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A multi-dimensional framework for modeling the energy system transition resilience: A Finnish case

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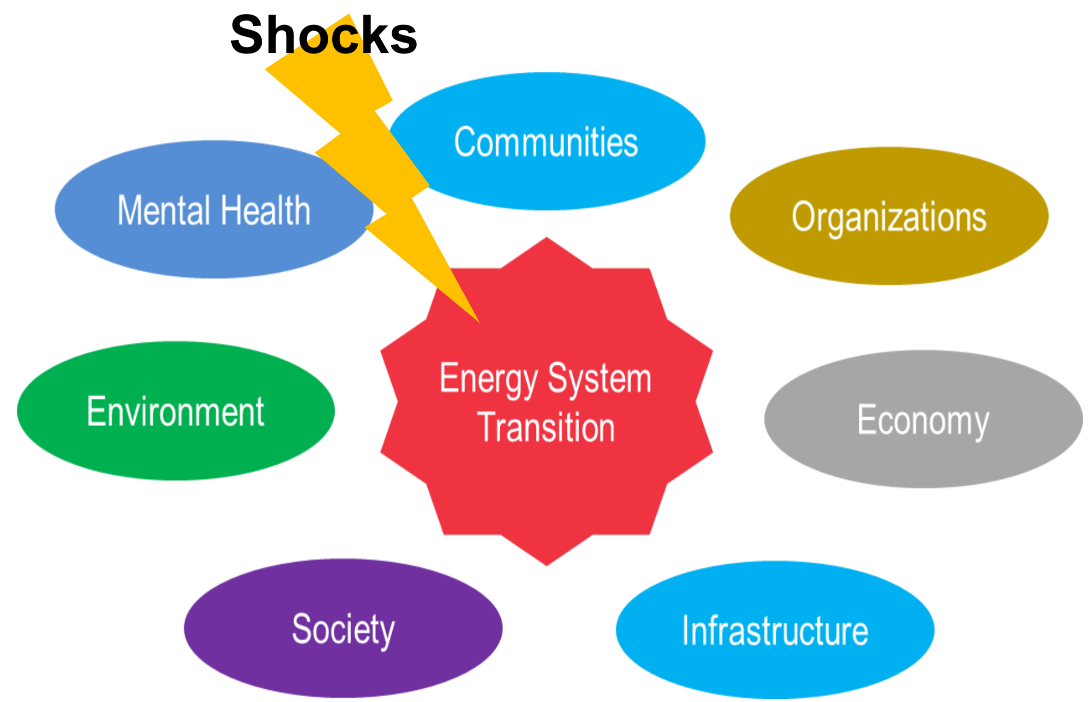
Introduction

- Energy transitions are complex and multi-dimensional processes.
- They are subject to deep uncertainty and vulnerable to shocks.
- Energy system models are used to evaluate the energy transition.

☞ **Multi-dimensional Framework for modeling energy system transition resilience**



Literature review: Definitions & Frameworks

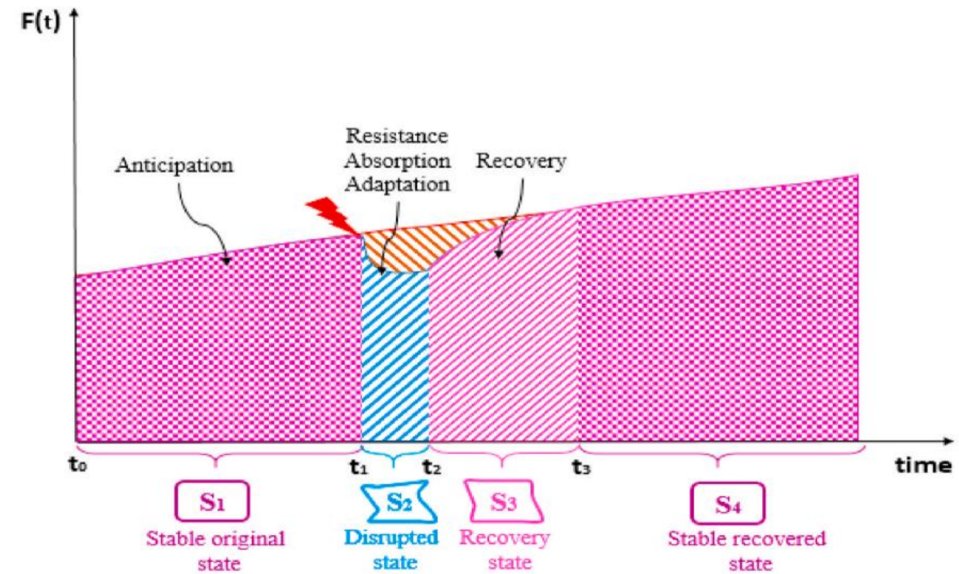
☞ **Cross-cutting themes of Resilience definitions across the fields: maintaining acceptable performance, absorbing and withstanding disruptions, adapting to change, and recovering functionality**

- Various frameworks have been developed to evaluate resilience: Single-dimensional and multi-dimensional resilience frameworks.

Sub-types	Hazard-specific frameworks	Geographic scope	Hierarchical (specific-level) frameworks
Description	Focus to a specific hazard, rather than all-hazard approach.	Bound to specific geographical definitions such as city, urban area, coastal zones...	Focus on different levels of resilience from micro, meso, to macro scales (From individual to global)
Examples	Earthquake resilience; Flood resilience; Drought resilience.	Urban; Coastal; Rural; City; Mountains region; Islands.	Individual; Household; Community; Sub-national; National; Global level resilience.

