The Near-Optimal Feasible Space of a Renewable Power System Model

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HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

KIT
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Open Energy System Modelling with PyPSA-Eur

Find the long-term cost-optimal energy system, including investments and short-term costs:

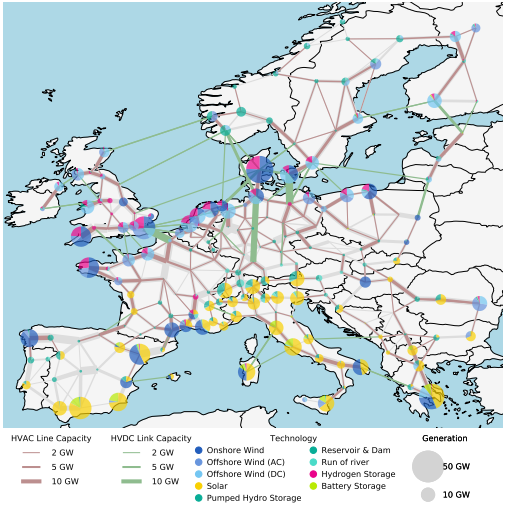
$$\textbf{Min}\left[\begin{array}{c}\textbf{Yearly}\\ \textbf{system costs}\end{array}\right] = \textbf{Min}\left[\sum_{n}\left(\begin{array}{c}\textbf{Annualised}\\ \textbf{capital costs}\end{array}\right) + \sum_{n,t}\left(\begin{array}{c}\textbf{Marginal}\\ \textbf{costs}\end{array}\right)\right]$$

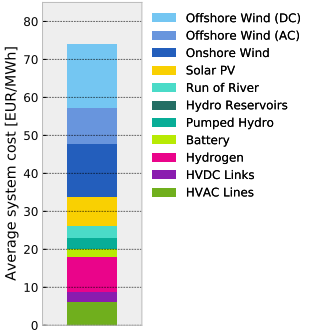
subject to

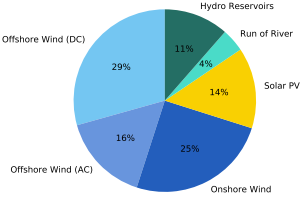
- meeting energy demand at each node n (e.g. region) and time t (e.g. hour of year)
- transmission constraints between nodes and linearised power flow
- wind, solar, hydro (variable renewables) availability time series $\forall\, n, t$
- installed capacity $\leq$ geographical potentials for renewables
- fulfilling CO_2 emission reduction targets
- Flexibility from gas turbines, battery/hydrogen storage, HVDC links

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

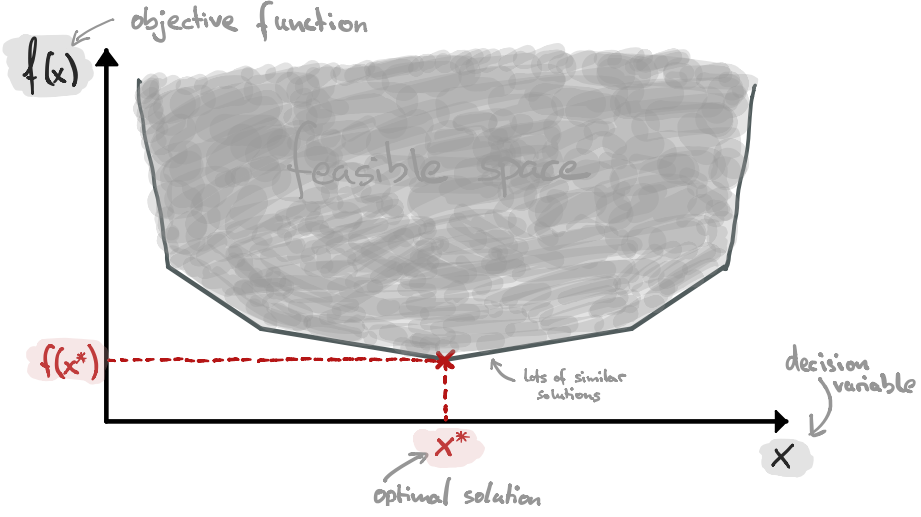
Optimal System Layout for 100% emission reduction

