Broad Ranges of Investment Configurations

for a Renewable European Electricity System
Robust to Cost Uncertainty and Near-Optimality

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EMP-E 2021

October 27, 2021

Karlsruhe Institute of Technology

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Setting: least-cost capacity expansion.

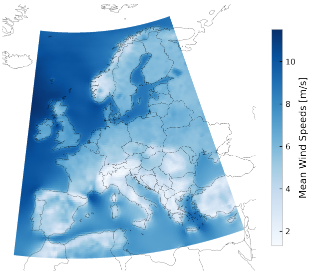
Co-optimise generation, storage and transmission infrastructure to see **interactions**:

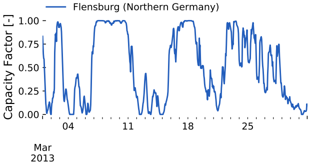
$$\textbf{Min}\left[\begin{array}{c}\textbf{Yearly}\\ \textbf{system costs}\end{array}\right] = \textbf{Min}\left[\sum_r \left(\begin{array}{c}\textbf{Annualised}\\ \textbf{capital costs}\end{array}\right) + \sum_{r,t}\left(\begin{array}{c}\textbf{Operating}\\ \textbf{costs}\end{array}\right)\right]$$

subject to **the usual techno-economic constraints...**

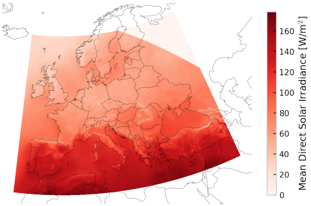
Source: pypsa-eur.readthedocs.io and pypsa.readthedocs.io

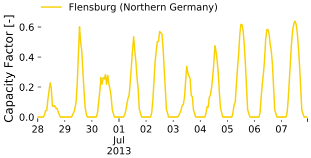
wind resources



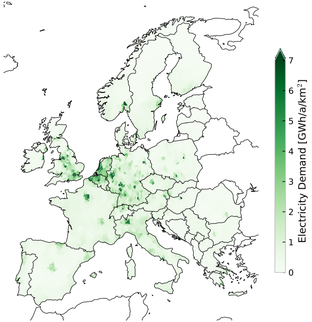


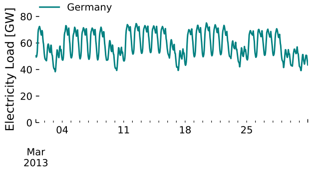
solar resources





electricity demand





Source: ERA5 global reanalysis, `https://doi.org/10/gg9wx7`,
SARAH-2 surface raidation, `https://doi.org/10/f77h`,
ENTSO-E Transparency Platform

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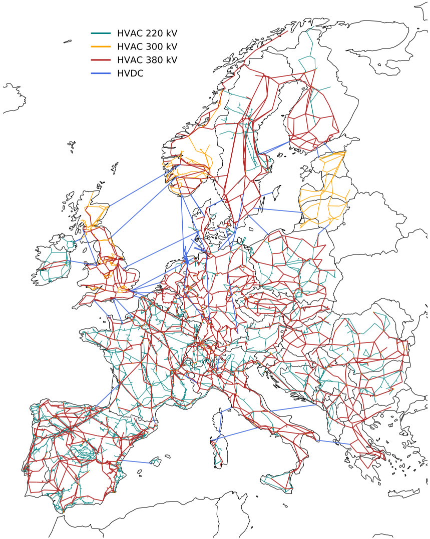
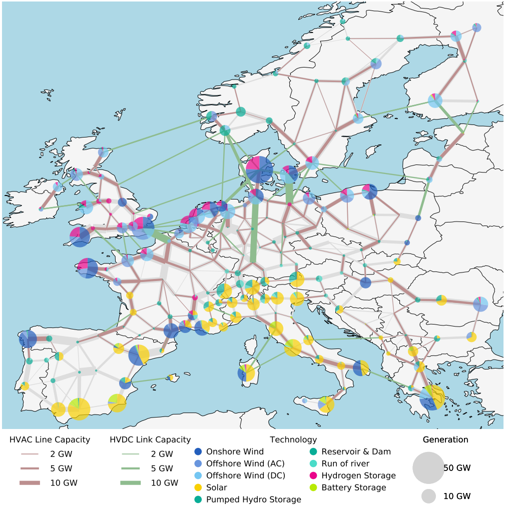
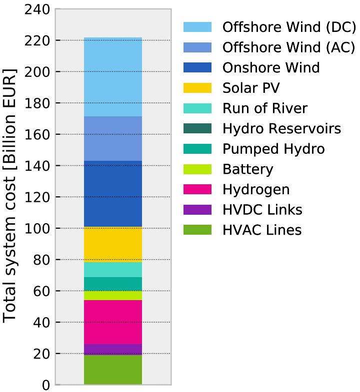


