Enabling agency: trade-offs between regional and European design flexibility in renewable energy systems

Joint work with Aleksander Grochowicz, Fred Espen Benth, Marianne Zeyringer
(University of Oslo)

Koen van Greevenbroek

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UiT The Arctic University of Norway

Outline

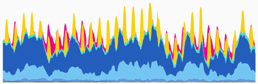
1. Background & transition to net-zero emissions
2. Near-optimal spaces of energy system models
3. Regional trade-offs

Basics of the capacity expansion problem for energy systems

We use **cost-optimisation models** to generate scenarios for long-term planning of energy systems.

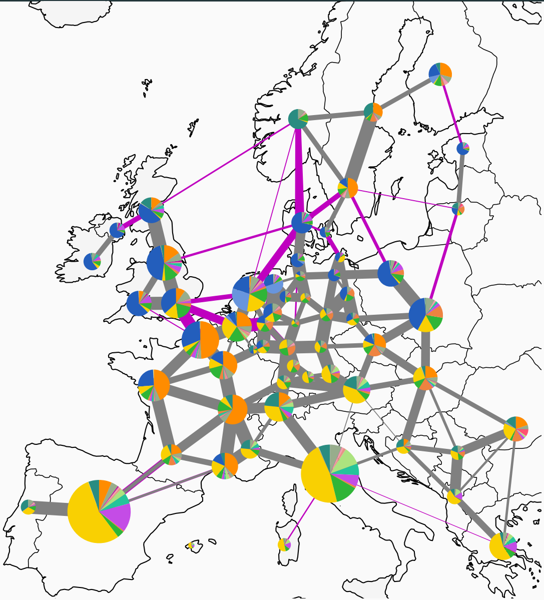
- **Decision variables** for capacity expansion (investment) as well as operations over a certain time period.
- **Constraints** to ensure that demand is met while the network operates within technical limits (transmission constraints, capacity factors).

capacities



operations

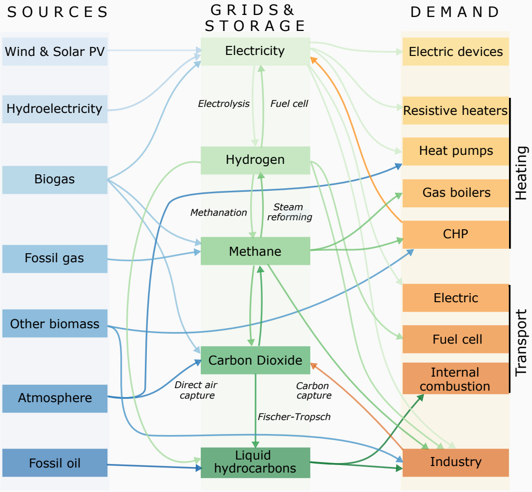
Context



- High-resolution model for the European energy system (based on PyPSA-Eur).
- Linear program.
- Net zero emissions enforced.
- Greenfield optimisation for 2050.

Caveat: some results in this presentation are from preliminary lower-resolution models.

Context



Source: `https://github.com/PyPSA/pypsa-eur/master/graphics/multisector_figure.pdf` (MIT license)

- High-resolution model for the European energy system (based on PyPSA-Eur).
- Linear program.
- Net zero emissions enforced.
- Greenfield optimisation for 2050.
- Sector-coupled.

Near-optimal spaces and dimension reduction

Definition: near-optimal space

Let "max cx s.t. $Ax \leq b$" be a linear program with optimum value c^*, where A is an $m \times n$ matrix. The *ε-near-optimal feasible space* of the linear program is

$$F_\varepsilon = \{x \in \mathbb{R}^n \mid Ax \leq b \text{ and } cx \leq (1+\varepsilon)c^*\}.$$

F_ε is a convex polyhedron, but has impractically many dimensions. We map down to a lower-dimensional space in two steps:

1. Project to *only* investment variables.
2. Aggregate to a small number of key solution variables.

Example key solution variables: total wind, solar, hydrogen investment etc.