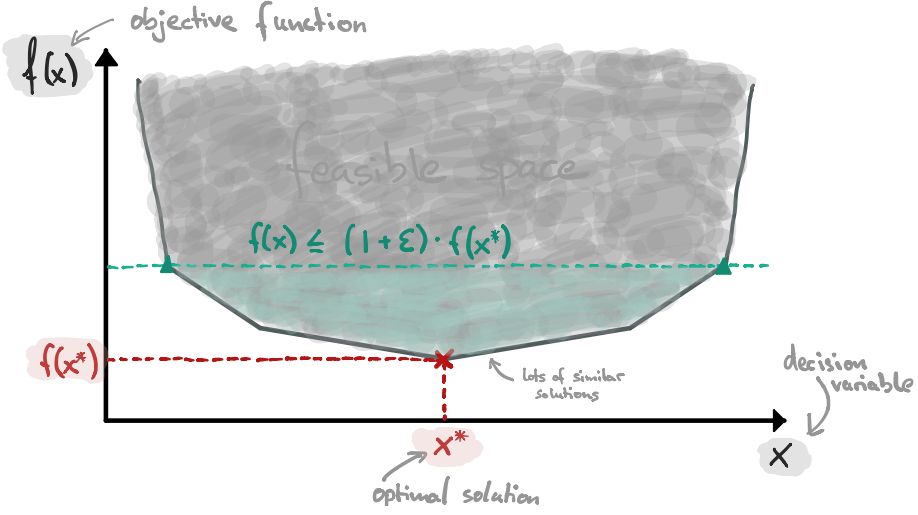


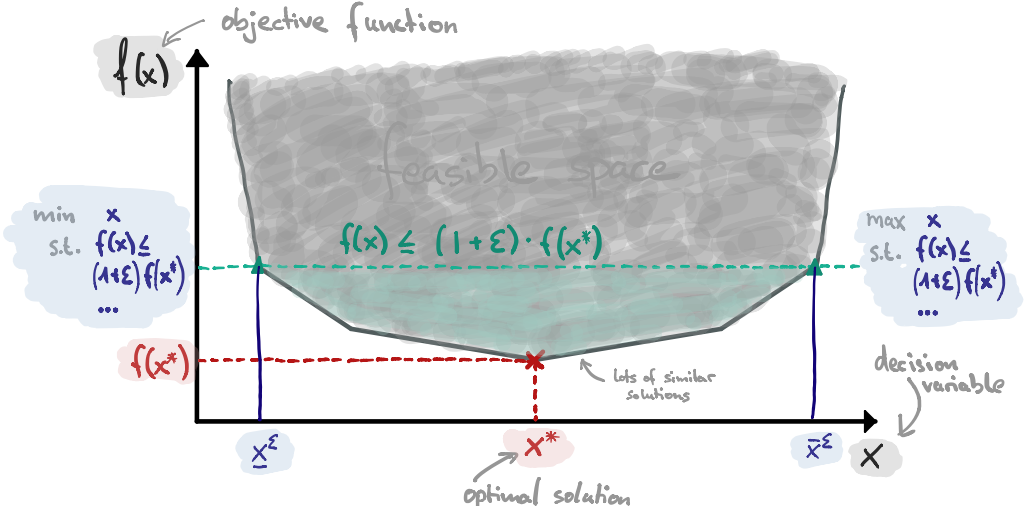




- power sector only
- ~~100~~ 200 nodes
- 4380 snapshots (2-hourly resolution for 1 year)
- greenfield (except grid, hydro, run of river)


