Navigating the unexpected: The impact of disruptive events on mitigation scenarios

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Abstract

Climate mitigation scenarios from Integrated Assessment Models (IAMs) typically assume smooth, predictable transitions, leaving them ill-equipped to assess the impacts of disruptive events. Here we introduce the Disruptive Events-Resilient Pathways (DERP) framework, a methodology that maps mitigation pathways along two dimensions: Mitigation Action Ambition and Resilience to Socioeconomic Impacts. The framework employs narrative-based societal archetypes to systematically explore how different resilience capacities shape mitigation strategies under disruption. Our application to stylised heatwave and technological disruptions reveals that socioeconomic resilience is a precondition for a capital-efficient transition, that a myopic

focus on single technologies creates hidden vulnerabilities by delaying structural change, and that a diversified, resilient strategy can hedge against these risks at little to no additional cost. The DERP framework is therefore a valuable diagnostic tool, advancing scenario analysis to a new frontier by considering long-term transition dynamics alongside the resilience required to navigate disruptions.

Main

Achieving the ambitious global temperature goal 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 anticipating and addressing them (Kopp et al., 2024; Taleb, 2008; Diamond, 2005).

Climate-related disruptive events like extreme precipitation, floods and droughts are projected to increase in frequency and severity, irrespective of the stringency of future climate action, and potentially intensifying dramatically if climate tipping points are crossed (Seneviratne et al., 2021; Kopp et al., 2024; Lenton et al., 2019). Such events often act as risk multipliers, creating feedback loops that can derail mitigation (Millward-Hopkins, 2022); for instance, when prolonged drought forces a revival of coal power to replace curtailed hydropower due to infrastructure vulnerability (Scheffran, 2023). Critically, the spectrum of disruptions extends beyond climate extremes to include geopolitical volatility, financial crises, and unanticipated technological breakthroughs. These can fundamentally alter mitigation pathways by disrupting funding, increasing borrowing costs, or shifting underlying socioeconomic conditions (O'Neill et al., 2022; Jalles et al., 2024; Phan et al., 2023).

While Integrated Assessment Models (IAMs) are the principal tools for generating long-term mitigation scenarios, they have not typically been applied to explore disruptive events and their impacts. Although the underlying models can technically capture non-linear dynamics and abrupt transitions when appropriately parameterised, this gap in standard practice stems from several factors: scenario exercises typically assume smooth, gradual change (Gambhir et al., 2023; Gambhir and Lempert, 2023; Grubb et al., 2022); the models' coarse spatiotemporal resolution constrains their ability to capture acute events at finer scales (McCollum et al., 2020); and foundational frameworks like the Shared Socioeconomic Pathways (SSPs) lack discontinuities in both their narratives and associated quantified datasets (O'Neill et al., 2017; O'Neill et al., 2013; Koasidis et al., 2023).

Although IAMs can technically represent disruptions, and some studies have explored specific shocks (e.g., Jäger et al., 2024), 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. The framework maps scenarios along two dimensions: mitigation action ambition (represents the strength and scope of deliberate emission reduction efforts) and resilience to socioeconomic impacts (represents the capacity of societies to recover from, and potentially thrive after, unexpected socioeconomic consequences of disruptions). Mapping pathways along these two dimensions allows for explicit analyses of how 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. This practical narrative-to-parameter mapping enables the representation of system responses to disruptions in three critical aspects: identifying which specific impacts manifest, determining how these impacts propagate through interconnected systems, and quantifying their magnitude.

In order to demonstrate practical implementation, we apply the DERP framework to two stylised disruptions: (i) intensifying heatwaves and droughts and (ii) a rapid, cost-driven acceleration of Direct Air Carbon Capture and Storage (DACCS). The analysis is implemented in four conceptually distinct IAMs: 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 feedbacks). Rather than seeking a definitive inter-model comparison, these illustrative cases are designed to showcase how the framework can be operationalised in practice as well as demonstrate the conceptual utility of the DERP framework elements (i.e., dimensions and narratives) across diverse modelling structure and philosophies (see **Methods**).

The application of the DERP framework across our stylised scenarios hints at three important takeaways. First, socioeconomic resilience is a dominant factor in determining outcomes, protecting systems from the costly inefficiencies of a fragile transition and enabling deep decarbonisation. Second, cost-driven technological uptakes that are narrowly focused on specific solutions, despite lowering perceived costs, can create concentrated vulnerabilities and slow structural change by rerouting decarbonisation efforts. Third, and most critically, a diversified and resilient strategy can often hedge against these risks at negligible additional system cost, making it the superior strategic choice. Identifying these findings confirms the utility of the DERP framework for exploring the hidden vulnerabilities within and strategic robustness of climate mitigation pathways.

Results

The Disruptive Events-Resilient Pathways (DERP) Framework

The DERP framework's narrative space is defined by its two dimensions: mitigation action ambition and resilience to socioeconomic impacts. Within this space, resilience is a context-specific concept; for instance, a system resilient to technological disruptions may still be vulnerable to extreme climate events. It also serves as an inverse indicator of vulnerability, where higher resilience implies lower vulnerability. Together, the dimensions span a possibility space within which different societal archetypes can be positioned to explore how they confront disruptions while pursuing climate goals. We introduce and define these five narratives in **Text Box 1**. These distinct approaches to capturing disruptions are also depicted in **Figure 1** and summarised **Table 1**.

Start of Text Box 1

The five DERP narratives described below represent distinct societal archetypes, each characterised by its inherent mitigation action ambition and resilience to socioeconomic impacts from disruption. For the analysis of any given disruptive event, these narratives provide a structured basis for translating the event's characteristics into specific and consistent model parameter adjustments. 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.

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 typically seen as positive (for example, sudden technological breakthroughs). Whether climatic, geopolitical, or technological, such disruptions create socioeconomic consequences for which conventional mitigation pathways may be ill-prepared.

DERP1 – Derailment: Limited mitigation action ambition with low resilience to socioeconomic impacts

In this narrative, society is characterised by two distinct, detrimental trends. Mitigation action ambition is scaled back 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 ambitious 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 more severe disruptions outside historical precedence. The two dimensions remain distinct but interact: moderate mitigation action reduces some future climate hazards and thus avoids associated socioeconomic impacts, while moderate resilience provides some capacity to deal with socioeconomic challenges arising from familiar disruptions.

DERP3 – Fragile Transition: Strong but narrowly focused mitigation action, with low resilience to socioeconomic impacts

This narrative involves ambitious but narrowly focused mitigation actions 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 technological and/or sectoral portfolio. Broader system considerations, such as supply-chain shocks, geopolitical volatility, feasibility limits, or public-acceptance limits, receive little attention. Institutional ability to face disruptions is limited. The interaction of the two dimensions finds narrow mitigation pathways lacking diversity and redundancy; separately, low resilience leaves systems with limited capacity to adapt when favoured solutions encounter unexpected disruptions, rendering the pathways vulnerable to unforeseen challenges.

DERP4 – Resilient Inertia: Limited mitigation action ambition with high resilience to socioeconomic impacts

This narrative features minimal proactive climate change mitigation, with societies prioritising maintenance of existing systems alongside developing 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, potentially eroding future resilience capacity.

DERP5 – Robust Transformation: High mitigation action ambition 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.