Literature review: Indicators

- The resilience frameworks employ indicators to demonstrate the resilience of systems.
- **Capacity-based** indicators evaluate resilience by quantifying a system's inherent capacities to absorb disturbances, adapt operations, and restore functionality through indicators such as infrastructural redundancy and operational flexibility, diversification.
- **Performance-based** indicators define resilience as the temporal trajectory of system performance under shock, characterizing the magnitude of performance loss, the duration of degraded operation, the slope of recovery, etc.



Capacity-based ☞ Proactive System Design

Performance-based ☞ Scenario-based Evaluation

Aim

- Here, we aim to develop a **multi-dimensional framework for modeling the energy systems transition resilience for Finland**, which covers:
  - ➢ A broader range of resilience dimensions, including technical, ecological, social, and economic
  - ➢ A more comprehensive set of performance-based indicators
- Focusing on performance-based resilience indicators
- Framework is developed to be generalizable!
- We demonstrate the framework application using FINTIMES.

Methodology: Resilience Framework

- Performance measures used in our framework, considering the model limitations

Dimension	Performance measures	Sub-measures	Proxy
Technical	Energy Price	–	–
Ecological	Air pollution	Particulate matter	Fine particulate matter (PM2.5)
	Biodiversity loss	–	Land use
	Climate	Climate change	CO_2 emissions
Economic	Employment	Job	Direct operational jobs
	Investment cost	–	–
	Net import	–	Net import of energy
	Energy expenses	Consumer energy expenses	Energy service expenses
		Industry energy expenses	
		Freight transport energy expenses	
		Commercial sector energy expenses	

- For social performance (JVPG): $\mathrm{Gini}\left(\frac{Jobs}{Vulnerable\ population\ (e.g.,\ low\ income)}\right)_{region}$ to capture distributional impacts

Methodology: Resilience Framework

- Indicators used in our framework to evaluate various aspects of system resilience

$$Composite\ index = \frac{F_D}{F_E}\frac{F_R}{F_E}(1 - SP) \qquad SP = 1 - \frac{t_D - t_E}{t_R - t_E} \qquad Recovery\_to\_loss = \frac{F_R - F_D}{F_E - F_D}$$

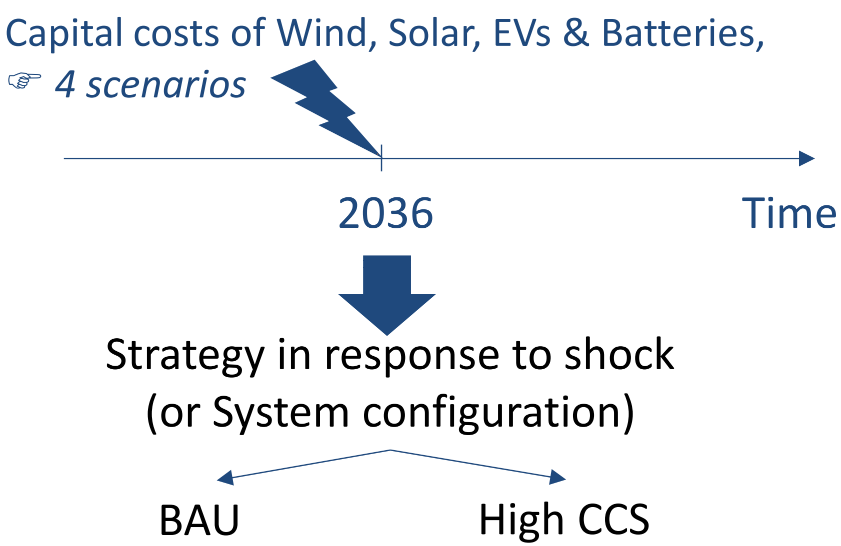
$$Area\_based = \frac{\int_0^T F(t)dt}{\int_0^T F_E(t)dt} \qquad Rapidity = \frac{F_R - F_D}{t_R - t_D} \qquad Robustness = \frac{F_D}{F_E}$$

$$Resilience\ triangle = \int_0^{t_D}(F(t) - 1)dt \qquad Global\ resilience = F_R - F_E \qquad Partial\ area\_based = \frac{\int_0^{t_D} F(t)dt}{\int_0^{t_D} F_E(t)dt}$$

Indicator	Speed (how fast recovery starts/proceeds)	Recovery (how fully/efficiently it rebounds)	Resistance/Robustness (how deep the drop is, up to nadir)	Total loss over time
SP	✓			
Composite index	✓	✓	✓	
Recovery-to-loss		✓		
Area-based				✓
Rapidity	✓			
Robustness			✓	
Resilience triangle			✓	
Global resilience		✓		
Partial area-based			✓	

