IAM COMPACT

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

# D5.5 – Modelling out-of-ordinary extremes – Update

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

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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 disruptive events on emission reduction pathways. It also serves as a resource for entities outside the consortium, illustrating how assessments and analyses related to the study of extreme events in the context of integrated assessment models (IAMs) and resilience pathways could be framed and addressed. The introduced framework and its application are intended to inform the design of more robust and resilient mitigation scenarios.

## 3. Short summary of results (<250 words)

This report updates the work on modelling extreme events by introducing a detailed framework called Disruptive Events-Resilient Pathways (DERP) framework, a systematic approach for incorporating disruptions into long-term mitigation scenarios. The previous deliverable of this task (D5.4) conducted a literature review and expert interviews to define extremes and identify system vulnerabilities, culminating in a preliminary multi-model analysis of technology constraints. It also included a preliminary version of the DERP framework. This update builds on that foundation by proposing an updated version of the DERP framework, which maps scenarios along two dimensions: mitigation action effectiveness and resilience to socioeconomic impacts.

We demonstrate the framework by applying it to a stylised disruption of intensifying heatwaves and droughts across a diverse set of IAMs. The results show that low-resilience pathways require significantly more infrastructure capacity to maintain function under stress, while high-resilience pathways enable a more effective energy transition. The analysis also reveals that narrowly optimised strategies can create concentrated vulnerabilities, whereas diversified approaches enhance systemic robustness. The framework thus provides a crucial diagnostic tool for stress-testing mitigation strategies against unexpected events.

## 4. Evidence of accomplishment

This report.

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# 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.

| | |
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# Executive Summary

This task aims to complement the scenario analyses of WP4 and WP5 by addressing a wide range of uncertainties, such as extreme environmental, technological, policy, and societal changes. The previous deliverable of this task (D5.4) established the groundwork for this analysis. It conducted a comprehensive literature review to define and categorise different types of extreme events and surveyed expert opinion through a series of interviews to identify key system vulnerabilities and challenges in adapting IAMs to capture such disruptions. That work culminated in a preliminary qualitative scenario framework and quantitative analysis of the impacts of technology constraints (on RES, biomass, and CCS) on EU decarbonisation pathways.

This deliverable (D5.5) builds directly on those findings by introducing and advancing a novel conceptual tool: the Disruptive Events-Resilient Pathways (DERP) framework. This framework provides a structured, systematic methodology for incorporating disruptive events into mitigation scenario design. It moves beyond ad-hoc analyses by mapping scenarios along two distinct dimensions: the effectiveness of mitigation action and the resilience of a society to the socioeconomic impacts of a disruption. This creates a narrative space with five distinct pathways, enabling a more nuanced exploration of how systems respond to stress.

As a proof of concept, we apply the DERP framework to a stylised disruption of intensifying heatwaves and droughts, implemented across a diverse suite of IAMs (GCAM, PROMETHEUS, and TIAM-Grantham as part of the IAM COMPACT model ensemble, as well as FRIDA as part of a synergy with the WorldTrans project). This application yields several critical insights. First, we find that socioeconomic resilience is a precondition for an effective and efficient energy transition; low-resilience systems require substantially higher capital investment to maintain function under stress. Second, our results demonstrate that resilience directly enables deeper decarbonisation, as key strategies like electrification are more viable in societies with greater adaptive capacity. Finally, the analysis highlights that narrowly optimised strategies can create concentrated, high-risk dependencies, whereas a diversified portfolio of solutions enhances systemic robustness.

Ultimately, the DERP framework provides a diagnostic tool to stress-test mitigation strategies, moving beyond standard assumptions of smooth transitions to explore the hidden costs of vulnerability and the strategic imperative of building resilience.

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# 1 Introduction

Achieving the ambitious global temperature goals of the Paris Agreement requires significant and immediate reductions in greenhouse gas emissions across all sectors. Such a societal transformation faces multiple challenges, including the possibility of disruptive events that can fundamentally influence transition pathways. By 'disruptive events', we refer to incidents that break apart, destabilise, or fundamentally alter expected development trajectories of natural or human systems, distinguished not merely through their magnitude but primarily through their departure from anticipated patterns. Such events—whether natural or human-made, abrupt or gradual, beneficial or detrimental, reversible or irreversible—may also involve feedback processes or cascading interactions that amplify their initial and isolated impacts, thereby further compounding their unpredictability in timing, scale, duration, or impact, hence posing significant challenges to anticipate and address them (Kopp et al., 2024; Taleb, 2008; Diamond, 2005).

Climate-related disruptive events—such as record-high temperatures, extreme precipitation, floods, and droughts—are projected to increase in frequency and severity irrespective of the stringency of future climate action (Seneviratne et al., 2021), potentially intensifying dramatically if climate tipping points are crossed (Kopp et al., 2024; Lenton et al., 2019). Such events can greatly impact energy systems, for instance, in the form of thermal power plants facing shutdown risks during heatwaves, transmission capacity reduction during extreme weather, and increasing weather-dependence of renewable energy deployment (Clarke et al., 2022; Auffhammer et al., 2017). Moreover, climate change often acts as a risk multiplier, intensifying resource scarcity, infrastructure vulnerabilities, and political instability (Scheffran, 2023). This creates potential feedback loops between different types of disruptions, generating derailment risks, while compounding future climate risks, such as when droughts force coal capacity revival to replace curtailed hydropower.

Critically, potential disruptive events extend beyond climate-related extremes and may include dramatic socioeconomic changes, geopolitical volatility, unanticipated technological breakthroughs, and radical policy shifts (O'Neill et al., 2022). These could directly impact climate action, for instance, by disrupting mitigation funding (Jalles et al., 2023) while increasing borrowing costs (Phan et al., 2023), or indirectly by pushing socioeconomic systems into fundamentally different states, thereby altering the potential for climate action.

