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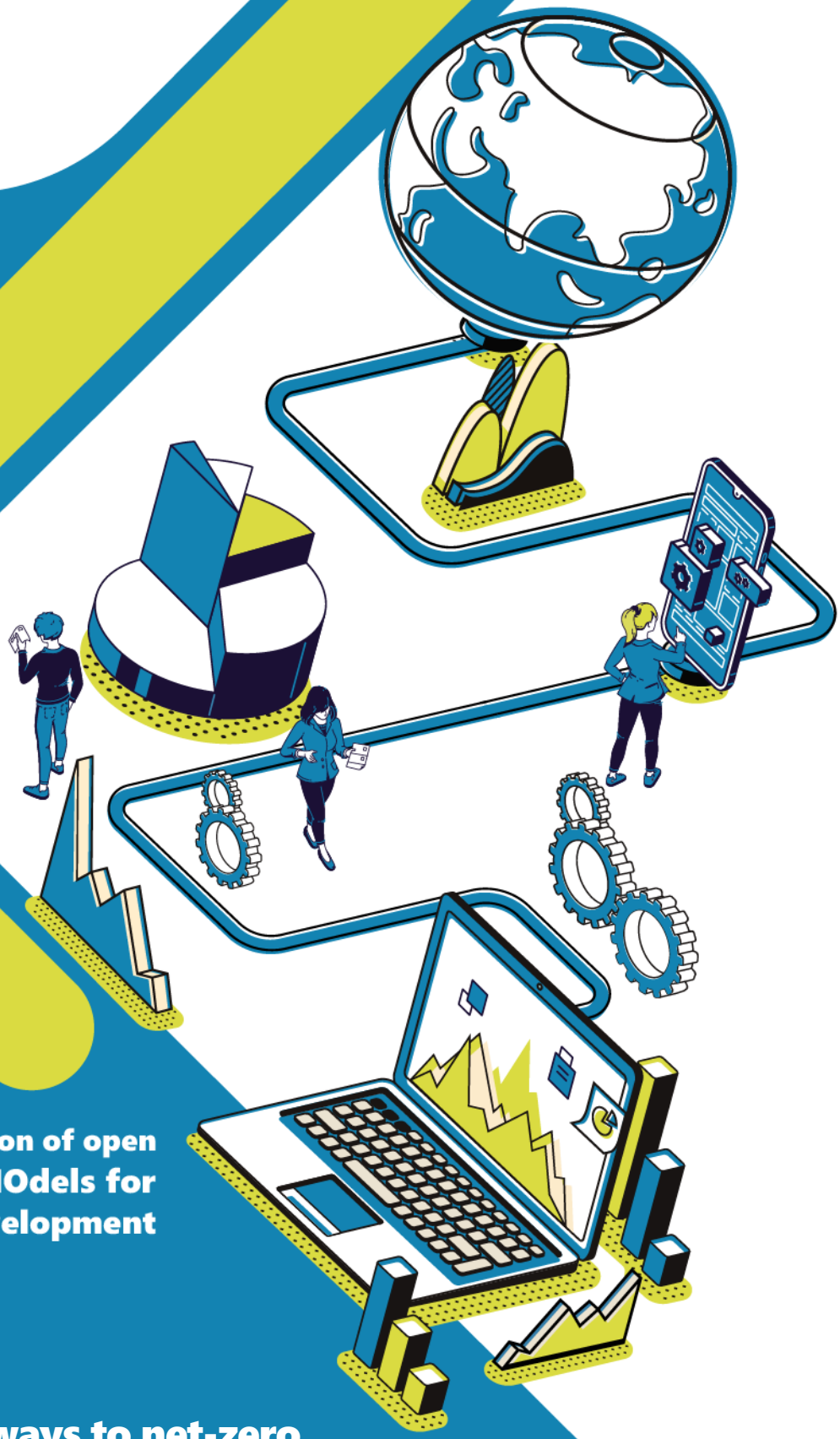

Delivering the next generation of open Integrated Assessment MOdels for Net-zero, sustainable Development

WP5 – Apply & Explore

D5.4 – Disrupted pathways to net-zero

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27/08/2026

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1. Changes with respect to the DoA

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

2. Dissemination and uptake

This deliverable is intended for use both within the DIAMOND project and by the wider community of researchers, policymakers, and analysts concerned with climate mitigation pathways, energy security, and the resilience of the European power system. Within DIAMOND, the scenario protocol documented here provides a common experimental design for the participating integrated assessment models, OMNIA and OPEN-PROM, and its results will inform the project's applied scenario analysis and final set of stakeholder engagement activities. Beyond the consortium, the deliverable offers a transparent, reproducible protocol for representing compound disruptions and concurrent climate and trade shocks, in long-term climate-energy-economy models. It is therefore of direct relevance to modelling teams seeking to stress-test decarbonisation pathways, to institutions assessing the energy-security implications of the transition, and more broadly to the scenario community. Findings will be disseminated through the DIAMOND project website, academic publications, conference presentations, and stakeholder engagement events.

Short summary of results (<250 words)

This deliverable documents the design, parameterisation, and implementation of a multi-model scenario exercise examining compound disruptive events in EU mitigation pathways. A compound disruption, in the form of a sustained heatwave co-occurring along with a trade shock on imported energy, is introduced into the project's NDC-LTT mitigation pathway over 2035-2045, in the EU, across two structurally different integrated assessment models from the project's enhanced model ensemble: OMNIA and OPEN-PROM. The heatwave shock operates through reduced capacity factors for thermal, hydro, wind, and solar generation (calibrated from Copernicus climate projections at country level), increased cooling degree days, and an increased cost of capital (20% for affected energy supply technologies, 10% for the rest of the economy). The trade shock raises the cost of gas and electricity imported into the EU by 25% or 50%. Two techno-economic resilience configurations are examined: a low-resilience variant, in which capacity additions are capped at benchmark levels, and a high-resilience variant, in which the system responds freely. Carbon prices are fixed at benchmark levels, so emissions rise under the compound shocks and effective ambition erodes. The deliverable presents five scenarios: the benchmark and four full compound disrupted runs with different configurations, forming two scenario pairs. The deliverable further documents the derivation of all disruption parameters. Among headline results from the two completed models, we find that constrained systems defend capacity at the cost of increase in emissions (median member-state power-sector CO_2 +31% under low versus +6% under high resilience at 2040), while intensifying the trade shock from 25% to 50% bears little further implications; finally, end-use electrification is projected to change, albeit not markedly (with median changes below one percentage point).

Evidence of accomplishment

This deliverable.

Preface

DIAMOND will update, upgrade, and fully open six Integrated Assessment Models (IAMs) that are emblematic in scientific and policy processes, improving their sectoral and technological detail, spatiotemporal resolution, and geographic granularity. It will further enhance modelling capacity to assess the feasibility and desirability of Paris-compliant mitigation pathways, their interplay with adaptation, circular economy, and other SDGs, their distributional and equity effects, and their resilience to extremes, as well as robust risk management and investment strategies. This will be done via integration of tools and insights from psychology, finance research, behavioural and labour economics, operational research, and physical science. The project will develop a transdisciplinary scientific approach to legitimise the implementation process and co-create research questions that stretch the frontiers of climate science, as well as establish vibrant communities of practice to transparently open model enhancements and to develop capacities, thereby lowering the entrance barriers to the established IAM community.

ICCS	INSTITUTE OF COMMUNICATIONS AND COMPUTER SYSTEMS	EL
BC3	ASOCIACION BC3 BASQUE CENTRE FOR CLIMATE CHANGE - KLIMA ALDAKETA IKERGAI	ES
CESAR	KRATENA KURT	AT
CICERO	CICERO SENTER FOR KLIMAFORSKNING	NO
CYI	THE CYPRUS INSTITUTE	CY
E4SMA	ENERGY ENGINEERING ECONOMIC ENVIRONMENT SYSTEMS MODELING AND ANALYSIS SRL	IT
HOLISTIC	HOLISTIC IKE	EL
COMILLAS	UNIVERSIDAD PONTIFICIA COMILLAS	ES
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Executive Summary

The European Union's power sector faces compound risks from climate change and geopolitical instability that may undermine the feasibility of planned decarbonisation pathways. Heatwaves reduce the output of thermal, hydro, and renewable generation assets, increase cooling demand, and raise the cost of capital for energy investments. At the same time, trade disruptions increase the cost of imported energy. These disruptions interact: a heatwave that suppresses domestic generation while import costs are elevated creates a compounding stress that linear, single-shock analyses cannot capture. Recent European experience, i.e., the 2022 drought and gas crisis and the June-July 2025 and 2026 heatwaves, illustrates both channels vividly. Yet standard integrated assessment model (IAM) scenarios typically assume smooth transitions and do not systematically test what happens when multiple shocks coincide under varying levels of system resilience. This deliverable addresses this gap.

The exercise is guided by two applied research questions.

- RQ1: in the presence of trade disruptions, how do heatwaves affect the robustness of the EU power sector under various resilience assumptions?
- RQ2: what are the cascading impacts of these power sector disruptions on electrification in the EU's end-use sectors?

A shared scenario protocol was implemented in two structurally different capacity-expansion IAMs from the project's enhanced model ensemble: OMNIA and OPEN-PROM. The disrupted scenarios build on the project's NDC-LTT mitigation pathway (combining national determined contributions – NDCs, with long term targets – LTTs). Two resilience configurations are examined: a low-resilience variant, in which capacity additions are capped at their benchmark levels, and a high-resilience variant, in which the system responds freely by investing in additional capacity. In both configurations, carbon prices are fixed at benchmark levels (NDC-LTT). The effective implication is that, when shocks occur, emissions rise as the systems expand capacity, and hence effective mitigation ambition erodes. The compound disruption is applied throughout 2035-2045, to EU member states only. The heatwave shock operates through three channels: reduced capacity factors for thermal, hydro, wind, and solar generation, calibrated at country level from Copernicus climate projections; increased cooling degree days; and an increased cost of capital (20% for affected energy supply technologies, 10% for the rest of the economy). The trade shock raises the price of gas and electricity imported into the EU by 25% or 50%. The deliverable presents five scenarios: the benchmark and four full compound disrupted runs, forming two scenario pairs at the two trade-shock levels.

The deliverable documents the protocol and its parameterisation, describes the two participating models, and records each team's model-specific implementation, including documented deviations from the protocol, which are essential for interpreting cross-model differences. These derivations are documented fully in Appendices A-B.

Across the two models, the compound disruption produces a characteristic capacity dynamic showing a rise above the benchmark in 2035, a trough around 2040, and a recovery after 2045. The differences between member states are much larger than the median change itself, reflecting capacities deployed, additional investments on capacities, and demand-side characteristics. The resilience configuration determines the margin of adjustment: capacity-constrained systems defend installed capacity resulting in a rise in emissions (median member-state power-sector CO2 +31% versus the benchmark in 2040 under low resilience, against +6% under high resilience, in the compound scenario with the 50% trade shock), while flexible systems shed capacity and defend decarbonisation. Intensifying the trade shock from 25% to 50% is found to add little to power-sector outcomes, and end-use electrification changes little, with median share changes below one percentage point, bounded below by the models' annual-average resolution.

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1 Introduction

1.1 Background and motivation

The European Union's power sector faces compound risks from climate change and geopolitical instability that may undermine the feasibility of planned decarbonisation pathways. Heatwaves reduce the output of thermal, hydro and renewable generation assets, increase cooling demand, and raise the cost of capital for energy investments. Trade disruptions, whether arising from geopolitical tensions or supply-chain failures, increase the cost of imported energy. Critically, these disruptions interact: a heatwave that suppresses domestic generation while import costs are elevated creates a compounding stress that linear, single-shock analyses cannot capture.

Recent European experience illustrates both channels vividly. The 2022 drought, described by the European Drought Observatory as Europe's worst in at least 500 years, cut EU hydropower generation by 19% year-on-year, from 349 TWh in 2021 to 283 TWh in 2022, while warm river temperatures forced curtailment of the French nuclear fleet (Ember, 2023). In the same year, the disruption of Russian pipeline gas, around 40% of EU pipeline-gas imports in 2021, triggered the most severe energy-price crisis in the Union's history. More recently, the June-July 2025 heatwave increased daily power demand by up to 14% in Spain, 9% in France and 6% in Germany, and drove a two- to three-fold increase in average daily power prices (Ember, 2025). The defining feature of heatwaves, distinct from other hazards, is that they push demand up and supply down simultaneously and sustain that pressure for days or weeks.

Integrated assessment models (IAMs) couple the energy, economy, land, end-use sectors, and to some extent, the implication on the climate system in a reduced form. Standard IAM-based scenarios typically assume smooth transitions and do not systematically test what happens when multiple shocks coincide under varying levels of system resilience (Weyant, 2017; Wilson et al., 2021). This deliverable addresses this gap. It documents the design, parameterisation and implementation of a multi-model scenario exercise, undertaken within Task 5.3 of the DIAMOND project, in which a compound disruption of a sustained heatwave co-occurring with a trade shock on imported energy is introduced into EU mitigation pathways across two structurally different IAMs, under two contrasting assumptions about the techno-economic resilience of the energy system.