End of Text Box 1

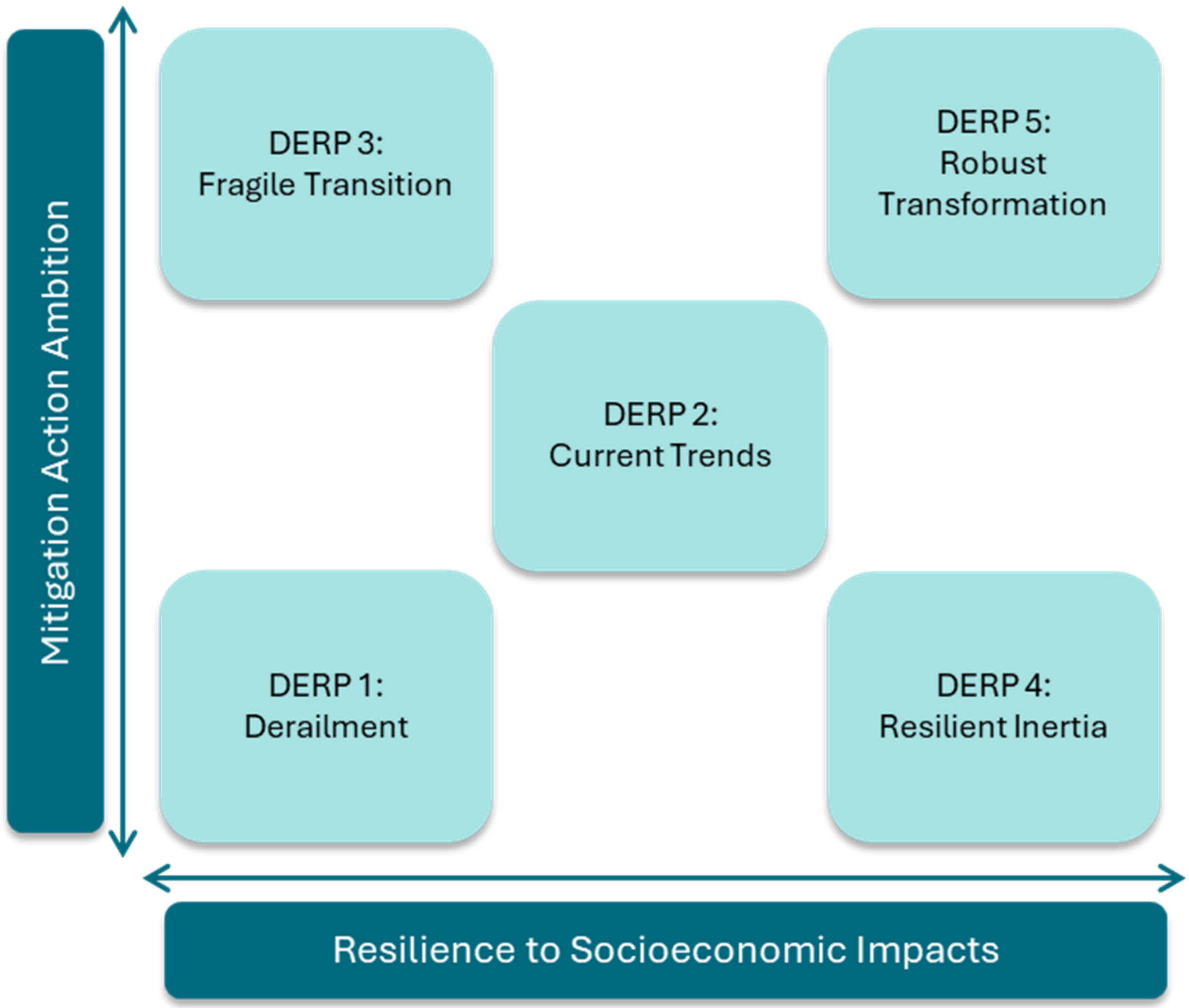

Figure 1: The DERP framework

For a summary of characteristics and driving forces behind each narrative, see **Table 1** below.

Whilst certain analogies can be drawn between individual DERP narratives and the SSPs, the two frameworks address fundamentally different questions. **Table A.1** (**Appendix**) offers a heuristic guide to which SSP backgrounds might provide a plausible socioeconomic context for each DERP narrative.

Summary characteristics and driving forces

Table 1 summarises the five DERP narratives by listing, side-by-side, the characteristics and key drivers that shape each narrative. The rows are grouped under the framework's two explicit dimensions, mitigation action ambition (Dimension 1) and resilience to socioeconomic impacts (Dimension 2), followed by a set of system characteristics. The latter summarises the dynamics that may emerge from the interplay of the two dimensions. It positions each narrative within a wider context of development storyline, before indicating the temporal dimension of how resilience and vulnerability might evolve, and finally flagging the persistent risks that may linger.

Table 1: Summary of the framework - Characteristics and driving forces

Characteristics	DERP1 - Derailment	DERP2 - Current Trends	DERP3 - Fragile Transition	DERP4 - Resilient Inertia	DERP5 - Robust Transformation
DIMENSION 1: Mitigation Action Ambition	*Low*	*Moderate*	*High (narrow focus)*	*Low*	*High*
Mitigation action approach	Retreat from proactive efforts and sustained reorientation to unsustainable fossil-based development	Informed by recent developments and current climate policies	Concentrated on specific sectors or technologies, prioritising short-term fixes	Strategic scaling back of mitigation with focus on crisis response	Ambitious, system-wide decarbonisation across all sectors
Technology prioritisation	Conventional technologies, limited innovation	Balanced but limited deployment across technologies	Concentrated investment in specific low-carbon technologies and/or particular sectors	Proven conventional technologies with backup features	Comprehensive deployment across all low-carbon technologies and sectors

DIMENSION 2: Resilience to Socioeconomic Impacts	*Low*	*Moderate*	*Low*	*High (incremental improvements)*	*High*
Response mechanisms and resource allocation	Diminishing institutional capacity with reactive crisis response and eroding capabilities	Reactive measures for familiar disruptions with moderate flexibility based on historical practices	Limited contingency planning concentrated on narrow technology portfolio as 'easy fixes'	Robust response capabilities with rapid conventional resource mobilisation for immediate needs	Adaptive redeployment capacity with comprehensive, deliberate redundancies and flexibility
System Characteristics					
Wider context	Growing ‘Derailment risk’, and unsustainable development	Continuation of current trends	Over-reliance on specific sectors or technologies	Emphasis on maintaining the status quo and resisting structural change	Minimisation of risks through systemic change
Temporal dimension of resilience and vulnerability	Continuously eroding capacity as risks compound overtime	Moderate resilience to familiar disruptions, but vulnerable to severe or unprecedented events	Short-term improvements masking long-term risks, increasing systemic vulnerabilities	Near-term stability maintained through reactive measures, with uncertain long-term sustainability	Progressive improvement in resilience across multiple timescales
Persistent risks	Risk of tipping points, cascading failures,	Vulnerability to severe or unprecedented	Sector-specific bottlenecks creating	Mounting response costs as climate	Residual risks from extreme events beyond planning

	and system collapse	disruptions	systemic risks	impacts intensify	scenarios

Bridging the qualitative narratives to model implementation

The quantitative application of the DERP framework differs fundamentally from that of the SSPs. Unlike the SSP framework, which for modelling exercises provides harmonised, pre-quantified socioeconomic trajectories (e.g., for GDP and population) as common input assumptions, the DERP framework operationalises targeted parameter adjustments relevant to the chosen DERP narrative and a specific disruption. The goal is therefore not to force models onto a single harmonised pathway, but to explore the distinct trajectories that emerge from different modelling logics when guided by the same narrative principle.

Table 2 below presents an illustrative mapping of parameters that capture both dimensions of the framework, and how these parameters should change with respect to the Current Trends narrative. 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 narrative logic. The parameter list is indicative rather than exhaustive, serving as a starting point for modellers implementing the framework. As shown in **Tables 3 and 4** (**Methods**), where we demonstrate the application of this approach to our two stylised scenarios, 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.