Integrated assessment models (IAMs), which are typically used to generate long-term mitigation scenarios by integrating complex energy-climate-economy systems, are well-positioned to explore the cross-sectoral implications of system-wide interactions. However, like their previous iterations going back decades, current-generation IAMs have not typically been applied to explore disruptive events and their impacts. Whilst the underlying solutions frameworks can capture non-linear dynamics and abrupt transitions when appropriately parameterised, standard scenario exercises predominantly produce smooth transition pathways driven by underlying assumptions of gradual change (Gambhir et al., 2023; Gambhir and Lempert, 2023; Grubb et al., 2022). Additionally, the perfect foresight optimisation logic commonly adopted in many IAMs further constrains their ability to realistically represent disruptive events, as such models would anticipate and implement countermeasures in advance of any projected disruption. IAMs' coarse spatiotemporal resolution (typically operating at a 5-year time step at regional to national levels) also constrains their capacity to capture extreme events occurring at finer scales (McCollum et al., 2020). Moreover, commonly used socioeconomic frameworks for IAMs, such as the Shared Socioeconomic Pathways (SSPs) (O'Neill et al., 2017), lack discontinuities in both their narratives (i.e., exclude disruptive events by design) (O'Neill et al., 2013; van Vuuren et al., 2025) and associated quantified datasets, further constraining IAMs' ability to represent disruptive dynamics (Koasidis et al., 2023).

Although IAMs can technically represent disruptions and some studies have explored specific shocks (Jäger et al., 2024; see also Keppo et al., 2021, for a review), the field lacks a systematic framework for designing and comparing disruptive scenarios across different resilience and mitigation contexts. Here, we introduce the

Disruptive Events-Resilient Pathways (DERP) framework for systematically conceptualising and incorporating disruptions into mitigation scenario design. The DERP framework employs a narrative-based, structured methodology to identify quantitative parameter adjustments that capture disruption dynamics under differing system characteristics, compatible with existing IAM structures. The framework maps scenarios along two dimensions: mitigation action effectiveness and resilience to socioeconomic impacts. Mapping pathways along these two dimensions allows for explicit analysis of how defined resilience characteristics interact with mitigation efforts. Like the SSP framework, the two-dimensional space can be split into four distinct narratives, plus one reflecting current trends. Collectively, they serve as a systematic basis for translating qualitative disruptive characteristics into quantitative modelling inputs, a capability essential for integrating such complex dynamics into formal modelling frameworks.

# 2 The Disruptive Events-Resilient Pathways (DERPs) Framework

## 2.1 Framework

To define the DERP framework's narrative space, we draw inspiration from the SSP approach (O'Neill et al., 2017). We establish two core dimensions designed to capture and incorporate disruptive events into mitigation pathway analysis. 'Mitigation action effectiveness' represents the strength and scope of deliberate emission reduction efforts, while 'resilience to socioeconomic impacts' represents the capacity of societies to recover from, and potentially thrive after, unexpected socioeconomic consequences of disruptions. 'Resilience to socioeconomic impacts' also serves as an inverse indicator of vulnerability, whereby higher resilience implies lower vulnerability, and vice versa. Moreover, resilience is highly context-specific; for instance, a system resilient to technological disruptions may still be vulnerable to extreme climate events. Together, these dimensions span a possibility space within which different societies can be positioned according to how they confront different disruptions whilst pursuing climate goals. The DERP framework is operable at any chosen spatial scale, from national to global, allowing scientists to match the narrative scope to the question at hand.

Unlike the SSP framework, which uses quantified socioeconomic factors like GDP and population as input assumptions, the DERP framework operationalises the disruptive events, mitigation action effectiveness and resilience through targeted parameters' adjustments. These adjustments involve modifying key modelling parameters to reflect both the chosen DERP narrative and the specific disruption being analysed.

The framework accommodates diverse disruption types, irrespective of perceptions about their desirability or initial impact. These include both events widely considered negative (such as conflicts or extreme weather events) and those seen as positive, for example sudden technological breakthroughs. Crucially, what distinguishes a 'disrupted trajectory' from normal transitions is not the element of surprise itself but a fundamental deviation from the pathways and patterns assumed in standard or conventional mitigation scenarios. Whether climatic, geopolitical, or technological, such deviations create socioeconomic consequences that existing mitigation plans have not prepared for. In the text box below, we define five narratives representing distinct approaches to capturing disruptions along the two identified dimensions (see Figure 1).

**DERP1 - Eroded Resilience**: Limited mitigation action effectiveness with low resilience to socioeconomic impacts

In this narrative, society is characterised by two distinct, detrimental trends. Mitigation action effectiveness deteriorates as societies retreat from proactive mitigation efforts in favour of short-term economic priorities and continued fossil-fuel development. Simultaneously, socioeconomic resilience erodes through diminishing institutional ability to respond to disruptions, entering a state of 'derailment risk' (Laybourn et al., 2023), whereby a safe operating space is increasingly undermined by interacting biophysical and resulting socioecological pressures. These dual weaknesses compound each other: weak climate action increases exposure to future climate hazards, whilst low resilience means any disruption – climate, geopolitical, or economic – can trigger cascading failures. As such, systems face increasingly impactful and frequent disruptions, and feedback loops emerge that rapidly destabilise societies and further constrain their capacity to recover.