1.2 Disruptive events in energy-economy models: state of the art

The literature relevant to this exercise is mature but channel-specific and weakly integrated. This section summarises the state of the art across three strands: compound climate extremes, trade and supply-chain shocks, and their joint treatment. It also identifies the methodological challenges that shape the study design.

1.2.1 Compound climate extremes

The compound-events literature provides the conceptual scaffolding. Zscheischler et al. (2018) argued that traditional risk assessment, by considering one driver or hazard at a time, systematically underestimates risk because the processes that cause extreme events often interact and are spatially and temporally dependent. Their subsequent typology distinguishes preconditioned, multivariate, temporally compounding and spatially compounding events, and identifies copula-based dependence modelling as the dominant analytical tool for representing correlated drivers using a statistical framework that separates the modelling of individual (marginal) distributions from the modelling of how variables depend on each other (Zscheischler et al., 2020). Bevacqua et al. (2021) operationalise the typology into practical guidelines. The storyline approach (Shepherd et al., 2018) offers a complementary, physically self-consistent way to represent deep uncertainty by stress-testing systems

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against plausible high-impact narratives rather than assigning probabilities. These frameworks matter here because the paradigmatic EU power-sector disruption, a compound heat-and-drought event, is precisely a multivariate, temporally compounding hazard.

Within energy modelling, demand-side climate impacts dominate the literature: most studies consider changes in space heating and cooling demand, while few models have examined the supply side (Cronin, Anandarajah and Dessens, 2018). The supply-side evidence base is nevertheless well established in dedicated hydrological-electricity studies. van Vliet et al. (2012) demonstrated the vulnerability of US and European electricity supply to warming river temperatures and reduced summer flows; van Vliet et al. (2016a) coupled a global hydrological-electricity framework across more than 24,500 hydropower and 1,400 thermoelectric plants and projected reductions in usable capacity for the majority of both plant types after 2040; and companion work found that during recent drought years hydropower utilisation fell on average by 5.2% and thermoelectric power by 3.8% (van Vliet et al., 2016b). For Europe specifically, Tobin et al. (2018) quantified vulnerabilities of wind, solar, thermal and hydropower generation under 1.5°C, 2°C and 3°C warming. Renewable variability adds a further dimension: the Dunkelflaute—a weather period with little wind and no sun, which stops solar and wind power—literature characterises prolonged wind-and-solar droughts as temporally compounding events (Kittel and Schill, 2026), with long-duration storage of up to 351 TWh (around 7% of yearly European electricity demand) required to cope with the most extreme historical event under policy-relevant interconnection assumptions (Kittel, Roth and Schill, 2026). Yet these physical impacts remain only partially embedded in IAMs and long-term energy system models, largely owing to technical and data challenges (Cronin, Anandarajah and Dessens, 2018). Notable exceptions include stochastic-robust optimisation for embedding extreme events in energy system design (Perera et al., 2020) and the extension of a long-term optimisation model to hurricane risk in Puerto Rico (Bennett et al., 2021). Another related methodological strand links operational power-system detail into long-term models, for instance through residual load duration curves (Ueckerdt et al., 2015), although this approach is aimed at short-term variability rather than climate extremes.

1.2.2 Trade and supply-chain shocks

The second strand concerns trade rather than climate. The 2022 European gas crisis became the field's principal modelled case study of a fuel-import shock, analysed mainly with computable general equilibrium (CGE) tools. Perdana, Vielle and Schenckery (2022) showed that an embargo on Russian coal and oil would substantially raise EU energy prices and welfare costs, roughly doubling if extended to gas; the JRC-GEM-E3 analysis found that indirect macroeconomic impacts via electricity-price spillovers exceeded the direct gas-price impact (Weitzel et al., 2024). Albrizio et al. (2025) showed that adverse impacts shrink roughly five-fold once integration with global LNG markets is accounted for. These studies illustrate both the strength of general-equilibrium tools for tracing price and welfare propagation and their limitations: the shock is typically exogenous, and smooth substitution elasticities may understate short-run rigidities. A second strand concerns the material and manufacturing dependencies of the transition itself: China's share in all manufacturing stages of solar PV exceeds 80% (IEA, 2022), with comparable concentration in battery supply chains (IEA, 2026), and material-demand accounting is increasingly embedded in IAM scenarios (Deetman et al., 2018). Supply constraints, however, are rarely endogenous: the feasibility of investment decisions in current-generation energy system models is not constrained by mineral availability (Moerenhout, Lee and Glynn, 2023). A parallel literature translates security concerns into indicators for long-term scenarios (Kruyt et al., 2009; Jewell, Cherp and Riahi, 2014), though these remain largely diagnostic overlays on scenario outputs rather than drivers of endogenous model behaviour.

1.2.3 Joint treatment of multiple disruptions

The frontier, and the thinnest-sourced area, is the joint modelling of concurrent disruptions. Hanna and Gross (2021) found that energy-system models and scenario studies represent socio-economic, political and technological disruption predominantly through qualitative foresight scenarios or agent-based models, and that conventional optimisation IAMs represent such discontinuities poorly. Explicit joint shock modelling remains rare: Avraam, Ceferino and Dvorkin (2023) coupled an optimal power flow model to a CGE model to trace the economy-wide impacts of a cyberattack timed with a heatwave, finding that the compound scenario drove unserved load to 13% versus 4% for the cyberattack alone, a result invisible to independent-shock analysis. Feng, Ouyang and Lin (2022) model a tropical-cyclone-blackout-heatwave compound hazard chain, showing that under RCP8.5 the expected share of customers exposed to multi-day compound events could increase by about a factor of 23 over the twenty-first century. To the authors' knowledge no peer-reviewed study to date explicitly models a climate extreme co-occurring with a trade or geopolitical shock inside an IAM or long-term energy-system optimisation model with a formal correlated-shock dependence structure. This deliverable contributes directly to closing this gap.

1.2.4 Methodological challenges

Four structural obstacles recur across these strands. First, the independence assumption: treating shocks one at a time underestimates correlated and cascading risk. Second, the foresight problem: under perfect foresight an anticipated shock is smoothed away because the model pre-positions investment, whereas myopic or recursive-dynamic formulations allow the system to be genuinely surprised (Babrowski et al., 2014). In other words, perfect-foresight optimisation is structurally incapable of representing an unanticipated shock. Third, exogeneity: material supply, manufacturing capacity and geopolitical availability enter most models exogenously, if at all. Fourth, integration across event-based and trend-based paradigms, and across physical and economic model layers, remains an unsolved coupling problem (Gambhir et al., 2019). Established uncertainty methods such as Monte Carlo analysis, stochastic programming, robust optimisation and modelling to generate alternatives (DeCarolis et al., 2016) address parametric and structural uncertainty but do not by themselves resolve these obstacles. The study design set out in the Methods section attempts to address these challenges: it adopts a storyline stress-test framing, applies the climate and trade shocks jointly rather than independently, represents the climate channel on both the demand and supply sides simultaneously, and exploits the structural diversity of the participating models, including their differing foresight assumptions.

1.3 Research questions

D2.5 and the stakeholder-informed research priorities highlighted the interconnected themes of electrification, trade and geopolitical vulnerabilities, cross-sectoral cascading impacts, and the role of resilience strategies in mitigating supply-chain and economic disruptions. Reflecting these priorities and the capabilities of the IAMs, this exercise is guided by two applied research questions:

RQ1: In the presence of trade disruptions, how do heatwaves affect the robustness of the EU power sector under various resilience assumptions?

RQ2: What are the cascading impacts of these power sector disruptions on electrification of the EU's end-use sectors?

RQ1 interrogates the supply side: how the generation mix, capacity expansion and emissions of the EU power sector respond when a sustained heatwave and elevated import prices coincide, and how far that response depends on whether the system can deploy new capacity beyond its baseline trajectory. RQ2 traces the

consequences downstream: electrification is the backbone of EU end-use decarbonisation strategies, and a power sector under compound stress may deliver electricity that is scarcer or more expensive, with knock-on effects for the electrification of transport, buildings and industry. RQ2 is assessed through the models' endogenous end-use responses, final energy demand by sector and by carrier, under the disrupted scenarios relative to the benchmark.

1.4 Approach and structure of this deliverable

The study applies a common scenario protocol to two capacity-expansion IAMs: OMNIA and OPEN-PROM. The protocol builds disrupted variants on top of the project's NDC-LTT mitigation pathway, distinguishing low- and high-resilience configurations, and introduces a compound disruption comprising a heatwave shock (reduced capacity factors, increased cooling degree days, and an increased cost of capital) and a trade shock (increased cost of imported gas and electricity) over the period 2035-2045, applied to EU member states only.

The remainder of this deliverable is organised as follows. Section 2 sets out the methods: the study design and scope, the scenario protocol and its parameterisation, descriptions of the two participating models, and model-specific implementation notes documenting where and why implementations deviate from the protocol. Section 3 presents the analysis and results across the two research questions. Section 4 concludes. Appendices A and B document the derivation of the climate-adjusted capacity factor parameters for wind and solar, and for thermal and hydroelectric generation, respectively.

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2 Methods

2.1 Study design and scope

The exercise is designed as a storyline stress test rather than a probabilistic risk assessment. Because a joint climate-plus-trade shock of the kind considered here is deeply uncertain and effectively unprecedented in the modelled record, the storyline approach (Shepherd et al., 2018), which asks what plausibly happens if a specified high-impact narrative unfolds, rather than how likely it is, provides the most defensible framing. In the typology of Zscheischler et al. (2020), the disruption is a multivariate and temporally compounding event: several correlated hazard channels (supply derating, demand amplification, financial stress and import-price escalation) act simultaneously and persistently over a decade.

The scope of the study is as follows. Spatially, the analysis is disaggregated at the EU level, with disruption parameters available mostly at country (NUTS0) resolution. Models that operate at coarser regional granularity aggregate the parameters as appropriate to their structure and document the aggregation (Section 2.5). From a sectoral perspective, the analysis covers the power sector and the end-use sectors (industry, buildings and transport). The time horizon extends to 2050, with the disruption applied over the 2035-2045 period only. The disruption parameters are applied only to EU member states; the rest of the world follows the benchmark pathway.

Two structurally different IAMs (OMNIA and OPEN-PROM) implement the same protocol. This multi-model design is deliberate: it exploits structural diversity: in solution concept (optimisation in the case of OMNIA versus simulation in the case of OPEN-PROM), in foresight (perfect foresight in the case of OMNIA, versus recursive-dynamic and myopic formulations in the case of OPEN-PROM), and in the representation of trade and demand, as a robustness device. In particular, because perfect-foresight optimisation structurally anticipates the shock window by pre-positioning investments, whereas recursive-dynamic (myopic) models do not, cross-model comparison provides a bounded, informal test of the foresight sensitivity highlighted in the energy-systems literature (Babrowski et al., 2014; see also Lambert, 2023).

2.2 Scenario protocol

2.2.1 Mitigation ambition and resilience configurations

The disrupted scenarios build on the NDC-LTT scenario, the project's reference mitigation pathway (see D5.2), which reflects Nationally Determined Contributions globally, National Energy and Climate Plans for the EU, and long-term targets implemented through economy-wide carbon prices. From this benchmark, two disrupted variants are constructed, distinguished by their techno-economic resilience configuration:

Low techno-economic resilience. An upper bound on capacity additions, by total capacity or by fuel, depending on the model, is imposed at the default NDC-LTT level. When the disruption is applied, the model would otherwise compensate by building more of some technologies; the bound prevents this accelerated deployment, representing a system whose supply chains, permitting and financing cannot expand beyond their planned trajectory.

High techno-economic resilience. No such constraint is applied; the system responds freely to the shock.

In both variants, mitigation ambition is treated identically: carbon prices are fixed at their default NDC-LTT trajectory following the introduction of the disruption. Emissions therefore increase relative to the benchmark, and the effective level of ambition is reduced, capturing the observation that systems under stress tend to sacrifice mitigation ambition rather than defend it at any cost.

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2.2.2 Disruptions

Both disrupted variants face the same compound disruption, comprising a heatwave shock and a trade shock, applied jointly throughout 2035-2045 to EU member states only.

In order to impose the heatwave shock, we rely on three channels:

Reduced capacity factors for energy supply technologies: thermal, hydroelectric, onshore and offshore wind, and solar PV. These are calibrated at NUTS0 level from climate-model projections under high-emissions pathways (SSP5-8.5/RCP8.5; Riahi et al., 2017), using the relative change in climate-adjusted capacity factors between high-emissions and moderate-mitigation pathways as the measure of heatwave-driven derating. The derivation is documented in Appendices A and B.

Increased cooling degree days (CDDs), amplifying electricity demand for space cooling. These are based on projections from the HadCM3 general circulation model under the SRES A2 scenario (Nakićenović and Swart, 2000), which is broadly aligned with RCP7-class radiative forcing, at NUTS0 level.

Increased cost of capital, reflecting the repricing of climate-related financing risk: a 20% increase for energy supply technologies affected by the heatwave (that is, those whose capacity factors are adjusted), and a 10% increase for the rest of the economy. This differentiated treatment is informed by recent evidence on country- and technology-differentiated costs of capital in climate-energy-economy models (Calcaterra et al., 2024).