Methodology: Scenarios

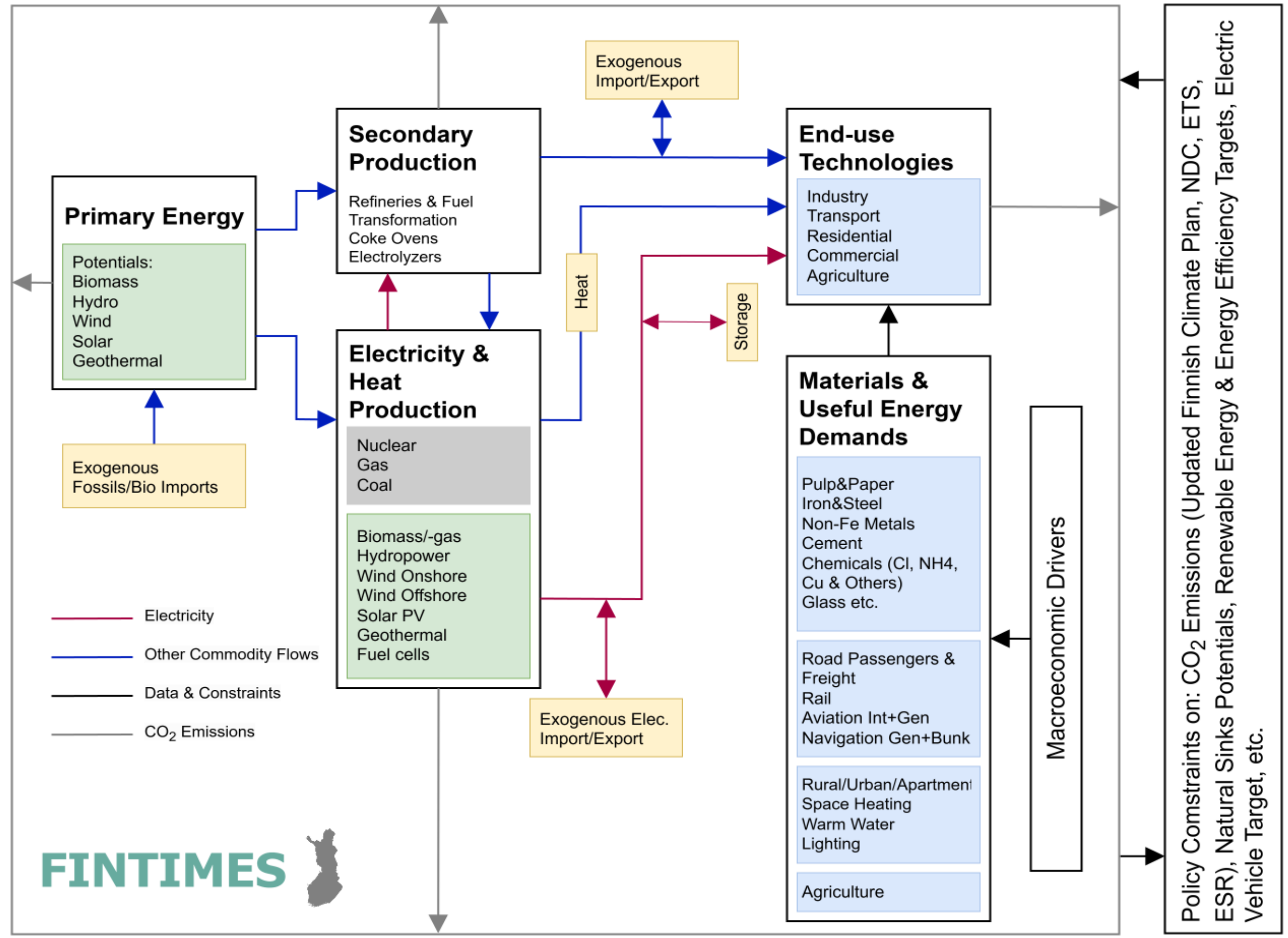
- Using four hypothetical shocks from 2036, and two coping strategies, in total 8 scenarios
- A fixed carbon budget is considered from 2018 to 2050 for Finland across all scenarios.



Strategy	*Description*	*Shock period*	*Shock characteristics (Technology capital cost increase)*
Business As Usual (BAU)	5% annual growth rate for CCS capacity from 2036, like before	2036-2038	Wind & Solar power plants: 50% ↑, Batteries & EVs: 100% ↑
			Wind & Solar power plants: 250% ↑, Batteries & EVs: 500% ↑
		2036-2040	Wind & Solar power plants: 50% ↑, Batteries & EVs: 100% ↑
			Wind & Solar power plants: 250% ↑, Batteries & EVs: 500% ↑
Higher CCS diffusion after the Shock (HighCCS)	7.5% annual growth rate for CCS capacity from 2036	2036-2038	Wind & Solar power plants: 50% ↑, Batteries & EVs: 100% ↑
			Wind & Solar power plants: 250% ↑, Batteries & EVs: 500% ↑
		2036-2040	Wind & Solar power plants: 50% ↑, Batteries & EVs: 100% ↑
			Wind & Solar power plants: 250% ↑, Batteries & EVs: 500% ↑

