UFZ HELMHOLTZ Centre for Environmental Research

MANOEUVRE

Energy System Modelling for Transition to a net-Zero 2050 for EU via REPowerEU

Risk mitigation through portfolio diversification

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cet Partnership

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etsap ENERGY TECHNOLOGY SYSTEMS ANALYSIS PROGRAM

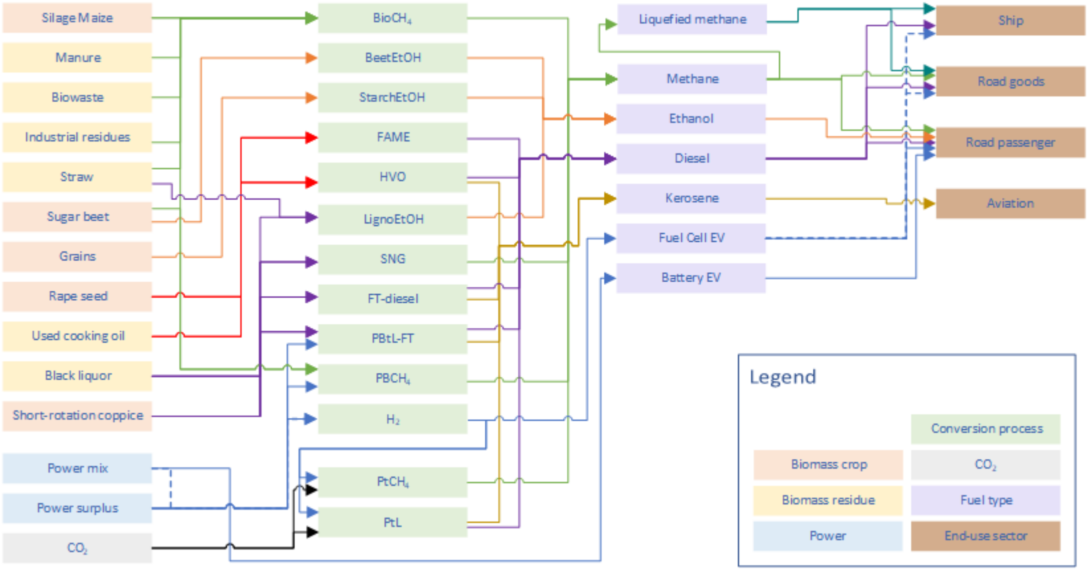
Background

- Policymakers have strongly supported the widespread adoption of variable renewable energies (VREs). Yet these energy sources are prone to weather and climate variability.
- The recent blackout in Spain and Portugal, impacting 55 million people, has been attributed to the high penetration of VREs, which contributed to widespread instability in the power system.
- Bioenergy, with its inherent flexibility, can mitigate the negative impacts of renewable energy intermittency on a net-zero emissions energy system.

Source: NASA Earth Observatory images by Lauren Dauphin, using Black Marble data courtesy of Ranjay Shrestha/NASA Goddard Space Flight Center. Story by Kathryn Hansen.

Background: BENOPTex

- Perfect foresight optimization model
- Models the optimal allocation of dispatchable renewable energy carries across different sectors and goal functions
    - Mainly the competition between different bioenergy technology options
    - Includes transport, power, heat, chemical industries sectors, as well as LULUCF and construction sectors.
- Goal functions
    - Maximizing GHG abatement
    - Minimizing costs



