Broad Ranges of Investment Configurations for Renewable Power Systems, Robust to Cost Uncertainty and Near-Optimality

Fabian Neumann, Tom Brown

fabian.neumann@kit.edu
Institute for Automation and Applied Informatics
Karlsruhe Institute of Technology (KIT), Germany

International Energy Workshop 2021

June 15, 2021

HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

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What we will look at.

Trade-offs between system cost and technology use in renewable European electricity system.

1. **explore** space of nearly cost-optimal alternatives
2. **analyse** impact of technology cost uncertainty
3. **strengthen** near-optimal solutions with robustness to cost uncertainty

Mix of results and methods to overcome computational challenges.

Goal is to convey an understanding of the decision freedom.

Least-cost capacity expansion from social planner perspective.

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

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

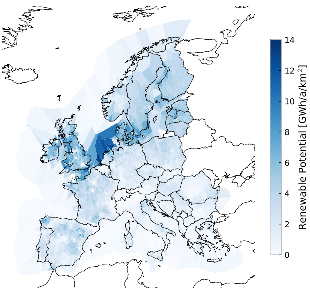
subject to

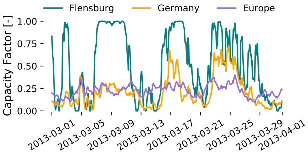
- meeting energy demand at each node n and time t
- transmission constraints between nodes with LOPF
- wind, solar, hydro availability time series $\forall\, n, t$
- geographical potentials for renewables
- emission reduction targets

Source: Tom Brown, and documentation at pypsa-eur.readthedocs.io and pypsa.readthedocs.io