**DERP2 - Current Trends**: Moderately effective mitigation action with moderate resilience to socioeconomic impacts

At the centre of the DERP framework space lies DERP2, representing a continuation of current trajectories. In this narrative, societies implement moderate mitigation efforts, which exist independently from, but parallel to, moderate resilience capacity. This capacity is primarily built on responses to familiar disruptions from experience (e.g., the COVID-19 pandemic), enabling societies to manage their socioeconomic impacts but leaving them vulnerable to novel or severe disruptions outside historical precedence. The two dimensions remain distinct but interact: moderate mitigation action reduces some climate disruption risks and thus avoids associated socioeconomic impacts, while moderate resilience provides some capacity to deal with socioeconomic challenges arising from familiar disruptions.

**DERP3 - Myopic Transition**: Strong but narrowly focused mitigation action, with low resilience to socioeconomic impacts

This narrative involves ambitious but narrowly-focused mitigation efforts concentrated on specific sectors or approaches. Societies implement climate policies strongly supporting favoured solutions that are generally considered consistent with ambitious climate goals. The high-ambition drive, however, is confined to a limited technology or sector portfolio. Broader system considerations, such as supply-chain shocks, geopolitical volatility, feasibility or public-acceptance limits, receive little attention, so resilience capacity remains low. Institutional ability to face disruptions is therefore limited. The interaction of the two dimensions finds narrow mitigation pathways lacking diversity and redundancy; separately, low resilience leaves systems with limited capacity and unable to adapt when favoured solutions encounter unexpected disruptions, rendering the pathways vulnerable to unforeseen challenges.

**DERP4 - Incremental Resilience**: Limited mitigation action effectiveness with high resilience to socioeconomic impacts

This narrative features minimal proactive climate change mitigation, with societies prioritising maintenance of existing systems over systemic transition. Separately, these societies develop strong reactive resilience capabilities focused on rapid crisis response and strategic resource allocation. These distinct approaches interact pragmatically: low mitigation action preserves resources for immediate response, whilst high resilience enables management of near-term disruptions. This creates a paradoxical situation where short-term stability is enhanced at the expense of long-term sustainability, as climate impacts intensify and response costs escalate, eroding future resilience capacity.

**DERP5 - Systemic Resilience**: Strong mitigation action effectiveness with high resilience to socioeconomic impacts

This narrative features comprehensive mitigation achieved through a diversified portfolio of low-carbon technologies and an economy-wide shift toward energy-efficient and low-emission production and consumption. Simultaneously, societies develop robust resilience capabilities through flexible infrastructure and redundant capacities. These distinct strengths interact synergistically: ambitious mitigation action reduces future disruption risks, whilst high resilience enables societies to manage both transition challenges and inevitable climate impacts through enhanced adaptive capacity and redundant systems.

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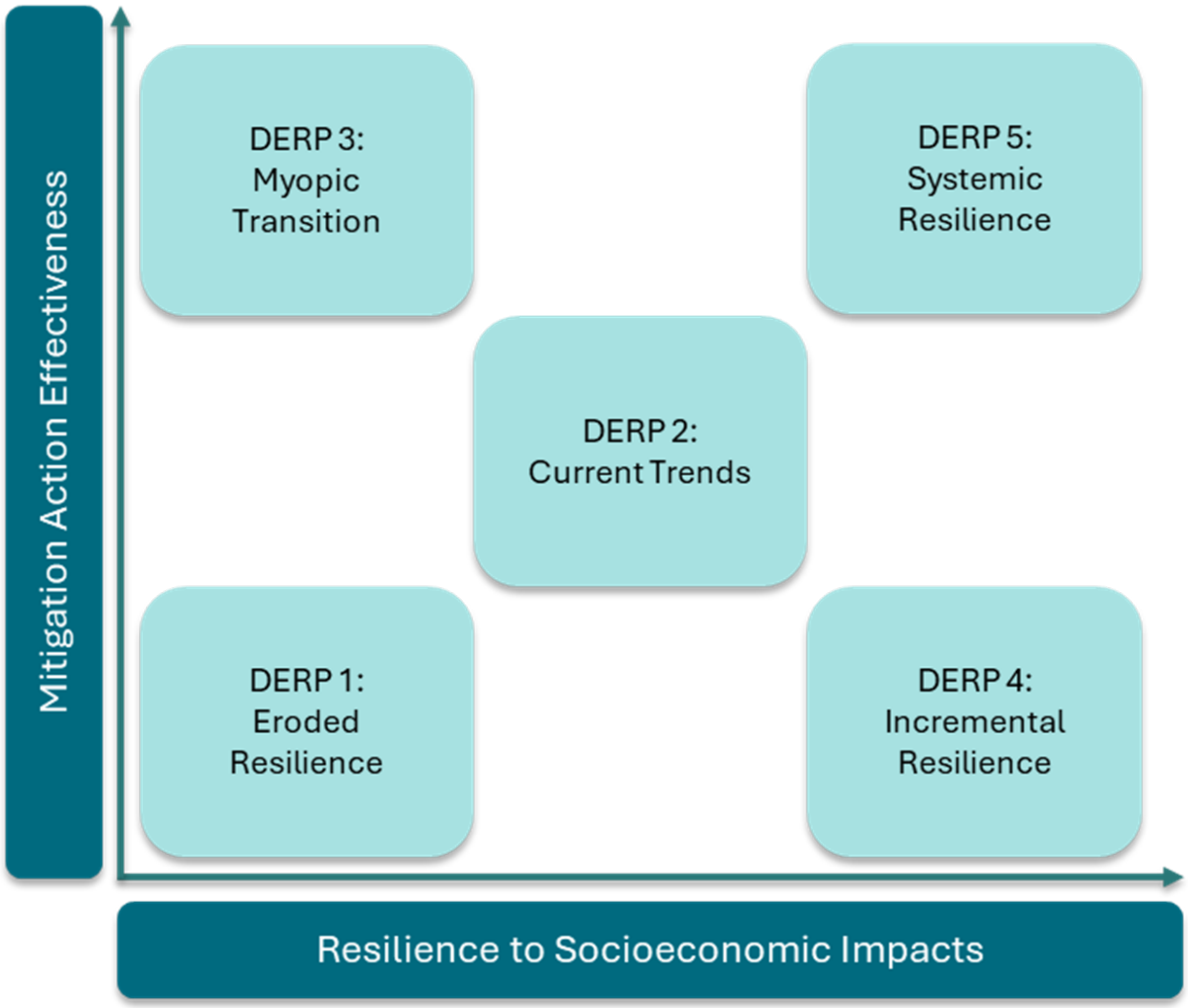


