in the basic NDC-LTT scenario. This means that the technology-constrained scenarios will not achieve the same level of emission reductions as the NDC-LTT and thus the EU's climate neutrality goal might be missed.

Table 3: Descriptions of the disruptive scenarios

Scenario	Description
NDC-LTT	Implement the NDC targets for 2030 and Long-term mitigation targets for 2050 (i.e. climate neutrality for the EU)
NDC-LTT-LimRES	This scenario is characterised by constraints on the expansion and growth of renewable energy sources (RES) and energy storage technologies, particularly batteries. This limitation is attributed to a combination of factors including material unavailability and geopolitical tensions. In this scenario, the costs associated with clean energy technologies (such as RES) experience an increase due to import constraints in materials and clean energy technologies quantified by the MARIO model. These elevated costs coupled with supply constraints act as moderating factors on the rate of growth for renewable energy and battery technologies.
NDC-LTT-LimBio	This scenario outlines a future where the utilisation of biomass for energy purposes is restricted, with a cap set approximately 5-6 EJ by 2050 in the EU27.
NDC-LTT- LimCCS	This scenario has the specific target of limiting carbon capture to a range of 10-20 MtCO2 by 2050 in the EU.

4.5 Results

4.5.1 CO2 emissions

Since renewable energy sources (RES) and batteries play a crucial role in reducing emissions by replacing fossil fuel-based energy, limiting their growth (and/or increasing their costs) would result in higher reliance on conventional, more carbon-intensive energy sources. PROMETHEUS and GCAM project that this will result in an increase of EU CO2 emissions of about 88MtCO2 compared to the basic scenario NDC-LTT in 2050, and only about 0,89MtCO2 according to TIAM, implying that the EU will most likely miss its climate neutrality goal by 2050.

The Conference of the Parties (COP) 26 identified bioenergy as a strategic solution to climate change mitigation because it can replace fossil fuels in the foreseeable future (IETA, 2021). However, many countries face issues expanding their bioenergy production due to food security concerns as similar crops and inputs are used in the production of both food and (conventional) bioenergy; this concern is somewhat alleviated by the production of advanced biofuels (which however commonly come with higher costs). Limiting the availability of biomass use for energy purposes, as in the NDC-LTT-LimBio scenario) would lead to a higher EU reliance on fossil fuels and higher carbon dioxide emissions (ranging from 255-636MtCO2 in 2040 and 125-449-1129MtCO2 in 2050 according to TIAM, PROMETHEUS and GCAM results respectively) compared to the basic NDC-LTT scenario, if alternative clean energy sources are not sufficiently developed. Interestingly, in 2040 TIAM project that the CO2 emissions in the NDC-LTT will be increased by 103MtCO2 compared to the limited biomass scenario due to the widespread use of CCS that the model assumes in response to biomass limitations. This highlights the crucial role of biomass as an option both to reduce emissions (when replacing fossil fuel use in demand sectors) and to generate net negative emissions when combined with CCS to produce electricity and/or hydrogen. The results indicate the strong reliance of the EU's effort towards net-zero emissions on bioenergy, reducing the resilience of its transformation pathways when this option is constrained.

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Technologies that can capture carbon dioxide (CO_2) at a source of emissions before it is released into the atmosphere (CCS) plays a crucial role in mitigating emissions from industrial processes and power generation. The constraints imposed in the NDC-LTT-LimCCS scenario would result to higher CO2 emissions in 2040 by 103-497 MtCO2 by 2040 (TIAM, PROMETHEUS and GCAM respectively) compared to the basic NDC-LTT scenario, while in 2050 the increased CO2 emissions range from 305-1148 MtCO2. This highlights the strong need to develop and upscale CCS technologies in a cost-efficient manner if the EU wants to achieve its climate neutrality goal by 2050. These technologies can capture large quantities of CO2 both from industrial processes and from power plants, and they can even generate net-negative emissions when combined with Biomass. In both LimBio and LimCCS scenario, the emission impacts are much higher in GCAM than in PROMETHEUS and TIAM, indicating the stronger reliance of the former model on biomass and CCS technologies, while the transition in PROMETHEUS and TIAM is based strongly on massive uptake of other mitigation options, including renewable energy technologies, electrification of the transport and heating sectors and energy efficiency improvements.

Overall, limiting the growth of key technologies would impede progress toward achieving ambitious emission reduction goals, requiring a more in-depth analysis of the potential impacts of technology constraints in the EU's pathway towards net-zero emissions. It is imperative for EU and national policy makers to understand the resilience of systemic transformations and the potential security effects of technology constraints.

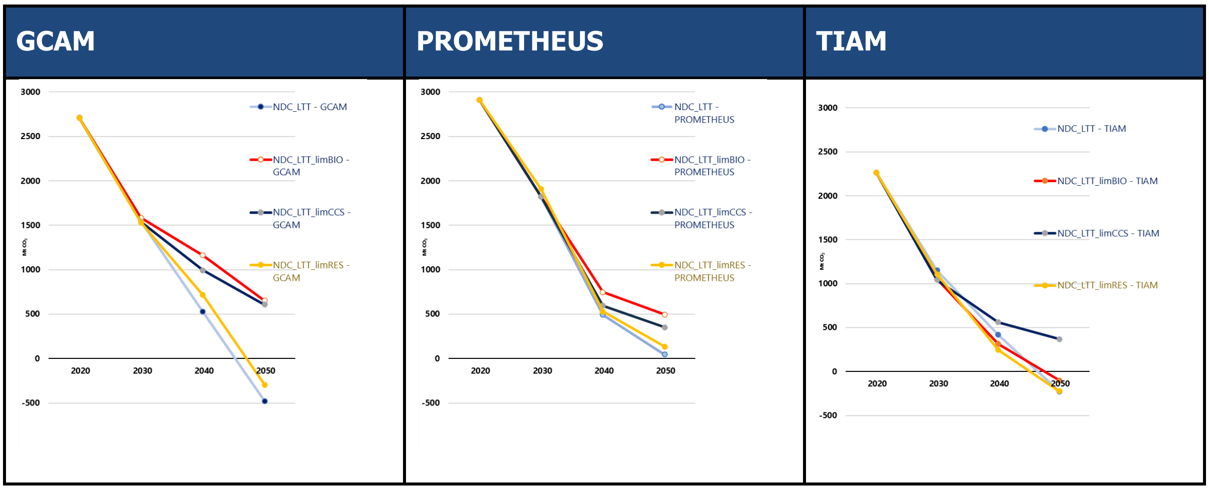

Figure 5. Evolution of CO2 emissions per scenario from 2020-2050, PROMETHEUS, GCAM, TIAM results