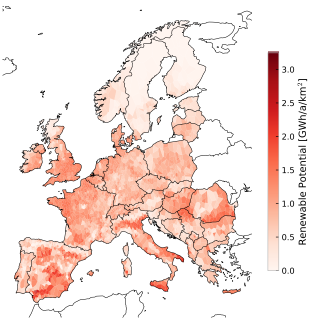
PyPSA-Eur – Inputs

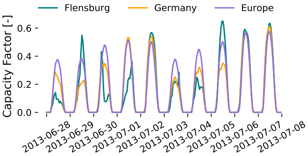
wind potential



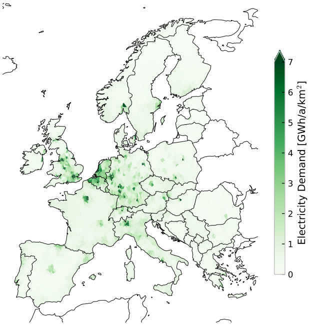


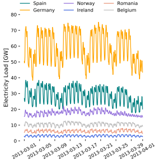
solar potential



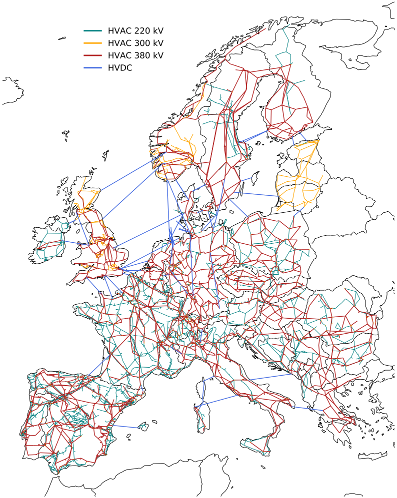


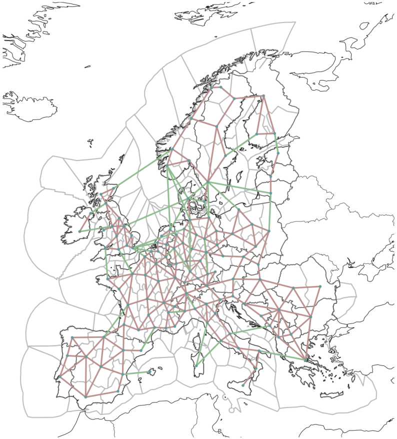
load





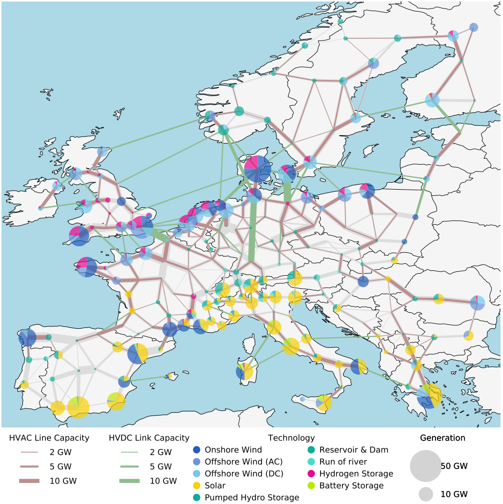
PyPSA-Eur – Inputs

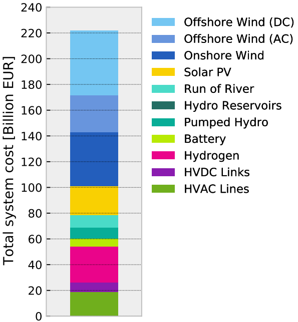




need **clustering** for solveability

PyPSA-Eur – Outputs





- electricity sector only
- 200 regions
- 4380 snapshots (2-hourly resolution for 1 year)
- greenfield (except grid, hydro, run of river)

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

Let's look at **degrees of freedoms** near the cost-optimum first.

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.

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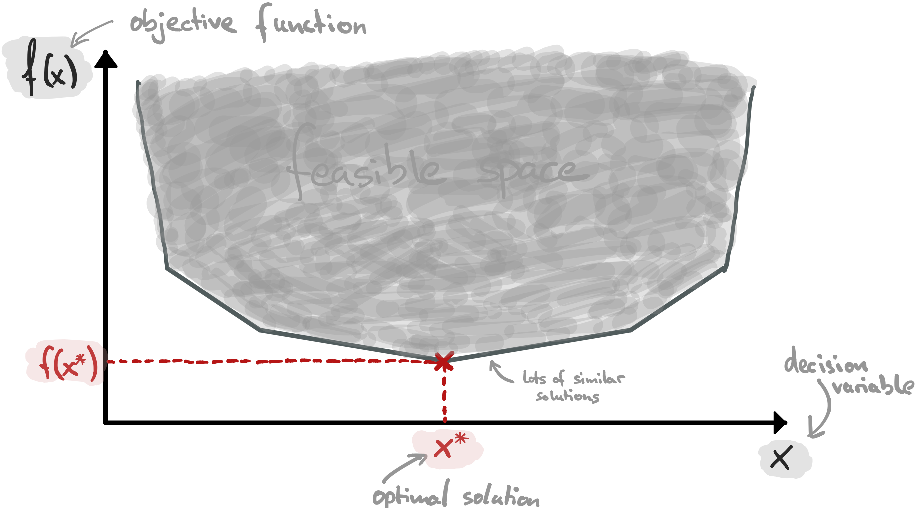
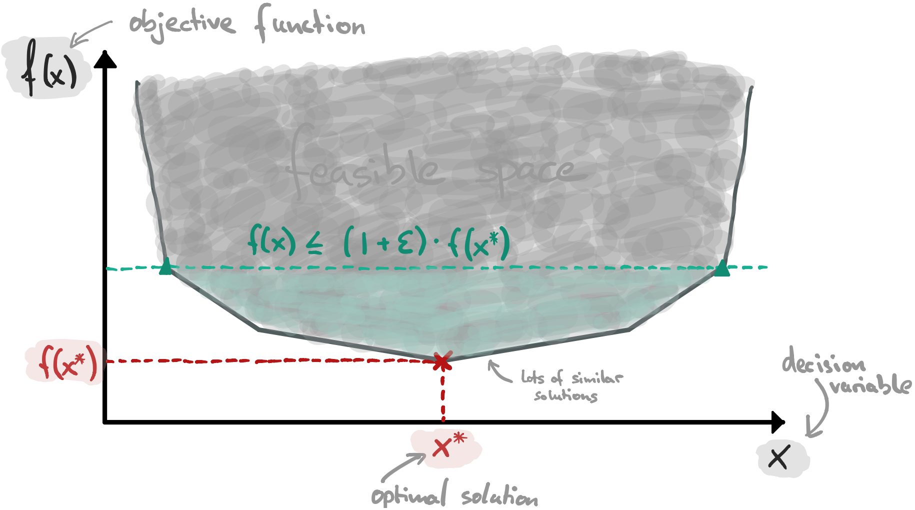
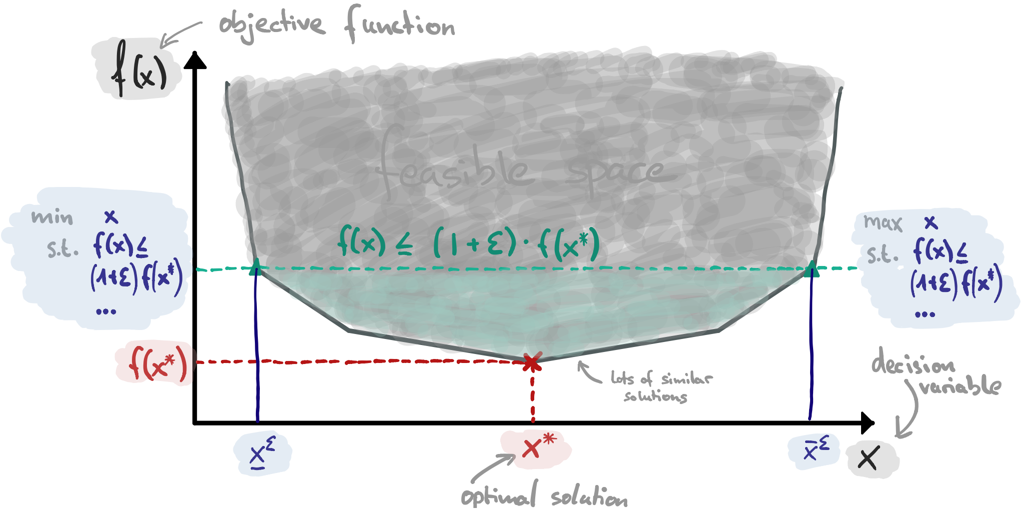