need **clustering** for solveability

Source: Extract from ENTSO-E Transmission System Map,
https://entsoe.eu/data/map

Motivation: a typical least-cost solution from PyPSA-Eur.





Pure least-cost optimisation will give a false sense of exactness.

Too often: a single solution for a single set of cost assumptions

1. underplays a large degree of freedom near the cost-optimum
2. neglects uncertainties inherent to technology cost projections

Alternative solutions are important for policy-makers to **accommodate social constraints**.

- overhead transmission lines
- onshore wind turbines
- regionally inequitable outcomes

→ systematically explore **near-optimal** and **uncertainty** spaces

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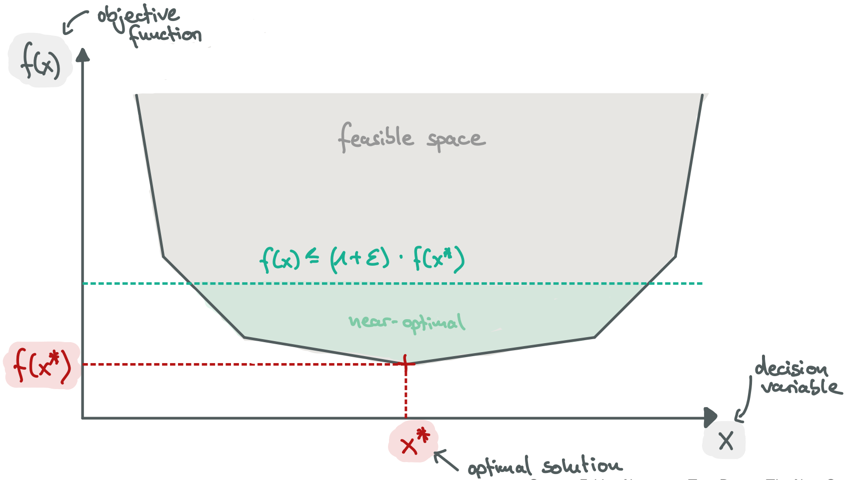
First:

degrees of freedoms near the cost-optimum

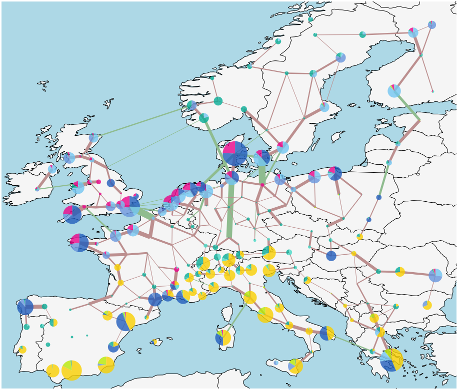
(no cost uncertainty)

Large degeneracy of different possible energy systems close to optimum.