4.5.2 PRIMARY ENERGY

The limitations imposed on biomass supply result in notable shifts in the energy mix by 2050, with increased utilisation of other energy sources to replace for the lost biomass compared to the NDC-LTT scenario. Overall, a relative turn to conventional fossil fuels is observed despite the implementation of long-term and net zero policies across countries due to challenges in fully replacing the role of biomass with other-low carbon alternatives in all sectors. The rise in EU's coal consumption (0,29EJ/yr and 0,18 EJ/yr according to GCAM and PROMEHTEUS respectively, compared to NDC-LTT) is driven by the fact that biomass restrictions lead to higher demand for traditional fossil fuels to meet energy needs, especially in sectors with limited low-carbon options (e.g. industry). The same is observed in oil consumption which increases by about 2-4EJ/yr (compared to NDC-LTT) because of intensified reliance on liquid petroleum fuels to compensate for the reduced contribution of biofuels. In the absence of biomass, nuclear energy as an alternative low-carbon source to produce electricity is projected to increase by 0,38-0,48EJ/yr. Global gas consumption is also projected to increase by 0,22 EJ/yr in PROMETHEUS and a

2,63EJ/yr increase in GCAM, suggesting a transition towards more carbon-intensive options when biomass availability is limited. The difference in the modelling outcomes indicates the different role for natural gas projected by the two models.

When the uptake of CCS is restricted, this influences negatively the deployment and attractiveness of biomass compared to other energy sources (6 EJ/yr drop in PROMETHEUS and 7EJ/yr drop in GCAM results) as the option to generate net negative emissions through BECCS is constrained. The limitations in CCS applications impact to a lesser extent the consumption of fossil fuels for electricity generation, as unabated coal has been almost completely phased out by 2040 and natural gas without CCS plays a progressively minor role and oil-based generation is vanished. On the other hand, the low-cost renewable energy potentials (solar, wind, hydro, geothermal) have already been exploited in 2050 leading to a slight increase in non-biomass renewable energy options, except wind energy which is projected to be about 27% higher (according to PROMETHEUS) compared to the basic NDC-LTT scenario.

The energy landscape regarding renewables is shaped by 2050 by NDCs and long-term net-zero targets. The European power sector is projected to reach about 1440 GW (more than double in size the next three decades) with renewable energy sources possessing the largest share in the overall capacity mix. As a result of this deployment, a limitation on RES expansion is unlikely to have a substantial impact on the overall RES growth in 2050 as these projects have been completed and the focus has shifted towards optimising and maintaining the existing renewable energy capacity rather than relying on further expansion to meet climate targets. GCAM suggests that the constraints in RES will result to an increase in nuclear energy from 2030 to 2050 of about 1,52EJ, as a low carbon alternative to compensate for the reduction in renewables. In contrast PROMETHEUS, suggests a drop in nuclear energy in 2050 compared to 2030 levels of about 1EJ, under the same limitation. PROMETHEUS envisions challenges specific to nuclear energy in the EU context despite the constraints on renewable sources as several EU Member States have declared their strong commitment to phase-out nuclear power and not construct any new nuclear capacities. On the other hand, the proactive stance of the European Commission and the focus on Small Modular Reactors (SMRs) as part of the Euratom programme are evident in GCAM's suggestion which indicate a push for nuclear energy after 2030, including advanced reactor technologies like SMRs (Monika Dulian, 2023).

The NDC-LTT scenarios project a reduced primary energy consumption in the EU driven by the ambitious NDC and Long-term target policies. The reduction is larger in PROMETHEUS than in GCAM, as the former includes a detailed representation of energy efficiency measures in end-use sectors and a more granular modelling of saving options and technologies. Primary energy consumption reduces even further in the LimBio and LimCCS scenarios driven by the substitution towards more efficient technologies, in particular clean energy technologies like wind power and solar PV.