objective function
f(x)
feasible space
f(x*)
lots of similar solutions
decision variable
x
x*
optimal solution

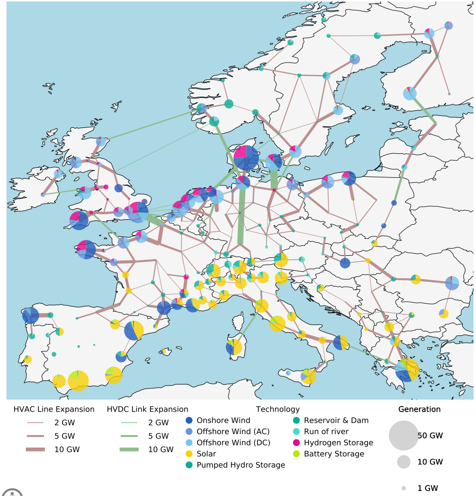

objective function
f(x)
feasible space
f(x) ≤ (1+ε)·f(x*)
f(x*)
lots of similar solutions
decision variable
x
x*
optimal solution



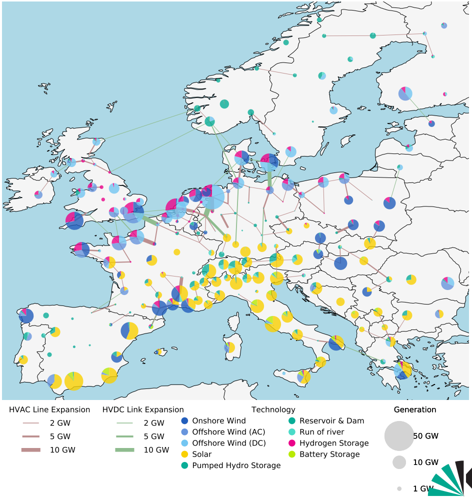
objective function
f(x)
feasible space
f(x) ≤ (1+ε)·f(x*)
min x
s.t. f(x) ≤ (1+ε) f(x*)
...
max x
s.t. f(x) ≤ (1+ε) f(x*)
...
f(x*)
lots of similar solutions
decision variable
x
optimal solution

Exemplary indication that feasible space is flat near cost-optimum.