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





Experiments

1. Find the **least-cost power system**.

2. For many $\varepsilon \in \{0.5, 1, , \ldots, 10\}\%$ **minimise/maximise** investment in
   - generation capacity (onshore and/or offshore wind, solar),
   - storage capacity (hydrogen, batteries, total storage) and
   - transmission volume (HVAC lines and HVDC links)

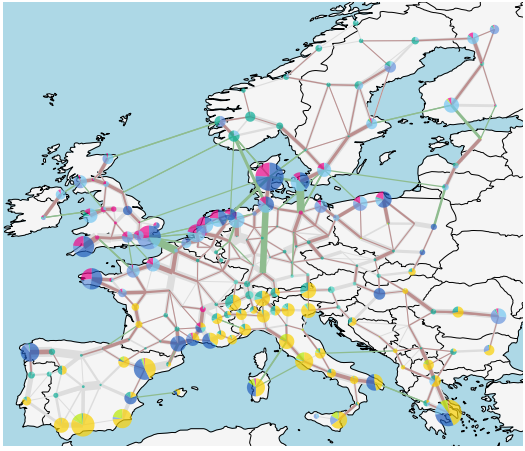
   such that **total annual system costs increase by less than** ε.

Can also perform minimisation/maximisation of investment **per carrier and country**!

Starting from the optimal solution, ...

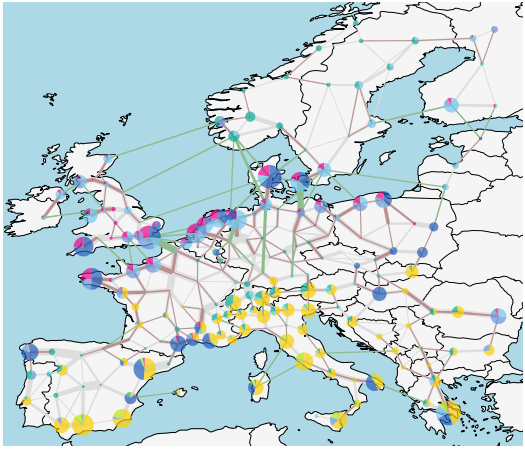
Optimal
Transmission
Volume
Epsilon:
0.0%

This is the optimal solution from earlier!



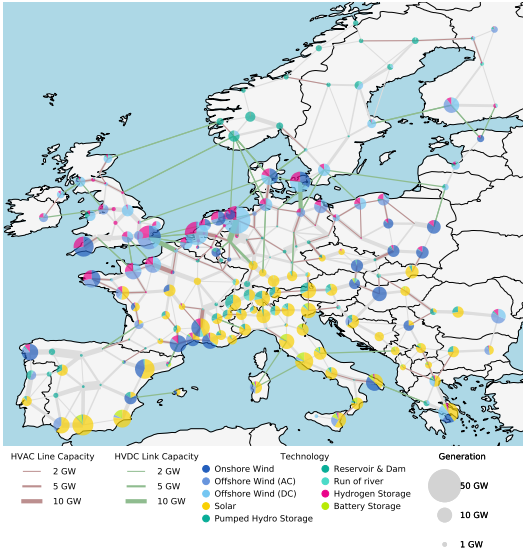
... seek the minimum transmission volume. ($\varepsilon = 1.0\%$)

Minimise
Transmission
Volume
Epsilon:
1.0%



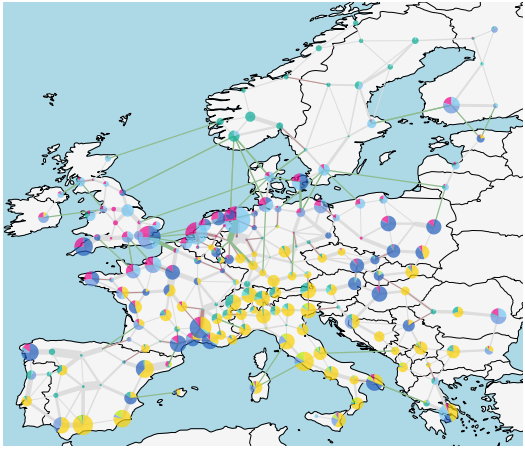
... seek the minimum transmission volume. ($\varepsilon = 5.0\%$)