The trade shock is a sustained increase in the cost of imported gas and electricity faced by the EU from outside the region, applied at two levels: +25% and +50%, over the same 2035-2045 window.

2.2.3 Scenario matrix

The protocol presented in this deliverable comprises five scenarios: the undisturbed benchmark (NDC-LTT) and four disrupted runs in which all disruption channels act together. Table 1 sets out the matrix. The scenario naming encodes the design. The prefix HD denotes the compound heatwave disruption family. LR and HR denote the low- and high-resilience configurations. The numeric pair 20_10 denotes the cost-of-capital uplift applied to energy supply technologies and to the rest of the economy. The final number (25 or 50) denotes the trade-shock level. Every disrupted scenario applies the reduced capacity factors, the increased CDDs, the cost-of-capital uplift and the trade shock jointly. The four disrupted runs form two scenario pairs, each pair combining the LR and HR variants that share the same trade-shock level. Results in Section 3 are presented pair by pair against the benchmark. Because the channels always act together, their individual contributions are not separately identifiable in this set. The difference between the two trade levels identifies the effect of trade intensification alone, conditional on the rest of the compound.

Table 1. Scenario protocol: the benchmark and four full compound disrupted scenarios forming two scenario pairs.

All disrupted scenarios apply the reduced capacity factors (SSP5-8.5/RCP8.5, NUTS0), the increased CDDs (SRES A2, NUTS0), the cost-of-capital uplift and the trade shock over 2035-2045, in the EU only, with carbon prices fixed at default NDC-LTT levels

#	Scenario name	Resilience	Cost of capital (energy supply / rest of economy)	Trade shock (imported gas and electricity)
1	NDC-LTT	— (benchmark NDC-LTT, no disruption)	—	—
2	HD_LR_20_10_50	Low	+20% / +10%	+50%
3	HD_HR_20_10_50	High	+20% / +10%	+50%
4	HD_LR_20_10_25	Low	+20% / +10%	+25%
5	HD_HR_20_10_25	High	+20% / +10%	+25%

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2.2.4 Protocol clarifications

Three clarifications are needed to complete the protocol specification. First, geographical application: no changes are made to non-EU regions: the capacity-addition bounds, capacity-factor adjustments, CDD increases and cost-of-capital uplifts apply to EU member states only, under the hypothesis that the shocks impact the EU alone. Second, the post-shock period: from 2046 onwards, models revert to their default capacity-factor and CDD parameters, and the cost-of-capital and trade-price uplifts are removed. Third, carbon prices: the default NDC-LTT carbon-price trajectories are fixed in all model regions, not only the EU; a standard practice with counterfactual scenarios of this kind that reduces computational complexity while preserving the ambition-erosion treatment.

2.2.5 Reported output variables

Model outputs are reported in the IAMC data template. The core reporting set covers electricity capacity by technology, final energy by sector and carrier, and CO_2 emissions, as set out in Table 2. Teams report final energy at the greatest sectoral and carrier disaggregation their model supports.

Table 2. Required output variables (IAMC template).

Variable group	Variables
Electricity capacity	Capacity|Electricity, and by technology: Biomass, Coal, Gas, Oil, Solar, Wind, Geothermal, Hydro, Nuclear
Final energy	Final Energy; Final Energy|Electricity; final energy by sector and by carrier at the greatest available disaggregation (e.g. Final Energy|Industry|Electricity)
Emissions	Emissions|CO2|Energy and Industrial Processes; Emissions|CO2|Energy|Supply|Electricity

2.3 Derivation of disruption parameters

2.3.1 Climate-adjusted capacity factors

The capacity factor parameters quantify, for each EU member state, five-year period and technology, the relative change in achievable capacity factors attributable to a high-emissions climate signal; the proxy used here for sustained heatwave conditions. Two complementary derivations were used, harmonised into a single dataset.

For wind and solar PV, hourly capacity-factor projections at NUTS0 level were obtained from the Pan-European Climate Database (PECD 4.2) of the Copernicus Climate Data Store, derived from the CMCC-CM2-SR5 global climate model under multiple Shared Socioeconomic Pathways (Copernicus Climate Change Service, 2025). Annual mean capacity factors were computed per country, and the relative change between SSP5-8.5 (high emissions) and SSP2-4.5 (moderate mitigation) was taken as the climate penalty (or benefit) for each country, period and technology. The procedure is documented in Appendix A.

For thermal and hydroelectric generation, country-level climate stress indicators (mean temperature for thermal plants; consecutive dry days for hydro) were retrieved from the Copernicus Climate Data Store, based on the IPSL-CM5A-MR global climate model downscaled with the WRF381P regional model, under RCP8.5 and RCP4.5. Country-specific stress multipliers relative to the European average, bounded to the interval [0.70, 1.05], were applied to Europe-wide baseline capacity factors from van Vliet et al. (2016a), and the relative change between RCP8.5 and RCP4.5 was taken as the climate signal. The procedure is documented in Appendix B.

The resulting dataset, relative changes in capacity factors for offshore wind, onshore wind, solar PV, thermal and hydroelectric generation, for 37 European and neighbouring countries at five-year steps is provided to modelling teams. Models apply the relative changes to their own native baseline capacity factors, preserving each model's internal calibration.

2.3.2 Cooling degree days

Increased CDDs amplify electricity demand for space cooling in the residential and services sectors. The parameters are taken from HadCM3 projections under the SRES A2 scenario at NUTS0 level. All models adopt these CDD trajectories, translating them into additional cooling-service demand through their native demand formulations; where a model's regional structure is coarser than NUTS0, the parameters are aggregated as documented in Section 2.5.

2.3.3 Cost of capital

The financing channel applies a 20% increase in the cost of capital for the energy supply technologies affected by the heatwave, and a 10% increase for the rest of the economy, over the disruption window. Models implement this through their native financing or discount-rate structures, as an increase in technology-specific discount rates, hurdle rates or weighted average cost of capital, as applicable, as documented in Section 2.5.

2.3.4 Trade disruption parameters

The trade shock is implemented as a multiplier of +25% or +50% on the price of gas and electricity imported into the EU from outside the Union, over 2035-2045. Models without an explicit representation of extra-EU import prices implement the closest structurally consistent equivalent and document the deviation (Section 2.5).

2.4 Participating models

Two capacity-expansion IAMs participate in the exercise. They span two structural families in the long-term climate-economy modelling literature: perfect-foresight cost optimisation (OMNIA) and recursive-dynamic simulation (OPEN-PROM), a contrast that is exploited deliberately in the study design (Section 2.1).

2.4.1 OMNIA

OMNIA is a TIMES-family energy system optimisation model developed under the coordination of E4SMA, extending the earlier TIMES-GEO model architecture (Loulou et al., 2016). As a TIMES-based model, it is solved as a linear cost-optimisation problem under perfect foresight, yielding the least-cost technology mix and associated emissions trajectory for the energy system. OMNIA has global coverage, disaggregated into twenty-eight regions, three of which represent the European Union; long-term EU climate targets are additionally tracked at member-state level within the scenario design. The model is calibrated to a 2019 base year against UN energy balances and runs to 2050, with electricity and heat represented at a temporal resolution of twenty day-night and seasonal timeslices. Sectoral coverage spans upstream fuel supply and trade (including hydrogen and synthetic fuels), power, industry (aluminium, steel and cement through explicit process routes, other branches via a generic energy-service approach), residential and services, transport, and agriculture.

The power sector represents generation, transmission and distribution, and storage through a technology-rich set of centralised and decentralised thermal, combined heat-and-power, heat-only and renewable plant. New generation capacity is invested endogenously under cost optimisation, while existing plant retires according to data-driven, plant-specific decommissioning profiles. Wind and solar potentials are represented through tiered resource-quality supply curves, alongside hydrogen and ammonia co-firing options, carbon capture and pumped-hydro storage. Energy-service demands are formulated as exogenous, driver-based trajectories rather than price-elastic demand curves, combining primary socioeconomic drivers (population, GDP, GDP per capita) with sector-specific intermediate drivers, including heating and cooling degree days and an income- and CDD-dependent logit function for air-conditioning penetration, a structure directly relevant to the cooling-demand channel of the heatwave shock. Inter-regional trade in energy commodities, including electricity, is represented endogenously

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through import/export processes constrained by investment and operating costs and capacity bounds. For Europe, interregional electricity exchange limits are refined using transmission-network-constrained exchange patterns derived from a higher-resolution electricity-system model soft-linked to OMNIA. Cost of capital for power-sector technologies is defined as an explicit, technology-specific exogenous input, which provides the entry point for the financing channel of the protocol.

2.4.2 OPEN-PROM

OPEN-PROM is the open-source version of the PROMETHEUS model: a modular, recursive-dynamic, simulation-based IAM implemented in GAMS (Fragkos, Kouvaritakis and Capros, 2015; Fragkos, 2020). The model is developed under the coordination of the Institute of Communications and Computer Systems (ICCS). Within DIAMOND, spatial resolution was expanded to 39 countries and regions, with EU member states represented individually alongside major global economies, supporting detailed EU-level as well as global analysis (Mikropoulos et al., 2025). The model covers energy demand in industry (ten subsectors), buildings, transport (seven passenger and freight modes) and international bunkers, and energy supply through dedicated power, heat, hydrogen and other-fuels modules, together with carbon dioxide removal technologies.

The power supply module represents electricity generation through a technology-rich portfolio spanning fossil-fuelled plants with and without carbon capture and storage, nuclear, hydropower, onshore and offshore wind, solar PV and concentrated solar power, biomass, and combined heat-and-power units. It simulates capacity expansion and annual operation, with new investment allocated across competing technologies and accounts for technology lifetimes, premature scrapping and technology maturity factors; renewable generation is bounded by exogenous capacity-factor assumptions, the entry point for the supply-side channel of the heatwave shock. The resulting electricity price, based on average generation cost, feeds back to influence demand-side fuel choices. OPEN-PROM does not assume perfect foresight: each simulation year is solved recursively, with fuel and electricity prices cleared through an iterative, partial-equilibrium, myopic process, making it, among the participating models, the formulation in which the disruption arrives closest to a genuine surprise. Useful energy demand follows an econometric, top-down formulation driven by GDP, population, household income and industrial activity, moderated by lagged energy-price elasticities. Primary fuel prices, including natural gas, are derived from regional supply-cost curves or set exogenously; a static trade mechanism determines imports and exports from fixed historical ratios.

2.5 Model-specific implementation of the protocol

The protocol is specified at NUTS0 level and in terms of generic model structures; each team translated it into their model's native representation. This section documents the implementations and, where applicable, the deviations from the protocol and their rationale. Such documentation is essential for interpreting cross-model differences in the results: where models disagree, part of the explanation may lie in implementation rather than in model structure or behaviour.

2.5.1 OMNIA

- Capacity-addition cap (low resilience): The aggregate annual new-capacity additions of all power technologies, centralised and decentralised, are capped at their NDC-LTT (baseline) levels, with all technology types capped together, consistent with the protocol's total-capacity formulation.
- Capacity factors: The NUTS0 parameters were regionalised to OMNIA's EU regions, and the reduction (or increase) in capacity factor was applied by technology type and region, starting from the NDC-LTT baseline.

- Cooling degree days: The CDD values were regionalised and grouped for OMNIA's EU regions and used to adjust the trajectory of the secondary driver governing demand growth for the air-conditioning energy service in the residential and services sectors. A new demand trajectory was calculated incorporating the CDD variation relative to the NDC-LTT baseline demand.
- Cost of capital: The 20% increase was applied to electricity supply technologies by increasing their technology-specific discount rates. The 10% economy-wide increase was not applied, because the technology discount-rate attribute is defined only for power technologies in OMNIA. This is a documented deviation from the protocol.
- Trade shock: The +25%/+50% increase was applied as a multiplier on the natural gas, LNG and electricity inter-regional import prices faced by EU regions over 2035-2045. It should be noted that in the baseline scenario the inter-regional import prices in OMNIA are placeholders: an assessment of trade-price inputs by region was not part of the model updates within DIAMOND, and the trade-shock results should be interpreted with this caveat in mind.

2.5.2 OPEN-PROM

- Capacity-addition cap (low resilience): OPEN-PROM deviates from the protocol's total-capacity bound for a structural reason: the model combines exogenous drivers for energy-service demand with exogenous capacity factors, and its demand, though not fully inelastic, as substitution operates across sectors, is considerably less elastic than a fully price-elastic demand curve. When the heatwave simultaneously raises electricity demand (cooling) and lowers capacity factors, bounding the additions of all generation technologies renders the demand balance infeasible. The implementation therefore caps the aggregate annual new-capacity additions of the heatwave-affected conventional technologies at their NDC-LTT levels, i.e. hydro (large and small), nuclear, and thermal (hard coal, lignite, natural gas, oil, biomass and waste, and their CCS variants), while wind (onshore, offshore) and solar (PV, CSP) remain uncapped and absorb the residual demand. This required a small upward adjustment of the renewables' maturity parameters to open sufficient deployment headroom within the disruption window.
- Trade shock:
    - Gas: applied. The +25%/+50% increase is applied as a multiplier on the natural gas price faced by EU member states over 2035-2045; OPEN-PROM uses a single gas price rather than a separate imported-gas price, and since EU gas supply is predominantly imported, this was judged the structurally consistent implementation.
    - Electricity: not applied. OPEN-PROM solves each region independently and has no inter-regional electricity-trade price, so the imported-electricity price shock cannot be represented. The only electricity-cost effect captured is indirect, through the higher gas price raising the cost of gas-fired generation. This is a documented deviation from the protocol.