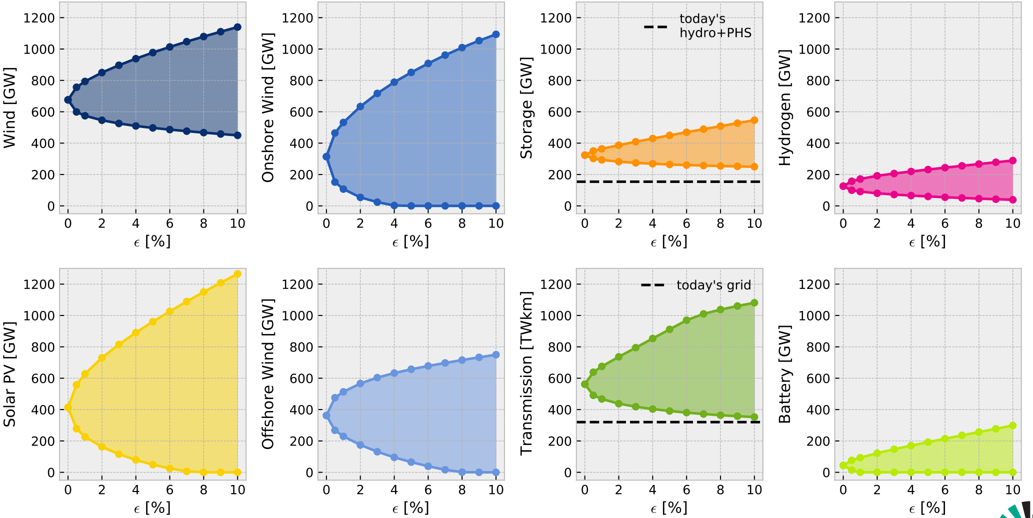
Least-Cost Transmission Volume $\epsilon = 0.0\%$



Minimise Transmission Volume $\epsilon = 5.0\%$



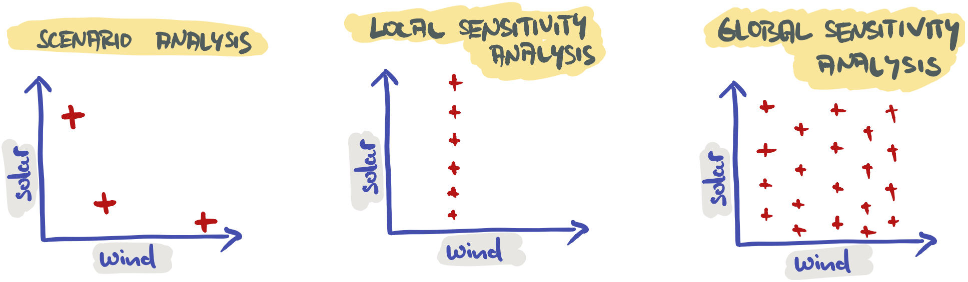
We can systematically draw a space of near-optimal solutions.



Now, let's look at the impact of **uncertain technology cost** projections.

Source: **Inspired by:** 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.

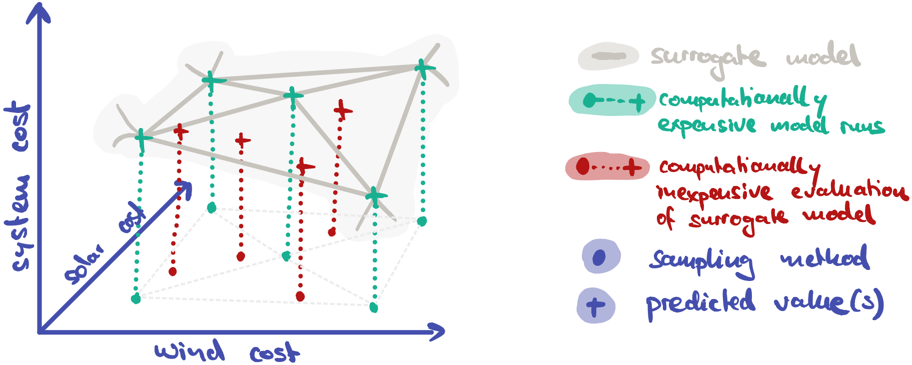
Because many samples are required to sweep full parameter space...



Low-discrepancy series can be used to efficiently sample from the parameter space.

...computational challenges make surrogate modelling attractive.

Same input-output behaviour as the original model, but computes much faster.



...computational challenges make surrogate modelling attractive.

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

One way is to use a **polynomial chaos expansion** with **regression** techniques for that.