Minimise
Transmission
Volume
Epsilon:
5.0%

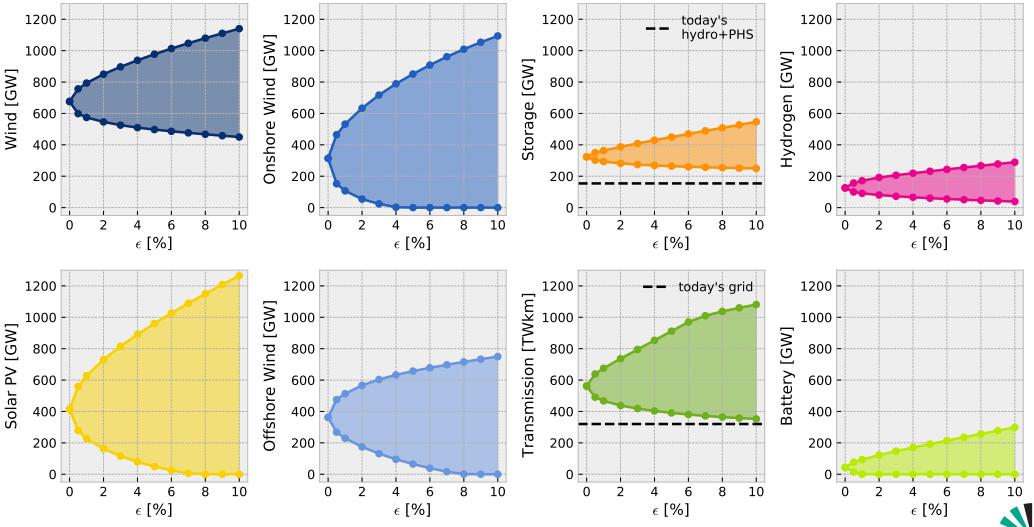


... seek the minimum transmission volume. ($\varepsilon = 10.0\%$)

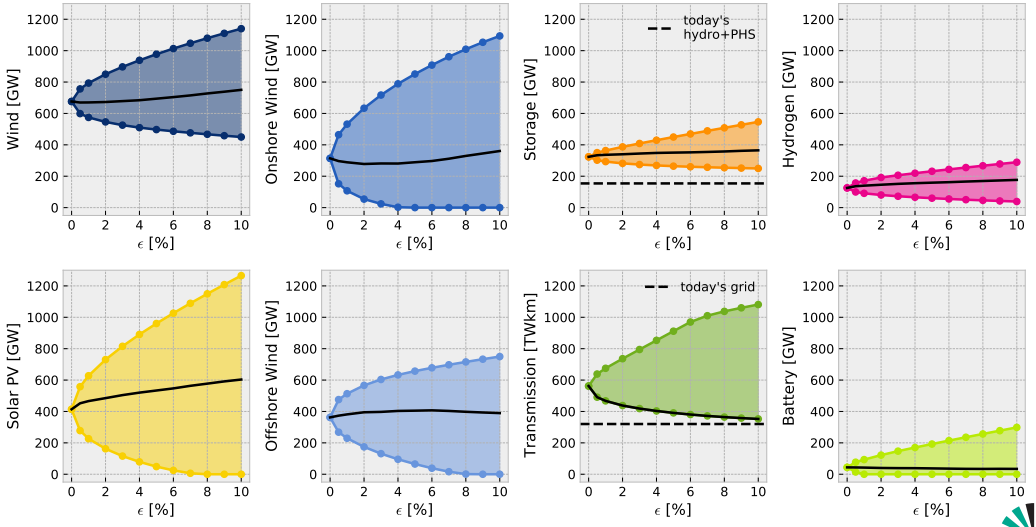
Minimise
Transmission
Volume
Epsilon:
10.0%