Near-optimal spaces and dimension reduction

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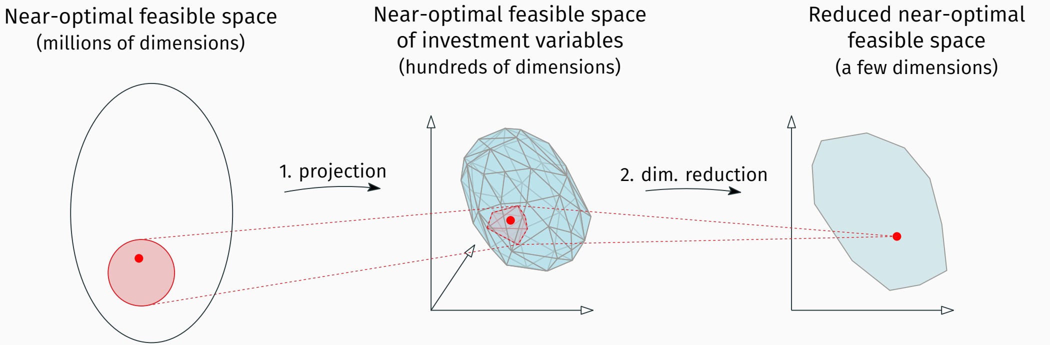
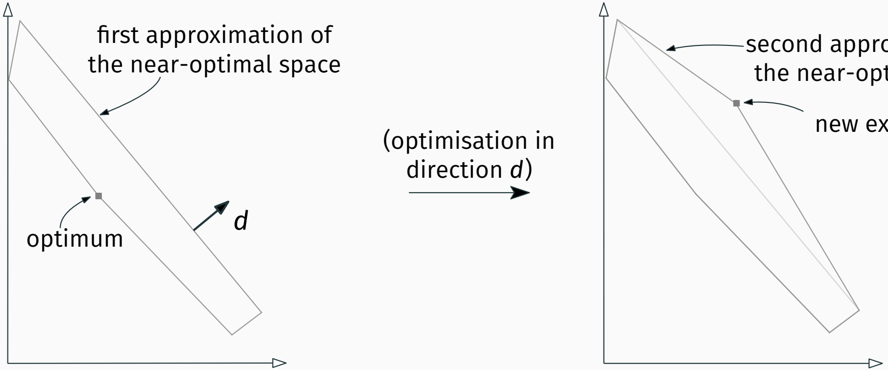


Ask: "If I only had a few variables to describe the feasibility of the whole system..."

Approximating the reduced near-optimal space

We approximate the reduced near-optimal space by finding vertices using model optimisations with different objectives *d*.



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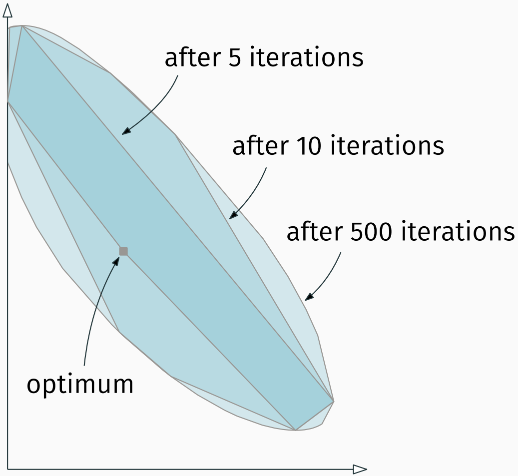
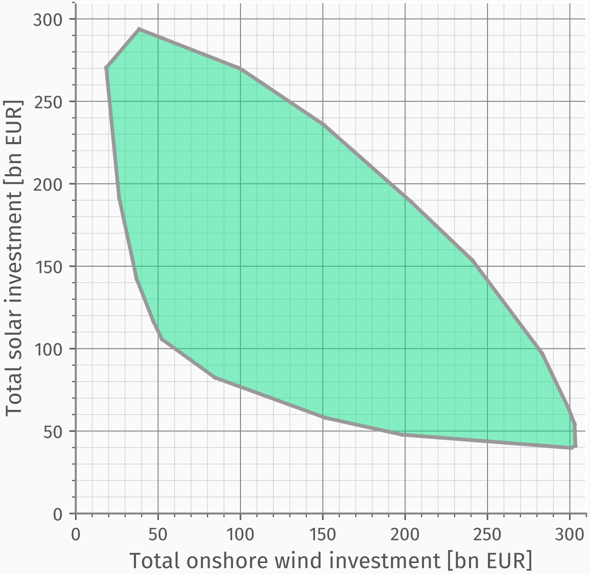


Example: wind vs. solar in Europe



- This is the near-optimal space for our model, projected to total wind and solar investment, 5% cost slack.