**Figure 1:** The DERP framework

## 2.2 Bridging the qualitative narratives to model implementation

Table 1 below presents an illustrative mapping of parameters that capture both dimensions (axes depicted in Figure 1) of the framework, and how these parameters should change with respect to the baseline. The mapping serves as a conceptual guide rather than a prescriptive template; actual implementations should select and adjust parameters based on the specific disruption being studied whilst maintaining consistency with the DERP dimensions and narratives logic. The parameter list is indicative rather than exhaustive, serving as a starting point for modellers implementing the framework. As we show in our application, disruption-specific implementations may require different parameter categories beyond those shown here to capture the unique characteristics of each disruption. In some cases, parameter adjustments may serve as indirect proxies to capture effects that cannot be directly represented in a model. These parameters should be implemented as interconnected sets rather than in isolation, as their interactions are essential to representing the coherent narratives of each DERP scenario.

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**Table 1**: DERPs indicative (non-exhaustive) narrative-to-parameter mapping.

Parameters are organised by the framework's two dimensions: mitigation action effectiveness and resilience to socioeconomic impacts. The notation (++, +, 0, -, --) indicates deviation magnitude from baseline trends. This illustrative mapping is non-prescriptive; actual parameter values should be tailored to specific disruptive events, models, and regional contexts.
* DERP4 prioritises immediate system robustness over efficiency gains; hence, energy intensity may rise even as resilience measures improve.
** Some parameters (investment risk, discount rate) influence both dimensions; placement here reflects the dominant narrative rationale

| Parameter category | Indicative parameters | DERP1 - Eroded Resilience | DERP2 - Current Trends | DERP3 - Myopic Transition | DERP4 - Incremental Resilience* | DERP5 - Systemic Resilience | Rationale |
|---|---|---|---|---|---|---|---|
| **DIMENSION 1: Mitigation action effectiveness** | | | | | | | |
| **Climate policy** | Carbon pricing | - - | 0 | + | - | + + | Reflects variation in climate ambition and scope of climate policy instruments |
| | Emissions constraints | - - | 0 | + | - | + + | Captures the strength and breadth of climate targets |
| | Energy efficiency standards | - - | 0 | + + (favoured techs) WITH + for others | 0 | + + | Represents regulatory approaches to climate action |
| **Technology** | Low-carbon technology learning rates | - - | 0 | + + (favoured techs) WITH - - OR 0 (for others) | - | ++ (diverse portfolio) | Captures differential investment patterns and innovation focus |

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| | Technology deployment rates (e.g., renewables share) | - - | 0 | + + (favoured tech) WITH<br><br>- - OR 0 (for others) | - | ++ (diverse portfolio) | Indicates speed of technology adoption |
| | | | | | | | |
| **DIMENSION 2: Resilience to socioeconomic impacts** | | | | | | | |
| **System vulnerability** | Capacity factors | - - | 0 | - | + | ++ | Captures infrastructure vulnerability to climate impacts |
| | Energy supply diversity | - - | 0 | - - | + | + + | Represents system redundancy and flexibility |
| | Infrastructure redundancy | - - | 0 | - - | + + | + + | Shows preparedness for disruptions. Use reserve-margin proxy in IAMs (e.g., firm-capacity requirement, transmission lines). |
| **Economic factors** | Investment costs (risk premiums)** | + + | 0 | + | + (due to resilience cost) | - | Reflects perceived investment risk in different futures |
| | Discount rates** | + + | 0 | + | 0 | - - | Captures time preference and intergenerational equity |
| | Labour productivity | - - | 0 | 0 | + | + | Indicates socioeconomic adaptive capacity |
| **Resource management** | Resource constraints (e.g. critical materials) | + + | 0 | + + (favoured tech) | + | - | Represents supply chain vulnerability |

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| | | | | | | | |
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| | Circularity (stock and flow of materials) | - - | 0 | 0 | + | + + | Indicates efficiency and reduced dependence on new resources |
| **International dynamics** | Trade barriers | + + | 0 | + | - | - - | Reflects international cooperation/geopolitical volatility |
| **Climate Impacts** | Heating/cooling degree days | + + or - - | 0 | + OR - | + OR - | + OR - | Represents differing system sensitivities to temperature due to variations in infrastructure (e.g., building efficiency, Urban Heat Island (UHI) effects) and adaptation levels inherent in each narrative, proxied via adjustments to baseline HDD/CDD inputs. |

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# 3 Application of the DERP Framework

As a proof of concept, we apply the DERP framework to stylised disruptions. In this deliverable, we present the results from a scenario of intensifying heatwaves and droughts. Such a stylised scenario could be particularly insightful for exploring DERP narratives 1, 2, and 4, investigating pathways of eroded resilience, current trends, and incremental resilience in the face of a game-changing mitigation technology. It is important to align the chosen disruptive event with the most relevant DERP narratives (subset of DERP1-5) to provide plausible and coherent storylines. Not all narratives are necessarily applicable or insightful for every disruption type. For stylised examples of DERP narratives 2, 3 and 5 (current trends, myopic resilience and systemic resilience), we provide pointers to potential examples in the Discussion section.