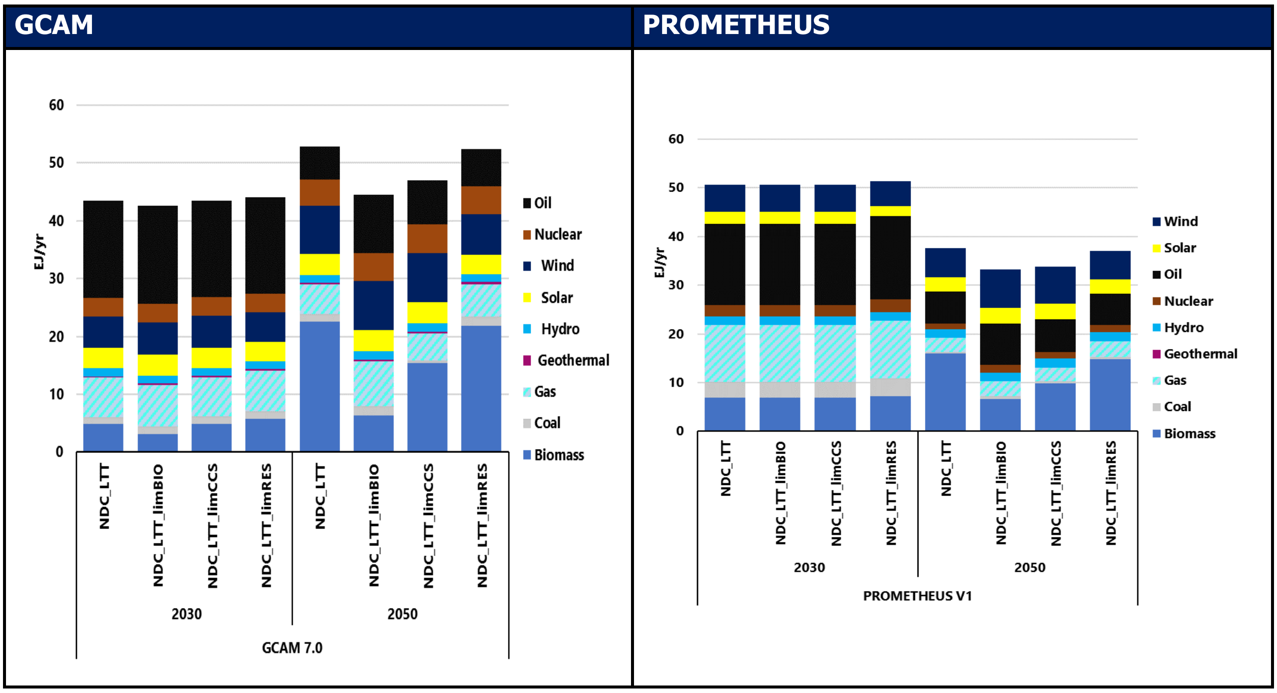

Figure 6. Primary energy consumption by fuel for different scenarios from 2030-2050, PROMETHEUS, GCAM results

4.5.3 ELECTRICITY GENERATION MIX

In 2015, power and centralised heating plants accounted for 24% of total GHG emissions in the EU, with coal and gas contributing the most. By 2030, modelling results suggest that the coal consumption in the EU will nearly halve, the consumption of renewables will triple (mostly driven by the massive expansion of solar PV and wind power), while hydropower and nuclear power will have limited changes.

Even with constrains on renewable energy sources, GCAM, TIAM and PROMETHEUS considers that the market driven push for sustainability and lower carbon emissions can incentivise the continued development of RES towards near full decarbonisation by 2050. The EU policies in 2050 (NDCs and LTTs) seem to be adequate to drive large expansion of renewables, even in the Lim-RES scenario (assuming cost increases for PV, wind and batteries due to geopolitical tensions). Although the limitations on CCS would reduce the electricity generated from biomass by 2,4EJ/yr in 2050 compared to NDC-LTT (as there is no incentive to generate net negative emissions), coal is projected to remain at similar levels as in the NDC-LTT scenario. The constraints in biomass lead to a slight increase in electricity generated from renewables, with even larger increase in gas-fired electricity (according to PROMETHEUS, TIAM and GCAM) despite the strong climate ambition of NDCs and LTTs by 2050. This is because the existing gas-based power generation infrastructure is already in place and capable of accommodating increased demand. The analysis suggests that despite technological limitations and geopolitical tensions, the models can find ways to decarbonise the EU's electricity system by 2040/2050 based on a multitude of technological options deployed including solar PV, wind onshore and offshore, nuclear power, biomass, and CCS. However, when limitations in biomass and CCS are assumed, there is no possibility to generate net-negative emissions from energy supply, which are required to counterbalance some residual emissions in hard-to-abate sectors, like heavy industry, aviation, navigation and agriculture. This creates significant challenges for the EU to achieve its climate neutrality goal by 2050, as already shown in figures above.

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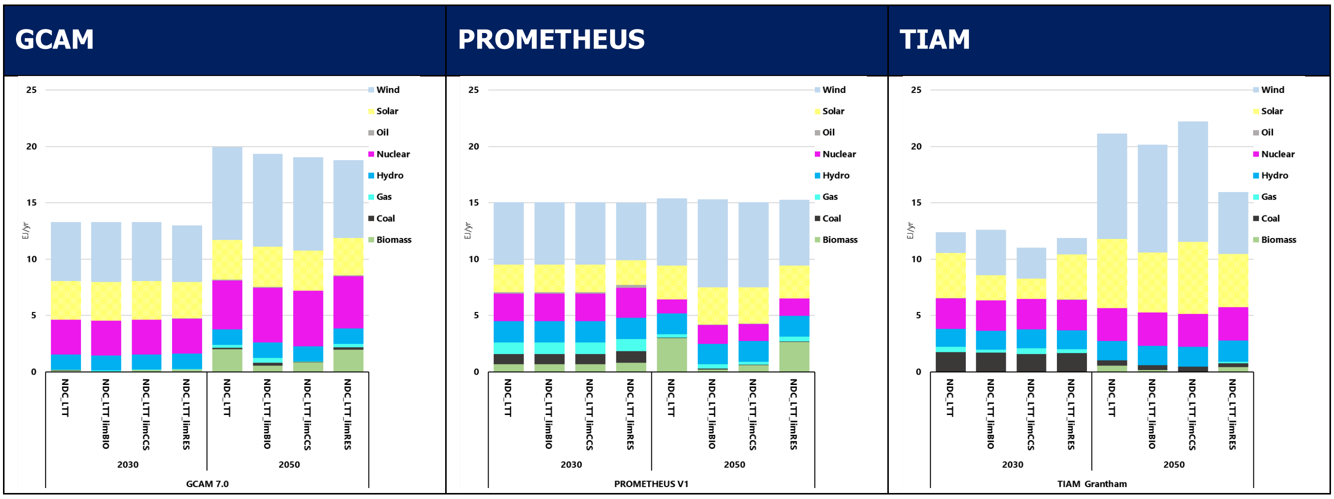

Figure 7. Electricity generation mix under different scenarios from 2020-2050, PROMETHEUS, GCAM, TIAM results

4.6 Conclusions

In the 2030 EU climate and energy targets together with national coal phase out decisions will reduce coal fired generation by around two thirds. In order to protect continued security of supply, renewable energy sources such as wind, solar, and other low-carbon resources such as biomass, biogas and hydropower plants, along with nuclear, and storage, will need to fill the gap left by these capacity reductions, while limited efficient use of the existing gas-fired capacity will help to cover peak demand.