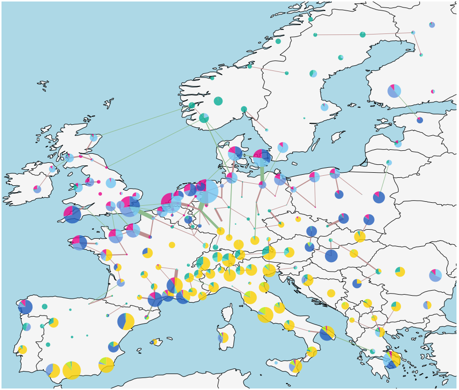


Source: Fabian Neumann, Tom Brown, The Near-Optimal Feasible Space of a Renewable Power System Model, Electric Power Systems Research, Volume 190, 106690, 2021, https://doi.org/10.1016/j.epsr.2020.106690.

Least-Cost Transmission Volume $\varepsilon = 0.0\%$



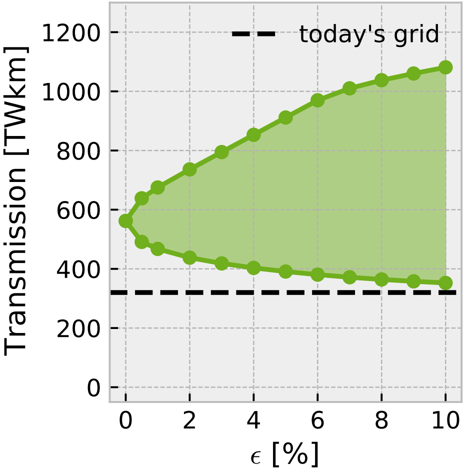
Minimise Transmission Volume $\varepsilon = 5.0\%$



HVAC Line Expansion: 2 GW, 5 GW, 10 GW
HVDC Link Expansion: 2 GW, 5 GW, 10 GW
Technology: Onshore Wind, Offshore Wind (AC), Offshore Wind (DC), Solar, Pumped Hydro Storage, Reservoir & Dam, Run of river, Hydrogen Storage, Battery Storage
Generation: 50 GW, 10 GW, 1 GW

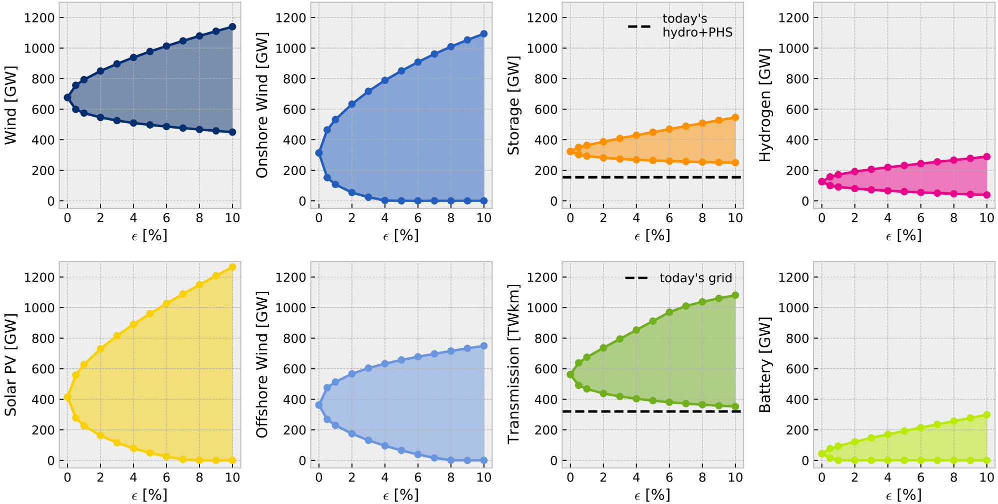
Source: Neumann and Brown (2021)

Pareto fronts to build cones of near-optimal solution space.



Source: Neumann and Brown (2021)

Flatness allows choosing solutions with higher public acceptance.