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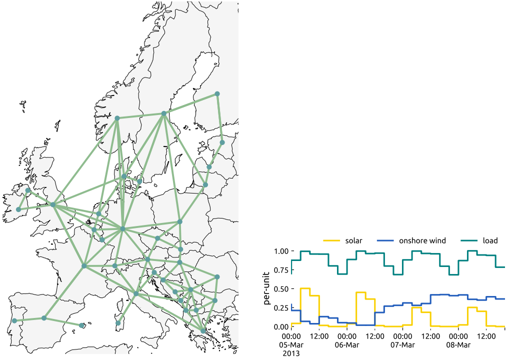
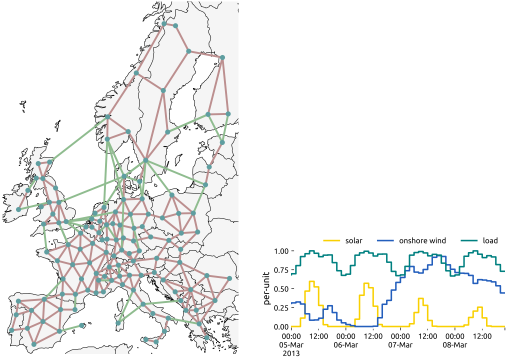
With surrogate modelling one can even combine multiple models.

low-fidelity: 37 nodes, 4-hourly, 500 samples

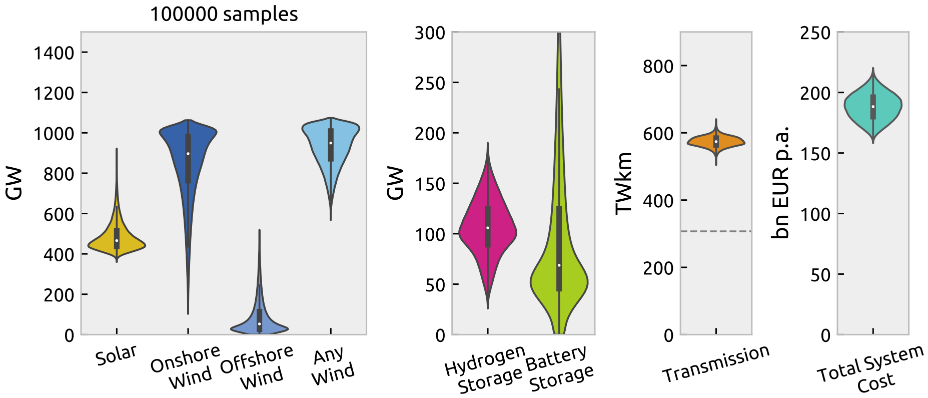


high-fidelity: 128 nodes, 2-hourly, 10 samples



Source: Like 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.

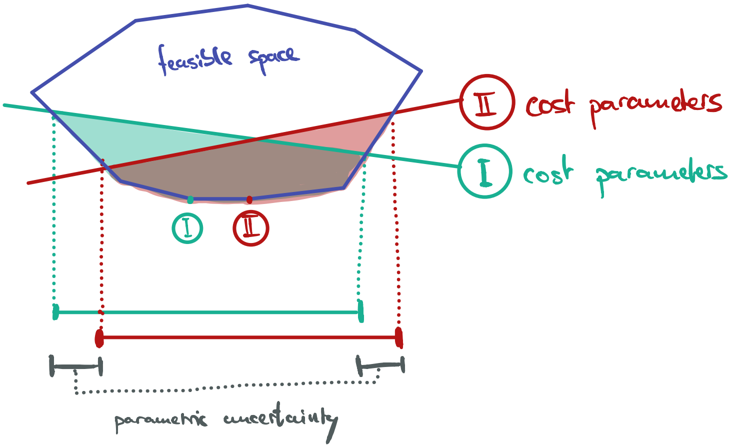
Distribution of system cost, generation, storage and transmission.



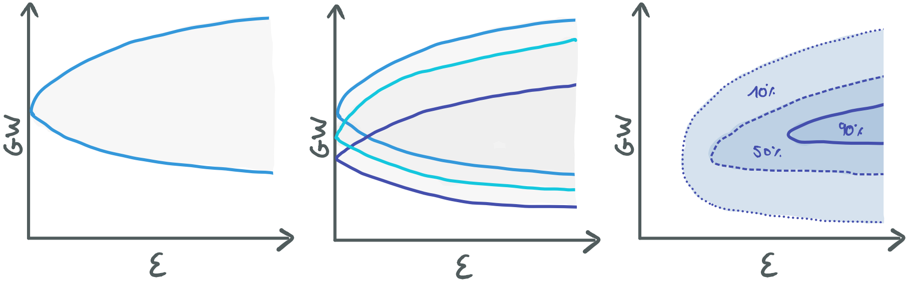
What does **technology cost uncertainty** mean for the analysis of **near-optimal trade-offs**?