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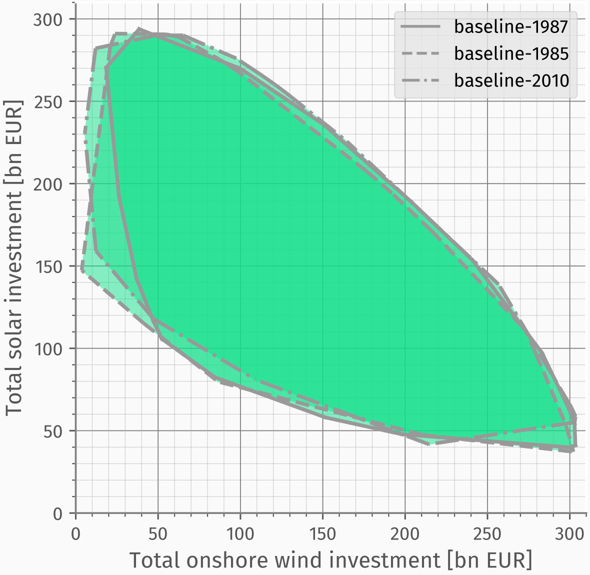

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- Weather years can have an effect on the space.

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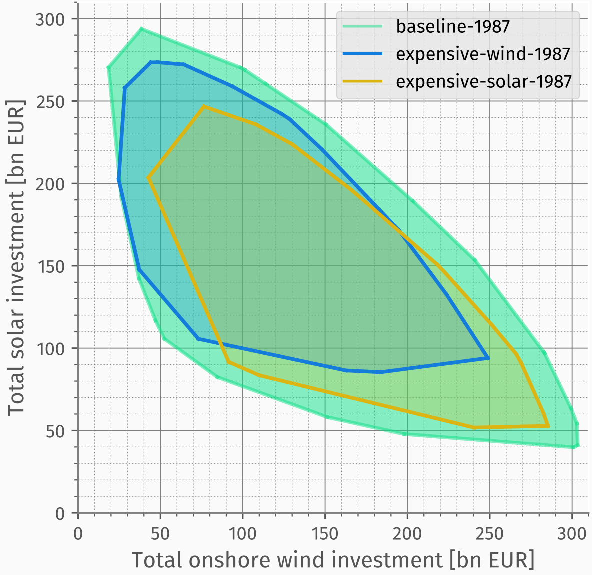

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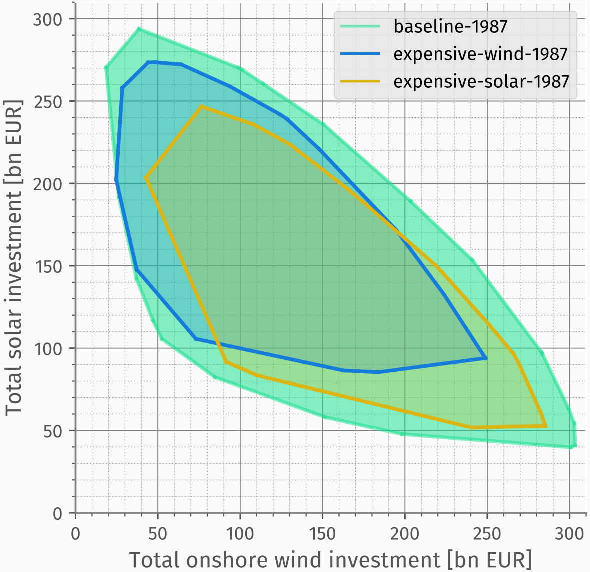

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- So can cost scenarios.
- Intersection represents robust designs.