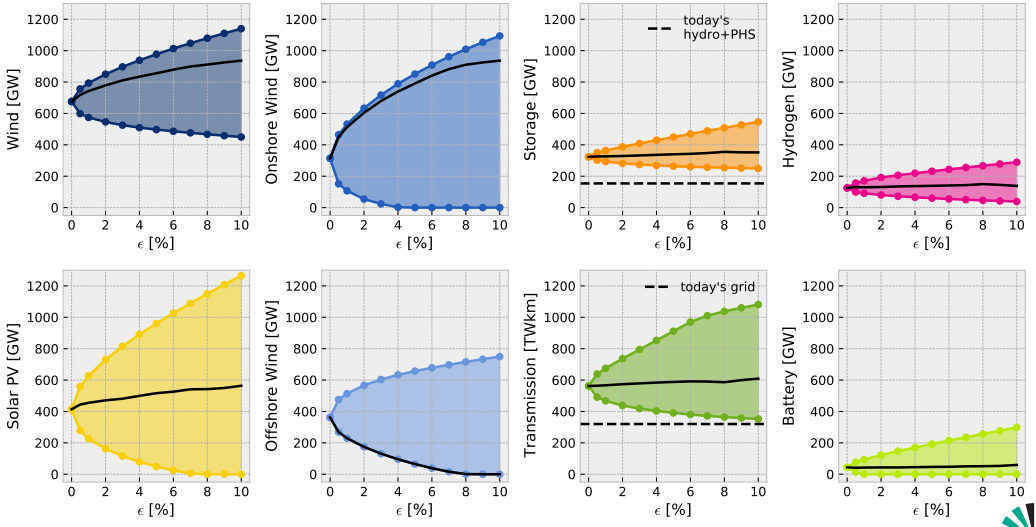
Near-optimal total system capacity ranges for varying ε



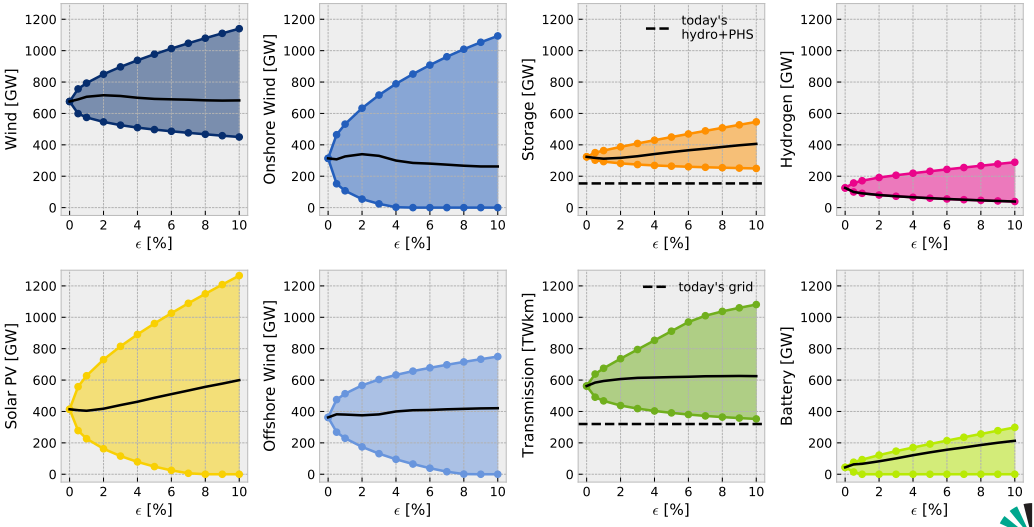
Correlations when minimising transmission extension



Correlations when minimising offshore wind



Correlations when minimising H_2 storage



Conclusion & Outlook

Goals

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

Results

- high variance in the deployment of individual system components
- either offshore or onshore wind and some H_2-storage and grid reinforcement