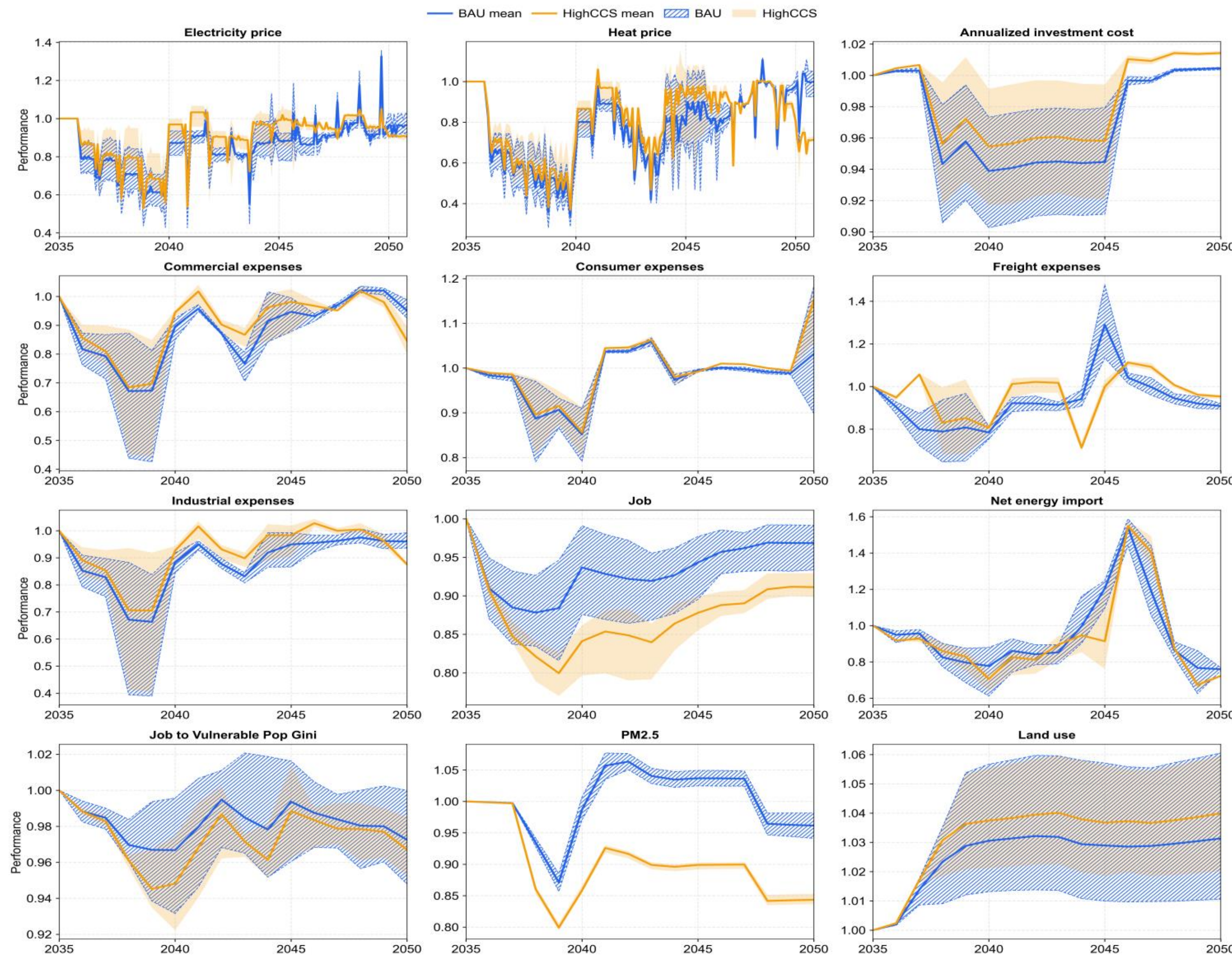
Methodology: Implementation

- Imposing shock involves several steps:
  1. Run from 2020 to 2050
  2. Fix the variables up to 2035
  3. Re-run the model with the imposed shock, mimicking its unexpected occurrence.
- Then, using the results, the performance measures are calculated *relative to the baseline*.