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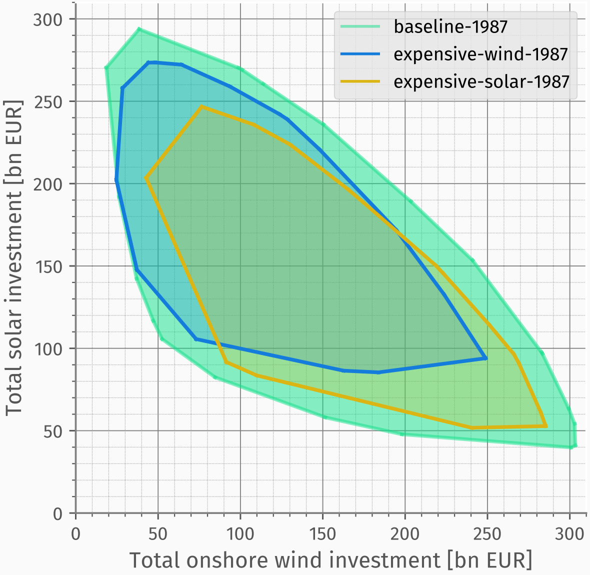
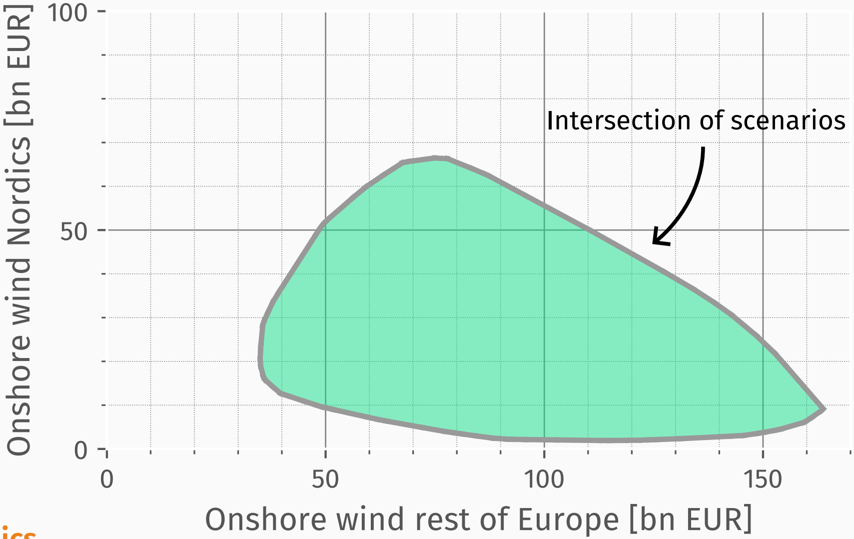


- This is the near-optimal space for our model, projected to total wind and solar investment, 5% cost slack.
- Weather years can have an effect on the space.
- So can cost scenarios.
- Intersection represents robust designs.
- **But how can we refine this to subregions of Europe?**

Set-up

1. Choose a region *R* of interest (ex: Germany, Nordics, British Isles, Iberia, etc.).
2. Increase spatial resolution of model in and around the region.
3. Introduce 75% net yearly energy self-sufficiency constraint.
4. Choose 12 scenarios: {1985, 1987, 2010} × {baseline, expensive wind, expensive solar, solar land-use restricted}
5. Compute near-optimal space for each scenario, reduced to 8 key variables:
    - Total investment in onshore wind in {R, Europe without R}
    - Total investment in offshore wind in {R, Europe without R}
    - Total investment in solar in {R, Europe without R}
    - Total investment in H2 infrastructure in {R, Europe without R}
6. Intersect above 12 spaces for robust designs.