The analysis is implemented in four conceptually distinct integrated assessment models: GCAM (recursive-dynamic partial equilibrium), TIAM-Grantham (perfect-foresight partial equilibrium), PROMETHEUS (recursive-dynamic energy system), and FRIDAv2.1 (system dynamics with endogenous climate-human feedback). Rather than seeking a definitive inter-model comparison, these illustrative cases are designed to: a) showcase how the framework can be operationalised in practice and b) demonstrate the conceptual utility of the DERP framework elements (i.e. dimensions and narratives) across diverse modelling philosophies (see Methods).

## 3.1 Intensifying heatwaves and droughts

We first examine how energy systems respond to intensifying heatwaves and droughts, whereby climate impacts simultaneously constrain energy supply through reduced power plant capacity factors and increasing energy demand via higher cooling loads (Clarke et al., 2022; Auffhammer et al., 2017; van Vliet et al., 2016). We model these compound stresses using consistent climate-driven disruption parameters whilst varying resilience characteristics across three DERP narratives: Current Trends (DERP2), Eroded Resilience (DERP1), and Incremental Resilience (DERP4).

All scenarios face the same fundamental disruption: reduced capacity factors for hydropower and thermal power (fossil-fuelled, biomass and nuclear) plants, and higher investment costs reflecting disruption risks. However, they differ in their ability to respond. Current Trends (DERP2) maintains baseline climate policies with moderate resilience. Eroded Resilience (DERP1) combines these disruptions with a limit on supply capacity additions, such that societies cannot expand capacity of the affected energy supply technologies. Furthermore, on the demand side, there is a diminished adaptive capacity where cooling demand surges but air conditioning access remains limited. Incremental Resilience (DERP4) faces identical climate stresses but with no restrictions on capacity additions, enabling societies to manage impacts through infrastructure investment. On the demand side, there is an enhanced adaptation, where universal air conditioning access (i.e. personal air conditioning) moderates the cooling demand increases, which remain lower than the demand increases under DERP1 (see Methods for implementation details).

The results from this stylised heatwaves and droughts scenario, illustrated in Figure 2 below, shed light on the conceptual utility of the DERP framework's elements (its dimensions and narratives) and how the underlying models' structure influences the resulting trajectories.

First, the results challenge a simplistic interpretation of resilience: A less resilient pathway may prove far more resource-intensive than a more resilient one, a crucial consideration for long-term investment strategies. The top-left panel shows that under the Eroded Resilience narrative (D1_ER), the recursive- and system-dynamic models (GCAM, PROMETHEUS, and FRIDA) project the highest overall electricity capacity compared to the other two scenarios, with a more significant difference under FRIDA. This suggests that a low-resilience society might over-

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invest in gross physical capacity to compensate for poor operational effectiveness, asset degradation, and an inability to manage demand flexibly. The perfect-foresight model (TIAM-Grantham), by contrast, optimises its way around this inefficiency. This reveals an important insight: resilience is not merely about surviving a disruption but about the system's fundamental capital efficiency under stress.

Second, the analysis establishes that socioeconomic resilience is a precondition for, not just a parallel goal to, effective mitigation action. The top-right panel shows a clear and consistent finding across different model structures: the share of electricity in final energy is systematically higher under Incremental Resilience (D4_IR) than under D1_ER. Both scenarios share the same low level of mitigation action effectiveness yet occupy opposite ends of the resilience spectrum. The consistently higher share of electrification under D4_IR therefore reveals the impact of the resilience dimension in isolation, demonstrating that it directly enables a higher level of energy transition, independent of the explicit climate policy ambition. This implies that key mitigation strategies, electrification in this case, become more viable in societies with the adaptive capacity to manage the associated system stresses. This holds true irrespective of the underlying model structure (GCAM, TIAM-Grantham and PROMETHEUS).

Third, the technology-level results in the polar charts show how different strategic approaches can lead to more vulnerabilities versus diversified robustness. TIAM-Grantham's response, particularly its large expansion of hydropower under the D4_IR narrative, shows a cost-optimisation logic that doubles down on a single solution to compensate for reduced performance, effectively risking future compound or multi-year droughts, should such a finding results in actual policy adoption. While seemingly economically efficient, this creates a highly concentrated vulnerability. In contrast, the other models show a more diversified shift towards unaffected technologies, such as biomass, wind and solar, and away from thermal fossil-based and nuclear technologies. This heterogeneity reveals the framework's utility in stress-testing transition strategies. It highlights how pathways that appear optimal under standard assumptions can hide high-risk dependencies, arguing for diversified portfolios that enhance systemic robustness, even if they appear sub-optimal from a perfect foresight perspective. The heightened role of oil-fired capacity in TIAM further suggests a reliance on dispatchable fossil-fuelled backup, creating another potential vulnerability.

Taken together, these insights demonstrate the conceptual value of the DERP framework's elements (i.e. dimensions and narratives). By structuring the analysis around the distinct dimensions of mitigation effectiveness and socioeconomic resilience, we move beyond simply quantifying disruption impacts. We uncover the fundamental dynamics of system vulnerability, the enabling role of resilience in the energy transition, and the hidden risks within seemingly (mode-driven) optimal mitigation strategies.