Source: Neumann and Brown (2021)

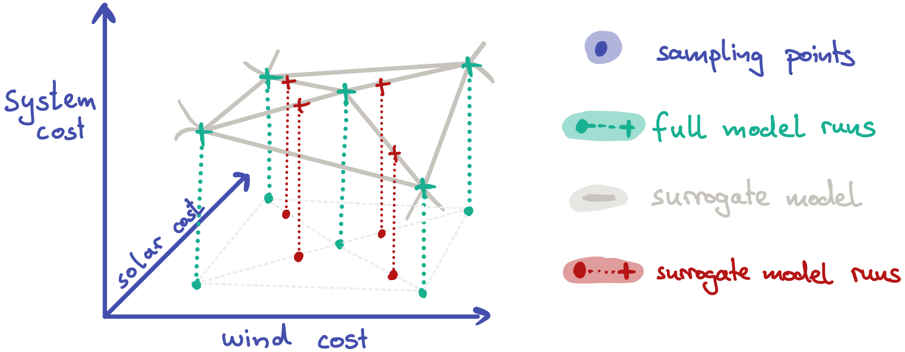
Next:

What about the uncertainty of cost projections?

(without near-optimal analysis)

Source: Please read: Tim Tröndle, Johan Lilliestam, Stefano Marelli, Stefan Pfenninger, Trade-Offs between Geographic Scale, Cost, and Infrastructure Requirements for Fully Renewable Electricity in Europe, Joule, Volume 4, Issue 9, 2020, Pages 1929-1948, https://doi.org/10.1016/j.joule.2020.07.018.

High burden of optimisation runs makes surrogate modelling attractive.



Same input-output behaviour as the original model, but compute much faster → interpolate

Source: See also: Tim Tröndle et al. (2020)

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High burden of optimisation runs makes surrogate modelling attractive.

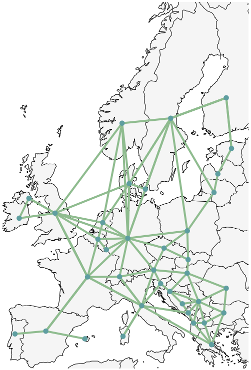
$$\text{cost uncertainty} \quad : \quad \begin{bmatrix} \text{onshore wind cost} \\ \text{offshore wind cost} \\ \text{solar cost} \\ \text{H}_2 \text{ storage cost} \\ \text{battery cost} \end{bmatrix} \xrightarrow[\text{surrogate model(s) predict}]{} \begin{bmatrix} \text{system cost} \\ \text{onshore wind GW} \\ \text{offshore wind GW} \\ \text{solar GW} \\ \text{H}_2 \text{ storage GW} \\ \text{battery GW} \\ \text{transmission TWkm} \end{bmatrix}$$

One way is to use a **polynomial chaos expansion (PCE)** for that.

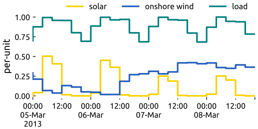
Source: See also: Tim Tröndle et al. (2020)

Can combine multiple surrogate models with PCE.

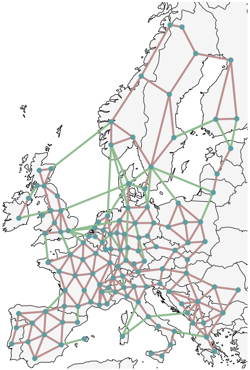
low-fidelity:



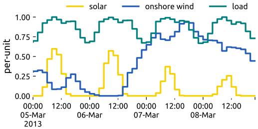
37 regions
4-hourly
500 samples
polynomial order 3



high-fidelity:



128 regions
2-hourly
10 samples
polynomial order 1



Correct **lower-order errors** of low-fidelity surrogate model with **corrective PCE**.