Outlook

- improve visualising dependencies (interactive website, more search directions)
- repeat with coupling between multiple energy sectors
- include parametric uncertainty of cost assumptions ("fuzzy" boundaries)

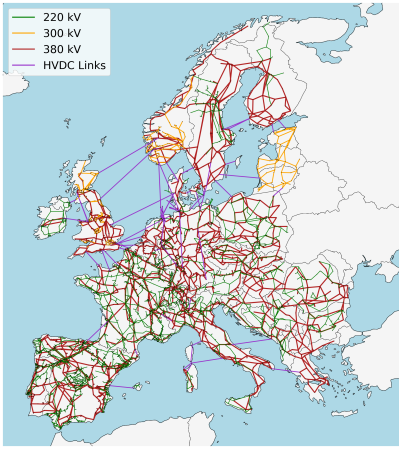
Resources

Find the slides:
https://neumann.fyi/assets/pscc2020-near-optimal.pdf

Send an email:
fabian.neumann@kit.edu

Find the energy system model:
https://github.com/pypsa/pypsa-eur

Open Energy System Modelling with PyPSA-Eur

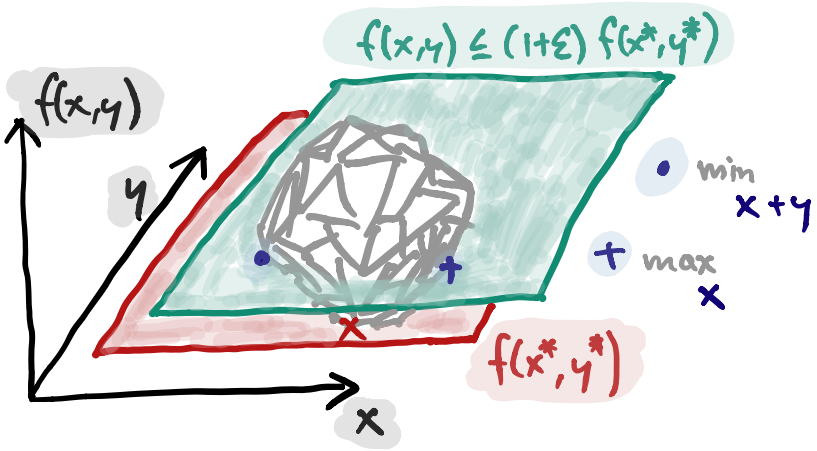


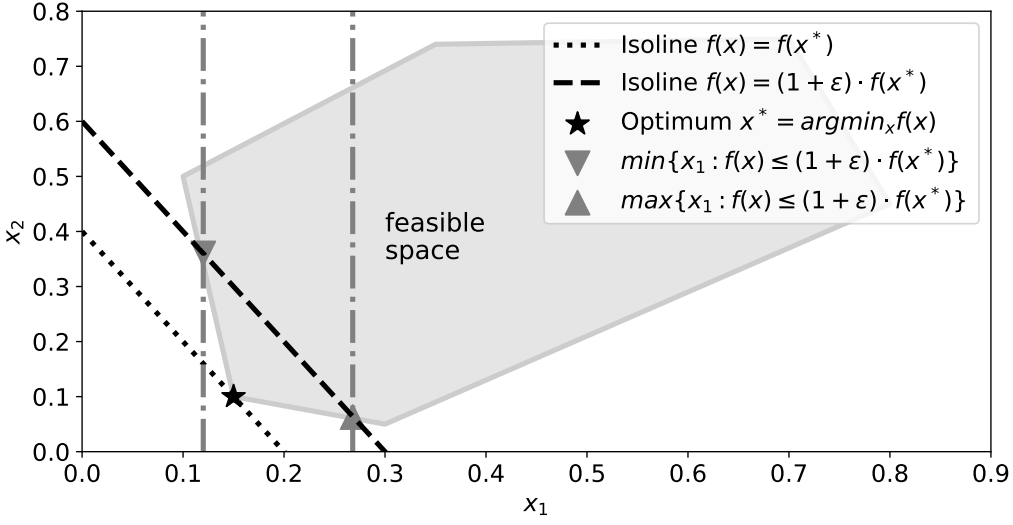
- Grid data from ENTSO-E transparency map
- Power plant database combines multiple open databases using matching algorithms
- Renewable energy time series from reanalysis (historical) weather data (ERA-5, SARAH-2)
- Geographic potentials from land use databases
- Time series aggregation (usually 8760h)
- Network clustering (k-means algorithm)