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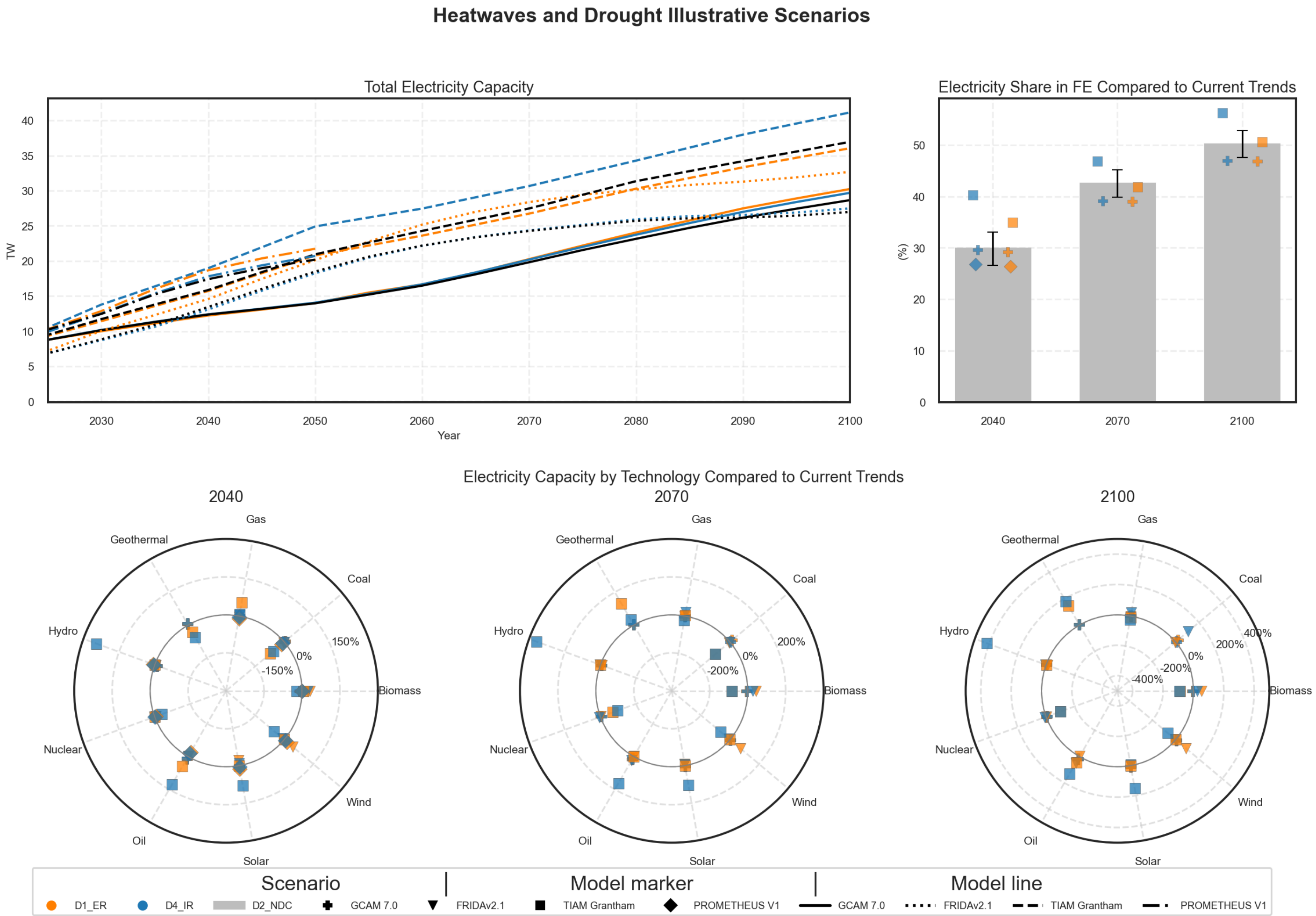


**Figure 2:** Energy system responses to intensifying heatwaves and droughts across DERP narratives and modelling approaches.

Top left: Total Electricity Capacity (TW) trajectories from 2025-2100 for GCAM (solid lines), FRIDAv2.1 (dotted lines), PROMETHEUS (dashed-dotted line), whose time horizon is up to 2050, and TIAM-Grantham (dashed lines). Top right: Electricity share of final energy (%), with grey bars showing average Current Trends scenario values across models (whiskers indicate models' range) and coloured markers showing individual model-scenario results. Note that FRIDAv2.1 does not produce a breakdown of final energy, hence it is not featured in the top-right panel. Note that PROMETHEUS' time horizon is up to 2050, hence it only appears in the 2040 bar. Bottom row: Percentage changes in electricity capacity by technology relative to Current Trends scenarios (2040, 2070, and 2100) displayed as polar charts where the 0% circle represents Current Trends. Across all panels: black/grey represents Current Trends (D2_NDC), orange represents Eroded Resilience - DERP1 (D1_ER), and blue represents Incremental Resilience - DERP4 (D4_IR). Model markers: squares (TIAM-Grantham), triangles (FRIDAv2.1), plus sign (GCAM), and diamond (PROMETHEUS). Note that PROMETHEUS' time horizon is up to 2050, hence it only appears in the 2040 polar chart.

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# 4 Methods

## 4.1 How to implement the DERP framework

In general, a scenario protocol using the DERP framework involves four steps:

1. Identification of the disruptive events (DEs): including their specified nature, scale, and spatiotemporal scope.
2. Link to DERP narratives: it is important to align the chosen disruptive event with the most relevant DERP narratives (a subset of DERP1-5) to provide plausible and coherent storylines.
3. Define DE parameters: these depend on the nature of the DE and the chosen DERP narratives. They are also limited by available evidence and model capabilities.
4. Define resilience characteristics (RCs) parameters: these determine the underlying resilience characteristics that differentiate societal responses following the relevant DERP narratives. These characteristics reflect the inherent capacities defined by the framework's Resilience to Socioeconomic Impacts dimension.