Example: onshore wind Nordics vs. rest of Europe

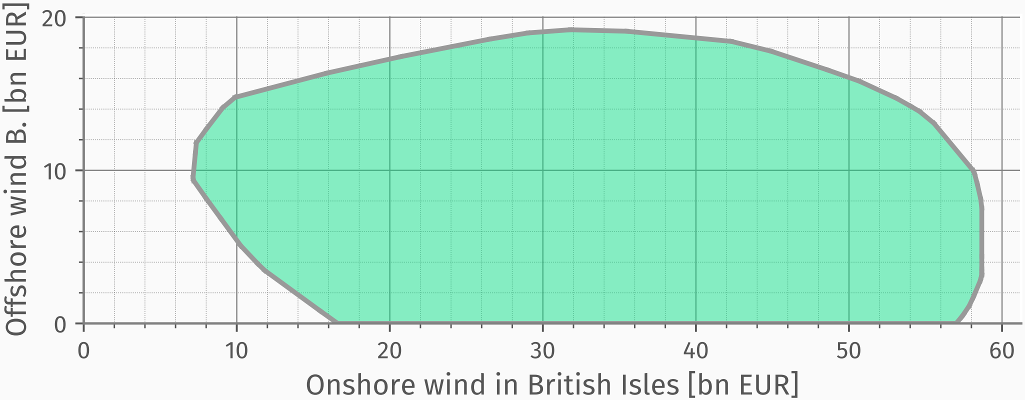


Model: **Nordics**

Questions about regional trade-offs

1. Are any technologies indispensable for certain regions?
2. Can decisions in one region significantly affect the feasible space for the rest of the system?
3. Can decisions in the rest of the system significantly affect the feasible space for the one region?

1: Are any technologies indispensable for certain regions?



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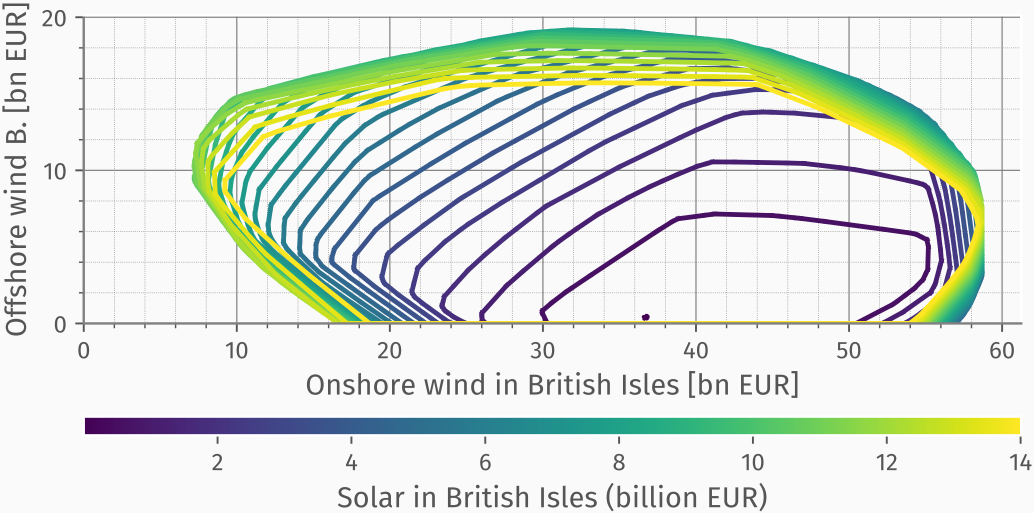

Model: **British Isles**

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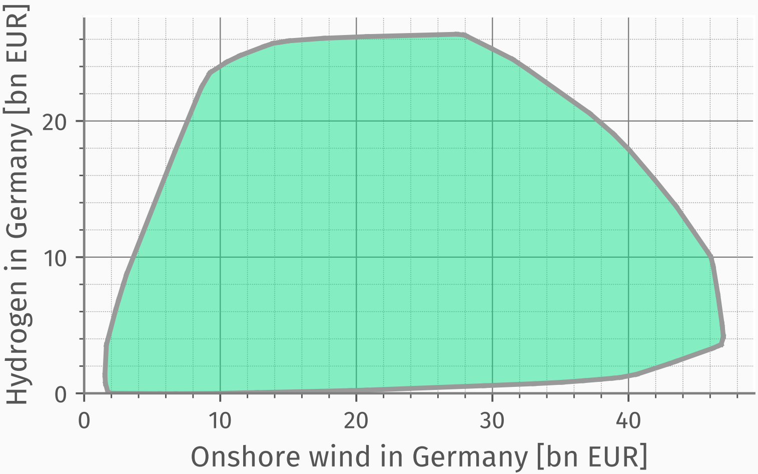