As the EU's ambition accelerates in achieving climate neutrality by 2050, the energy system is set to change a lot from the one we see today. This is driven by ambitious climate targets; the electricity sector especially is taking great strides in reducing GHG emissions by replacing fossil fuel generators with renewable energy. However, the inherent variability of renewable generation (e.g. solar PV and wind power) brings new challenges. The electricity system needs to become much more flexible than it is today to accommodate the rising share of renewables and new flows of electricity that come with it. The variable production of wind and solar means that renewable energy deployment alone will not eliminate the dependence on fossil fuels, as backup gas generators are used to cover renewables energy shortfalls at times of low production. If the EU is to meet its climate targets in time and integrate even higher shares of renewables as stated in the REPowerEU plan, reliance on fossil fuel imports and backup gas generation must be replaced with alternative low emission solutions.

This study explored scenarios under the NDC-LTT framework introducing additional cases with technology limitations. These limitations presented on **Table 3**, include constraints on renewable energy sources, on biomass and on carbon capture and storage. The NDC-LTT framework upon which this study builds its analysis, is a comprehensive and forward-looking framework designed to guide the European Union towards meeting its climate objectives. This scenario, integrated NDCs for 2030 and Long-Term Targets for 2050, with the aim of achieving climate neutrality. By adopting the NDC-LTT scenario as a foundation, the goal of this study is to provide a baseline against which the impacts of limiting crucial technologies on CO2 emissions, primary energy consumption and the electricity generation mix within the EU can be assessed. In this direction, three well-established IAMs employed including PROMERHEUS, GCAM, TIAM, to provide insights into the potential challenges and trade-offs associated with constraints on these pivotal technologies.

Global climate and energy system models often deploy carbon capture and sequestration (CCS) technologies to reduce CO2 emissions and mitigate climate change. This is because CCS technologies make it possible to use existing infrastructure, avoiding the need to construct new energy systems. Furthermore, they can complement renewables as part of a broad portfolio of low-carbon power generation assets. Although decarbonisation means

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massive electrification, for non-electrified sources, CCS could prove vitally important. Many visions for the future of natural gas in a deeply decarbonised world hinge on CCS, and the modelling results showed that in case of limitation/failure of CCS technology, the EU cannot achieve its climate neutrality by 2050, even if all the economic sectors were shifting to clean renewable energy through rapid electrification and phaseout of fossil fuels, as net negative emissions cannot be generated through BECCS to compensate for residual fossil use in some hard-to-abate sectors (e.g. heavy industry, aviation, maritime).

Biomass continues to be the main source of renewable energy in the EU which uses 10.3EJ/yr of biomass of which 40% is for materials and 60% for energy. The prospect of the EU to achieve net-zero emissions by 2050 becomes significant challenging if biomass-based electricity generation encounters failure and cannot be effectively implemented. PROMETHEUS, TIAM and GCAM suggest that limiting total biomass use to only 5 EJ by 2050 could lead to substantial increase in CO_2 emissions ranging from about 125-429-1100 $MtCO_2$/yr (TIAM, PROMETHEUS and GCAM respectively) compared to NDC-LTT. Biomass is considered a key option in the EU's energy transition roadmap; its limitation is associated with a reduced reliance on carbon-neutral or carbon-negative energy sources. This leads to an uptick in oil and gas fired plants in 2050 (although still in much lower levels compared to 2020) which are considered back-up sources (due to their existing facilities and infrastructure) in meeting energy demands.

The limitation on renewable energy sources would lead to an upward trajectory in CO_2 emissions after 2040, resulting in higher emissions by 88-100 $MtCO_2$ in 2050 according to PROMETHEUS and GCAM results respectively. This trajectory is heavily influenced by the regulatory environment; if policies supporting the renewable expansion are limited and geopolitical tensions increase (e.g. reducing clean technology imports), this leads to a slowdown in the deployment of RES technologies. On the other hand, existing policies and commitments contribute to a very high growth of renewable energy even under limitations. The EU's long-term targets and commitments drive a continuous, albeit slower, adoption of RES beyond 2030.

[1] The carbon price profile cp(t) is up to 2025 similar to each model's current policies (cpNPI(t), from DIAG-NPI), after which it becomes a linearly increasing tax as follows, expressed in US dollars (2010) and time t in years. More information on Dekker et al

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ANNEX

Experts list

Dr. Ajay Gambhir, Director, Systemic Risk Assessment - Accelerator for Systemic Risk Assessment (UNF ASRA), UK

Dr. Benjamin K. Sovacool, Professor of Energy Policy, Science Policy Research Unit (SPRU), University of Sussex Business School, UK

Dr. David L McCollum, Senior Scientist, Oak Ridge National Laboratory, USA

Prof. Paul A. Griffin, Emeritus Distinguished Professor, University of California, Davis campus, USA

Dr. Peter Alexander DR Senior Lecturer, School of Geosciences, University of Edinburgh, UK

References

Alicia Valero, Antonio Valero, Guiomar Calvo, Abel Ortego, Material bottlenecks in the future development of green technologies, Renewable and Sustainable Energy Reviews, Volume 93, 2018, Pages 178-200, https://doi.org/10.1016/j.rser.2018.05.041.

André Månberger, Bengt Johansson, The geopolitics of metals and metalloids used for the renewable energy transition, Energy Strategy Reviews, Volume 26, 2019, 100394, https://doi.org/10.1016/j.esr.2019.100394

Auffhammer, M., Baylis, P., & Hausman, C. H. (2017). Climate change is projected to have severe impacts on the frequency and intensity of peak electricity demand across the United States. PNAS, 114(8), 1886-1891.