2.6 Methodological limitations

Several limitations qualify the interpretation of the results and should be kept in mind throughout Section 3.

First, the cascade from power-sector stress to end-use electrification (RQ2) is assessed through the models' internal, annual-average responses. None of the participating models resolves sub-annual operational reliability (e.g., price spikes, scarcity events or non-served energy) so the end-use consequences of short-lived operational stress are captured only insofar as they are reflected in annual prices and quantities. The cascading-impact estimates should therefore be read as conservative lower bounds on operational-stress effects.

Second, the heatwave is represented through sustained, decade-long parameter changes (derated capacity factors, elevated CDDs and financing costs) rather than as discrete extreme events. This storyline treatment captures the persistent component of compound heat stress but not its interannual peaks; the capacity-factor derating is itself derived from the difference between high-emissions and moderate-mitigation climate projections, a scenario-difference proxy rather than an event-based measure.

Third, the foresight assumptions of the participating models differ, and this materially affects how each model experiences the shock. OMNIA's perfect-foresight optimisation anticipates the 2035-2045 window and pre-positions investment accordingly; OPEN-PROM, being recursive-dynamic, responds only as the shock unfolds. Rather than a defect, this diversity is treated as an informal sensitivity analysis on foresight, but individual-model results must be interpreted in light of it.

Fourth, the trade shock is an exogenous price uplift, not an endogenous representation of geopolitical supply reallocation, e.g., general-equilibrium adjustments through global LNG markets, which have been shown to attenuate such shocks substantially (Albrizio et al., 2025), are outside the scope of the participating models' trade structures.

Fifth, implementation deviations documented in Section 2.5, notably the absence of the economy-wide cost-of-capital uplift in OMNIA and of the imported-electricity price shock in OPEN-PROM, mean the ensemble is not perfectly harmonised; cross-model differences partly reflect these implementation asymmetries.

Sixth, the country-level capacity-factor relative-change series inherit substantial interannual variability from the underlying climate projections. Over 2025-2045 the difference between the high-emissions and moderate-mitigation trajectories is small relative to internal climate variability, so the wind and solar series in particular hover around zero and are non-monotonic in time and across countries. This signal-to-noise caveat is documented rather than smoothed away (the thermal and hydro indicators are five-year smoothed at source; see Appendix B). A related nuance interacts with foresight: in a perfect-foresight optimisation, investment decisions integrate over technology lifetimes and thereby dampen year-to-year capacity-factor fluctuations, potentially muting the visible response relative to a myopic model, while operational decisions still reflect the year-specific values. How each model responds to the climate-driven capacity-factor shocks is therefore itself a model-structure comparison, and is treated as such in Section 3.3.

Finally, the disruption parameters are applied to EU member states only, so global spillovers, for example, disruption-induced changes in world fuel prices feeding back into EU markets, are not represented beyond each model's native global dynamics.

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3 Analysis and results

This section presents results from the scenario ensembles: OPEN-PROM at member-state resolution and OMNIA at the resolution of its three EU regions.

Three presentation rules apply throughout. First, each model is shown at its native regional resolution, and cross-model comparison is by sign and shape, rather than by level. Second, every figure axis is relative, percentage change versus Ref, an index with Ref = 1, or percentage-point changes for shares, with absolute values available in the workbook underpinning each figure. Third, percentage changes in power-sector CO_2 are masked where the reference level falls below 1 Mt CO2/yr, because relative measures lose meaning as the denominator approaches zero in deeply decarbonised country-years. Trade effects are reported only as the difference between the two trade-shock levels, conditional on the rest of the compound (Section 2.2).

Member-state conclusions rest on OPEN-PROM: it resolves the 27 member states individually and, being recursive-dynamic, experiences the disruption without anticipating it. OMNIA complements rather than replicates this evidence. It reports three EU regions rather than member states; it solves under perfect foresight and therefore adjusts before the window opens (Section 3.1). Its results are therefore shown alongside the NUTS0 models as corroborating regional evidence, in the forms its structure supports.

3.1 Power sector robustness under compound disruption (RQ1)

Figure 1 shows, for the two scenario pairs, the distribution across the 27 member states of the change in total electricity capacity relative to Ref. Capacity first rises above Ref in 2035, as reduced capacity factors and additional cooling demand call for more plants: in the full compound scenario with the 50% trade shock, the cross-country median peaks at +3.6% under LR (Low Resilience). It then declines through the window to a trough around 2040 and recovers after the disruption ends. The distribution, not the median, provides insights here: the cross-country interquartile range reaches roughly five percentage points in 2040, with Romania and Bulgaria at the positive extreme and Finland, the Netherlands and Belgium at the negative one.

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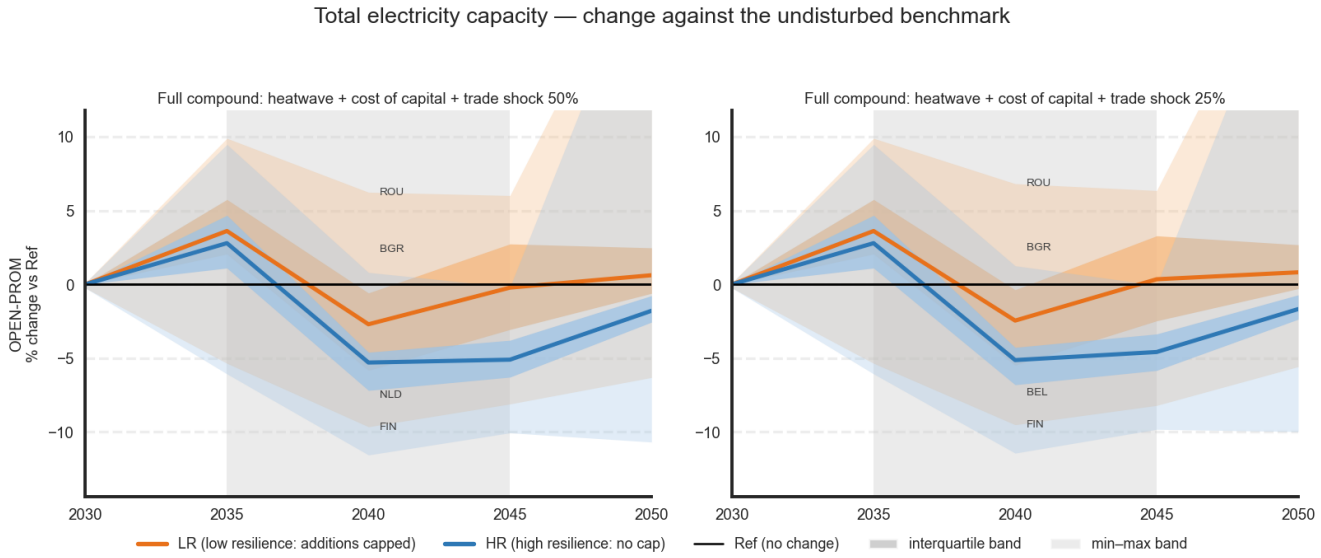

Figure 1. Total electricity capacity across the two scenario pairs (change versus Ref (%), distribution across the 27 EU member states (OPEN-PROM, LR and HR)).

Fans show the median, interquartile and min–max bands; LR extremes are labelled in 2040. One common robust y-scale applies across all panels (5th–95th percentile pooled across pairs), so band extremes can exceed the scale (values in the accompanying data workbook). The disruption window (2035–2045) is shaded. Pronounced impacts are illustrated in labelled member states: BEL Belgium; BGR Bulgaria; FIN Finland; NLD Netherlands; ROU Romania.

OMNIA's regional parallel (Figure 2) corroborates the trough and the recovery: every region bottoms out at 2040 and recovers by 2045 to 2050, with the HR trough being deeper than the LR one (EUE −3.9%, EUM −12.8%, EUW −8.8% under HR at 2040 in the 50% pair - EUE eastern, EUM Mediterranean, EUW western EU aggregate regions). Two qualifications follow. OMNIA shows no rise above the benchmark at 2035, apart from EUW under HR at +1.6%, so the early build-up belongs to OPEN-PROM alone. And EUM sits 4.1% below the benchmark already in 2030, which is perfect-foresight anticipation rather than disruption response, so its whole path reads as offset.

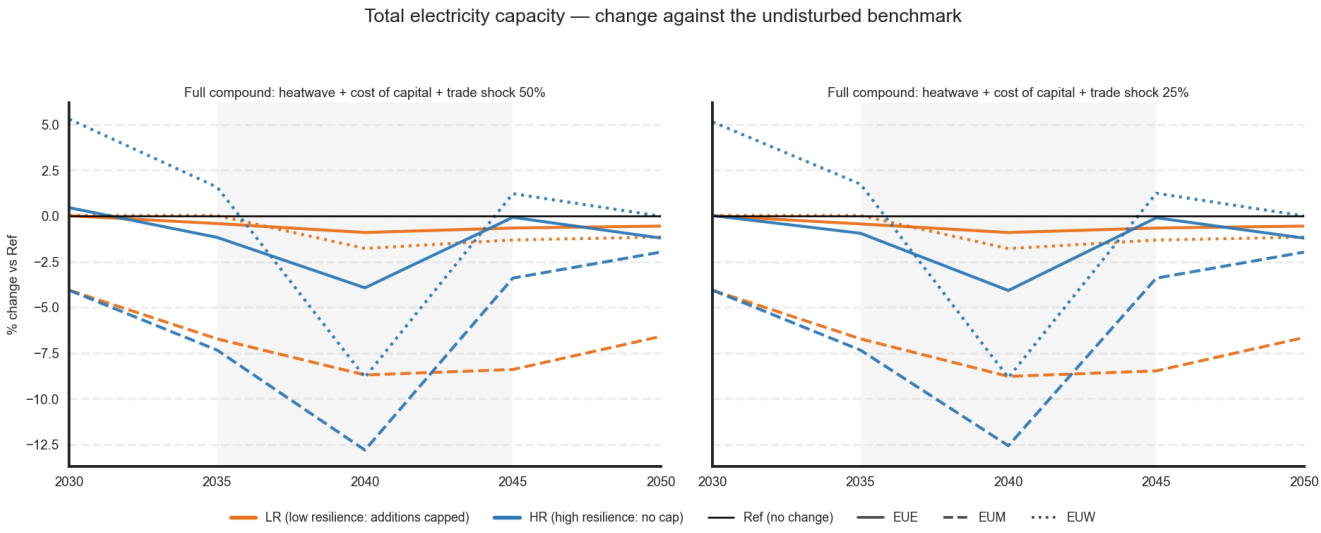

Figure 2. Total electricity capacity, OMNIA regions, change versus Ref (%), one line per region per configuration, one column per scenario pair.

The disruption window (2035–2045) is shaded. Region codes: EUE eastern, EUM Mediterranean, EUW western EU aggregate regions, as delivered.

The resilience configuration determines not how much capacity survives, but on which margin the system adjusts.

Figure 3 reports, for each member state, the resilience gap: the change under HR minus the change under LR, in points of percentage change versus Ref, for total capacity in 2040 in the full compound pair. A positive gap would mean that the flexible system ends the window with more capacity than the capped one; the data show the opposite almost everywhere (cross-country median around −2.4 points, Malta approximately −7). The two systems solve different problems: the capped (LR) system cannot reshape its build programme, so it holds on to what it has and runs it harder; the flexible (HR) system re-optimises and replaces part of the lost output with a smaller fleet of better-suited plants. Lifting the capacity bound therefore does not appear as additional installed capacity; its value appears in emissions, as the next paragraphs show.