Source: https://www.ufz.de/index.php?en=37180

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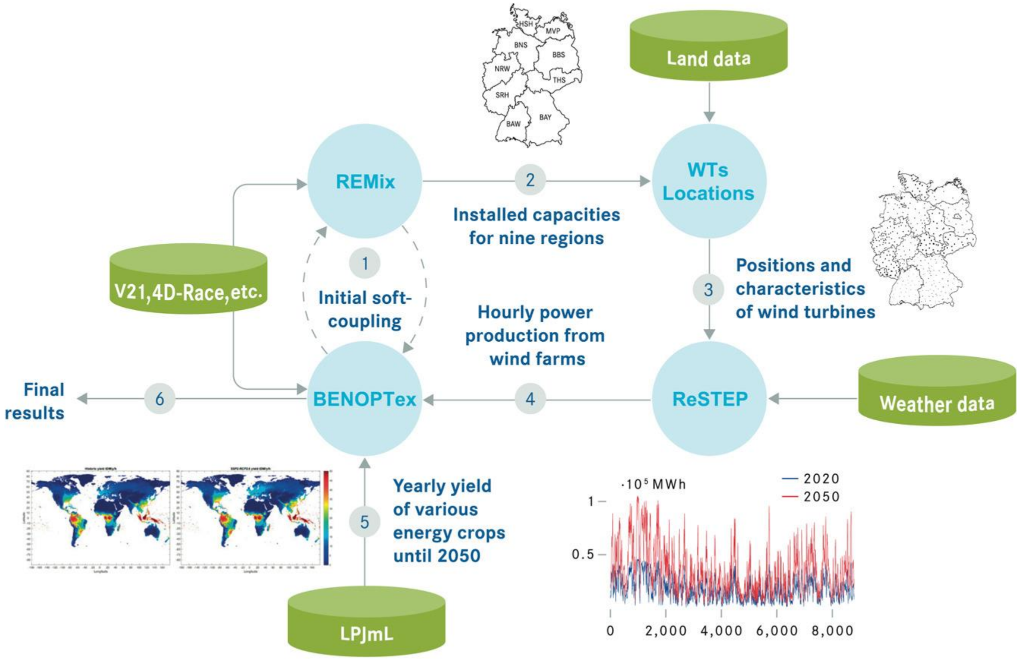
Background

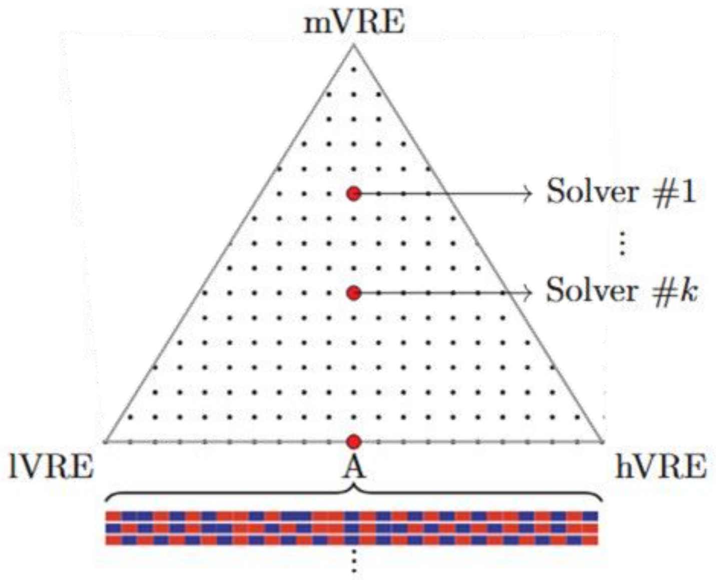
- We link spatially, temporally, and technologically detailed power and energy optimization models with a physical simulation model for wind power production, taking into account climate and weather scenarios.
- Our results indicate that significant reductions in biomass production due to climate change may profoundly compromise reaching climate targets.
- The study was limited to only four scenarios (2 wind x 2 bioenergy) due to the complexity of linking and adjusting multiple models.



Esmaeili Aliabadi, Danial, et al. "Climate change may impair the transition to a fully renewable energy system: A German case study." *Energy* (2025): 138684.