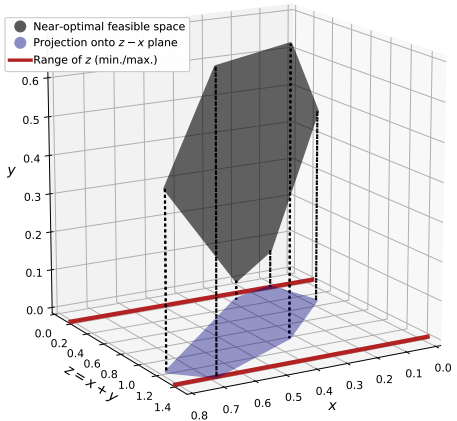
Code and Documentation

- https://pypsa-eur.readthedocs.io
- https://github.com/PyPSA/pypsa-eur

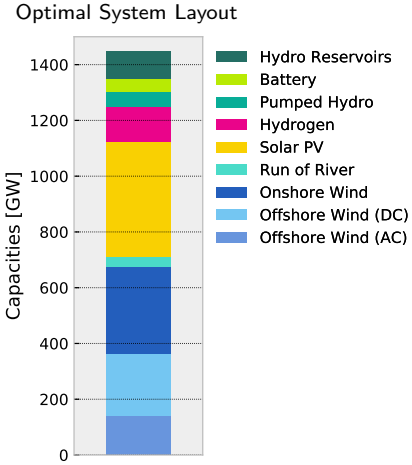
Source: Tom Brown, and documentation at pypsa-eur.readthedocs.io and pypsa.readthedocs.io

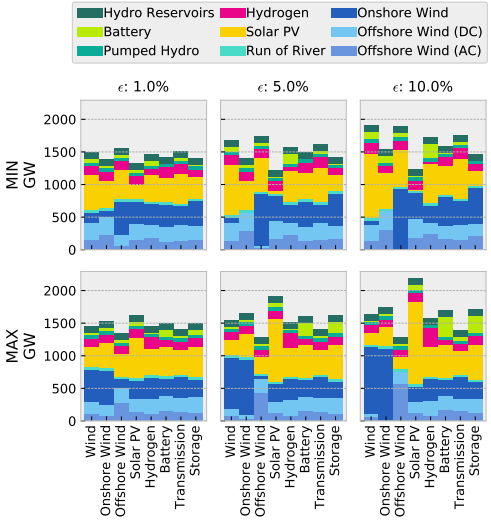



Isoline $f(x) = f(x^*)$
Isoline $f(x) = (1+\varepsilon) \cdot f(x^*)$
Optimum $x^* = argmin_x f(x)$
$min\{x_1 : f(x) \leq (1+\varepsilon) \cdot f(x^*)\}$
$max\{x_1 : f(x) \leq (1+\varepsilon) \cdot f(x^*)\}$
feasible space
x_1
x_2
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9