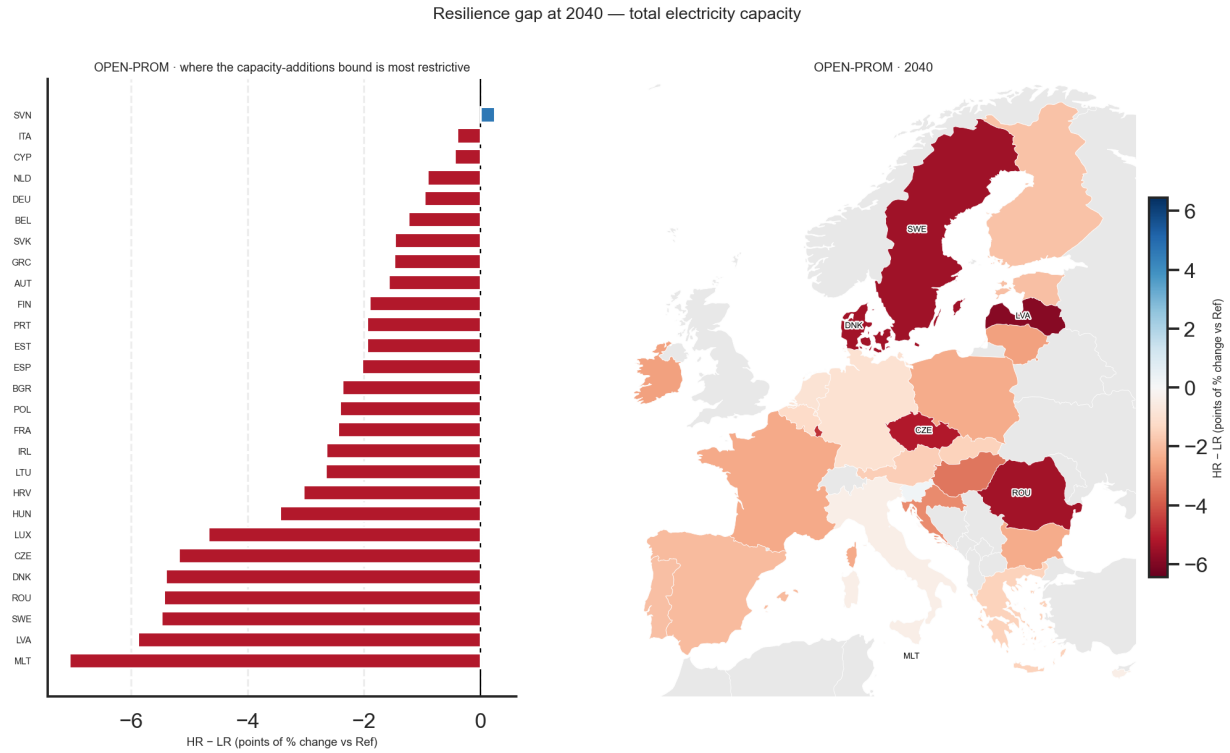

Figure 3. Resilience gap in 2040 of total electricity capacity based on OPEN-PROM

HR − LR in points of percentage change versus Ref, full compound pair with the 50% trade shock (OPEN-PROM member states; sorted bars and map). The summary statistic is the median across member states of the country-level HR − LR gap. Negative values indicate that the flexible (HR) system holds less capacity through the disrupted window than the capped (LR) one. Member states shown (all 27): AUT Austria; BEL Belgium; BGR Bulgaria; CYP Cyprus; CZE Czechia; DEU Germany; DNK Denmark; ESP Spain; EST Estonia; FIN Finland; FRA France; GRC Greece; HRV Croatia; HUN Hungary; IRL Ireland; ITA Italy; LTU Lithuania; LUX Luxembourg; LVA Latvia; MLT Malta; NLD Netherlands; POL Poland; PRT Portugal; ROU Romania; SVK Slovakia; SVN Slovenia; SWE Sweden. In the map, red marks negative gaps (HR below LR) and blue positive ones.

The OMNIA parallel (Figure 4) shows the same sign in all three regions: gaps of −3.0 (EUE), −4.1 (EUM) and −7.1 (EUW) points in 2040 in the 50% pair, median −4.1. The gaps are essentially unchanged at the 25% trade level (−3.2, −3.8 and −7.1), so the negative gap is a property of the capacity bound rather than of the trade intensity.

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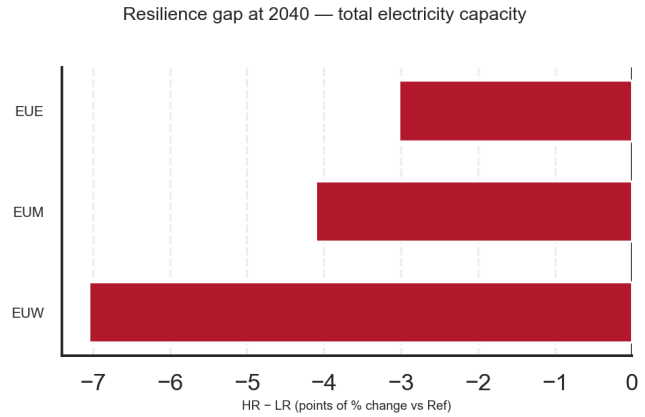

Figure 4. Resilience gap in 2040 of total electricity capacity based on OMNIA

HR − LR in points of percentage change versus Ref, OMNIA regions, full compound pair with the 50% trade shock. Negative values indicate that the flexible (HR) system holds less capacity through the disrupted window than the capped (LR) one. Values for the 25% pair are in the accompanying workbook. EUE eastern, EUM Mediterranean, EUW western EU aggregate regions.

The value of resilience appears instead in emissions. In 2040 and in the same scenario, the cross-country median increase in power-sector CO_2 is +31% under LR against +6% under HR (member states with reference emissions below 1 Mt CO_2/yr masked; 14 of 27 retained). The low-resilience configuration is constrained to its benchmark build programme. It compensates for lost output by running its existing, disproportionately fossil, fleet harder. High resilience converts the same physical shock into an investment response rather than an emissions response.

The two trade-shock levels support one clean comparison (Figure 5): the compound effect against Ref at each level, and the difference between the two levels, which isolates the effect of intensifying the trade shock from 25% to 50%, conditional on the rest of the compound. The individual channels within the compound are not separately identifiable in the presented set (Section 2.2). For OPEN-PROM in 2040, the compound raises power-sector CO_2 by around +30 points at the cross-country median under LR at either trade level, against +5 to +6 points under HR. The trade-intensification increment is an order of magnitude smaller: below one point at the median in both configurations. The stress within the compound therefore does not come from the trade price level. In OMNIA, expressed in absolute terms (Figure 5, left), the compound deviations are small, within roughly 3.5 Mt CO2/yr across its regions in 2040 and about 5 Mt in 2045, and the trade-intensification increment is negligible, at 0.2 Mt or less.

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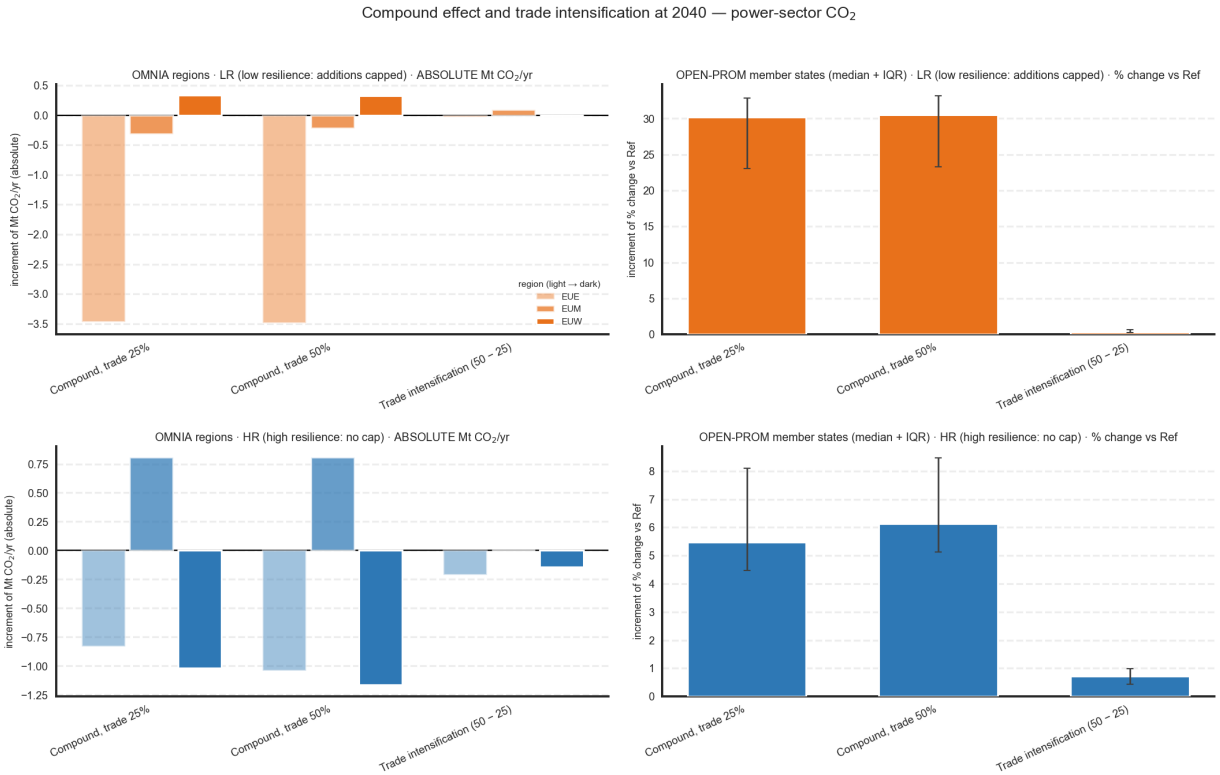

Figure 5. Compound effect and trade intensification, power-sector CO_2 in 2040

LR (top) and HR (bottom). Bars: the compound change versus Ref at the 25% and 50% trade levels, and the trade-intensification increment (50 minus 25). Left: OMNIA's three EU regions, in absolute Mt CO2/yr, since regional reference emissions approach zero under BECCS, making percentage increments arithmetically unstable. Right: OPEN-PROM member states (median across member states, interquartile whiskers), in % change versus Ref. Note the differing units across the two blocks. Region codes: EUE, EUM and EUW are OMNIA's eastern, Mediterranean and western EU aggregate regions, as delivered.

Figure 6 maps the member-state pattern through time under both configurations (LR and HR rows, one shared colour scale): widespread increases are observed in power-sector CO_2 in the magnitude of 20-45% for the 2040–2045 period—strongest in Sweden, Denmark, Romania and Bulgaria in 2040—and fading by 2050 once the disruption has passed. Under HR the same maps remain pale, with increases rarely exceeding roughly 10%, making the value of the flexible configuration directly visible. OMNIA's three EU regions, shown beside the maps, corroborate the direction inside the window in 2040 but approach zero reference emissions thereafter; its power sector reaches near-zero net CO_2 in the 2040s under BECCS deployment, so its late-window percentage responses are dominated by small denominators and its decomposition is meaningful only in absolute terms. OMNIA also anticipates: solving under perfect foresight, its mean absolute divergence from Ref in 2030 across the headline metrics is 2.8 percentage points, against effectively zero for the recursive-dynamic OPEN-PROM. Notably, this anticipation appears almost exclusively under HR: under LR, the capacity-additions cap suppresses pre-building. Both behaviours are accepted as features of the delivered perfect-foresight implementation.

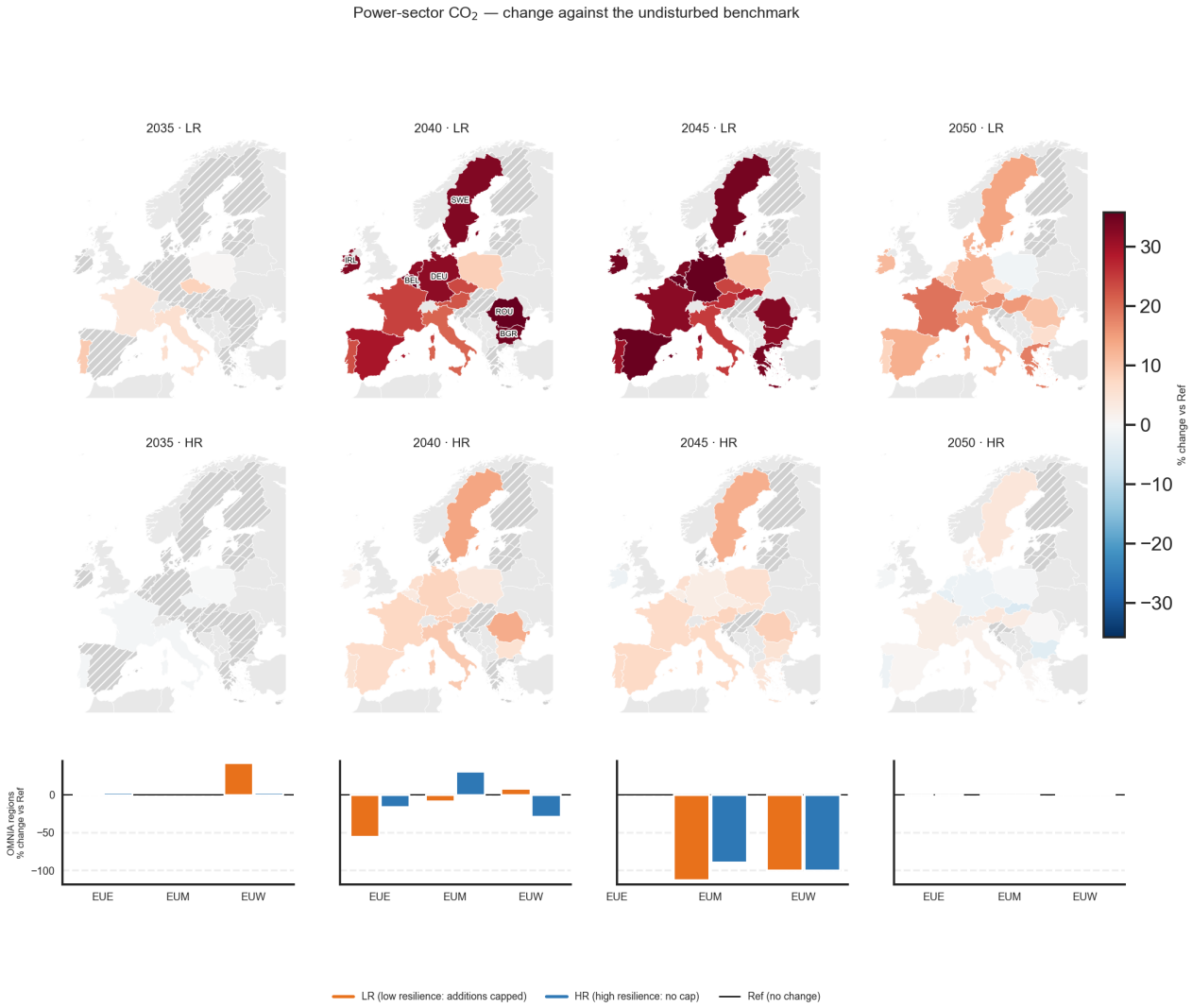

Figure 6. Power-sector CO_2 percentage change versus Ref under the full compound pair (50% trade shock).