Model: **Germany**

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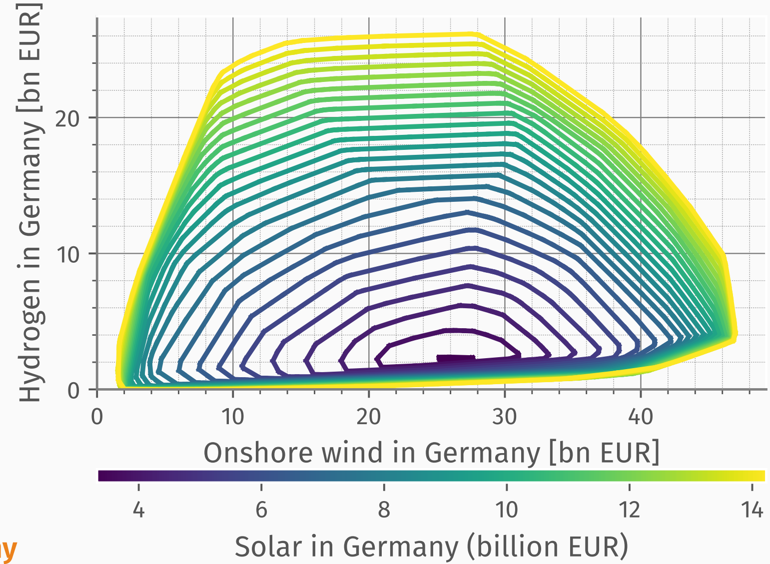

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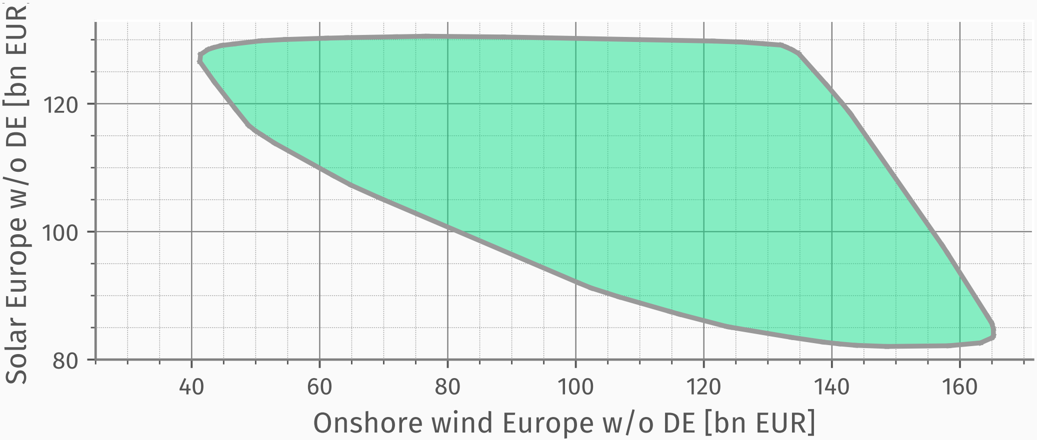
2: Effect of choices in one region on rest of system