Blondeel, M., Price, J., Bradshaw, M., Pye, S., Dodds, P., Kuzemko, C., & Bridge, G. (2024). Global energy scenarios: A geopolitical reality check. Global Environmental Change, 84, 102781. https://doi.org/10.1016/j.gloenvcha.2023.102781

Byers, E., Krey, V., Kriegler, E., Riahi, K., Schaeffer, R., Kikstra, J., Lamboll, R., Nicholls, Z., Sandstad, M., Smith, C., van der Wijst, K., Lecocq, F., Portugal-Pereira, J., Saheb, Y., Stromann, A., Winkler, H., Auer, C., Brutschin, E., Lepault, C., Müller-Casseres, E., Gidden, M., Huppmann, D., Kolp, P., Marangoni, G., Werning, M., Calvin, K., Guivarch, C., Hasegawa, T., Peters, G., Steinberger, J., Tavoni, M., van Vuuren, D., Al - Khourdajie, A., Forster, P., Lewis, J., Meinshausen, M., Rogelj, J., Samset, B., & Skeie, R. (2022). AR6 Scenarios Database (Version 1.0) [Data set]. Zenodo. https://doi.org/10.5281/zenodo.5886912

Caldecott, J.O. Implications of Earth system tipping pathways for climate change mitigation investment. Discov Sustain 3, 37 (2022). https://doi.org/10.1007/s43621-022-00105-7

Cheong, S.-M., Sankaran, K., & Bastani, H. (2022). Artificial intelligence for climate change adaptation. WIREs Data Mining and Knowledge Discovery. https://doi.org/10.1002/widm.1459

Clarke, L., Y.-M. Wei, A. De La Vega Navarro, A. Garg, A.N. Hahmann, S. Khennas, I.M.L. Azevedo, A. Löschel, A.K. Singh, L. Steg, G. Strbac, K. Wada, 2022: Energy Systems. In IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. doi: 10.1017/9781009157926.008

Cowls, J., Tsamados, A., Taddeo, M., & Floridi, L. (2023). The AI gambit: leveraging artificial intelligence to combat climate change—opportunities, challenges, and recommendations. AI & Soc, 38, 283–307. https://doi.org/10.1007/s00146-021-01294-x

Darina Blagoeva, Alain Marmier, Patricia Alves Dias, Claudiu C Pavel, A new methodology to assess the EU resilience to materials supply along the value chain: case of lithium for lithium-ion batteries in electric vehicles, 2020, MedCrave, Available online: https://medcraveonline.com/MSEIJ/MSEIJ-04-00130.pdf

Decarb America 2023, Competing Net Zero Visions, Available online: https://decarbamerica.org/scenarios/

Dekker, M.M., Daioglou, V., Pietzcker, R. et al. Identifying energy model fingerprints in mitigation scenarios. Nat Energy (2023). https://doi.org/10.1038/s41560-023-01399-1

Elimbi Moudio, M. P., Bolin, R., Carpenter, A., Reese, S. B., Shehabi, A., & Rao, P. (2022). Characterizing manufacturing sector disruptions with targeted mitigation strategies. Environmental Research: Infrastructure and Sustainability, 2, 042001. https://doi.org/10.1088/2634-4505/ac9c8c

Emmerling, J., Drouet, L., van der Wijst, K.-I., van Vuuren, D., Bosetti, V., & Tavoni, M. (2019). The role of the discount rate for emission pathways and negative emissions. Environmental Research Letters, 14(10), 104008. https://doi.org/10.1088/1748-9326/ab3cc9

Energy Agency, Abu Dhabi.

Gambhir, A., & Lempert, R. (2023). From least cost to least risk: Producing climate change mitigation plans that are resilient to multiple risks. Frontiers in Climate, 5. https://doi.org/10.3389/fclim.2023.1149309

Gambhir, A., George, M., McJeon, H., Arnell, N. W., Bernie, D., Mittal, S., Köberle, A. C., Lowe, J., Rogelj, J., & Monteith, S. (2022). Near-term transition and longer-term physical climate risks of greenhouse gas emissions pathways. Nature Climate Change, 12, 88–96. https://doi.org/10.1038/s41558-021-01236-x

Gaupp, F., Hall, J., Mitchell, D., & Dadson, S. (2019). Increasing risks of multiple breadbasket failure under 1.5 and 2 °C global warming. Agricultural Systems, 175, 34-45. https://doi.org/10.1016/j.agsy.2019.05.010

Griffin, P. A. (2020). Energy finance must account for extreme weather risk. Nature Energy, 5, 98–100. https://doi.org/10.1038/s41560-020-0548-2

Grubb, M., C. Okereke, J. Arima, V. Bosetti, Y. Chen, J. Edmonds, S. Gupta, A. Köberle, S. Kverndokk, A. Malik, L. Sulistiawati, 2022: Introduction and Framing. In IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. doi: 10.1017/9781009157926.003

Guivarch, C., Le Gallic, T., Bauer, N., Fragkos, P., Huppmann, D., Jaxa-Rozen, M., Keppo, I., Kriegler, E., Krisztin, T., Marangoni, G., Pye, S., Riahi, K., Schaeffer, R., Tavoni, M., Trutnevyte, E., van Vuuren, D., & Wagner, F. (2022). Using large ensembles of climate change mitigation scenarios for robust insights. Nature Climate Change, 12, 428–435. https://doi.org/10.1038/s41558-022-01349-x

Gundlach, J. (2020). Climate risks are becoming legal liabilities for the energy sector. Nature Energy, 5, 94–97. https://doi.org/10.1038/s41560-019-0540-x

Hao, Z., Hao, F., Xia, Y., Feng, S., Sun, C., Zhang, X., Fu, Y., Hao, Y., Zhang, Y., & Meng, Y. (2022). Compound droughts and hot extremes: Characteristics, drivers, changes, and impacts. Earth-Science Reviews, 235, 104241.