Rows 1 and 2: LR and HR map strips, OPEN-PROM member states, 2035-2050, on one shared colour scale; hatching masks countries with reference emissions below 1 Mt CO2/yr; non-EU countries in grey; labels mark the six most affected member states at 2040 (LR row). Row 3: OMNIA's three EU regions (LR orange, HR blue). Labelled member states: BEL Belgium; BGR Bulgaria; DEU Germany; IRL Ireland; ROU Romania; SWE Sweden.

3.2 Cascading impacts on end-use electrification (RQ2)

The cascade from the power sector to end-use electrification is small at the member-state median. Even under the full compound scenario with the 50% trade shock, the median change in the electricity share of final energy in 2040 is −0.8 percentage points under LR, and smaller under HR; every member state falls within roughly −1.5 to −0.3 points. Figure 7 shows the sectoral pattern: small, consistently negative changes across nearly all countries and end-use sectors, with the largest retreats concentrated in a handful of member states (Luxembourg, Greece, Cyprus) and, from a sectoral perspective, in industry. Electrification of end-use demand changes little under this compound disruption, even as the power sector supplying that electricity comes under substantial stress. OMNIA is omitted from Figure 7 because its three-region resolution cannot be displayed at member-state level.

The OMNIA parallel (Figure 8) confirms the stickiness at regional resolution: all nine region and sector cells under LR move within ±1.3 percentage points. The sign is not uniform. EUE shifts electrification upward in all three sectors (+0.1 to +0.8 points), and EUW industry under HR falls by 4.7 points, the one place in either model where

electrification stalls outright.

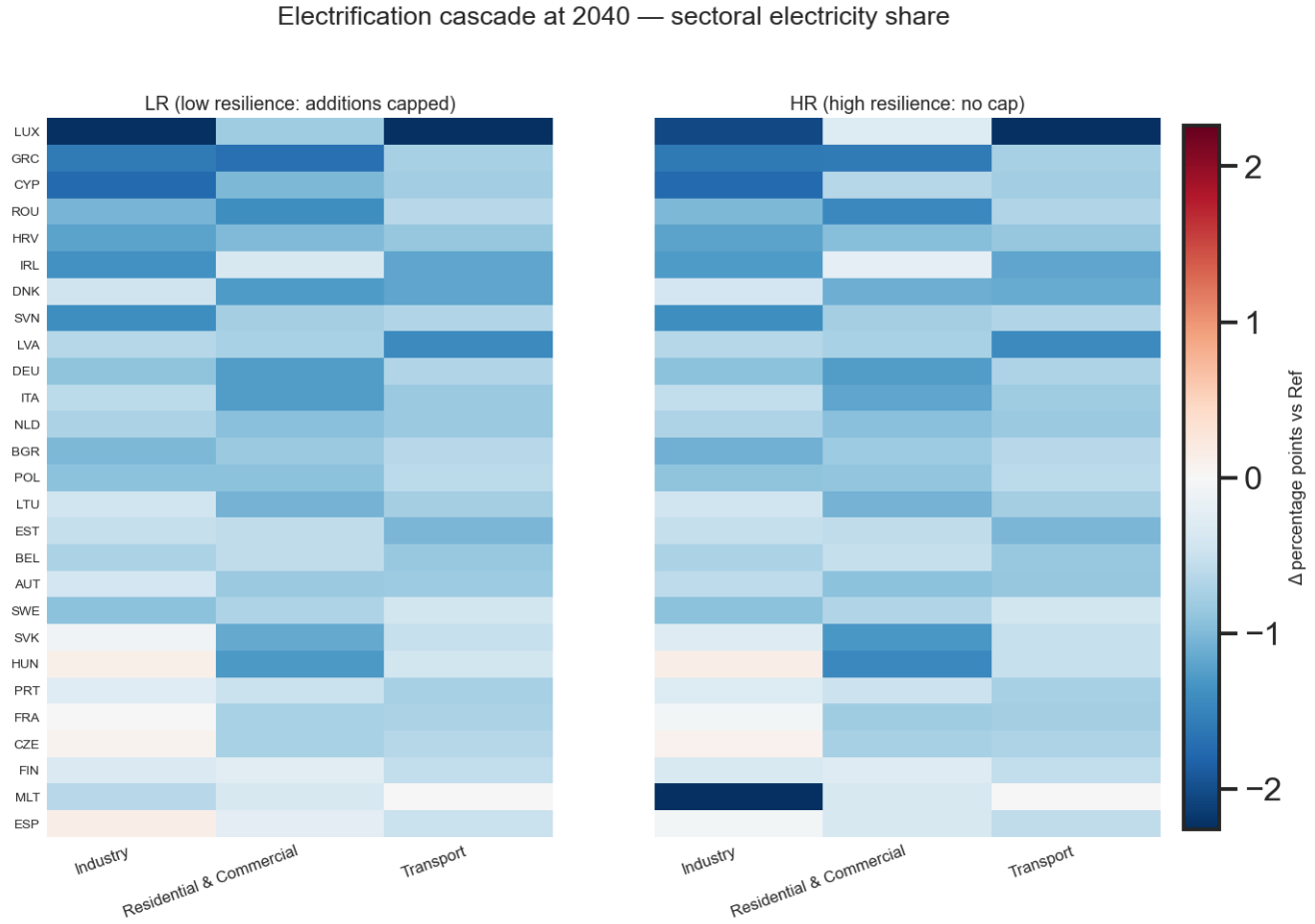

Figure 7. Change in the sectoral electricity share of final energy (percentage points versus Ref) in OPEN-PROM under the full compound pair (50% trade shock)

OPEN-PROM member states, LR (left) and HR (right). Member states as listed in the caption of Figure 3.

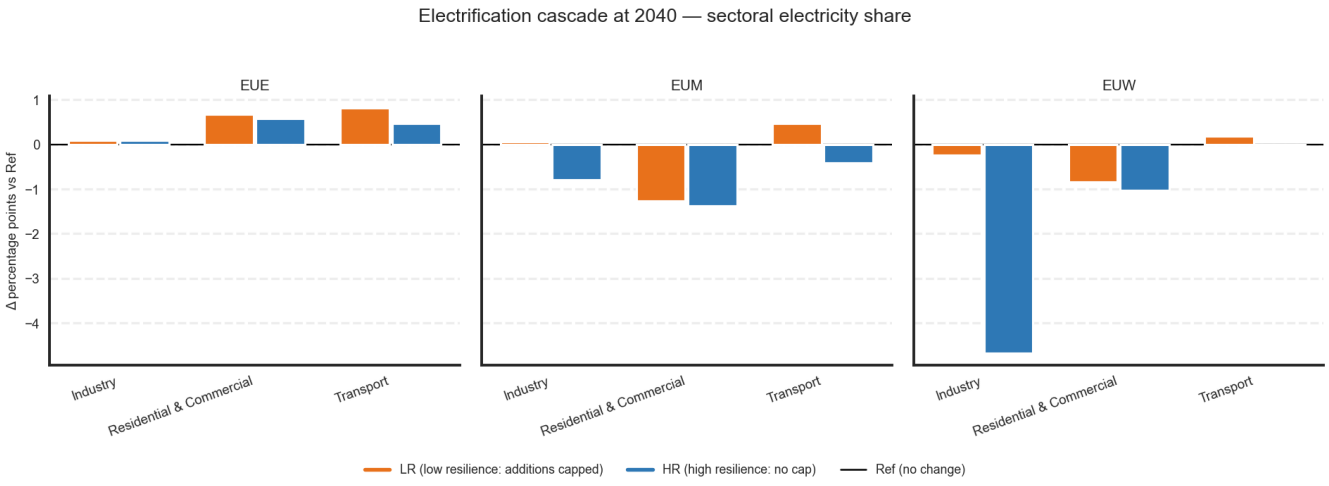

Figure 8. Change in the sectoral electricity share of final energy (percentage points versus Ref) in OMNIA under the full compound pair (50% trade shock)

This stickiness must be read with the limitation set out in Section 2.6. The participating models resolve annual averages, so the cascade estimated here excludes the effect of short-lived operational stress, price spikes and

reliability events, on electrification choices. The result is therefore a conservative lower bound: end-use electrification is robust to the compound disruption as represented in annual-average terms, while sub-annual channels remain outside the protocol.

3.3 Cross-model comparison and robustness

Where the models can be compared, by sign and shape at their native resolutions, they agree on the essentials of RQ1 and RQ2. They produce the rise-trough-recovery capacity dynamic around the disruption window; and show the low-resilience configuration paying for the shock in emissions rather than capacity; as well as end-use electrification barely moving. The clearest remaining disagreement sits in the trade-intensification increment: raising the trade shock from 25% to 50% nudges OPEN-PROM's power-sector CO_2 up, by below one point at the 2040 median, while OMNIA's regional responses are negligible and slightly negative in absolute terms. The increment is small in both models. The disagreement is about sign at the margin, not about magnitude.

Two structural differences must inform any reading of cross-model differences. The first is foresight: OMNIA anticipates the window (Section 3.1), so its in-window responses are flatter, and part of its adjustment occurs before 2035; OPEN-PROM responds only as the shock arrives. The second is fleet composition. In 2030 under Ref, the EU-summed capacity is 2,407 GW in OMNIA against 1,298 GW in OPEN-PROM, a factor of 1.9, while generation and final energy sit far closer; the implied fleet-average capacity factors are 0.22 and 0.28 respectively, reflecting OMNIA's substantially more solar- and wind-heavy pathway (around 2 TW of PV by 2040, from a 2024 base consistent with the observed EU fleet). These are provided in reference tables in this deliverable; but composition differences of this kind can colour even relative responses, a solar-heavy fleet has more low-capacity-factor gigawatts to shed per unit of lost generation, which is why cross-model comparison here is confined to sign and shape.

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4 Conclusions

On RQ1, the compound disruption stresses the EU power sector substantially, while intensifying the trade shock from 25% to 50% adds little on top: i.e., within the compound, the stress does not come from the trade price level. The techno-economic resilience configuration determines the margin on which the system adjusts rather than the size of the shock it absorbs: a capacity-constrained system defends its installed base and pays in emissions, a median member-state increase in power-sector CO_2 of +31% versus the benchmark in 2040, against +6% when capacity can respond freely, while a flexible system sheds capacity, rebuilds around the derating, and defends decarbonisation. Cumulatively over 2035-2050 in the 50% compound scenario, the capped system emits some 290 Mt CO_2 more than the benchmark from the EU power sector, against under 50 Mt when capacity responds freely (OPEN-PROM, EU sum); OMNIA's cumulative deviations are small in absolute terms and lie below the benchmark (−22 Mt under LR, −31 Mt under HR) against a near-zero, BECCS-dominated reference. Because carbon prices are fixed at benchmark levels throughout, these responses measure ambition erosion, not policy relaxation.

On RQ2, the cascade from power-sector stress to end-use electrification is weak at the member-state median: electricity shares of final energy move by less than a percentage point in nearly every member state even under the strongest compound scenario. Electrification is a robust margin of EU mitigation pathways under compound stress. The conclusion is bounded below by the models' annual-average resolution, which excludes sub-annual reliability and price-spike channels by construction.

In future work, the natural next step would be to pass the scenario capacity mixes and demand levels to an hourly dispatch model for an annual snapshot, under domestic-priority and renewable-priority configurations. This would allow extracting results on wholesale prices, cross-border flows, curtailment and non-served energy back into the assessment of end-use electrification. This would test directly the sub-annual reliability channel that annual-average results exclude by construction.