Background

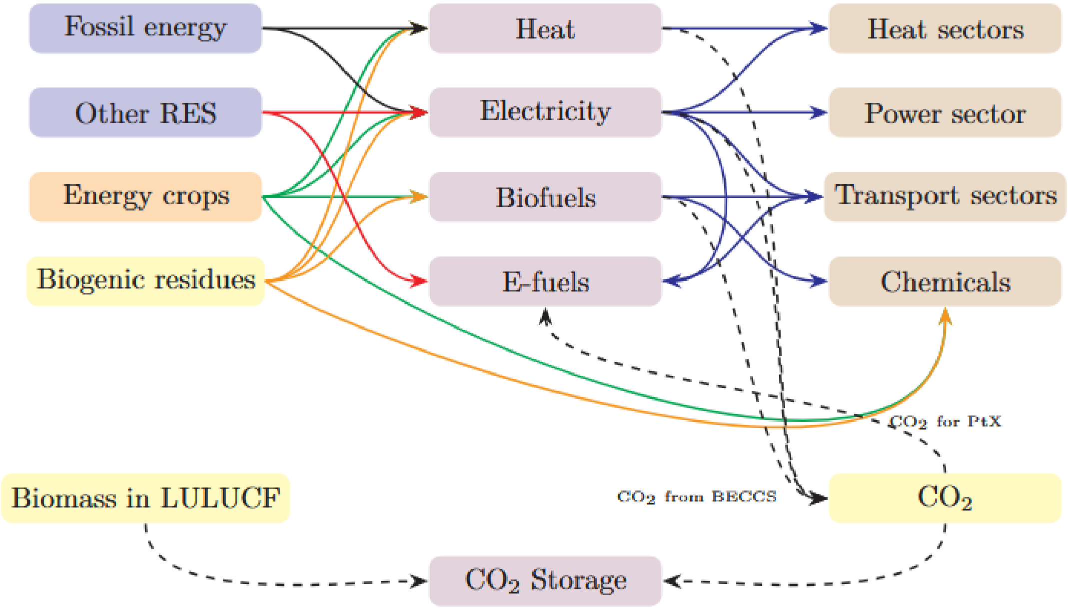
- Stochastic modeling developed as a method to represent short-term variability, particularly from natural phenomena, in long-term energy models.
- Unlike deterministic models, where decisions are based on a single operational scenario with complete certainty, stochastic models define scenarios by considering the likelihood of different outcomes.
- Risk-sensitivity can also impact how decision-makers respond to uncertain events.



Gutjahr, Sandra Franziska, Daniela Thrän, and Danial Esmaeili Aliabadi. "Tango of Renewables in the Triangle of Uncertainty: A German Case Study." *Available at SSRN 5434794*.

Contribution

- We investigate the interplay between VRE and dispatchable energy resources in the German energy system, including part of non-energy sectors, via a stochastic model (BENOPTex).
  - How can bioenergy (as an energy vector) help mitigate the intermittency of VREs?
  - How does risk affect the achievement of climate targets?
  - What is the joint impact of climate change and weather variabilities on regional renewable energy investments in Germany?



Fossil energy
Other RES
Energy crops
Biogenic residues
Heat
Electricity
Biofuels
E-fuels
Heat sectors
Power sector
Transport sectors
Chemicals
CO_2 for PtX
Biomass in LULUCF
CO_2 from BECCS
CO_2
CO_2 Storage

Methodology: Risk-Neutral to CVaR

1 $$E^{el}_{tjir} \leq \beta_j \; k_{ti} \; C_{tir}$$

Dispatchable sources

2 $$E^{el}_{tjir} \leq \beta_j \; k_{ti} \; \tilde{C}_{tjir} + \tilde{P}_{tjir}$$

$$\sum_{j,i} P_{tjir} \leq \hat{P}_{tr}$$

VREs

3 $$E^{el}_{tjir} \leq \beta_j \; k_{ti} \; C^{s}_{tir} + P^{s}_{tjir}$$

Transform stochastic variables into scenarios.