Table 2: DERP indicative (non-exhaustive) narrative-to-parameter mapping

Notation relative to Current Trends: ++ (much higher/stronger), + (higher/stronger), 0 (unchanged), - (lower/weaker), - - (much lower/weaker)

Parameter category	Indicative parameters	DERP1 - Derailment	DERP2 - Current Trends	DERP3 - Fragile Transition	DERP4 - Resilient Inertia	DERP5 - Robust Transformatio n	Rationale
DIMENSION 1: Mitigation action ambition							
Climate policy	Carbon pricing	- -	0	+ + (targetted sectors)	-	+ +	Reflects variation in strength and scope of climate policy instruments
	Emissions constraints	- -	0	+ + (targetted sectors)	-	+ +	Captures the strength and breadth of climate targets
	Energy efficiency standards	- -	0	+ + (targetted sectors)	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
	Technology deployment rates (e.g.,	- -	0	+ + (favoured tech) WITH - - OR 0 (for	-	++ (diverse portfolio)	Indicates speed of technology adoption

	renewables share)			others)			
	Energy efficiency	- -	0	+	-	+ +	Efficiency improvements reflect mitigation action ambition
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).
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	-	+	+	Indicates socioeconomic adaptive capacity
Resource management	Resource constraints (e.g. critical materials)	+ +	0	+ + (favoured tech)	+	-	Represents supply chain vulnerability
	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.

* Some parameters (investment risk, discount rate) influence both dimensions; placement here reflects the dominant narrative rationale.

Stylised scenarios: applying the DERP framework

In order to demonstrate practical implementation, we apply the DERP framework to two stylised disruptions. In this paper we implement the framework at the global scale. Whilst this is an abstraction from real-world regional heterogeneity, it serves our purpose of demonstrating the practical implementation of the DERP framework and the conceptual value of its elements (i.e., dimensions and narratives) across diverse modelling frameworks and philosophies. Furthermore, our implementation treats disruptions as sustained pressures over extended periods rather than discrete timed events. This approach is methodologically well-suited to the long-term horizons and coarse temporal granularity of the IAMs used. It allows us to test how a system's inherent characteristics, as defined by a given DERP narrative, determine its long-term response to disruption. Nonetheless, this implementation choice does not constrain the framework itself, which can readily be used to analyse future, timed, or transient shocks, particularly with models of finer temporal resolution. Finally, we align the chosen disruptive event with the most relevant DERP narratives (subset of DERP1-5) to provide plausible and coherent storylines.

Intensifying heatwaves and droughts

We first examine how energy systems respond to intensifying heatwaves and droughts. In this stylised scenario, DERP2 (Current Trends) serves as the undisrupted base scenario. We then apply a consistent climate disruption to two different societal archetypes: DERP1 (Derailment) and DERP4 (Resilient Inertia). The disruption, based on impacts from a high-warming trajectory, involves a compound stress: (i) simultaneous supply constraints, modelled as reduced capacity factors for hydropower and thermal (fossil fuel, biomass, nuclear) power plants (van Vliet et al., 2016), and (ii) increased electricity demand for cooling (Byers et al., 2024). Both disrupted scenarios also face higher investment costs reflecting heightened systemic risk. The two narratives differ in their resilience. The low-resilience DERP1 world faces limits on new capacity for affected technologies, and has diminished adaptive capacity leading to surging cooling demand. In contrast, the high-resilience DERP4 world can invest in new infrastructure without limits and exhibits enhanced demand-side adaptation, which moderates the increase in cooling demand (see **Methods** for details).

The application of the DERP framework to this scenario yields three key insights, illustrated in **Figure 2**, regarding the interplay of resilience, investment strategy, and technology choice. First, the results challenge a simplistic interpretation of resilience, revealing that a low-resilience pathway can be far more resource-intensive than a resilient one. Under DERP1, the recursive- and system-dynamic models (GCAM, PROMETHEUS, and FRIDA) project a higher total electricity capacity than in the other scenarios (Figure 2a), with a more significant difference, compared to Current Trends, under FRIDA. This suggests a low-resilience society might over-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 around this inefficiency. This reveals a crucial insight: resilience is not merely about surviving a disruption but is fundamental to a system's capital efficiency under stress.

Second, the analysis establishes that socioeconomic resilience is a precondition for, not merely a parallel goal to, effective mitigation action. Across all model structures, the share of electricity in final energy is almost always higher under DERP4 than DERP1 (Figure 2b). As both scenarios share the same low mitigation ambition, this contrast isolates the impact of the resilience dimension. It demonstrates that resilience directly enables higher levels of electrification, independent of the explicit climate action ambition, as resilience here allows for higher deployment rates. This implies that key mitigation strategies become more viable in societies with the adaptive capacity to manage the associated system stresses.

Third, the technology-level results reveal a tension between narrow cost-optimisation and diversified robustness (Figure 2c). TIAM-Grantham's perfect-foresight response, particularly its large expansion of hydropower under DERP4, shows a "winner-takes-all" logic that doubles down on a single solution to compensate for its reduced performance. This highlights a critical risk for policymaking: a purely cost-optimal strategy, when viewed without a resilience lens, can perversely recommend investing heavily in the very technologies most vulnerable to the disruption (e.g., future compound or multi-year droughts). The heightened role of oil-fired capacity in TIAM-Grantham further suggests reliance on dispatchable fossil-fuelled backup, creating another potential vulnerability. While seemingly economically efficient, this approach creates concentrated vulnerability. In contrast, the other models prioritise a diversified shift towards unaffected technologies like wind and solar. This heterogeneity reveals the framework's utility in stress-testing transition strategies, arguing for diversified portfolios that enhance systemic robustness—even if such a strategy appears suboptimal from a purely deterministic, least-cost perspective.