International Journal of Greenhouse Gas Control, Volume 120, 2022, 103766, https://doi.org/10.1016/j.ijggc.2022.103766

IPCC, 2021: Arias, P.A., N. Bellouin, E. Coppola, R.G. Jones, G. Krinner, J. Marotzke, V. Naik, M.D. Palmer, G.-K. Plattner, J. Rogelj, M. Rojas, J. Sillmann, T. Storelvmo, P.W. Thorne, B. Trewin, K. Achuta Rao, B. Adhikary, R.P. Allan, K. Armour, G. Bala, R. Barimalala, S. Berger, J.G. Canadell, C. Cassou, A. Cherchi, W. Collins, W.D. Collins, S.L. Connors, S. Corti, F. Cruz, F.J. Dentener, C. Dereczynski, A. Di Luca, A. Diongue Niang, F.J. Doblas-Reyes, A. Dosio, H. Douville, F. Engelbrecht, V. Eyring, E. Fischer, P. Forster, B. Fox-Kemper, J.S. Fuglestvedt, J.C. Fyfe, N.P. Gillett, L. Goldfarb, I. Gorodetskaya, J.M. Gutierrez, R. Hamdi, E. Hawkins, H.T. Hewitt, P. Hope, A.S. Islam, C. Jones, D.S. Kaufman, R.E. Kopp, Y. Kosaka, J. Kossin, S. Krakovska, J.-Y. Lee, J. Li, T. Mauritsen, T.K. Maycock, M. Meinshausen, S.-K. Min, P.M.S. Monteiro, T. Ngo-Duc, F. Otto, I. Pinto, A. Pirani, K. Raghavan, R. Peters, G. P., Al Khourdajie, A., Sognnaes, I., & Sanderson, B. M. (2023). AR6 scenarios database: an assessment of current practices and future recommendations. npj Climate Action, 2, Article number: 31. https://doi.org/10.1038/s44168-023-00050-9

IPCC, 2022: Annex III: Scenarios and modelling methods [Guivarch, C., E. Kriegler, J. Portugal-Pereira, V. Bosetti, J. Edmonds, M. Fischedick, P. Havlík, P. Jaramillo, V. Krey, F. Lecocq, A. Lucena, M. Meinshausen, S. Mirasgedis, B. O'Neill, G.P. Peters, J. Rogelj, S. Rose, Y. Saheb, G. Strbac, A. Hammer Strømman, D.P. van Vuuren, N. Zhou (eds)]. In IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. doi: 10.1017/9781009157926.022

IRENA (2023), Geopolitics of the energy transition: Critical materials, International Renewable

IRENA (2023), World Energy Transitions Outlook 2023: 1.5°C Pathway, Volume 1, International Renewable Energy Agency, Abu Dhabi.

Irrgang, C., Boers, N., Sonnewald, M., Barnes, E. A., Kadow, C., Staneva, J., & Saynisch-Wagner, J. (2021). Towards neural Earth system modelling by integrating artificial intelligence in Earth system science. Nature Machine Intelligence, 3, 667–674. https://doi.org/10.1038/s42256-021-00374-3

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Jalles, J.T. Financial Crises and Climate Change. Comp Econ Stud (2023). https://doi.org/10.1057/s41294-023-00209-7

Juhola, S., Filatova, T., Hochrainer-Stigler, S., Mechler, R., Scheffran, J., & Schweizer, P.-J. (2022). Social tipping points and adaptation limits in the context of systemic risk: Concepts, models and governance. Frontiers in Climate. https://doi.org/10.3389/fclim.2022.1009234

Kemp, L., Xu, C., Depledge, J., et al. (2022). Climate Endgame: Exploring catastrophic climate change scenarios. PNAS, 119(34), e2108146119. https://doi.org/10.1073/pnas.2108146119

Ken Oshiro, Shinichiro Fujimori, Tomoko Hasegawa, Shinichiro Asayama, Hiroto Shiraki, Kiyoshi Takahashi, Alternative, but expensive, energy transition scenario featuring carbon capture and utilisation can preserve existing energy demand technologies, One Earth, Volume 6, Issue 7, 2023, Pages 872-883, ISSN 2590-3322, https://doi.org/10.1016/j.oneear.2023.06.005

Keywan Riahi, Elmar Kriegler, Nils Johnson, Christoph Bertram, Michel den Elzen, Jiyong Eom, Michiel Schaeffer, Jae Edmonds, Morna Isaac, Volker Krey, Thomas Longden, Gunnar Luderer, Aurélie Méjean, David L. McCollum, Silvana Mima, Hal Turton, Detlef P. van Vuuren, Kenichi Wada, Valentina Bosetti, Pantelis Capros, Patrick Criqui, Meriem Hamdi-Cherif, Mikiko Kainuma, Ottmar Edenhofer, Locked into Copenhagen pledges — Implications of short-term emission targets for the cost and feasibility of long-term climate goals, Technological Forecasting and Social Change, Volume 90, Part A, 2015, Pages 8-23, https://doi.org/10.1016/j.techfore.2013.09.016

Koasidis, K., Nikas, A., & Doukas, H. (2023). Why integrated assessment models alone are insufficient to navigate us through the polycrisis. One Earth, 6(3), 205-209.

Lamperti F, Bosetti V, Roventini A, Tavoni and M, Treibich T (2021). Three green financial policies to address climate risks. J Financ Stab 54:100875

Lenton, T. M. (2011). Early warning of climate tipping points. Nature Climate Change, 1, 201–209. https://doi.org/10.1038/nclimate1143

Lenton, T. M., Rockström, J., Gaffney, O., Rahmstorf, S., Richardson, K., Steffen, W., & Schellnhuber, H. J. (2019). Climate tipping points — too risky to bet against. Nature Comment, 575, 592-595. https://doi.org/10.1038/d41586-019-03595-0

McCollum, D. L., Gambhir, A., Rogelj, J., & Wilson, C. (2020). Energy modellers should explore extremes more systematically in scenarios. Nature Energy, 5, 104-107. https://doi.org/10.1038/s41560-020-0555-3

Milkoreit, M., Hodbod, J., Baggio, J., Benessaiah, K., Calderón-Contreras, R., Donges, J. F., Mathias, J-D., Rocha, J. C., Schoon, M., & Werners, S. E. (2018). Defining tipping points for social-ecological systems scholarship—an interdisciplinary literature review. Environmental Research Letters, 13(3), 033005. https://doi.org/10.1088/1748-9326/aaaa75.