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

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



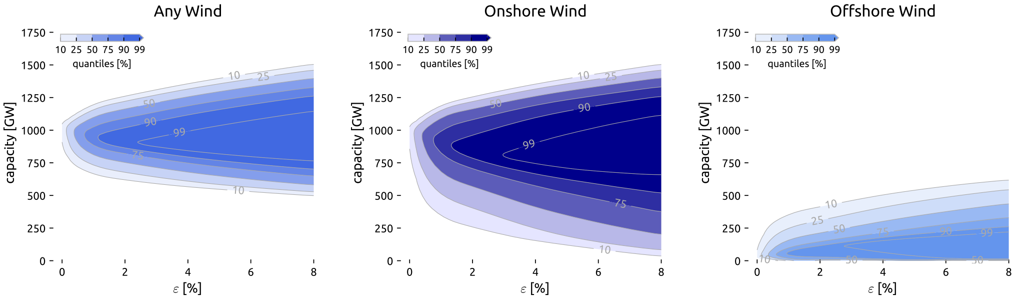
How does cost uncertainty impact near-optimal trade-offs?



Using **surrogate modelling** from before, but now also for different ϵ and search directions.

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

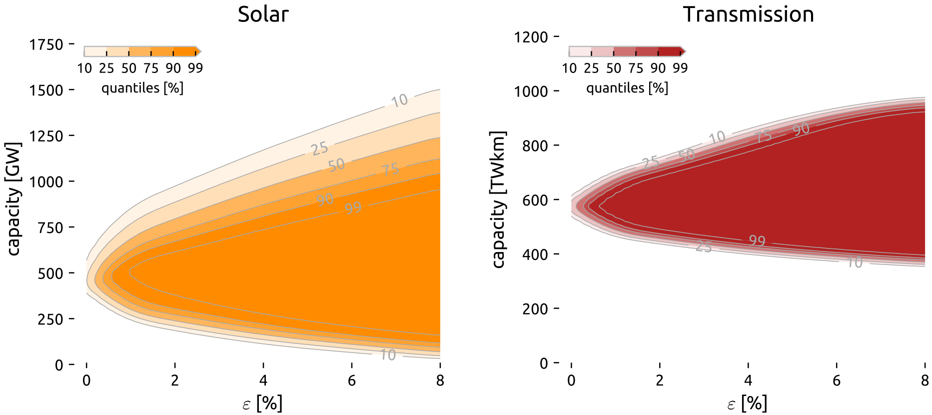
Fuzzy but robust trade-offs between system cost and technology use.



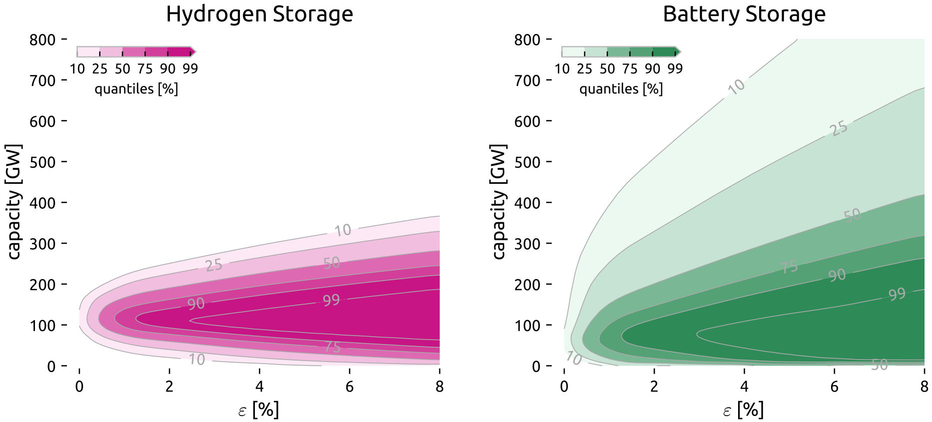
Example interpretations:

- In 99% of cases, building 750 GW of onshore wind is within 4% of the least-cost solution.
- At least 400 GW of onshore wind are needed to have a 75% chance of being within 8%.