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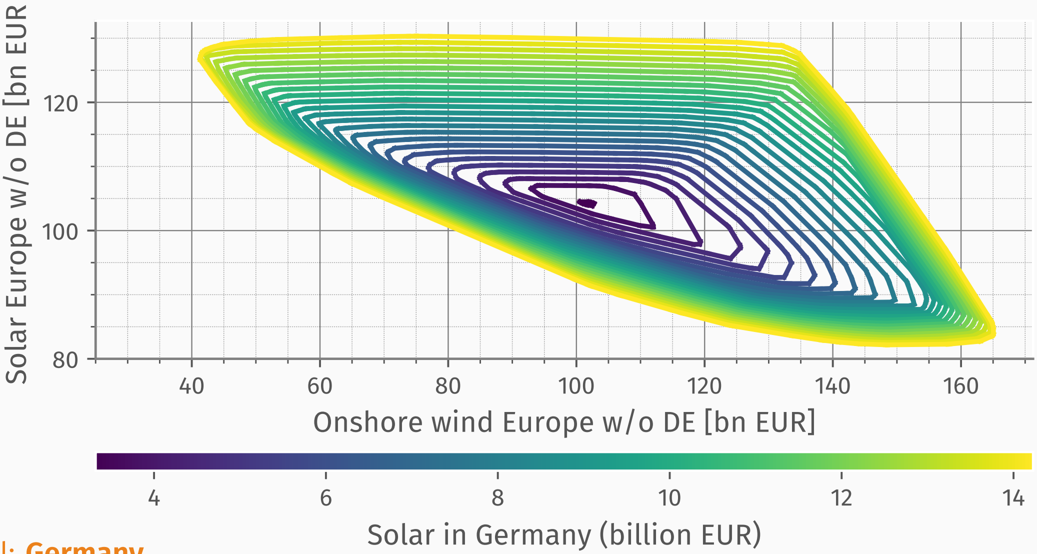

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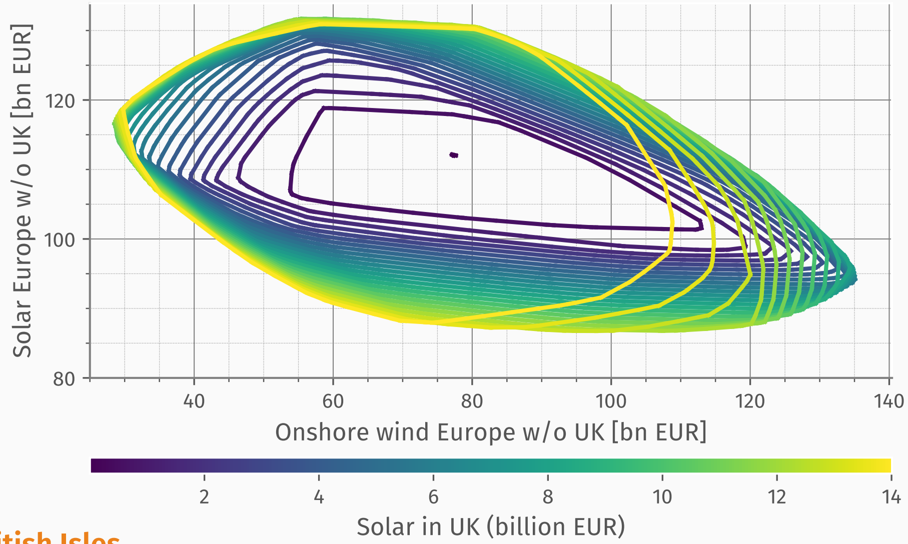
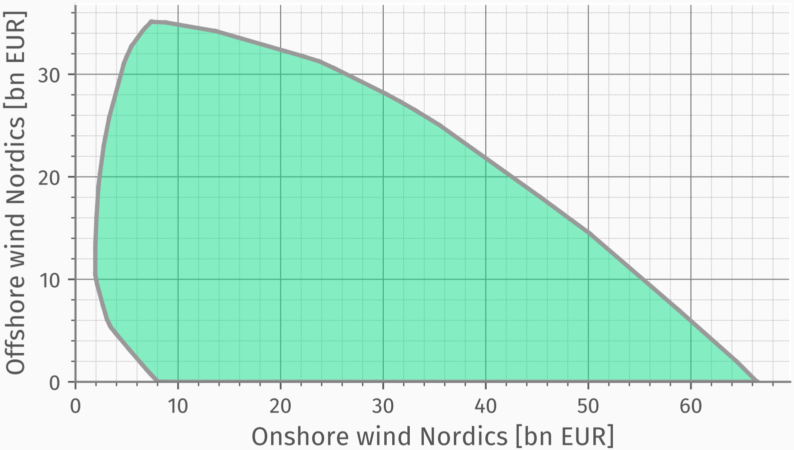