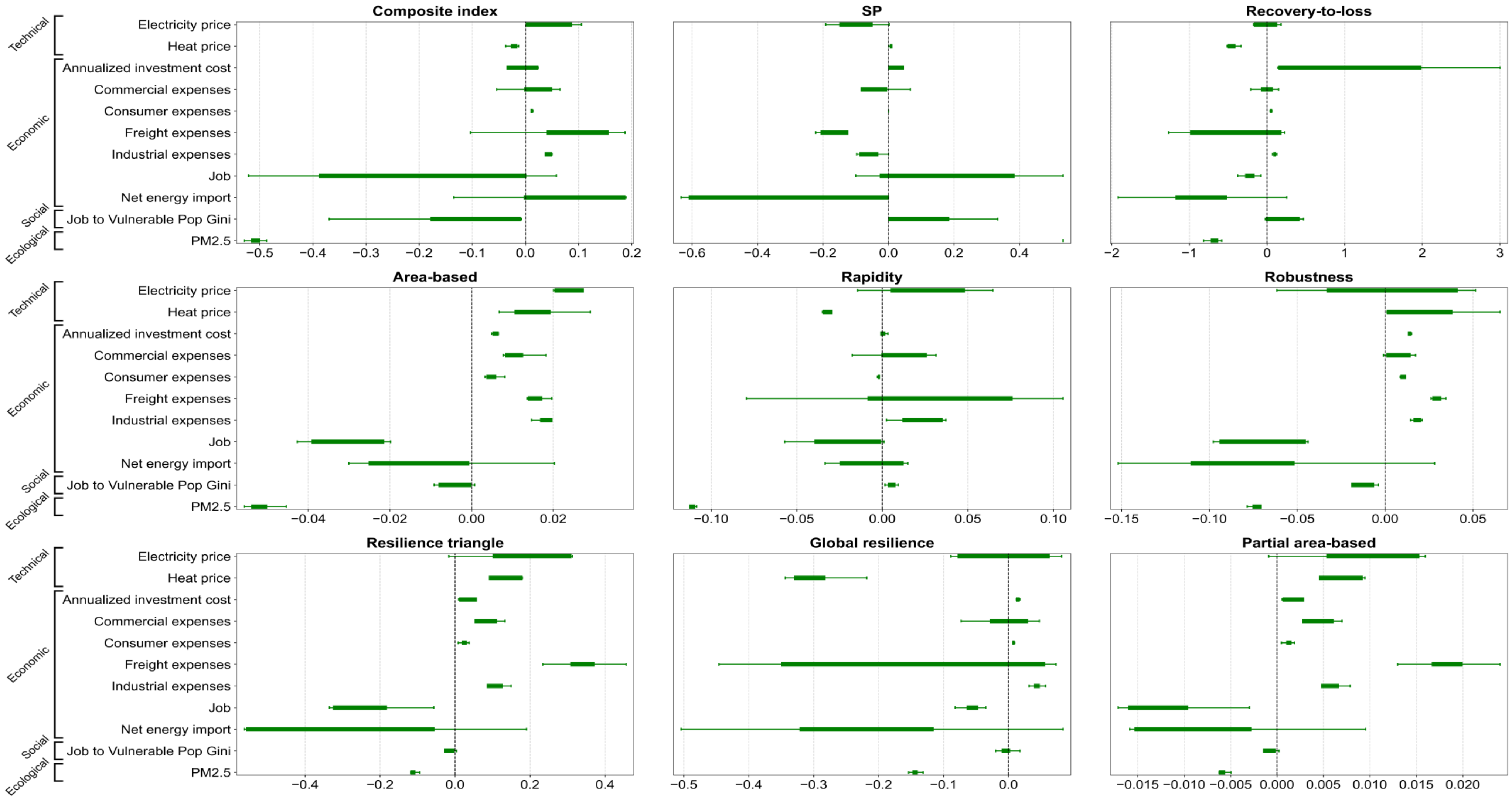


Resilience analysis

- For technical, economic, and social measures: A decline, sometimes even drastically, and then improvement to a limited or full recovery
- For ecological measures:
  - ➢ PM2.5 drops and then improves.
  - ➢ Land use improves due to less deployment of renewables.



Resilience analysis



Conclusions & Future Work

- Our results also revealed that a strategy could strengthen resilience on some dimensions (e.g., technical) while weakening others (e.g., social).
- The results showed that under the same response strategy, some performance measures within a given dimension (e.g., expenses and annualized investment costs) may improve, while others (e.g., job and net energy import) may deteriorate.
- Likewise, resilience indicators that reflect the same aspect (e.g., speed)—such as SP and Rapidity—can yield conflicting results.
- These findings underscore the need to use multiple, complementary measures and indicators, each illuminating a different facet of resilience.
- A multi-criteria method could be applied to identify the best strategy.

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Thank you!

Questions?