4 $$z_t = \overbrace{\sum_i (z_{ti})}^{\text{deterministic term}} + \overbrace{\mathbb{E}\left[\sum_{ijs} (p^{el}_{ti} \cdot P^{s}_{tjir})\right]}^{\text{stochastic term}}$$

$$= \sum_i z_{ti} + \sum_{ijs} (p^{el}_{ti} \cdot \mathbb{E}\left[P^{s}_{tjir}\right])$$

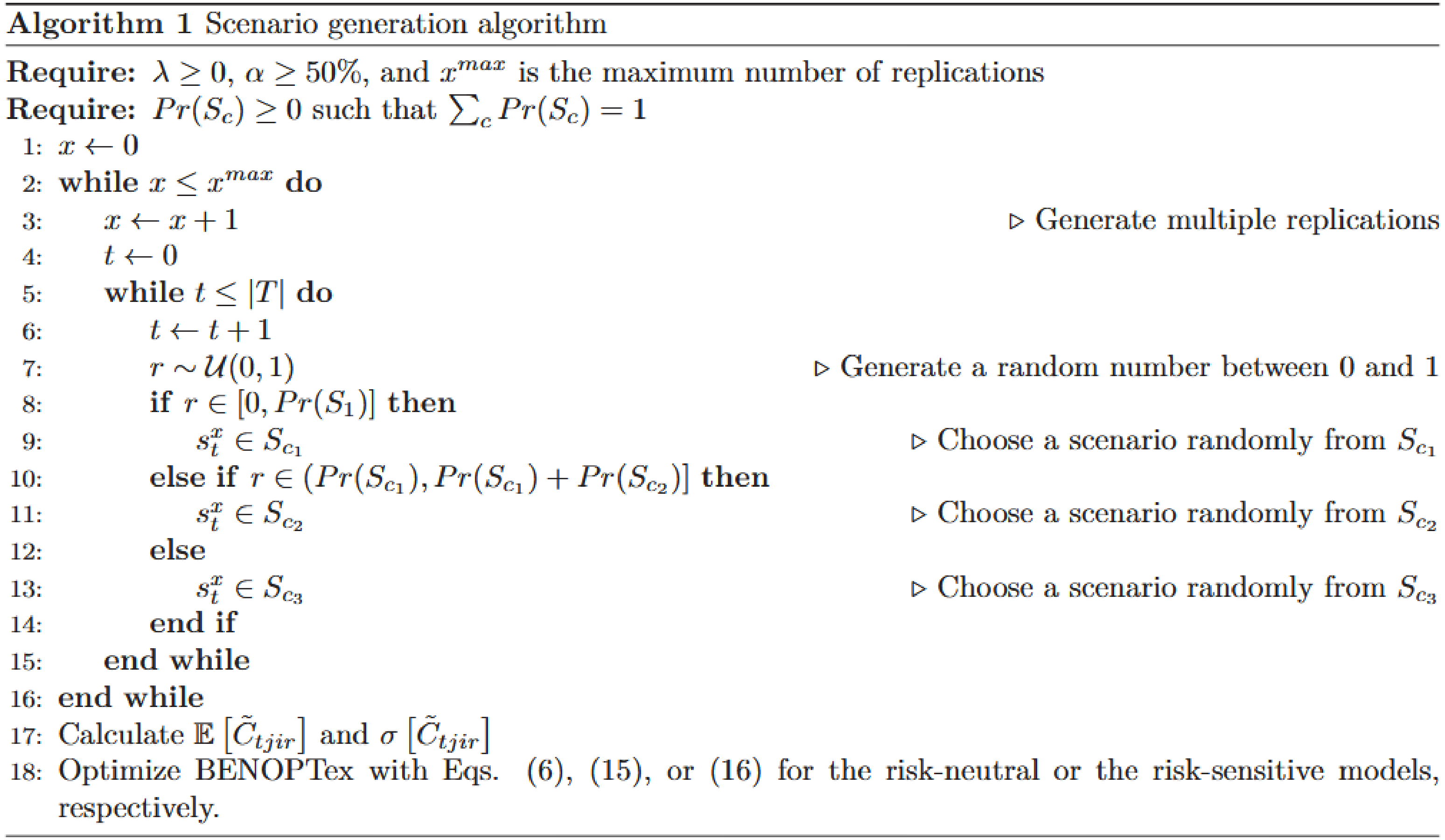
Penalizing purchased power

5 $$\min \sum_t z_t = \sum_t \left(\sum_i (z_{ti}) + \lambda \sum_{ijs} \left(p^{el}_{ti} \cdot \left(\mathbb{E}[P^{s}_{tjir}] + Z_\alpha \cdot (\beta_j \; k_{ti}) \cdot \sigma\left[\tilde{C}_{tjir}\right]\right)\right)\right)$$

6 $$\min \sum_t z_t = \sum_t \left(\sum_i (z_{ti}) + \lambda \sum_{ijs} \left(p^{el}_{ti} \cdot \left(\mathbb{E}[P^{s}_{tjir}] + \frac{\Phi(Z_\alpha)}{1-\alpha} \cdot (\beta_j \; k_{ti}) \cdot \sigma\left[\tilde{C}_{tjir}\right]\right)\right)\right)$$

Methodology: Scenario Generation

- For 10K replications (x^{max}), we run Algorithm 1 with a resolution of 25% and 730 time slices. Moreover, we set λ = 1, since both the risk-neutral and risk-sensitive cases share the same cost unit (i.e., million euros).
- For each setting on the ternary plot, the GAMS optimizer is configured to allocate six threads to the CPLEX solvers: One thread each for the primal and dual simplex algorithms, and four threads for the interior point method.
- The optimization models corresponding to these settings are generated and executed in parallel.