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Appendix A — Wind and solar PV capacity factor parameters

A.1 Data acquisition

Hourly projections of renewable-energy capacity factors were obtained from the Copernicus Climate Data Store (CDS), operated by the European Centre for Medium-Range Weather Forecasts (ECMWF) under the Copernicus Climate Change Service (C3S). The dataset used is Climate and energy related variables from the Pan-European Climate Database (PECD) derived from reanalysis and climate projections, version PECD 4.2.

The data correspond to future climate projections produced with the CMCC-CM2-SR5 global climate model and bias-adjusted to the European domain. Four Shared Socioeconomic Pathways (SSPs) were included: SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5. The PECD provides harmonised, energy-relevant indicators derived from climate-model outputs at country-level (NUTS0) spatial resolution and hourly temporal resolution.

Two variable groups were extracted: wind_power_onshore_capacity_factor and wind_power_offshore_capacity_factor, each for Resource Grade B and Technological specifications 20 and 30 (existing technologies); and solar_photovoltaic_generation_capacity_factor for Technological specification 61 (residential rooftop PV). The data span 2020–2100 in five-year increments, covering the full European region. The Copernicus open licence applies, permitting unrestricted scientific reuse with attribution.

A.2 Data pre-processing

Hourly country-level (NUTS0) capacity-factor time series were ingested from the Copernicus PECD 4.2 downloads (CSV format) for wind (onshore and offshore, existing technologies) and solar PV (residential rooftop), spanning selected years between 2020 and 2100 across SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5. Each CSV contains a metadata block followed by a date-headed table. For each file: (i) the metadata were parsed to retain only fields pertinent to modelling (title/technology, unit, temporal and spatial resolution, temporal coverage, resource grade where applicable, and the CMIP6 origin including SSP); (ii) column headers were harmonised by stripping offshore suffixes and mapping NUTS0 acronyms (e.g. EL, UK, XK) to full country names; and (iii) annual mean capacity factors were computed per country by averaging hourly values (missing values ignored). Outputs are organised per technology as Excel workbooks containing a metadata sheet (one row per input file) and an annual sheet in tidy form (technology, SSP, year, country, mean capacity factor), with optional SSP-specific wide matrices for quick inspection.

A.3 Relative change calculation

To isolate the climate impact of emission-pathway choice, capacity factors were processed for both SSP5-8.5 (high emissions) and SSP2-4.5 (moderate mitigation) from the CMCC-CM2-SR5 model. The relative change in capacity factors was calculated as:

$$\Delta_{c,y,t} = \frac{\mathrm{CF}_{c,y,t}^{\mathrm{SSP5\text{-}8.5}} - \mathrm{CF}_{c,y,t}^{\mathrm{SSP2\text{-}4.5}}}{\mathrm{CF}_{c,y,t}^{\mathrm{SSP2\text{-}4.5}}}$$

where $\Delta_{c,y,t}$ is the fractional change in capacity factor for country c, year y and technology t (offshore wind, onshore wind or solar PV) between the two emission scenarios. This metric quantifies the climate penalty or benefit from higher emissions relative to a moderate-mitigation baseline, enabling consistent treatment with the thermal and hydroelectric capacity factors (which use RCP8.5 versus RCP4.5).

The resulting spatial patterns are shown in Figures A.1–A.3.

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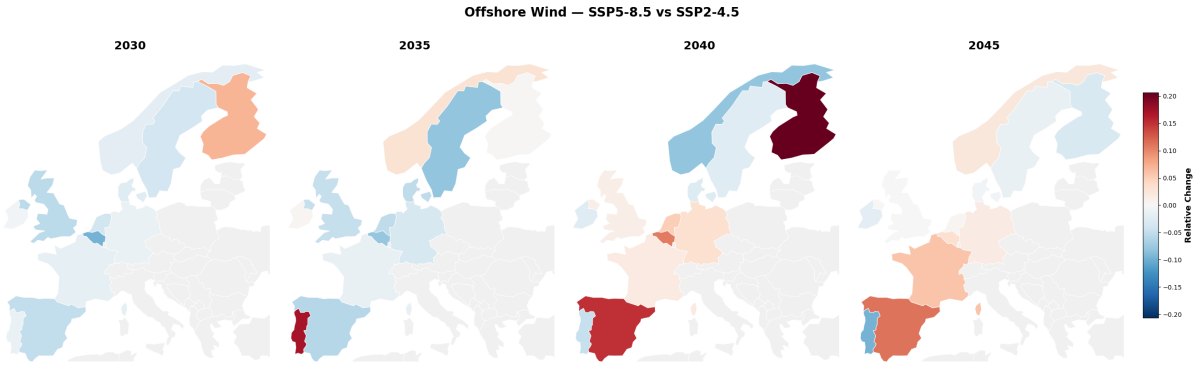

Figure A.1. Relative change in offshore wind capacity factors between SSP5-8.5 and SSP2-4.5 emission scenarios for 2030, 2035, 2040 and 2045.

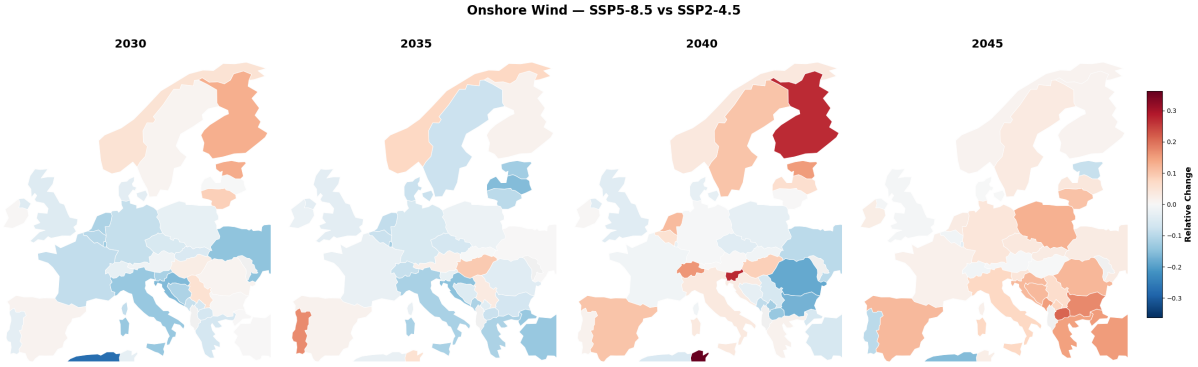

Figure A.2. Relative change in onshore wind capacity factors between SSP5-8.5 and SSP2-4.5 emission scenarios for 2030, 2035, 2040 and 2045.

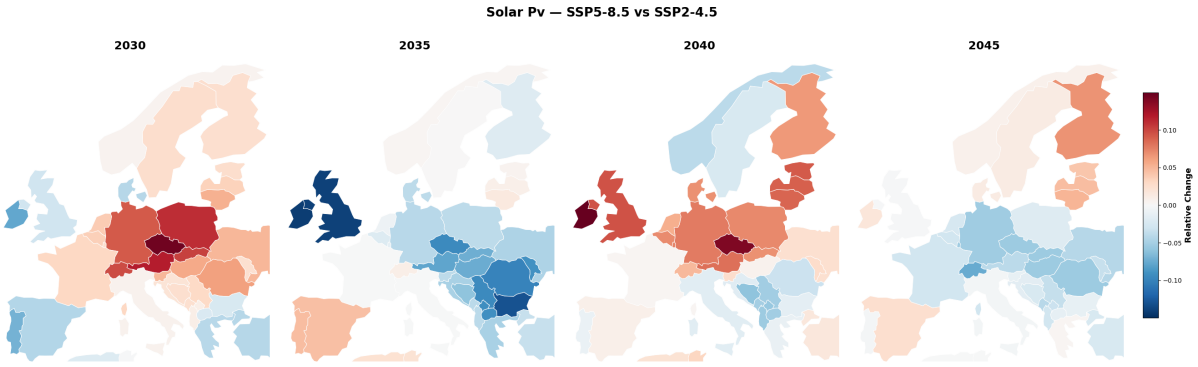

Figure A.3. Relative change in solar photovoltaic capacity factors between SSP5-8.5 and SSP2-4.5 emission scenarios for 2030, 2035, 2040 and 2045.

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Appendix B — Thermal and hydroelectric capacity factor parameters

B.1 Data acquisition

Country-level climate stress indicators were retrieved from the Copernicus Climate Data Store (CDS) on 30 October 2025 to quantify climate impacts on thermal and hydroelectric generation capacity. Two separate datasets were acquired:

Thermal plant indicators. Variables included mean temperature, cooling degree days, hot days (>35°C threshold) and climatological heatwaves. Data originated from the IPSL-CM5A-MR global climate model downscaled with the WRF381P regional climate model (ensemble member r1i1p1). Experiments covered the RCP4.5 and RCP8.5 scenarios with yearly temporal aggregation at NUTS0 (country-level) spatial resolution across Europe.

Hydroelectric indicators. Variables included consecutive dry days, duration of meteorological droughts and magnitude of meteorological droughts. The model chain, scenarios, ensemble member and spatial–temporal aggregation matched the thermal plant indicators.

All data span 1951–2100 at annual resolution and are provided as NetCDF files. Two emission scenarios were processed to calculate relative climate impacts: RCP8.5 (high emissions) and RCP4.5 (moderate mitigation), enabling isolation of the climate-change signal by comparing capacity factors under divergent emission pathways.

B.2 Data pre-processing

Each NetCDF file was processed to: (i) extract the primary data variable (e.g. tasAdjust for temperature in Kelvin, cdd for consecutive dry days, dmd for drought metrics); (ii) parse temporal coordinates to extract calendar years; and (iii) map NUTS0 acronyms to full country names using a standardised dictionary, with ISO alpha-2 codes assigned to non-EU countries without official NUTS codes. Data were consolidated into a unified dataframe with columns: NUTS code, country, year, variable, scenario, value and technology (thermal/hydro).

The dataset was filtered to: (i) the RCP8.5 scenario (matching the emissions pathway of the Europe-wide baseline capacity factors from van Vliet et al., 2016a); (ii) target years 2020–2100 in five-year increments (aligning with the wind and solar projections); and (iii) two key indicators: mean temperature (°C) for thermal plants and consecutive dry days (days/year) for hydroelectric plants. These indicators most directly reflect water-availability constraints for cooling systems and streamflow-dependent generation, respectively.

Annual climate indicator values were smoothed using a five-year centred rolling average to reduce interannual weather variability whilst preserving the underlying climate trend. For thermal generation, a level-based anomaly was applied (absolute temperature difference: country temperature minus European average temperature, in °C) rather than a warming-rate anomaly, as cooling-system stress depends on proximity to discharge-temperature thresholds, not the rate of warming. Mediterranean countries with higher absolute temperatures thus receive downward adjustments, whilst Nordic countries remain less thermally stressed despite faster warming rates. For hydroelectric generation, a normalised differential anomaly was applied, comparing each country's relative change in consecutive dry days against the European average relative change. The pre-processing workflow is shown in Figure B.1.

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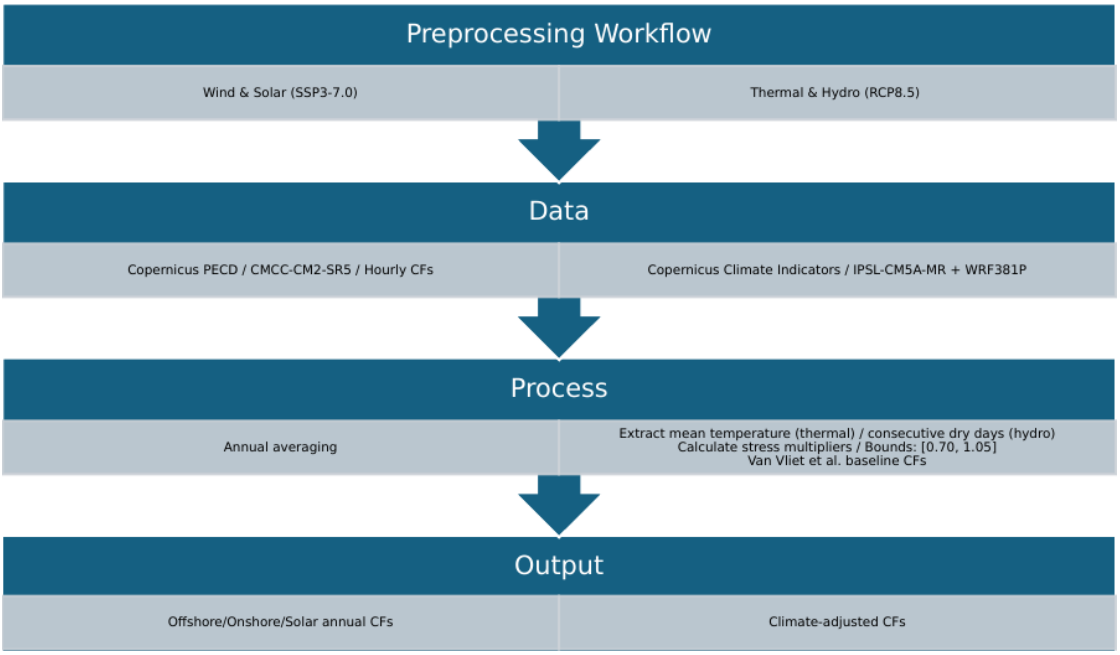

Figure B.1. Pre-processing workflow.