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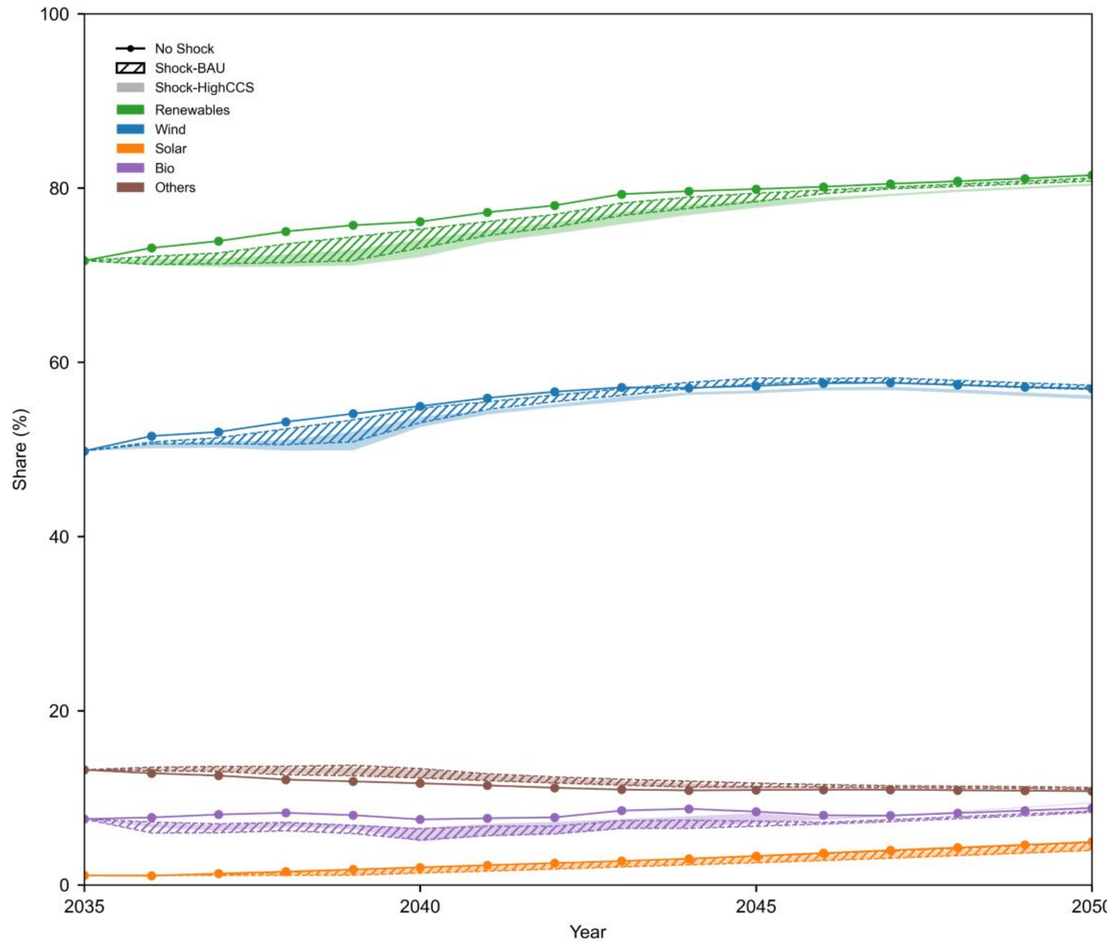
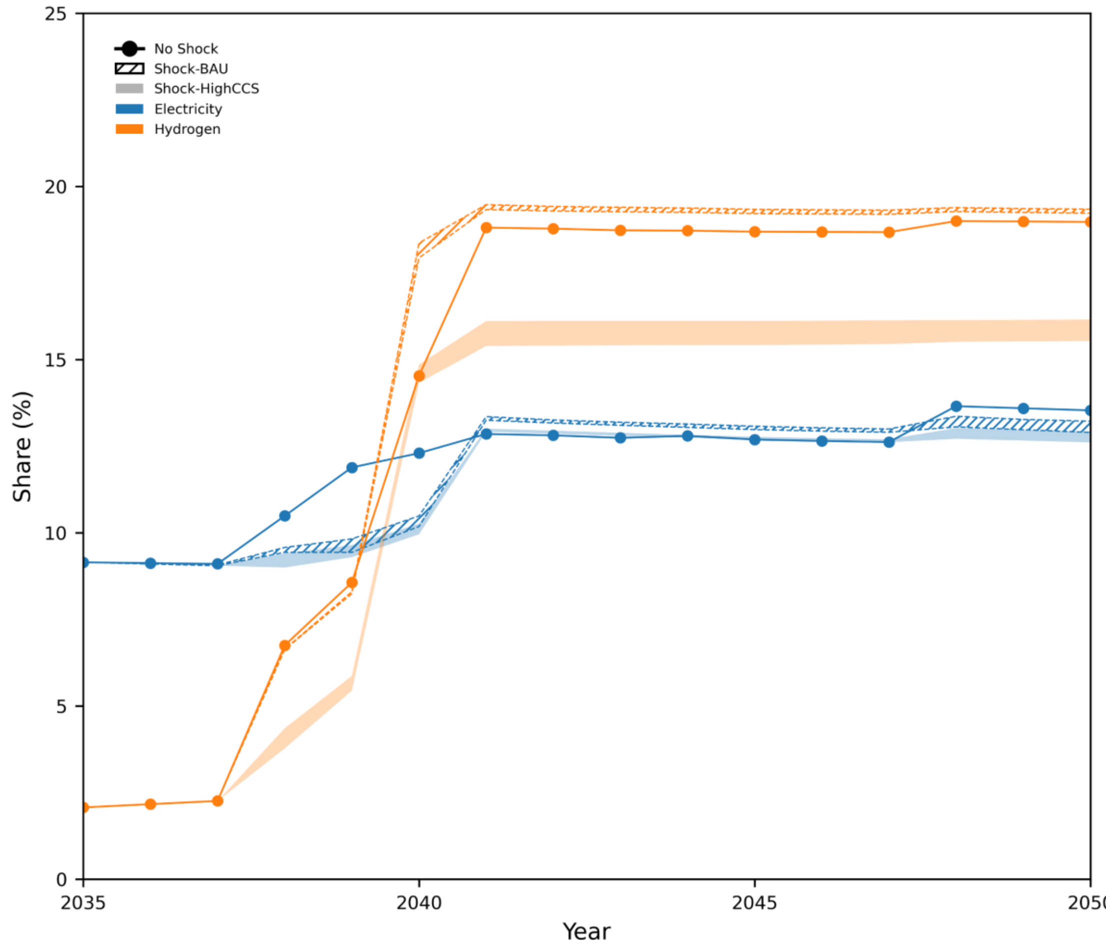
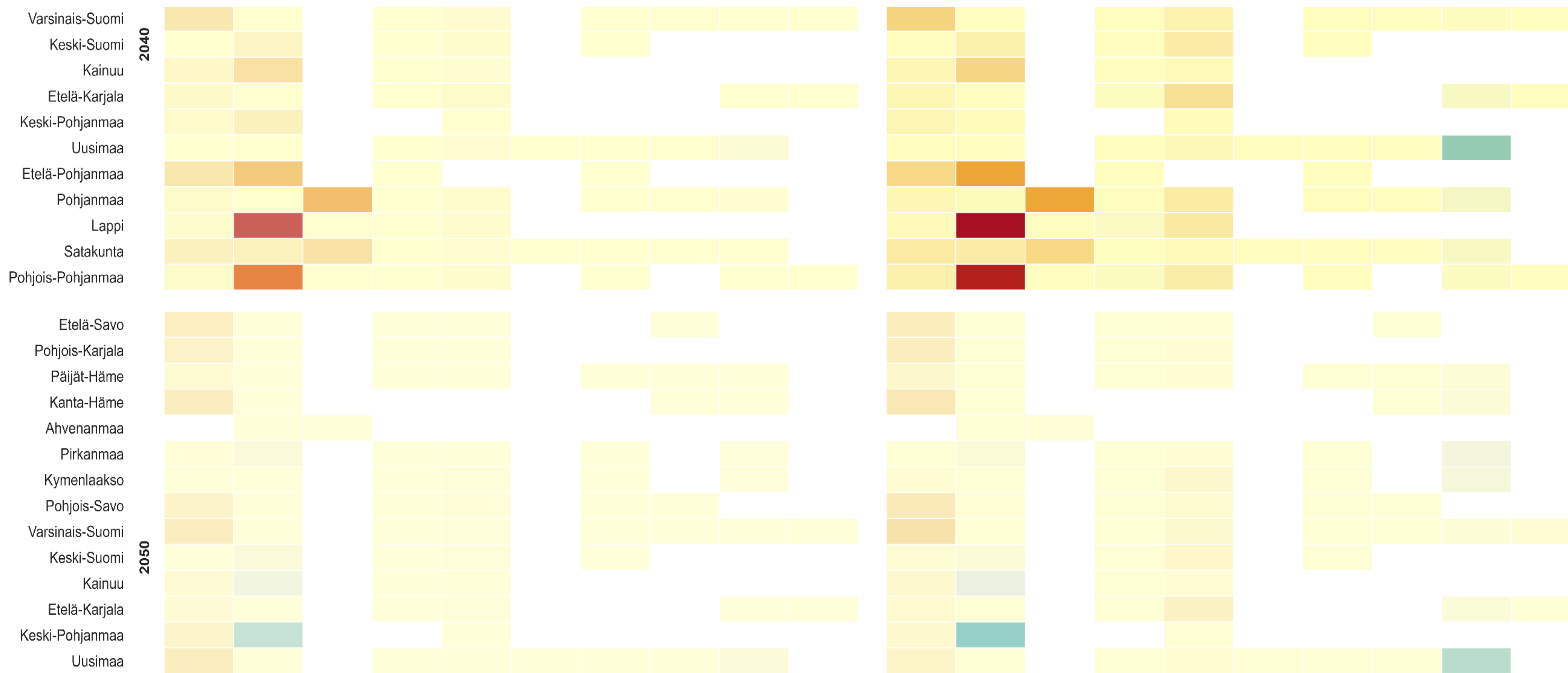
More information: Share of renewables