Algorithm 1 Scenario generation algorithm

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Require: $\lambda \geq 0$, $\alpha \geq 50\%$, and $x^{max}$ is the maximum number of replications
Require: $Pr(S_c) \geq 0$ such that $\sum_c Pr(S_c) = 1$
$x \leftarrow 0$
while $x \leq x^{max}$ do
    $x \leftarrow x + 1$                                        ▷ Generate multiple replications
    $t \leftarrow 0$
    while $t \leq |T|$ do
        $t \leftarrow t + 1$
        $r \sim \mathcal{U}(0, 1)$                              ▷ Generate a random number between 0 and 1
        if $r \in [0, Pr(S_1)]$ then
            $s_t^x \in S_{c_1}$                                 ▷ Choose a scenario randomly from $S_{c_1}$
        else if $r \in (Pr(S_{c_1}), Pr(S_{c_1}) + Pr(S_{c_2})]$ then
            $s_t^x \in S_{c_2}$                                 ▷ Choose a scenario randomly from $S_{c_2}$
        else
            $s_t^x \in S_{c_3}$                                 ▷ Choose a scenario randomly from $S_{c_3}$
        end if
    end while
end while
Calculate $\mathbb{E}\left[\tilde{C}_{tjir}\right]$ and $\sigma\left[\tilde{C}_{tjir}\right]$
Optimize BENOPTex with Eqs. (6), (15), or (16) for the risk-neutral or the risk-sensitive models,
respectively.
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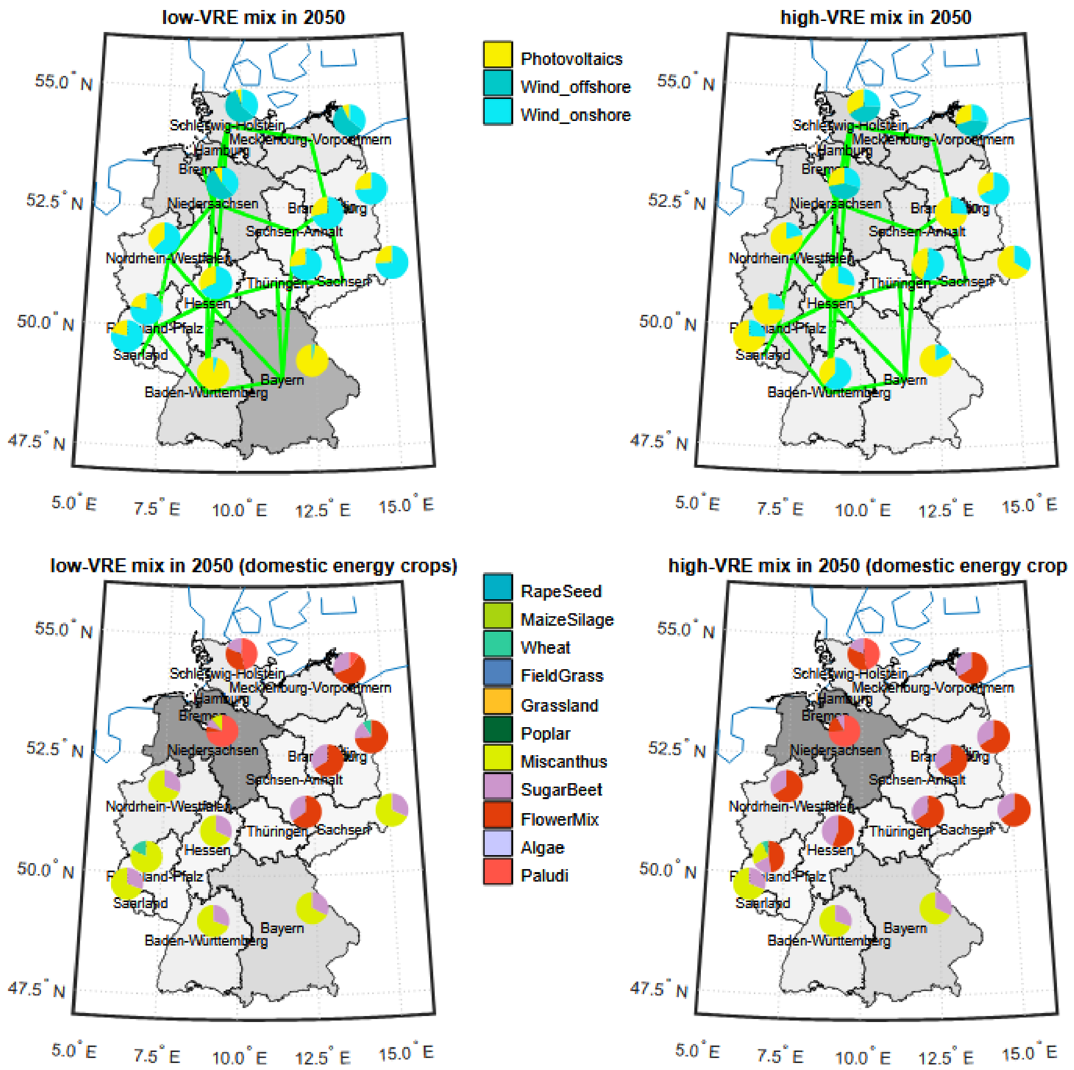
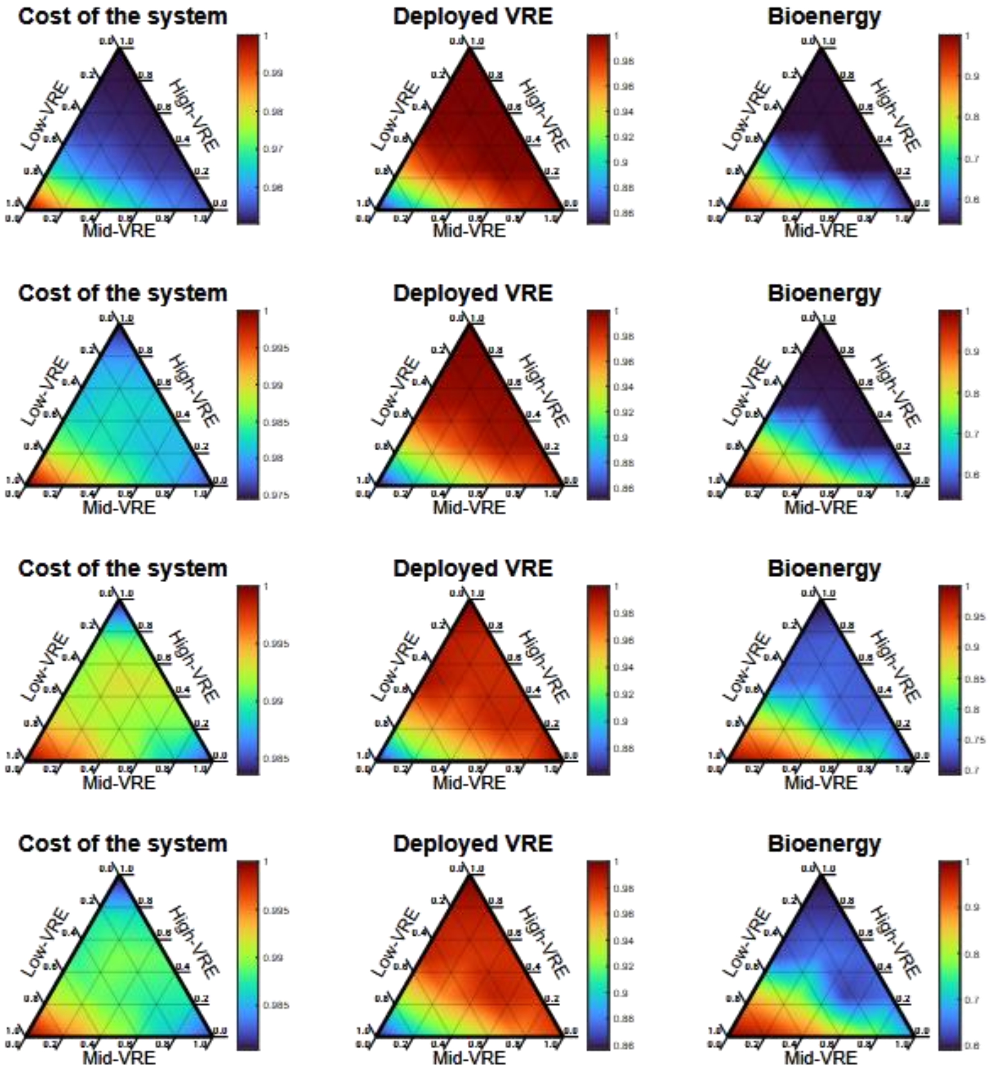
Results