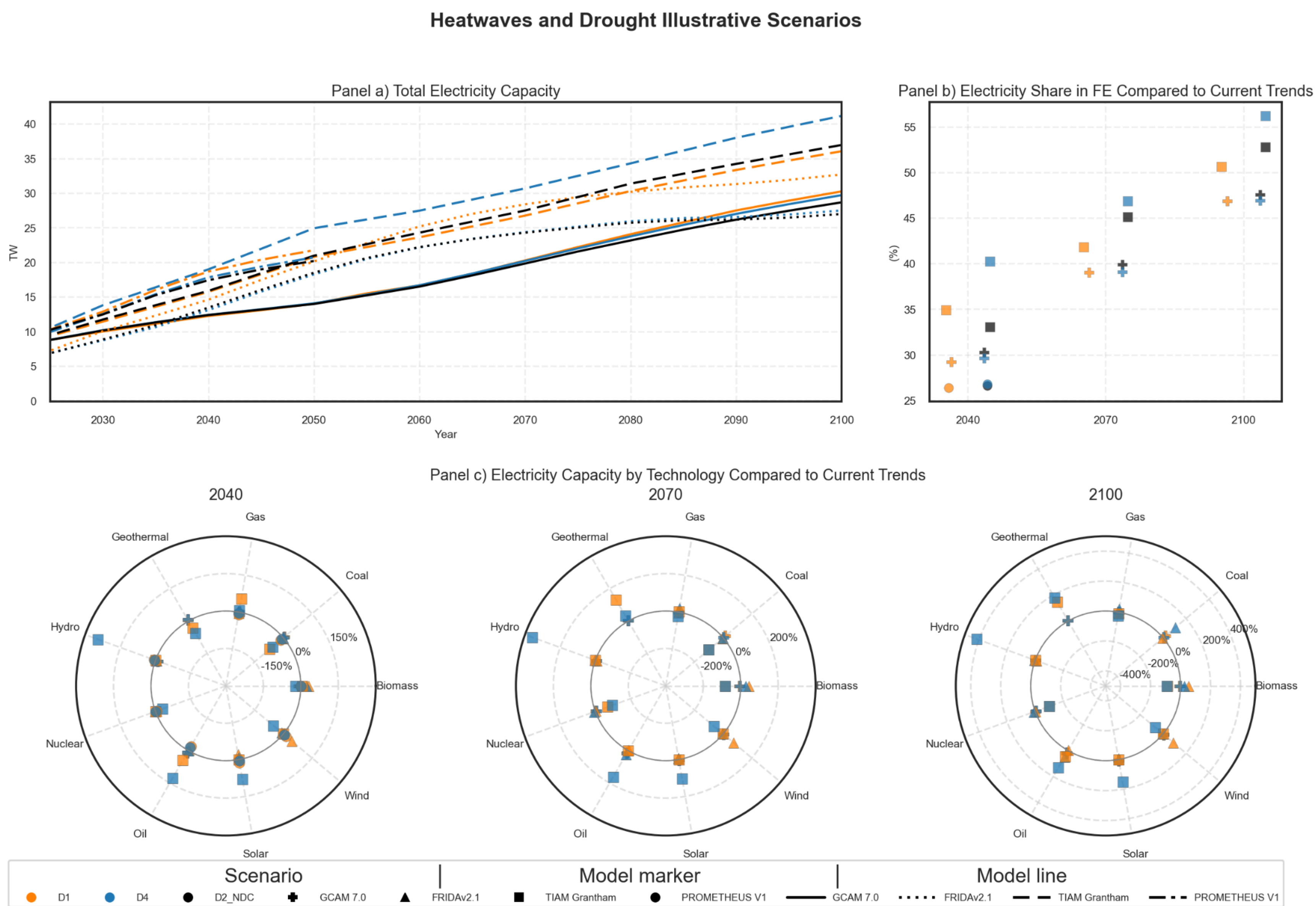
Heatwaves and Drought Illustrative Scenarios
Panel a) Total Electricity Capacity
TW
Year
0
5
10
15
20
25
30
35
40
2030
2040
2050
2060
2070
2080
2090
2100
Panel b) Electricity Share in FE Compared to Current Trends
(%)
25
30
35
40
45
50
55
2040
2070
2100
Panel c) Electricity Capacity by Technology Compared to Current Trends
2040
2070
2100
Gas
Coal
Biomass
Wind
Solar
Oil
Nuclear
Hydro
Geothermal
150%
0%
-150%
200%
0%
-200%
400%
200%
0%
-200%
-400%
Scenario
D1
D4
D2_NDC
Model marker
GCAM 7.0
FRIDAv2.1
TIAM Grantham
PROMETHEUS V1
Model line
GCAM 7.0
FRIDAv2.1
TIAM Grantham
PROMETHEUS V1

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

Panel a (top left) shows 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). Panel b (top right) shows Electricity Share of Final Energy (%). Note that FRIDAv2.1 does not produce a breakdown of final energy, hence it is not featured in this panel. Note also that PROMETHEUS' time horizon is up to 2050, hence it only appears in the 2040 bar. Panel c (bottom row) Percentage changes in Electricity Capacity by Technology Compared to Current Trends (2040, 2070, and 2100) displayed as polar charts where the 0% solid circles in the middle represent Current Trends. Across all panels: black represents Current Trends (D2_NDC), orange represents DERP1 (D1), and blue DERP4 (D4). Model markers: squares (TIAM-Grantham), triangles (FRIDAv2.1), plus sign (GCAM), and circle (PROMETHEUS).

Rapid uptake of DACCS technology

For our second stylised case, we analyse a disruption driven by a technological breakthrough: the rapid, cost-driven acceleration of Direct Air Carbon Capture and Storage (DACCS). While DACCS features prominently in ambitious mitigation scenarios, it faces significant uncertainties regarding its cost, scalability, and system integration, leading to a heated debate over its role (Young et al., 2023; Anderson et al., 2023). We explore an atypical trajectory where technological advances and/or strong policy intervention drive rapid cost reductions, albeit narrowly creating new system dependencies and vulnerabilities. Our analysis contrasts two high-uptake narratives, DERP3 (Fragile Transition) and DERP5 (Robust Transformation), against a DERP2 (Current Trends) base scenario that meets long-term climate targets but assumes only limited DACCS deployment. To operationalise this, we first implement a rapid and sustained reduction in DACCS technology costs in the DERP3 and DERP5 scenarios, making it a highly competitive mitigation option. To test the resulting vulnerabilities, we then introduce a temporary energy price shock from 2040–2050, involving a 50% increase in natural gas and electricity prices above Current Trends levels, leading to a sustained pressure on response capacity. The narratives are differentiated by their resilience to this shock. DERP3 represents an ambitious but narrowly focused pursuit of DACCS, which we explore in two variants to test technological lock-in: one relying solely on energy-intensive, natural gas-powered DACCS (NG) and another on more efficient, electricity-powered DACCS using heat pump (HP). In contrast, DERP5 depicts a systemically resilient approach, reflected in its diversified adoption of both DACCS technologies to manage these risks (see **Methods** for details).

The application of the DERP framework to the DACCS scenario yields three key insights, illustrated in Figure 3, regarding the risks of technological lock-in and the value of strategic diversification.

First, the results demonstrate how a technological breakthrough can create new, model-dependent strategic dilemmas. A rapid cost reduction triggers large-scale DACCS deployment in both GCAM and TIAM-Grantham, though more so in GCAM (Figure 3a). However, the models interpret the DERP3 variants differently. GCAM's recursive-dynamic logic favours the natural gas-dependent DACCS variant, likely due to its lower initial capital costs. Crucially, GCAM aligns the trajectory of DERP3 NG variant closely with DERP5's diversified scenario. In contrast, while TIAM-Grantham perfect-foresight logic also favours DERP3 NG variant over HP one, it also favours it over DERP5's diversified scenario, likely optimising for lower operational costs. This reveals that a "diversified" strategy is not a simple prescription; its perceived optimality depends on the decision-making logic (myopic vs. perfect foresight) of the system in question.

Second, the results reveal how a myopic focus on a single technological solution, a hallmark of the DERP3 narrative, can create systemic risks. The system-wide investment in DACCS is enabled by slowing the structural decarbonisation of the wider energy system, evidenced by the reduced share of electrification and increased reliance on fossil fuels relative to the baseline (Figures 3b & 3c). For policymakers, this highlights that an overemphasis on technological carbon removal, without complementary policies driving end-use sector change (e.g., industrial efficiency standards, transport electrification mandates), can inadvertently delay the primary transition away from fossil energy and lock societies into vulnerable infrastructure.

Third, and perhaps most importantly, the analysis suggests that diversifying to achieve systemic resilience can come at little to no additional system cost. The cost differences between the DERP3 variants and the diversified DERP5 scenario are minimal when compared to DERP2 (Figure 3d). This is despite how the high-DACCS pathways compare to the base scenario across the two models. While our specific price shock did not allow the diversified strategy to show a cost advantage, the fact that it provides a hedge against a wider range of potential technology-specific risks (e.g., a gas-only price shock) for essentially no extra cost makes it the overwhelmingly logical and superior strategic choice.