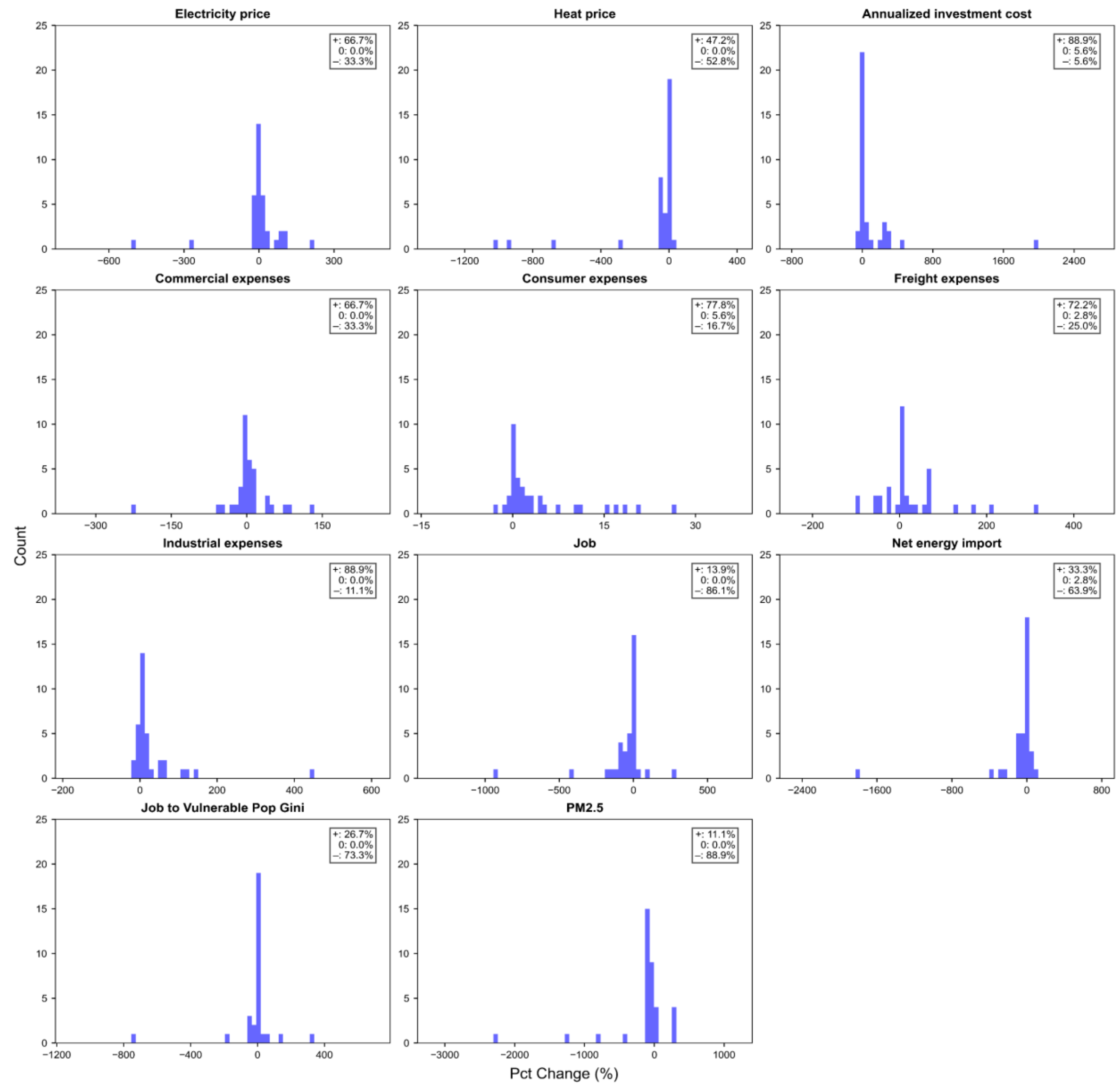
More information: Fuel shares in transport