- Under the high-VRE scenario, the model invests in VREs more uniformly across states, primarily due to the widespread availability of solar energy.
- In contrast, under the low-VRE scenario, northern states focus more on wind energy and southern states prioritize solar energy, while states located in the central region invest less overall compared to those in the north or south.



Results

- The key takeaway is that bioenergy and VRE complement each other: When power production from VRE is low, bioenergy compensates, albeit at a higher cost.
- As the model's risk-aversion increases from risk neutral to VaR and CVaR, the blue sections of the cost plot turn yellowish. This cost increase can be associated with the greater tendency of the model to invest in dispatchable power (e.g., bioenergy) when the intermittency of VREs is high.
- Excessive risk sensitivity may drive greater dependence on dispatchable fossil energy, which poses a serious threat to achieving climate targets.



Conclusions

- Modelling dispatchable renewable options alongside VREs using a stochastic approach can yield more realistic results than deterministic scenarios.
- VREs are the cornerstone of Germany’s clean energy system, while bioenergy, as a flexible technology, can help mitigate the variabilities amid extreme weather years with limited VRE availability.
- A risk-neutral approach can result in lower total system cost, while excessive risk aversion can undermine emission reduction efforts by persuading decision makers to invest in more peaker plants that burn natural gas.
- VRE deployment in various German federal states shows sensitivity to the availability of renewable sources: Under low VRE, states in the middle of Germany demonstrate a lower interest in VREs.

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