B.3 Mathematical formulation

For each indicator I, year y and technology t, the European regional average across all $N = 37$ countries (EU member states and neighbouring regions) was calculated:

$$\bar{I}_{y,t} = \frac{1}{N}\sum_{c=1}^{N} I_{c,y,t}$$

Country-specific stress multipliers were computed as:

$$M_{c,y,t} = \frac{\bar{I}_{y,t}}{I_{c,y,t}}$$

where $M_{c,y,t}$ is the stress multiplier for country c, year y and technology t; $\bar{I}_{y,t}$ is the European regional average of the climate indicator; and $I_{c,y,t}$ is the climate indicator value for country c. For thermal plants, $I_{c,y,\text{thermal}}$ is the mean annual temperature (°C); for hydro plants, $I_{c,y,\text{hydro}}$ is the annual consecutive dry days (days/year).

This inverse formulation ensures that countries experiencing above-average climate stress (more heatwaves or dry days) receive capacity-factor reductions ($M < 1$), while countries with below-average stress receive increases ($M > 1$). Multipliers were bounded to prevent extreme outliers:

$$M_{c,y,t}^{\text{bounded}} = \text{clip}\left(M_{c,y,t},\ 0.70,\ 1.05\right)$$

This asymmetric bounding ensures that no country loses more than 30% of the baseline capacity factor (lower bound 0.70), whilst recognising that climate change rarely improves thermal or hydroelectric generation capacity (upper bound 1.05). Comparison across alternative climate stressors confirmed mean temperature and consecutive dry days as the most stable indicators with the highest signal-to-noise ratios (Figures B.4 and B.5).

B.4 Baseline capacity factors

Europe-wide baseline capacity factors for hydroelectric (0.45) and thermoelectric generation (0.75) were sourced from van Vliet et al. (2016a), which provides RCP8.5 projections showing reductions of 0.7% (hydro) and 8%

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(thermal) by the 2020s (2020–2039 average), and 4.2% (hydro) and 15% (thermal) by the 2050s (2040–2069 average). These projections were linearly interpolated to derive EU-wide baseline capacity factors for each five-year time step between 2020 and 2100:

$$\mathrm{CF}_{\mathrm{EU},y,t}^{\mathrm{baseline}} = \begin{cases} \mathrm{CF}_{2030,t} & \text{if } y \leq 2030 \\ \mathrm{CF}_{2030,t} + \dfrac{y-2030}{2060-2030}\left(\mathrm{CF}_{2060,t} - \mathrm{CF}_{2030,t}\right) & \text{if } 2030 < y < 2060 \\ \mathrm{CF}_{2060,t} & \text{if } y \geq 2060 \end{cases}$$

where $\mathrm{CF}_{2030,\mathrm{hydro}} = 0.44685$, $\mathrm{CF}_{2060,\mathrm{hydro}} = 0.43110$, $\mathrm{CF}_{2030,\mathrm{thermal}} = 0.6885$ and $\mathrm{CF}_{2060,\mathrm{thermal}} = 0.6360$.

B.5 Climate-adjusted capacity factors

Country-specific capacity factors were calculated as:

$$\mathrm{CF}_{c,y,t} = \mathrm{CF}_{\mathrm{EU},y,t}^{\mathrm{baseline}} \times M_{c,y,t}^{\mathrm{bounded}}$$

Outputs are organised as Excel workbooks containing: NUTS0 code, country name, year, technology, scenario comparison (RCP8.5 versus RCP4.5), baseline capacity factor (RCP4.5), high-emission capacity factor (RCP8.5), and relative change. This format directly quantifies the climate impact of emission-pathway choice on generation capacity, preserving the Europe-wide climate signal from van Vliet et al. (2016a) whilst accounting for spatial heterogeneity in climate impacts across 37 European and neighbouring countries.

B.6 Relative change between emission scenarios

To isolate the climate impact of emission-pathway choice on generation capacity, the methodology was applied to both RCP8.5 (high emissions) and RCP4.5 (moderate mitigation). The relative change in capacity factors attributable to climate impacts was calculated as:

$$\Delta_{c,y,t} = \frac{\mathrm{CF}_{c,y,t}^{\mathrm{RCP8.5}} - \mathrm{CF}_{c,y,t}^{\mathrm{RCP4.5}}}{\mathrm{CF}_{c,y,t}^{\mathrm{RCP4.5}}}$$

where $\Delta_{c,y,t}$ is the relative change in capacity factor for country c, year y and technology t; $\mathrm{CF}^{\mathrm{RCP8.5}}$ is the climate-adjusted capacity factor under high emissions; and $\mathrm{CF}^{\mathrm{RCP4.5}}$ is the capacity factor under moderate mitigation. This approach isolates the climate penalty from higher emissions, removing baseline technology performance and enabling direct comparison across countries and time periods. Negative values indicate degradation under higher emissions; positive values (rare for thermal and hydro) indicate relative improvement.

The resulting spatial patterns are shown in Figures B.2 and B.3, and the indicator-selection diagnostics in Figures B.4 and B.5.

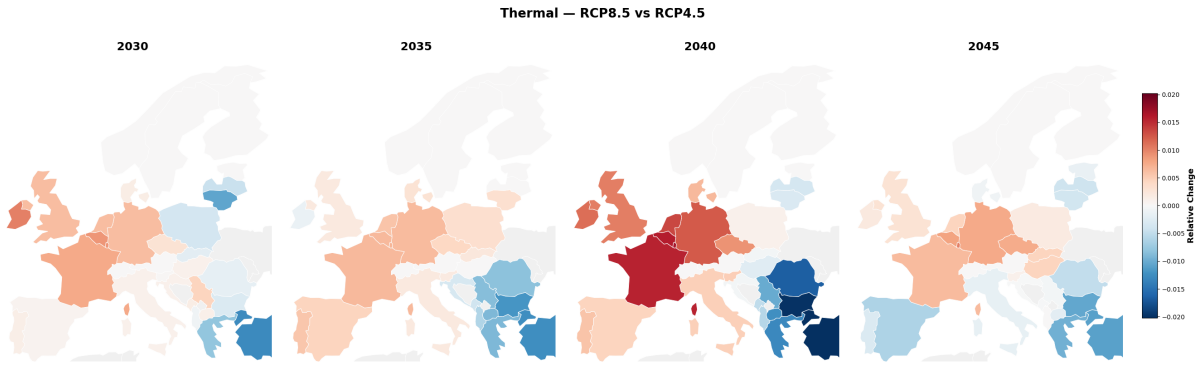

Figure B.2. Relative change in thermal generation capacity factors between RCP8.5 and RCP4.5 emission scenarios for 2030, 2035, 2040 and 2045, adjusted for mean-temperature stress.

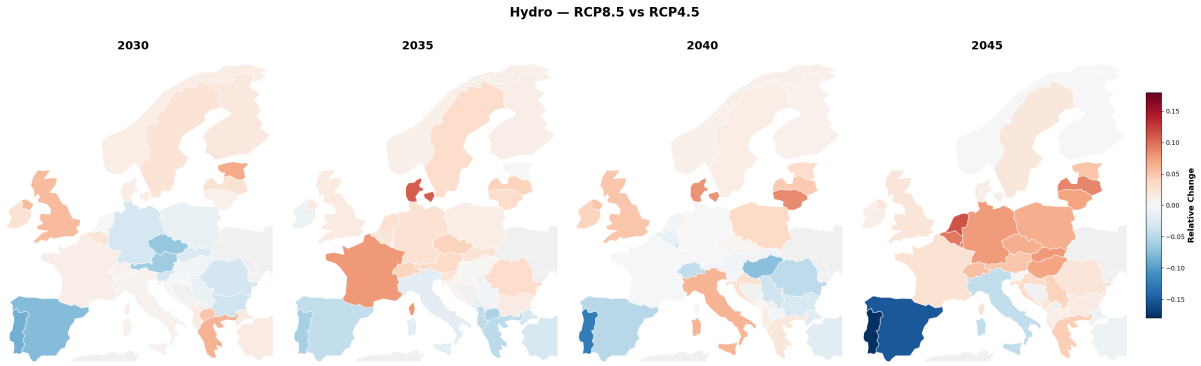

Figure B.3. Relative change in hydroelectric generation capacity factors between RCP8.5 and RCP4.5 emission scenarios for 2030, 2035, 2040 and 2045, adjusted for consecutive-dry-day stress.

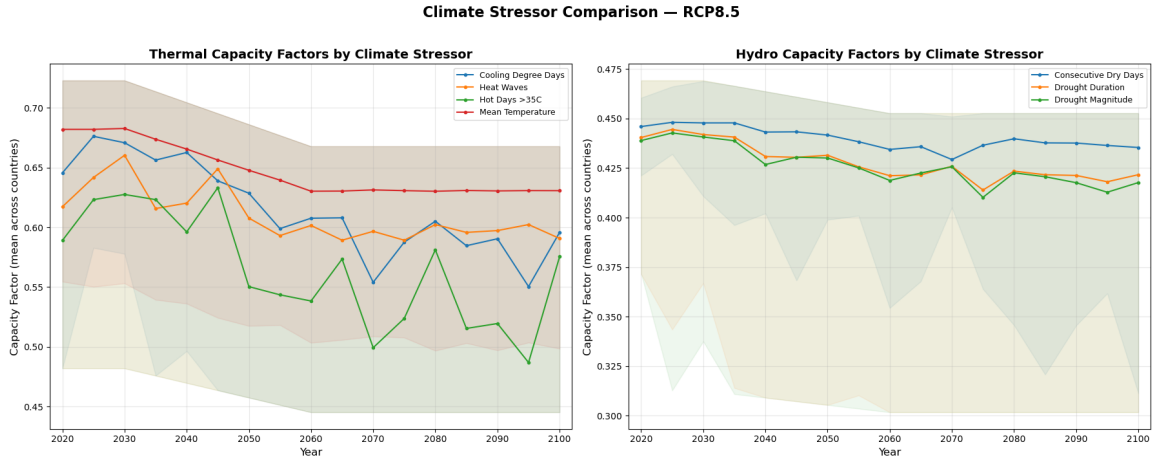

Figure B.4. Capacity-factor trajectories under alternative climate stressors for thermal (left) and hydroelectric (right) generation. Lines show mean values across 37 countries (excluding micro-states); shaded regions span minimum to maximum country values. Mean temperature produces the smoothest thermal trajectory with minimal interannual volatility; consecutive dry days provides the clearest hydro signal, capturing Mediterranean drought intensification whilst avoiding the high variability of drought-magnitude metrics. RCP8.5 scenario; five-year smoothed annual data.

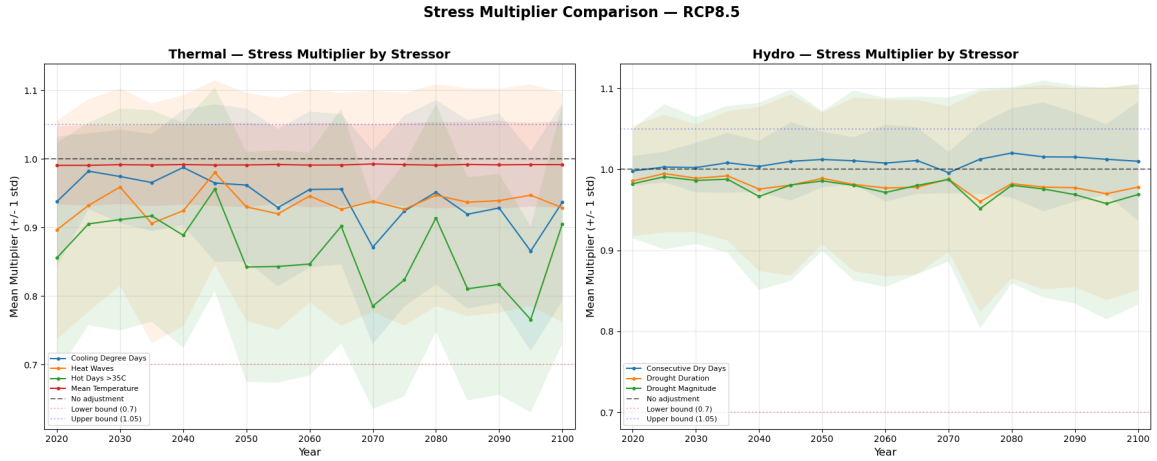

Figure B.5. Stress-multiplier distributions (mean ± 1 standard deviation across countries) for thermal (left) and hydroelectric (right) generation under alternative climate indicators. The dashed line at 1.0 indicates no climate adjustment; dotted lines show the bounds [0.70, 1.05]. Mean temperature (thermal) and consecutive dry days (hydro) exhibit the most physically plausible behaviour: progressive stress intensification without implausible improvements or extreme outliers. Hot days (>35°C) show high volatility due to discrete threshold effects; drought magnitude exhibits non-monotonic artefacts from compound metric construction. RCP8.5 scenario.

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