Model: **British Isles**

3: Impact of European decisions on subregions



Model: **Nordics**

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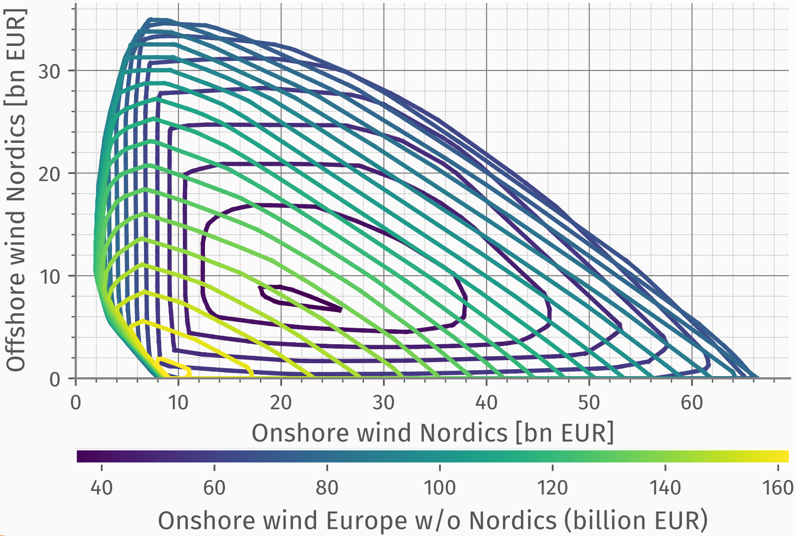

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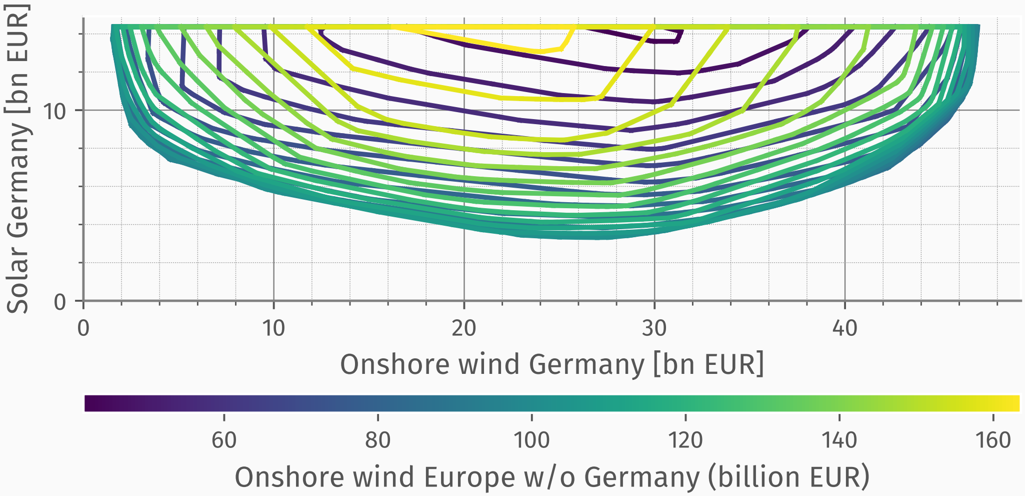

Model: **Germany**

Conclusion & Outlook

Insights:

- Decomposing near-optimal spaces into spatial components is an effective tool for revealing regional trade-offs.
- There is significant geographical and technological flexibility for renewable investments within 5% of cost-optimality.
- Lack of investment in one region can force the hand of the rest of Europe in some cases.

Keep in mind:

- Numbers can be sensitive to model assumptions & cost slack.
  (Still, intersection of multiple scenarios is an attempt at robustness.)

Thank you! Questions?

Link to the Github repo:

Contents lists available at ScienceDirect

Energy Economics

journal homepage: www.elsevier.com/locate/eneeco

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Intersecting near-optimal spaces: European power systems with more resilience to weather variability

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ABSTRACT

We suggest a new methodology for designing robust energy systems. For this, we investigate so-called near-optimal solutions to energy system optimisation models; solutions whose objective values deviate only marginally from the optimum. Using a refined method for obtaining explicit geometric descriptions of these

Feel free to talk with me (Koen van Greevenbroek) or Aleksander Grochowicz about this!