Source: See also: Tim Tröndle et al. (2020)

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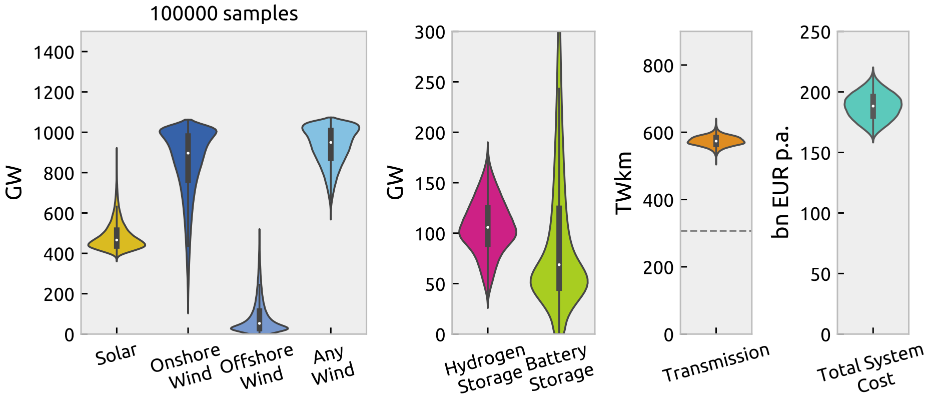
Distribution of system cost, generation, storage and transmission.

... and sensitivity indices etc.



Source: Technology cost ranges based on technology database of Danish Energy Agency for 2050, https://ens.dk/en/our-services/projections-and-models/technology-data

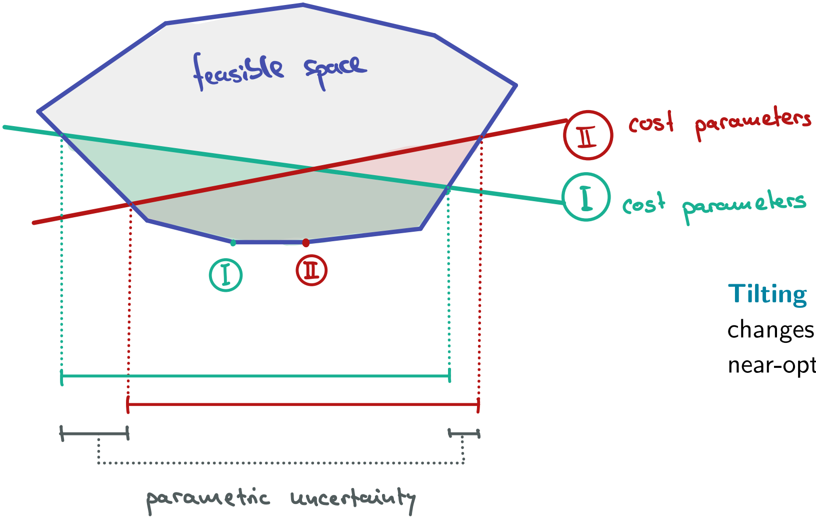
Now:

What does **cost uncertainty** mean for **near-optimal trade-offs**?

(near-optimal space + cost uncertainty)

Source: https://neumann.fyi/files/neumann-2021-broad-ranges.pdf

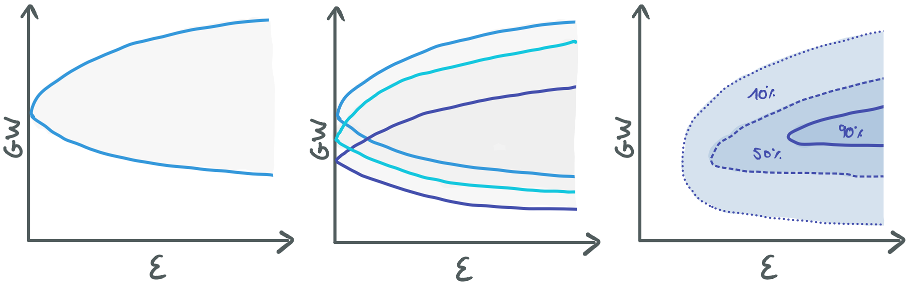
How does cost uncertainty impact near-optimal trade-offs?