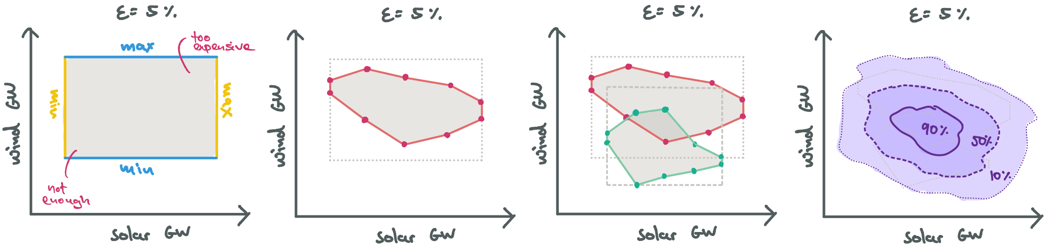
Fuzzy but robust trade-offs between system cost and technology use.



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



We can also look at trade-offs between technologies.



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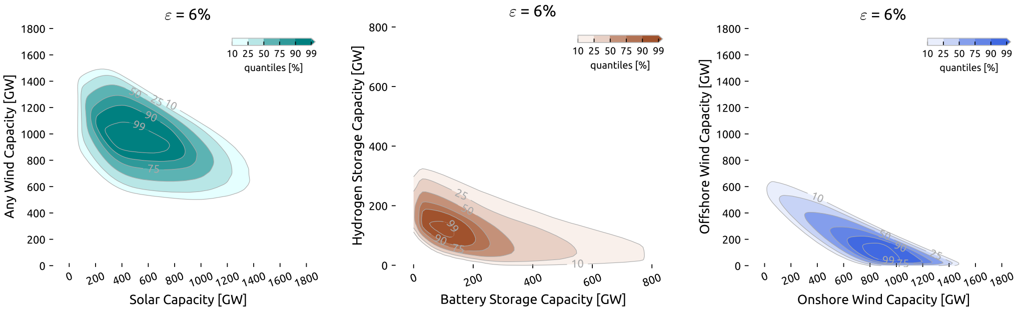

To wrap up...

Goals

- set of robust technology-specific boundary conditions for pre-defined cost ranges

Results

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

Outlook and Limitations

- just techno-economic perspective, not actually about social acceptance
- only electricity sector, repeat with coupling between multiple energy sectors
- no pathway analysis, no endogeneous technological learning

Resources

Find the slides:

https://neumann.fyi/assets/iew-2021.pdf

Find the code:

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

Find the preprint:

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

Send an email:

fabian.neumann@kit.edu

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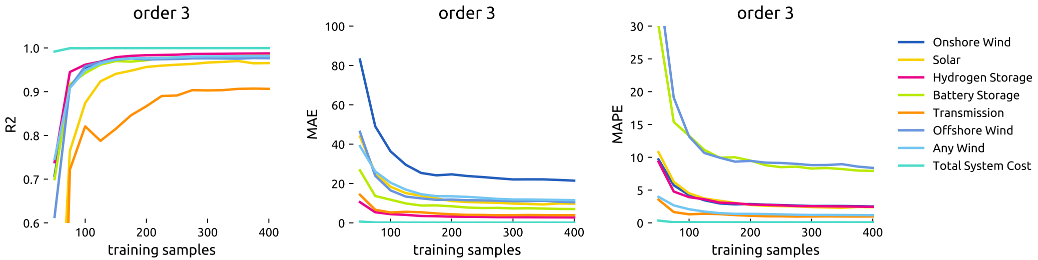
Backup: Cost Assumptions from Danish Energy Agency

technology	lower annuity	upper annuity	unit
Onshore Wind	70	110	EUR/kW/a
Offshore Wind	175	250	EUR/kW/a
Solar	35	55	EUR/kW/a
Battery	25	125	EUR/kW/a
Hydrogen	100	275	EUR/kW/a

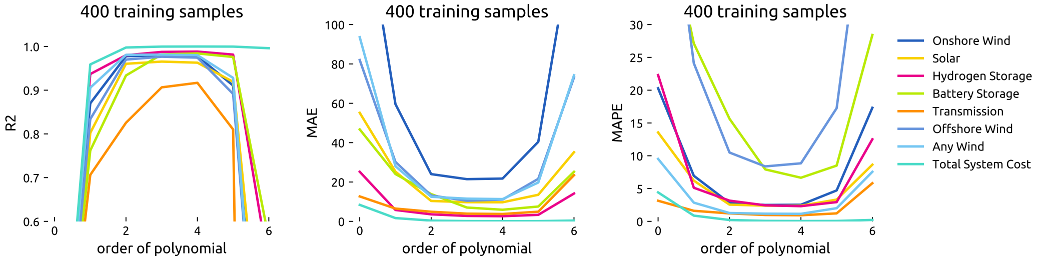
Assumed to be uniformly distributed following **maximum-entropy approach**.