DE parameters representing the disruptions are generally applied consistently across the chosen DERP narratives being compared for a specific disruption, while RCs parameters vary by DERP narrative to reflect different underlying societal capacities.

## 4.2 Scenario Protocol for Intensifying Heatwaves and Droughts (H&D)

This scenario explores how intensifying heatwaves and droughts affect energy systems through simultaneous supply constraints and demand pressures. We apply the DERP framework to three narratives: DERP2 (Current Trends), DERP1 (Eroded Resilience), and DERP4 (Incremental Resilience). It is important to align the chosen disruptive event with the most relevant DERP narratives (subset of DERP1-5) to provide plausible and coherent storylines. Not all narratives are necessarily applicable or insightful for every disruption type

Climate change increasingly stresses energy systems through heatwaves and droughts that reduce thermal and hydroelectric capacity factors whilst increasing cooling demand (Clarke et al., 2022; Auffhammer et al., 2017; van Vliet et al., 2016). These compound stresses can trigger infrastructure failures, blackouts and brownouts, making it crucial to understand how different resilience characteristics shape system responses. In this stylised implementation, drought impacts are captured through their effects on hydropower availability and thermal plant cooling constraints, as reflected in the capacity factor reductions. Whilst broader drought impacts (e.g., on bioenergy feedstocks or water resources beyond the power sector) are not explicitly modelled, this focused approach serves our illustrative purpose.

Disruptive Event (DE) parameters: We model three primary impact channels, applied consistently across narratives:

- Capacity factor reductions: Hydropower and thermoelectric plants (fossil, biomass, nuclear) face reduced capacity factors based on RCP8.5 climate projections from van Vliet et al. (2016), applied progressively from the 2020s (2020-2040) with higher impacts in the 2050s (2040-2070) for both DERP1 and DERP4 variants. Vliet et al., (2016) estimates are regionally differentiated and mapped onto model regions as closely as possible (Supplementary Material **Table SM.1**).
- Investment risk: cost of capital increases by 20% for climate-vulnerable technologies (thermoelectric and hydropower) and 10% for other power sector technologies, reflecting heightened financial risks.

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- Cooling demand: Adjusted based on projections from Byers et al. (2024), with regional mapping in Supplementary Material **Table SM.2**. For DERP1, we use 95th percentile projections assuming SSP2 air conditioning access trends and a 23°C set point, representing high vulnerability. For DERP4, we use 50th percentile projections assuming universal AC access by 2050 and a 23°C set point, reflecting the incremental efforts.

All scenarios incorporate consistent baseline weighted average cost of capital (WACC) assumptions based on Calcaterra et al. (2024).

Whilst cooling demand conceptually represents a disruptive impact, its implementation varies between DERP1 (95th percentile, limited air conditioning access) and DERP4 (50th percentile, universal access) to reflect how resilience characteristics mediate climate pressures into actual energy demand.

Resilience Characteristic (RC) parameters capture how system responses may vary by narrative:

- DERP2 (Current Trends): Maintains baseline parameters reflecting post-2030 continuation of emissions intensity improvements of announced NDCs. This scenario is harmonised across all models.
- DERP1 (Eroded Resilience): Imposes upper bounds on capacity additions for affected technologies (hydropower, thermoelectric), implemented as constraints on additions relative to Current Trends projections (TIAM-Grantham, PROMETHEUS) or total capacity (GCAM). In FRIDA, any initial investment allocation above the baseline for affected technologies is re-allocated to unaffected energy sources.
- DERP4 (Incremental Resilience): No additional capacity constraints, reflecting reactive adaptation within existing systems

A key aspect of this experimental design is how the DERP narratives are used to frame the comparison. The DERP2 (Current Trends) scenario serves as the undisrupted baseline, representing a world with "moderate" mitigation effectiveness. The DERP1 and DERP4 scenarios are then constructed by applying the heatwave and drought disruption to this baseline under different resilience contexts. The disruption itself inherently degrades the system's ability to decarbonise, making it harder to achieve mitigation goals compared to the undisrupted world, hence having "lower" mitigation effectiveness. The resilience parameters then determine the severity of this degradation, allowing us to use the undisrupted DERP2 scenario as a benchmark to analyse the distinct impacts of a low-resilience versus a higher resilience response.

## 4.3 Integrated Assessment Models

The study uses four IAMs (GCAM, PROMETHEUS, TIAM, and FRIDA) 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 I²AM PARIS platform[1].

### 4.3.1 TIAM-Grantham

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

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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 ($N_2O$).

### 4.3.2 GCAM

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).

### 4.3.3 PROMETHEUS

PROMETHEUS is a fully fledged global, partial equilibrium energy system model that simulates the evolution of the world energy system to 2050 with annual time resolution (Fragkos et al., 2015). The model integrates both top-down and bottom-up features. PROMETHEUS combines econometrically estimated demand equations (based on income and price elasticities) with detailed representations of energy supply technologies across sectors and fuels (E3 Modelling 2018). PROMETHEUS models energy demand by sector and subsector, including industry, transport, buildings, and captures the interaction between demand and supply to endogenously project energy prices at regional and global scales. It features a modular structure, covering macroeconomic, final energy demand, electricity generation, fossil fuel markets, technology learning, and climate policy. Currently, the model includes 26 competing technologies for power generation. Energy prices are formed endogenously based on supply-demand balances and fossil resource constraints, while the model also simulates learning by doing and research driven technological progress. PROMETHEUS provides a consistent framework to assess climate and energy policy impacts (Fragkos et al., 2018; Fragkos et al., 2024), fossil fuel markets, CO2 emissions (van der Zwaan et al., 2025), and energy technology evolution across ten world regions.