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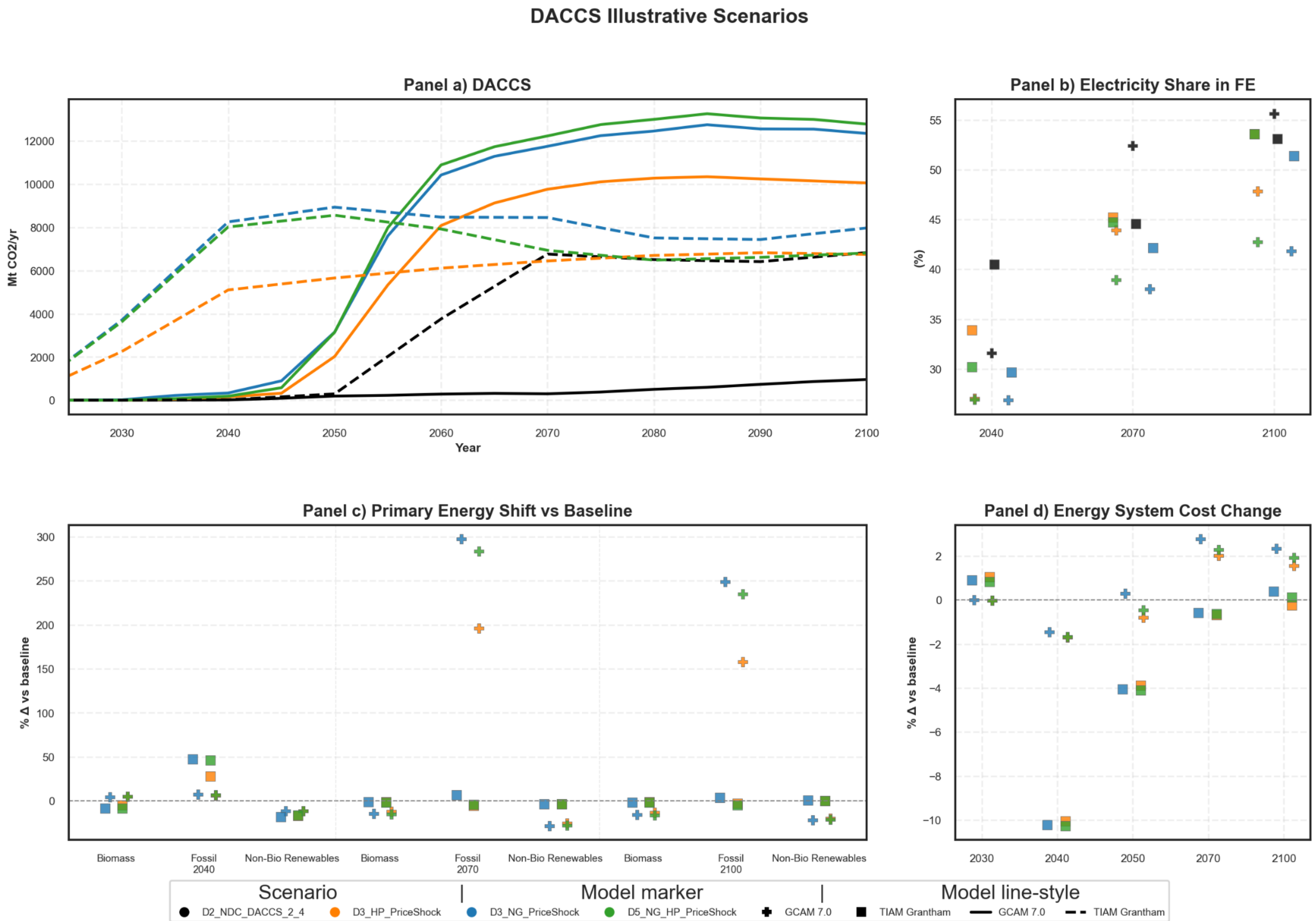

DACCS Illustrative Scenarios
Panel a) DACCS
Mt CO2/yr
Year
Panel b) Electricity Share in FE
(%)
Panel c) Primary Energy Shift vs Baseline
% Δ vs baseline
Biomass
Fossil 2040
Non-Bio Renewables
Biomass
Fossil 2070
Non-Bio Renewables
Biomass
Fossil 2100
Non-Bio Renewables
Panel d) Energy System Cost Change
% Δ vs baseline
Scenario
D2_NDC_DACCS_2_4
D3_HP_PriceShock
D3_NG_PriceShock
D5_NG_HP_PriceShock
Model marker
GCAM 7.0
TIAM Grantham
Model line-style
GCAM 7.0
TIAM Grantham

Figure 3: System-wide impacts of rapid DACCS across DERP narratives and modelling approaches

Panel a: Total DACCS sequestration ($MtCO_2$ /yr) from 2025-2100 for GCAM (solid lines) and TIAM-Grantham (dashed lines). Panel b: Electricity share of final energy (%), with black represents Current Trends (D2_NDC_DACCS_2_4), orange DERP3 Heat Pump variant with a price shock (D3_HP_PriceShock), blue DERP3 Natural Gas variant with a price shock (D3_NG_PriceShock) and green DERP5 diversified scenario (D5_NG_HP_PriceShock). Panel c: Shifts in Primary Energy compared to Current Trends for Biomass, Fossil Fuels and Non-Biomass Renewables (2040, 2070, and 2100). Panel d: Shift in Energy System Cost under each scenario, compared to Current Trends (dashed line). Model markers: squares (TIAM-Grantham), plus signs (GCAM). Note that FRIDA and PROMETHEUS do not feature in the DACCS scenarios due to a lack of detail of DACCS technologies.

Discussion

This study introduces the Disruptive Events-Resilient Pathways (DERP) framework to systematically incorporate disruptive events into climate mitigation analysis. By focusing on the interplay of Mitigation Action Ambition and Resilience to Socioeconomic Impacts, the framework advances a frontier in scenario studies: the simultaneous consideration of long-term transition goals and the resilience required to navigate disruptions. Here, we reflect on our study's overarching insights, the methodological choices in our implementation, the relationship to existing approaches, and the agenda for future research.

Our application of the framework across two distinct, stylised disruptions yields a set of complementary insights. The heatwave and drought scenario reveals that resilience is a precondition for an efficient energy transition, as low-resilience systems are not just vulnerable but fundamentally fragile and capital-intensive. The DACCS scenario, conversely, demonstrates the strategic imperative of diversification, showing how a myopic focus on a single technology can shift decarbonisation efforts away from necessary structural change, and that a diversified approach can hedge against this risk at little to no additional cost. Taken together, these findings make a compelling case that a diversified, robust strategy is superior to a narrow, optimised one, particularly when resilience can be achieved without significant economic penalty. The most robust mitigation pathway is unlikely to be the one that appears cheapest or easiest under the assumption of a predictable future.

A key methodological choice in the two stylised scenarios was to model disruptions as sustained pressures rather than as sudden, transient disruptive events. This framing was a pragmatic choice to align with the typical temporal resolution of the IAMs used, which are not designed to capture acute, short-term disruptions. This approach also allows us to test the inherent robustness of different systemic configurations, conceived as distinct ‘what if’ futures, to chronic stress. Our analysis therefore explores a system’s resilience to a fundamental shift in background conditions, rather than its reactive capacity to a timed, surprising event. The framework itself, however, is not limited to this approach and can readily be used to analyse a range of transient or acute disruptions.

Our use of multiple IAM archetypes further highlights that the interpretation of resilience is intertwined with model structure. While the DERP framework can be mapped consistently across models, the resulting pathways display characteristic differences. For example, perfect-foresight optimisation models like TIAM-Grantham often make large, concentrated investments to hedge against a known future disruption. In contrast, myopic, recursive-dynamic models like GCAM and PROMETHEUS tend to show more incremental adjustments. The system dynamics model FRIDA, with its emphasis on feedback effects, exhibits substantial adjustments to the new conditions. These contrasts are a strength of the framework: they highlight the importance of using a diversity of tools and explicitly stating the modelling lens through which disruption is viewed.

The DERP framework is intended to be complementary to, not a replacement for, existing frameworks like the SSPs. Unlike the SSPs, which provide comprehensive, pre-quantified socioeconomic trajectories, the DERP framework provides a structured lens for translating specific disruptions into model parameters. As such, an SSP can provide the broad socioeconomic context, while a DERP narrative is used to “stress-test” pathways within that context (see Appendix Table A.1 for a heuristic mapping). This approach of focusing on specific risk-related aspects of the transition bears similarity to the Network for Greening the Financial System (NGFS) scenarios (NGFS 2024), suggesting the DERP framework could be a valuable tool for such climate-related risk assessments.