More information: Capacity downscaling



More information



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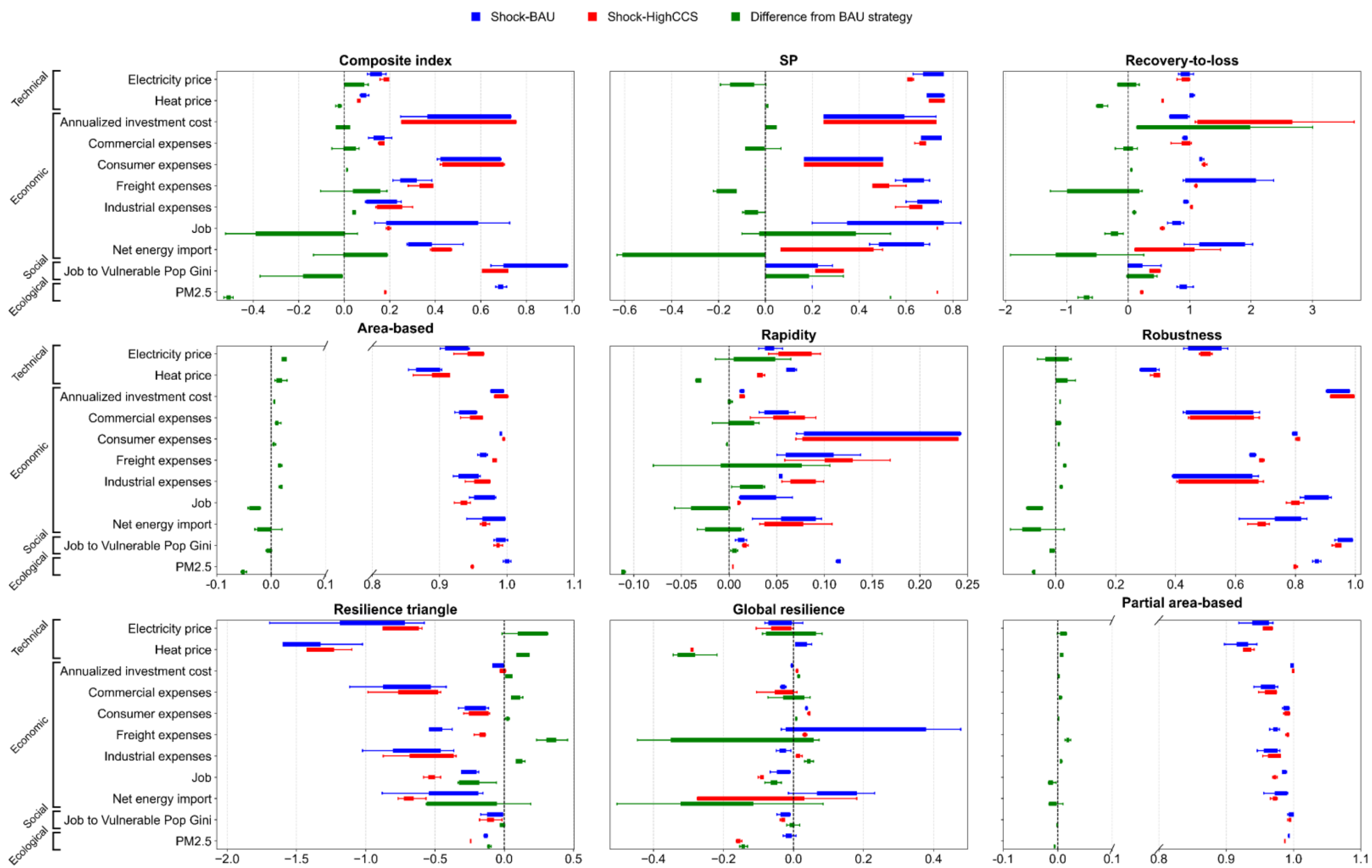

More information: Indicator formulas

In the following equations, t_E, t_R, t_D, and T are the shock start year, recovery year, worst performance year between the shock start year and the recovery year, and time horizon duration, respectively. In the analysis, we consider t_R as a point when the performance measure climbs back to at least 95% and stays above this threshold for a stability window of 2 years, and if this does not happen, the final year of the time horizon (i.e., 2050) is considered as the recovery year. Also, F_E, F_D, and F_R are the system performance right before that shock, performance at its lowest point, and performance at the recovery year, respectively.

$$Composite\ index = \frac{F_D}{F_E}\frac{F_R}{F_E}(1 - SP)$$

$$SP = 1 - \frac{t_D - t_E}{t_R - t_E}$$

$$Recovery\_to\_loss = \frac{F_R - F_D}{F_E - F_D}$$

$$Area\_based = \frac{\int_0^T F(t)dt}{\int_0^T F_E(t)dt}$$

$$Rapidity = \frac{F_R - F_D}{t_R - t_D}$$

$$Robustness = \frac{F_D}{F_E}$$

$$Resilience\ triangle = \int_0^{t_D} (F(t) - 1)dt$$

$$Global\ resilience = F_R - F_E$$

$$Partial\ area\_based = \frac{\int_0^{t_D} F(t)dt}{\int_0^{t_D} F_E(t)dt}$$