Backup: Error versus number of samples (low-fidelity)



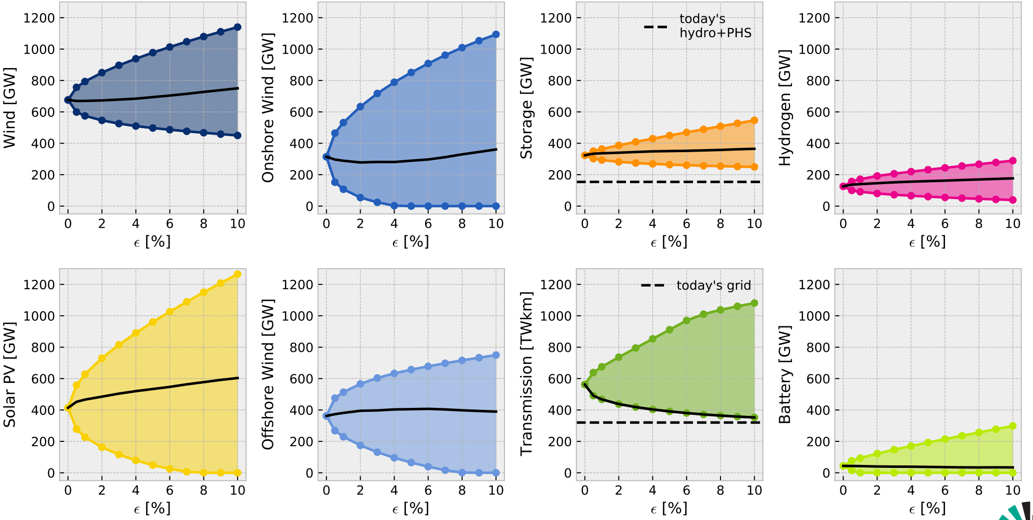
- order of the polynomial fixed to 3
- improvements beyond 200 samples are small
- relative error mostly below 5%, prediction of system cost very accurate
- higher relative errors where technology is not built (logical, skewed)

Backup: Error versus PCE order (low-fidelity)

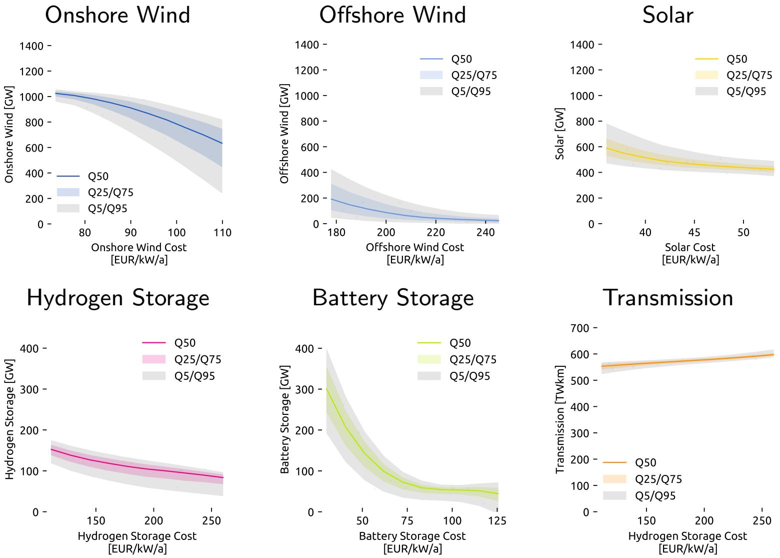


- order of 2 and below is too simple (underfitting)
- order of 5 and above is too flexible (overfitting)
- order of 3 appears to be a suitable compromise

Backup: We can systematically draw a space of near-optimal solutions.



Backup: We can also look at the effect of cost on built capacity.



Backup: Sensitivity indices tell which inputs contribute to output uncertainty.

Total **Sobol indices** allocate the observed variance to cost uncertainties.