This foundational study has several limitations that point towards a rich agenda for future research. First, our implementation remains primarily techno-economic. Future work should aim to explicitly integrate broader socioeconomic and political factors, such as inequality and behavioural responses (e.g., Andrijevic et al., 2020; Petrova et al., 2023; Beckage et al., 2022). Second, our deterministic approach could be enhanced. Future applications could usefully incorporate stochastic modelling to better capture uncertainty and assess the robustness of strategies against a wider range of potential disruptive events. Third, the framework could be extended to new domains. This includes an expansion to cover a wider array of climate impacts beyond the energy sector, such as those on agriculture, labour productivity, and health. This would, in turn, necessitate a more systematic typology of disruptive events, which itself constitutes an important area for future research.

Methods

Scenario Protocol

Here, we detail the scenario protocol for two stylised disruptions: (i) intensifying heatwaves and droughts (H&D) that simultaneously constrain electricity supply and raise cooling demand, and (ii) a rapid, cost-driven acceleration of Direct Air Carbon Capture and Storage (DACCS).

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 (likely a subset of DERP1-5) to provide plausible and coherent storylines. Not all narratives are necessarily applicable or insightful for every disruption type.
3. **Define DE parameters**: these depend on the nature of the DE. They are also dependent on or limited by available evidence in the climate impacts literature as well as the participating models' capabilities. We outline general guiding principles in **Table 2** above.
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 societal capacities (such as economic, institutional or technological) defined by the framework's Resilience to Socioeconomic Impacts dimension and influence how societies absorb and react to the disruptive event. Similar to the DE parameters, these are also dependent on or limited by available evidence in the underlying literature as well as the models' capabilities.

DE parameters representing the disruptions are generally applied consistently across the chosen DERP narratives being compared for a specific disruption, i.e. same disruption occurs under all narratives, while RCs parameters vary by DERP narrative to reflect different underlying societal capacities, along the Resilience to Socioeconomic Impact axis. Below, we detail the specific implementation for the H&D and DACCS stylised scenarios.

The 'Resilience to Socioeconomic Impacts' dimension is a high-level descriptor of systemic societal capacity. In this study's implementation using IAMs, this broad concept is necessarily represented through a set of techno-economic parameters that serve as proxies for the system's ability to withstand disruptions and maintain function.

Intensifying heatwaves and droughts (H&D)

This scenario explores how intensifying heatwaves and droughts, under a high climate sensitivity scenario, affect energy systems through simultaneous supply constraints and demand pressures. We apply the DERP framework to three narratives: DERP2 (Current Trends), DERP1 (Derailment), and DERP4 (Resilient Inertia).

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 with wider societal impact (Stone et al., 2023), making it crucial to understand how different resilience characteristics shape system responses. In this stylised implementation, the impacts are captured through their effects on hydropower availability and thermal plant cooling constraints, including biomass and nuclear, all of which are reflected in the capacity factor reductions. Whilst broader impacts (e.g., 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 (high climate sensitivity scenario) 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 (Supplementary Material **Table SM.1**). The impacts beyond 2070 are based on the 2070 values. Vliet et al., (2016) estimates are regionally differentiated and mapped onto model regions as closely as possible.
- 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.
- 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 adaptation efforts.

All scenarios use a consistent base scenario for the weighted average cost of capital

(WACC), adopting empirical 2018 data from Calcaterra et al. (2024). Crucially, these values are not adjusted for the high inflation observed in the post-COVID period and may therefore be lower than current estimates.

Whilst cooling demand conceptually represents a disruptive impact, its implementation varies between DERP1 (95th percentile, SSP2-based 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 its parameters reflecting post-2030 continuation of emissions intensity improvements of announced NDCs. This scenario is harmonised across all models.
- DERP1 (Derailment): we impose upper bounds on capacity for affected technologies (hydropower, thermoelectric) to reflect diminished institutional capacity. This constraint is implemented consistently with each model's logic:
    - TIAM-Grantham: A constraint on the total installed capacity for each affected technology relative to the Current Trends projections.
    - GCAM & PROMETHEUS: A constraint on capacity additions for affected technologies.
    - FRIDA: An investment-based limit, where any planned investment in affected technologies above Current Trends is re-allocated to unaffected energy sources.
- DERP4 (Resilient Inertia): No capacity bounds, 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 base scenario, representing a world with "moderate" mitigation ambition. The DERP1 and DERP4 scenarios are then constructed by applying the heatwave and drought disruption to this DERP2 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 ambition. 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.

Table 3 below presents these parameters following the logic of **Table 2**, with notation indicating parameter changes relative to DERP2 conditions.

Table 3: Parameter adjustments for heatwave and drought scenarios across DERP narratives

Parameter category	Parameter	DERP1 (Derailment)	DERP2 (Current Trends)	DERP4 (Resilient Inertia)
Disruptive Event (DE) Parameters				
Power plant capacity factors	Hydropower and Thermoelectric capacity factor	RCP8.5 impacts	N/A	RCP8.5 impacts
Energy demand	Cooling degree days	+95th percentile, SSP2 AC access	N/A	+50th percentile, universal AC access
Investment risk	cost of capital increase (thermoelectric and hydropower)	+20%	N/A	+20%
	cost of capital increase (other technologies)	+10%	N/A	+10%
Resilience Characteristic (RCs) Parameters				
Institutional capacity	Hydropower and Thermoelectric capacity bounds	Upper bound imposed	N/A	No constraints

This implementation follows Table 2's framework, where DE parameters capture the disruption's direct impacts whilst RC parameters reflect varying capacities to respond.

Rapid uptake of Direct Air Carbon Capture and Storage (DACCS)

This scenario explores the system-wide disruptive potential of a cost-driven acceleration in DACCS deployment, which could be driven by technological breakthroughs or a strong policy push, fundamentally altering mitigation strategies. We apply the DERP framework to narratives that reflect different strategic approaches to technology adoption and system planning: DERP2 (Current Trends), two variants of DERP3 (Fragile Transition), and DERP5 (Robust Transformation).

DACCS is increasingly featured in ambitious mitigation scenarios as a necessary measure to address residual emissions from hard-to-abate processes and to manage potential temperature overshoot (Bataille et al., 2025; Edwards et al., 2024; Fuhrman et al., 2021). However, its future prospects are highly uncertain, with wide-ranging estimates of future costs, energy requirements, and achievable scale-up rates (Young et al., 2023; Edwards et al., 2024). This uncertainty creates a dual disruption potential: rapid, cost-effective deployment could be a beneficial disruption, while over-reliance on a technology that fails to deliver at scale presents a significant moral hazard (Fuhrman et al., 2021).

We present an atypical trajectory: technological advance or strong policy intervention driving rapid cost reductions. Under such a scenario, we analyse resulting disruptions that may fundamentally alter mitigation pathway choices whilst creating new dependencies and vulnerabilities.

Disruptive Event (DE) parameters: We model the disruption through two primary channels, applied consistently across the DERP3 and DERP5 narratives to isolate the effects of different system responses.

- Technology cost reduction: An abrupt, rapid reduction in DACCS technology costs is assumed, following trajectories consistent with SSP5-based assumptions that stimulate significant uptake potential (Fuhrman et al., 2021).
- Energy price shock: To test the vulnerability of DACCS deployment to its energy inputs, a simultaneous price shock is imposed between 2040 and 2050. This involves a 50% increase in the average regional natural gas and electricity prices relative to the Long-Term Target (NDC_LTT) scenario (DERP2). These price shocks are applied to the DERP3 and DERP5 scenarios to specifically test the resilience and vulnerability of pathways that become heavily reliant on DACCS. As the DERP2 (Current Trends) scenario does not feature this high reliance, it is excluded from this particular stress test.