Mittnik, S., Semmler, W., & Haider, A. (2020). Climate Disaster Risks—Empirics and a Multi-Phase Dynamic Model. Econometrics, 8(3), 33. https://doi.org/10.3390/econometrics8030033

Monasterolo, I. (2020). Climate Change and the Financial System. Annual Review of Resource Economics, 12, 299-320. https://doi.org/10.1146/annurev-resource-110119-031134

Morgan Bazilian, Michael Bradshaw, Johannes Gabriel, Andreas Goldthau, Kirsten Westphal, Four scenarios of the energy transition: Drivers, consequences, and implications for geopolitics, 2019, Wires climate change, https://doi.org/10.1002/wcc.625

Neil Grant, Ajay Gambhir, Shivika Mittal, Chris Greig, Alexandre C. Köberle, Enhancing the realism of decarbonisation scenarios with practicable regional constraints on CO2 storage capacity,

NGFS, 2019. A call for action: Climate change as a source of financial risk. Network for Greening the Financial System, First Comprehensive Report.

Nijsse, F. J. M. M., Mercure, J.-F., Ameli, N., Larosa, F., Kothari, S., Rickman, J., Vercoulen, P., & Pollitt, H. (2023). The momentum of the solar energy transition. Nature Communications, 14, Article number: 6542.

Nordgren, A. (2023), "Artificial intelligence and climate change: ethical issues", Journal of Information, Communication and Ethics in Society, Vol. 21 No. 1, pp. 1-15. https://doi.org/10.1108/JICES-11-2021-0106

Odenweller, A., Ueckerdt, F., Nemet, G. F., Jensterle, M., & Luderer, G. (2022). Probabilistic feasibility space of scaling up green hydrogen supply. Nature Energy, 7, 854–865.

O'Neill, B., M. van Aalst, Z. Zaiton Ibrahim, L. Berrang Ford, S. Bhadwal, H. Buhaug, D. Diaz, K. Frieler, M. Garschagen, A. Magnan, G. Midgley, A. Mirzabaev, A. Thomas, and R.Warren, 2022: Key Risks Across Sectors and Regions. In: Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 2411–2538, doi:10.1017/9781009325844.025.

Otto, C., Piontek, F., Kalkuhl, M., & Frieler, K. (2020). Event-based models to understand the scale of the impact of extremes. Nature Energy, 5(2), 111-114.

Oughton, E. J., A. Skelton, R. B. Horne, A. W. P. Thomson, and C. T. Gaunt (2017), Quantifying the daily economic impact of extreme space weather due to failure in electricity transmission infrastructure, Space Weather, 15, 65–83, doi:10.1002/2016SW001491.

Peng Wang et al 2022, Critical mineral constraints in global renewable scenarios under 1.5 °C target, Environ. Res. Lett. 17 125004

Perdana, S., Vielle, M. Carbon border adjustment mechanism in the transition to net-zero emissions: collective implementation and distributional impacts. Environ Econ Policy Stud 25, 299–329 (2023). https://doi.org/10.1007/s10018-023-00361-5

Perdana, S., Xexakis, G., Koasidis, K., Vielle, M., Nikas, A., Doukas, H., Gambhir, A., Anger-Kraavi, A., May, E., McWilliams, B., & Boitier, B. (2023). Expert perceptions of game-changing innovations towards net zero. Energy Strategy Reviews, 45, 101022. https://doi.org/10.1016/j.esr.2022.101022.

Peters, G.P., A. Al Khourdajie, I. Sognnæs, & B. Sanderson (2023). “AR6 scenarios database: An assessment of current practices and recommendations.” . npj Clim. Action 2, 31 (2023). https://doi.org/10.1038/s44168-023-00050-9

Phan, T., & Schwartzman, F. (2023). Climate Defaults and Financial Adaptation (Working Paper No. WP 23-06). Federal Reserve Bank of Richmond. Retrieved from http://www.richmondfed.org/publications/

Ranasinghe, A.C. Ruane, L. Ruiz, J.-B. Sallée, B.H. Samset, S. Sathyendranath, S.I. Seneviratne, A.A. Sörensson, S. Szopa, I. Takayabu, A.-M. Tréguier, B. van den Hurk, R. Vautard, K. von Schuckmann, S. Zaehle, X. Zhang, and K. Zickfeld, 2021: Technical Summary. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 33−144, doi:10.1017/9781009157896.002

Reisinger, A., & O. Geden (2023). Temporary overshoot: Origins, prospects, and a long path ahead. One Earth, 6(12), 1631-1637. https://doi.org/10.1016/j.oneear.2023.11.008

Richardson, K., Steffen, W., Lucht, W., Bendtsen, J., Cornell, S. E., Donges, J. F., Drüke, M., Fetzer, I., Bala, G., von Bloh, W., Feulner, G., Fiedler, S., Gerten, D., Gleeson, T., Hofmann, M., Huiskamp, W., Kummu, M., Mohan, C., Nogués-Bravo, D., Petri, S., Porkka, M., Rahmstorf, S., Schaphoff, S., Thonicke, K., Tobian, A., Virkki, V., Wang-Erlandsson, L., Weber, L., & Rockström, J. (2023). Earth beyond six of nine planetary boundaries. Science Advances, 9(37). https://doi.org/10.1126/sciadv.adh2458

Ringsmuth, A. K., Otto, I. M., van den Hurk, B., Lahn, G., Reyer, C. P. O., Carter, T. R., Magnuszewski, P., Monasterolo, I., Aerts, J. C. J. H., Benzie, M., Campiglio, E., Fronzek, S., Gaupp, F., Jarzabek, L., Klein, R. J.