### 4.3.4 FRIDA

The Feedback Repository for IntegrateD Assessments (FRIDA) is a newly developed global-scale IAM (Schoenberg et al., 2025), produced in the context of the WorldTrans project. FRIDA integrates climate and human systems through feedback processes. It represents the carbon, energy, and water cycles alongside human demographics change, economics, agriculture, and energy use. Built using the System Dynamics method (Forrester, 1961;

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Sterman, 2000), it represents the feedback between the major components of the world-Earth system (Donges et al., 2021), while retaining a very fast runtime to allow for uncertainty exploration. FRIDA aims to represent each part of the world-Earth system with an equivalent level of complexity, to better study problems that cross traditional system/field boundaries. It does this at the expense of detail at the process-level, and without spatial disaggregation. FRIDA natively incorporates climate impacts endogenously, with its climate module based on the widely used FaIR simple climate model (Smith et al 2018; Leach et al. 2020).

The FRIDA model is validated both from a behavioural and structural perspective. Behaviourally, the model is calibrated to reproduce 1980-2023 behaviour across 159 different time series of variables spanning the full conceptual scope of the model. Structurally, the model is validated following the process laid out by Barlas (1996), which includes ensuring dimensional consistency, ensuring proper extreme conditions behaviour, and ensuring that the processes that give rise to that behaviour match with subject matter expert, and the literature's conceptualisations for how those same real-world processes function. FRIDAv2.1 [https://doi.org/10.5281/zenodo.15310860] is used in this study. As part of its representation of connections between system components, FRIDA simulates a wide range of climate impacts, based where possible on available literature (Wells et al. 2025), including several of the impact channels incorporated into the DERPs protocol. These crossover impacts were switched off in the NDC run in FRIDA.

## 4.4 Concluding Remarks

This study introduces the Disruptive Events-Resilient Pathways (DERP) framework, designed to systematically incorporate the impacts of disruptive events into the analysis of climate change mitigation scenarios. By focusing on the interplay between mitigation action and socioeconomic resilience, the framework moves to a frontier in mitigation scenario studies: the simultaneous consideration of long-term transition goals and the resilience to navigate disruptions. We demonstrated its application using IAMs of diverse architecture and methodologies to explore a stylised disruption of intensifying heatwaves and droughts. Here we reflect on the framework's overarching insights, its relationship to existing approaches, and avenues for future development and research.

The application of the DERP framework yields a set of complementary insights. The heatwave and drought scenarios reveal that resilience is a precondition for an efficient and effective energy transition. A low-resilience system is not just more vulnerable to failure; it is fundamentally fragile and capital-intensive, requiring greater gross investment to deliver the same energy services under stress. It should be noted that this analysis compares resilience versus no resilience rather than resilience versus enhanced mitigation efforts, and the climate-related nature of the disruption may particularly strengthen the synergies between resilience and mitigation strategies.

The framework's utility extends to a range of other stylised disruptions. For instance, a technological breakthrough scenario, such as the rapid, cost-driven acceleration of Direct Air Carbon Capture and Storage (DACCS), could be used to explore different strategic approaches to innovation. A DERP3 (Myopic Transition) narrative could model a narrow, ambitious bet on a single DACCS variant (e.g., one dependent on natural gas), revealing significant vulnerability to energy price shocks. In contrast, a DERP5 (Systemic Resilience) narrative would explore a diversified portfolio of both gas- and electricity-powered DACCS technologies, enhancing robustness against specific risks. Similarly, a non-technological disruption, such as a geopolitical event that fragments supply chains for critical minerals, could be modelled to test the resilience of pathways reliant on imported clean technologies versus those with stronger domestic circular economies.

A key methodological choice in this study was to model disruptions as sustained pressures rather than sudden, one-off events. This framing was a pragmatic choice to align with the typical temporal resolution (e.g., 5-year time steps) of the IAMs used, which are not designed to capture acute, short-term shocks. This approach allows for the exploration of how systems adapt to new, chronic stresses, revealing inherent vulnerabilities and resilience characteristics. We acknowledge this means our current implementation does not model the element of "surprise" that is often associated with disruptive events. Instead, it provides insights into the long-term resilience of pathways when faced with fundamental shifts in background conditions, which is a critical yet distinct challenge.

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Our use of multiple IAM archetypes highlights that the interpretation of resilience is intertwined with model structure. The exercise shows that while the DERP protocol can be mapped consistently across models, the resulting pathways display characteristic differences. For example, perfect-foresight optimisation models like TIAM-Grantham show how agents might pre-emptively alter investments to hedge against future disruption, often making large, concentrated bets. In contrast, myopic, recursive-dynamic models like GCAM and PROMETHEUS tend to show more incremental adjustments based on near-term conditions. These contrasts do not signal a weakness but rather a strength of the framework: they highlight the importance of explicitly stating the modelling lens through which disruption is viewed and encourage complementary explorations with a diversity of tools.

This proof-of-concept study has several limitations that point towards a rich agenda for future research. First, while our narratives are built on the dimension of "resilience to socioeconomic impacts", our implementation, in line with common IAM practice, remains primarily technoeconomic. Future work should aim to explicitly integrate broader socioeconomic and political factors, such as inequality, institutional strength, and human behavioural responses (e.g., see Andrijevic et al., 2020; Petrova et al., 2023; Beckage et al., 2022; Beckage et al., 2018). Second, our approach is deterministic. Future applications could usefully incorporate stochastic modelling or extensive sensitivity analyses to better capture the uncertainty associated with disruptive events, moving beyond stylised scenarios to assess the robustness of strategies against a wider range of potential shocks. Third, the framework could be extended to adaptation planning, offering a structured approach to evaluating resilient strategies across both mitigation and adaptation domains. This would necessitate a more systematic typology of disruptive events, which itself constitutes an important area for future research.

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