While energy prices are typically endogenous model outputs, this imposed price increase is a stylised representation of an exogenous disruptive event, such as a sudden geopolitical supply crisis. It is implemented in GCAM as a temporary fuel tax on top of the model's endogenously calculated prices. In TIAM, it is implemented by applying an equivalent tax on top of the endogenously calculated prices.

The +50% temporary price increase for natural gas and electricity is a stylised shock designed to test system vulnerability, with a magnitude that is grounded in historical precedent. Real-world energy crises have consistently produced price shocks far exceeding this level. During the 2022 European gas crisis, for instance, protracted market pressure saw year-on-year wholesale gas and electricity prices increase by +163% and +125%, respectively. The Dutch TTF benchmark gas price, which averaged ~€47/MWh in 2021, spiked to a peak of ~€311/MWh in August 2022—a roughly 15-fold surge from early-2021 levels—and expensive gas-fired generation drove parallel increases in electricity prices across the continent (Baget et al., 2024).

The 10-year duration of the shock is a stylised choice reflecting both the nature of long-term modelling and the type of disruption being represented. Within an IAM that operates on a 5-year time step, a shock must persist for at least two consecutive periods to meaningfully alter long-term capital investment decisions. Conceptually, this decade-long pressure does not represent a single price spike, but rather a sustained era of heightened market volatility and risk for energy security driven by protracted geopolitical tensions or a series of compounding climate-related impacts. It tests the resilience of a pathway not just to an acute crisis, but to a fundamental, medium-term shift in the stability of the energy system.

Resilience Characteristic (RC) parameters capture how system responses and underlying strategic choices differ by narrative, reflecting varying levels of resilience to technological and economic shocks.

- DERP2: Serves as the base scenario, representing limited DACCS deployment under existing Long-Term Target scenarios, with sequestration limits of 2 $GtCO_2$ in 2030 and 4 $GtCO_2$ in 2050, and no specific preference for a specific DACCS technology.
- DERP3: Reflects ambitious but narrowly focused strategies with no sequestration limits, implemented as two distinct variants to explore concentrated vulnerabilities:
    - DERP3-NG: Exclusively favours deployment of liquid-solvent, natural gas-powered DACCS (L-DACCS-NG).
    - DERP3-HP: Exclusively favours deployment of solid-sorbent, electric heat-pump-powered DACCS (S-DACCS-HP).

- DERP5: Represents a balanced and diversified strategy, with no sequestration limits, that assumes a 50:50 deployment mix of both L-DACCS-NG and S-DACCS-HP to manage technology-specific risks.

The two DERP3 variants allow us to explore different types of technological lock-in. The L-DACCS-NG pathway leverages a technology with potentially faster scalability but creates high temperature (c. 900°C) thermal energy demand and direct vulnerability to natural gas price shocks. The S-DACCS-HP pathway, conversely, relies on a less mature technology but offers potential long term advantages through lower temperature (c. 80–100°C) energy requirements that can be met with electricity and integrated with industrial waste heat, reducing fossil fuel dependency (Bakkaloglu et al., 2024).

It is important to clarify the role of the DERP2 narrative in this specific experiment. While labelled “Current Trends”, it is benchmarked to a Long-Term Target (LTT) scenario to compare disruption scenarios under a level of climate ambition. Here, DERP2 represents the “current trend” in that ambitious climate goals are pursued but DACCS is assumed to play only a limited role (in line with current expectations). The DERP3 and DERP5 scenarios thus explore a “disruption” to this specific technological assumption, assessing how the energy system reacts if DACCS plays a bigger role than currently anticipated as feasible in decarbonisation.

Energy System Costs variable was calculated as the undiscounted annual sum of investment, variable, fixed, fuel, and carbon pricing costs across all energy-related sectors, including end-use sectors (agriculture, transport, residential, commercial, industry), electricity generation, bioenergy conversion, hydrogen production, carbon capture and storage technologies, mining, and refining, whilst excluding non-energy technologies.

Table 4: Parameter adjustments for the DACCS scenarios across DERP narratives

Parameter category	Parameter	DERP2 (Current Trends)	DERP3-NG (Fragile Transition - Natural Gas)	DERP3-HP (Fragile Transition - Electric)	DERP5 (Robust Transformation)

Disruptive Event (DE) Parameters					
Technology cost	DACCS capital cost	SSP2	SSP5-based rapid reduction	SSP5-based rapid reduction	SSP5-based rapid reduction
Energy price shock	Natural gas price (2040-2050)	N/A	+50%	+50%	+50%
	Electricity price (2040-2050)	N/A	+50%	+50%	+50%
Resilience Characteristic (RC) Parameters					
Technology preference	DACCS deployment constraint	Limited (2-4 GtCO2/yr)	High for L-DACCS-NG only	High for S-DACCS-HP only	Balanced mix (50:50)

Integrated Assessment Models

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.It can be used to explore a variety of questions on how to mitigate climate change through energy system and transformations. 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, 2008). 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).

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., 2019).In the version used here (GCAM 7.0) (Patel et al., 2023), the model creates a two-way coupling between the scale of economic activity, measured as GDP, and the existing energy sector module.

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, CO_2 emissions (van der Zwaan et al., 2025), and energy technology evolution across ten world regions.

FRIDA

The Feedback Repository for IntegrateD Assessments (FRIDA) is a newly developed global-scale IAM (Schoenberg et al., 2025). 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; 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., 2021).

The FRIDA model is validated both from a behavioral and structural perspective. Behaviorally, the model is calibrated to reproduce 1980-2023 behaviour across 158 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 behavior, and ensuring that the processes that give rise to that behavior match with subject matter expert, and the literature’s conceptualizations 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 DERP protocol. These crossover impacts were switched off in the NDC run in FRIDA.

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Data and Code Availability

Data and code will be made publicly available on GitHub upon publication.

Appendix

Indicative mapping between DERP and SSP frameworks

While the DERP framework is distinct from the SSPs, any quantitative application requires a set of background socioeconomic assumptions. As the SSPs are the community standard for providing this context, **Table A.1** below serves as a heuristic guide for researchers on how to plausibly combine the two frameworks. The pairings indicate which SSP storyline can provide a coherent socioeconomic backdrop for a given DERP narrative; they do not imply a direct equivalence. The “Key modifications” column lists at least one lever for each DERP dimension (mitigation action ambition and resilience to socioeconomic impacts); concrete examples of such levers appear in **Table 2**.

Table A.1: Indicative Mapping between DERP Narratives and Compatible SSP ones

Notation: ✓ = particularly suitable SSP, △ = usable SSP with additional adjustments

DERP Narrative	Compatible SSP(s)	Key modifications (mitigation axis / resilience axis)	Rationale and implementation guidance
DERP1 - Derailment	**✓ SSP3** **△ SSP4**	Mitigation: relax climate-policy stringency and technology learning. Resilience: amplify regional fragmentation, raise investment risk premiums, reduce institutional response capacity.	SSP3’s rivalry and weak cooperation mirror low resilience SSP4’s inequality can generate similar vulnerabilities. Emphasise cascading vulnerability and limited recovery capacity.
DERP2 - Current Trends	**✓ SSP2** **△ any other SSP as status-quo variant**	Mitigation: continue announced NDCs, medium techology diffusion. Resilience: maintain historical adaptive capacity with moderate contingency funding.	SSP2’s “middle of the road” trajectory already sits near DERP2. Apply moderate disruptions while keeping socioeconomic trajectory largely unchanged.
DERP3 - Fragile Transition	**✓ SSP5** **△ SSP1**	Mitigation: concentrate policy incentives on a single low-carbon option (e.g. CCS or EVs), restrict diversity elsewhere.	SSP5’s techno-optimism fits high, narrow mitigation SSP1 can also yield a “green but myopic” variant if policy over-favours one solution. Highlight over-reliance and weak fallback capacity.