T., Knaepen, H., Mechler, R., Mysiak, J., Sillmann, J., Stuparu, D., & West, C. (2022). Lessons from COVID-19 for managing transboundary climate risks and building resilience. Climate Risk Management, 35, 100395.

Ruane, A. C., Vautard, R., Ranasinghe, R., Sillmann, J., Coppola, E., Arnell, N., ... & Zaaboul, R. (2022). The Climatic Impact-Driver Framework for Assessment of Risk-Relevant Climate Information. Earth's Future. https://doi.org/10.1029/2022EF002803

Scheffran, J. (2023). Limits to the Anthropocene: geopolitical conflict or cooperative governance? Frontiers in Political Science, 5. https://doi.org/10.3389/fpos.2023.1190610

Seneviratne, S.I., X. Zhang, M. Adnan, W. Badi, C. Dereczynski, A. Di Luca, S. Ghosh, I. Iskandar, J. Kossin, S. Lewis, F. Otto, I. Pinto, M. Satoh, S.M. Vicente-Serrano, M. Wehner, and B. Zhou, 2021: Weather and Climate Extreme Events in a Changing Climate. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1513–1766, doi:10.1017/9781009157896.013.

Seth Monteith, Laura Aldrete, Tim Lau, Achieving global climate goals by 2050, Pathways to a 1.5oC future, Climateworks, 2023, Available online: https://www.climateworks.org/report/achieving-global-climate-goals-by-2050-pathways-to-a-1-5-c-future/

Simpson, N. P., Mach, K. J., Constable, A., Hess, J., Hogarth, R., Howden, M., Lawrence, J., Lempert, R. J., Muccione, V., Mackey, B., New, M. G., O'Neill, B., Otto, F., Pörtner, H.-O., Reisinger, A., Roberts, D., Schmidt, D. N., Seneviratne, S., Strongin, S., van Aalst, M., Totin, E., & Trisos, C. H. (2021). A framework for complex climate change risk assessment. One Earth, 4(4), 489-501. https://doi.org/10.1016/j.oneear.2021.03.005

Simpson, N. P., Williams, P. A., Mach, K. J., Berrang-Ford, L., Biesbroek, R., Haasnoot, M., Segnon, A. C., Campbell, D., Musah-Surugu, J. I., Joe, E. T., Nunbogu, A. M., Sabour, S., Meyer, A. L. S., Andrews, T. M., Singh, C., Siders, A. R., Lawrence, J., van Aalst, M., & Trisos, C. H. (2023). Adaptation to compound climate risks: A systematic global stocktake. iScience, 26(2), 105926. https://doi.org/10.1016/j.isci.2023.105926

Staffell, I., & Pfenninger, S. (2018). The increasing impact of weather on electricity supply and demand. Energy, 145, 65-78. https://doi.org/10.1016/j.energy.2017.12.051

Thaler, T., Hanger-Kopp, S., Schinko, T., & Nordbeck, R. (2023). Addressing path dependencies in decision-making processes for operationalizing compound climate-risk management. iScience, 26(7), 107073. https://doi.org/10.1016/j.isci.2023.107073

van der Wijst, K.-I., Hof, A. F., & Van Vuuren, D. P. (2021). On the optimality of 2°C targets and a decomposition of uncertainty. Nature Communications, 12, Article number: 2575. https://doi.org/10.1038/s41467-021-22826-5

van Ginkel, K. C. H., Botzen, W. J. W., Haasnoot, M., Bachner, G., Steininger, K. W., Hinkel, J., Watkiss, P., Boere, E., Jeuken, A., Sainz de Murieta, E., & Bosello, F. (2020). Climate change induced socio-economic tipping points: review and stakeholder consultation for policy relevant research. Environmental Research Letters, 15(2)

van Ruijven, B. J., De Cian, E., & Sue Wing, I. (2019). Amplification of future energy demand growth due to climate change. Nature Communications, 10, Article 2762. https://doi.org/10.1038/s41467-019-10399-3

van Vuuren, D. P., van der Wijst, K.-I., Marsman, S., van den Berg, M., Hof, A. F., & Jones, C. D. (2020). The costs of achieving climate targets and the sources of uncertainty. Nature Climate Change, 10, 329–334. https://doi.org/10.1038/s41558-020-0732-1

van Westen, R. M., Kliphuis, M., & Dijkstra, H. A. (2024). Physics-based early warning signal shows that AMOC is on tipping course. Science Advances, 10(6), eadk1189.

Westra, S., & Zscheischler, J. (2023). Accounting for systemic complexity in the assessment of climate risk. One Earth, 6(6), 645-655. https://doi.org/10.1016/j.oneear.2023.05.005

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Yalew, S. G., van Vliet, M. T. H., Gernaat, D. E. H. J., Ludwig, F., Miara, A., Park, C., ... & van Vuuren, D. P. (2020). Impacts of climate change on energy systems in global and regional scenarios. Nature Energy, 5, 794-802. https://doi.org/10.1038/s41560-020-0664-z

Zeyen, E., Victoria, M., & Brown, T. (2023). Endogenous learning for green hydrogen in a sector-coupled energy model for Europe. Nature Communications, 12, 532–538 (2022). https://doi.org/10.1038/s41558-022-01356-y

Zscheischler, J., Westra, S., van den Hurk, B. J. J. M., Seneviratne, S. I., Ward, P. J., Pitman, A., AghaKouchak, A., Bresch, D. N., Leonard, M., Wahl, T., & Zhang, X. (2018). Future climate risk from compound events. Nature Climate Change, 8(5), 469–477. https://doi.org/10.1038/s41558-018-0156-3