Tilting of the ε-constraint changes what is defined as near-optimal.

Source: https://neumann.fyi/files/neumann-2021-broad-ranges.pdf

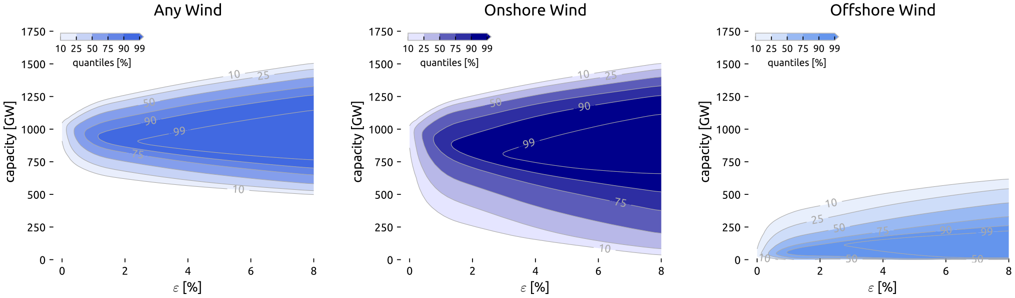
How can we portray fuzzy near-optimal trade-offs?



Want to know solutions with high chance of limited cost increase, and identify regions that are unlikely to become cost-efficient.

Source: https://neumann.fyi/files/neumann-2021-broad-ranges.pdf

Fuzzy but robust trade-offs between system cost and technology use.

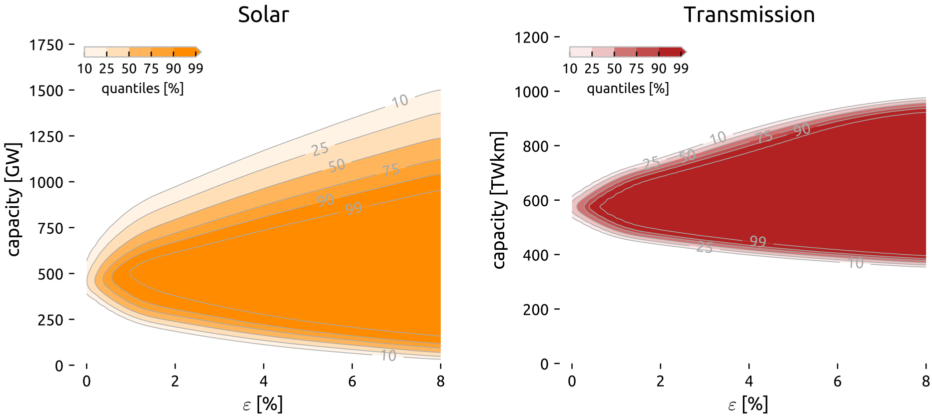


Example interpretations:

- No solutions with less than 500 GW of wind capacity.
- 99% chance that building 750 GW of onshore wind is within $\varepsilon = 4\%$.

Source: https://neumann.fyi/files/neumann-2021-broad-ranges.pdf

Fuzzy but robust trade-offs between system cost and technology use.



Compared to other technologies, the level of **grid expansion** required has very low uncertainty.

Source: https://neumann.fyi/files/neumann-2021-broad-ranges.pdf

To wrap up...

Goals

- robust boundary conditions for given cost ranges

Results

- wide range of trade-offs with diverse solutions *in any case*
- must-haves: off-/onshore wind, some grid reinforcement and long-term storage

Outlook and Limitations

- better indicators of public acceptance, here just use of technology
- only electricity sector, repeat with sector coupling
- no pathway analysis, no endogeneous learning
- only system-level variables, no disaggregation

Resources

Find the slides:

https://neumann.fyi/files/empe-neumann-2021.pdf

Find the code:

https://github.com/fneum/broad-ranges

Find the preprint:

https://neumann.fyi/files/neumann-2021-broad-ranges.pdf

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