		Resilience: keep supply-chain diversity low, limit redundancy, increase price sensitivity.	
DERP4 - Resilient Inertia	**△ Any SSP (often SSP2)**	Mitigation: scale back long-term climate ambition, extend fossil infrastructure lifetime. Resilience: harden existing assets, add redundancy for known threats, improve emergency logistics.	DERP4 is about disruption management rather than socioeconomic transformation. Choose a suitable SSP context and then layer resilience measures focused on hardening existing systems and maintaining the status quo, rather than enabling systemic change
DERP5 - Robust Transformation	**✓ SSP1**	Mitigation: ambitious, economy-wide carbon pricing and diversified low-carbon portfolio. Resilience: build adaptive institutions, system redundancy, and flexible infrastructure.	SSP1 supplies a sustainability-oriented baseline; additional levers must lift institutional adaptiveness and engineered redundancy beyond the SSP1 default to achieve high resilience.

See Table 2 for indicative parameter categories (e.g., carbon pricing, energy supply diversity, risk premiums) that can operationalise the qualitative modifications listed above.

Additional Results - FRIDA

Here we present additional results from the model FRIDA to illustrate the driving forces behind the uncertainties of its 1,000 ensemble members, as shown in Figure A.1 below.

Changes in fossil capacity are minimal under D1 with narrow ranges, since their addition is constrained. Slight reductions are seen as plants are phased out, or rendered redundant by the rapid increases in renewable capacity. This renewable increase is dominated by wind power over solar in the median response, but with huge uncertainties on their relative contributions.

The uncertainty parameters most strongly correlated with the capacities of solar and wind power relative to the baseline scenario in 2050 under D1 are the sensitivity of their costs to grid storage needs (not shown). Each of the two source's capacity is most strongly (negatively) correlated with their own cost sensitivity – i.e. with lower capacity for stronger cost increases – while they are positively correlated with the source's cost sensitivity, indicating the competition between solar and wind in these ensembles. While these correlations are only around 0.1-0.2, the number of parameters is large (626).

All ensemble members see rising wind power in the near term, and in extreme cases, the learning-by-doing dynamic accelerates wind rollout at the expense of solar, with capacity doubling compared to the baseline in 2070. At the other end of the range, some members see wind capacity track back to under the baseline level by 2100, with solar instead increasing to meet demand. Biomass energy also increases robustly, with rising uncertainty throughout the period.

In the D4 scenario, total capacity is slightly higher than the baseline due to the higher energy needs, with a similar range, without the shock in the renewable sector seen in D1 due to the lack of limits on fossil capacity. At the technology level, however, there is uncertainty in the role of particularly coal towards the end of the scenario, and to a lesser extent gas. Coal and gas capacity in 2050 were found to be most correlated with their cost parameters, with the tendency of pollutant emissions per coal use to decrease over time also playing a role due to the effect on energy investment under future climate policy.

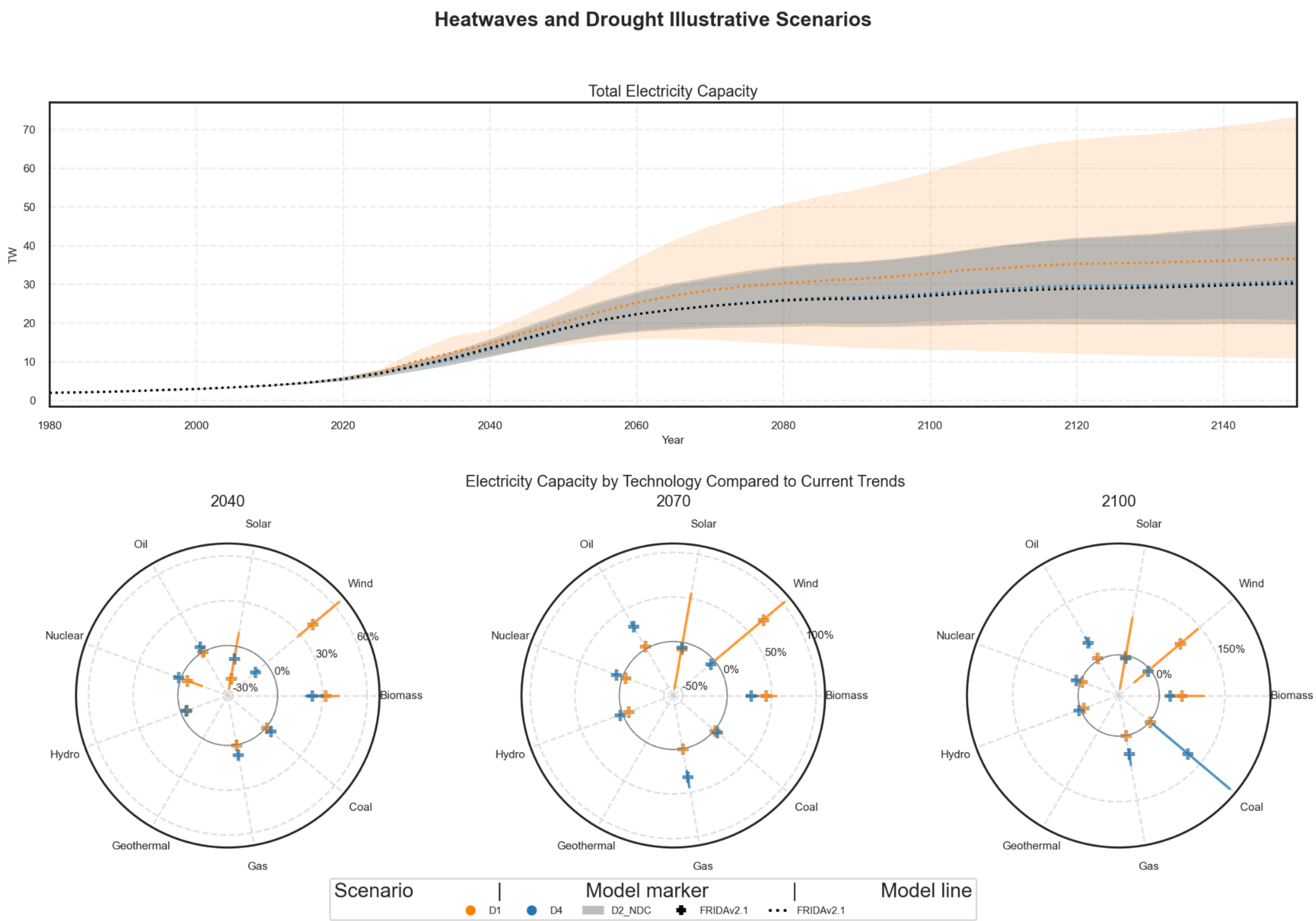
Heatwaves and Drought Illustrative Scenarios
Total Electricity Capacity
TW
70
60
50
40
30
20
10
0
1980
2000
2020
2040
2060
2080
2100
2120
2140
Year
Electricity Capacity by Technology Compared to Current Trends
2040
2070
2100
Solar
Wind
Biomass
Coal
Gas
Geothermal
Hydro
Nuclear
Oil
-30%
0%
30%
60%
-50%
0%
50%
100%
0%
150%
Scenario | Model marker | Model line
D1
D4
D2_NDC
FRIDAv2.1
FRIDAv2.1

Figure A.1: Energy system responses to intensifying heatwaves and droughts across DERP narratives - FRIDA 2.1 ensemble members

Panel a (top row) shows Total Electricity Capacity (TW) trajectories from 2025-2100 for FRIDAv2.1, 5th to 95th percentile, with medians as dotted lines. Panel b (bottom row) Percentage changes in Electricity Capacity by Technology Compared to Current Trends (2040, 2070, and 2100) displayed as polar charts where the 0% solid circles in the middle represent Current Trends, ranges shown with plus sign for medians.

Supplementary Material

Table SM.1 (Capacity factors).

Table SM.2 (Cooling demand).

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