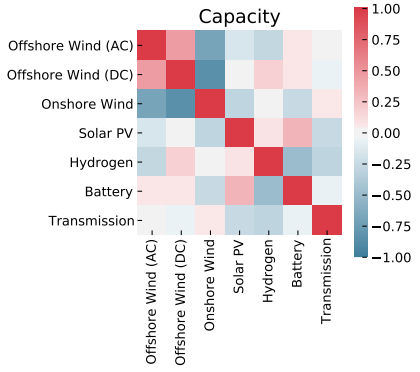


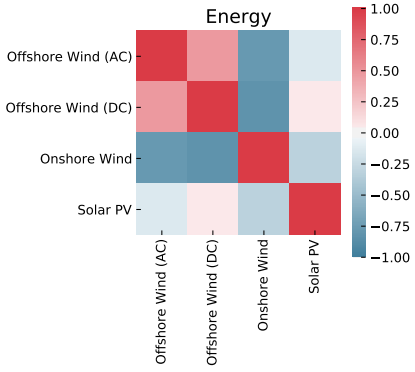
Dependencies: Extremes cannot be achieved simultaneously.



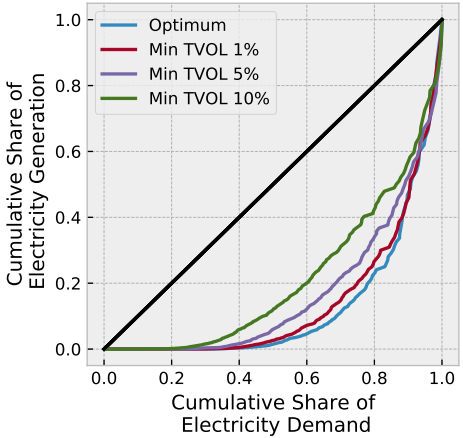


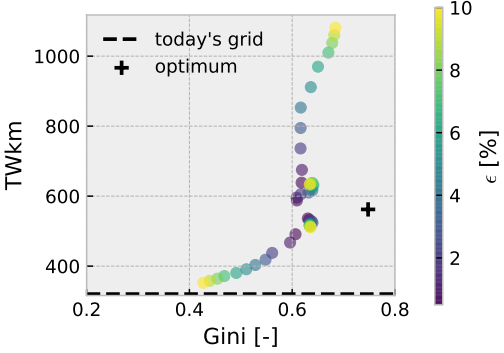
Correlations of Investment in Technologies

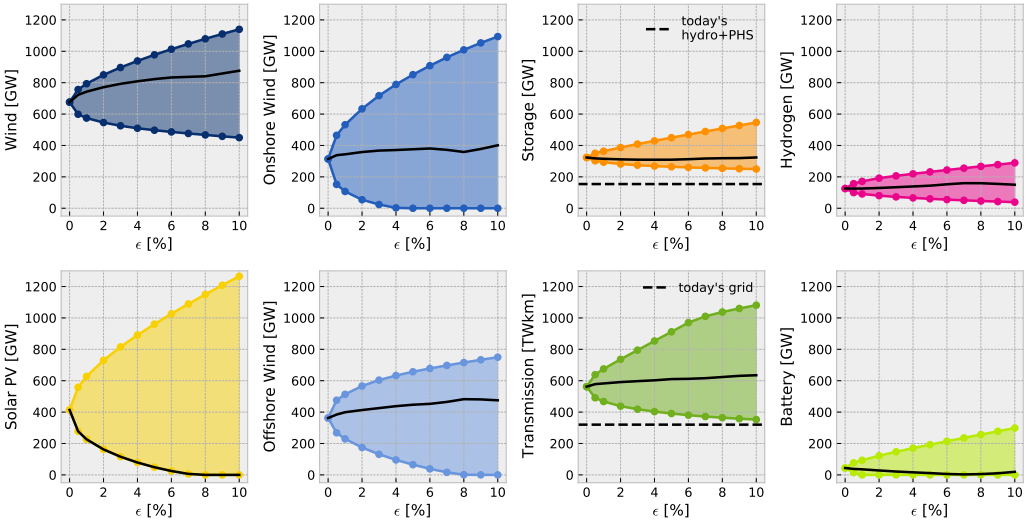


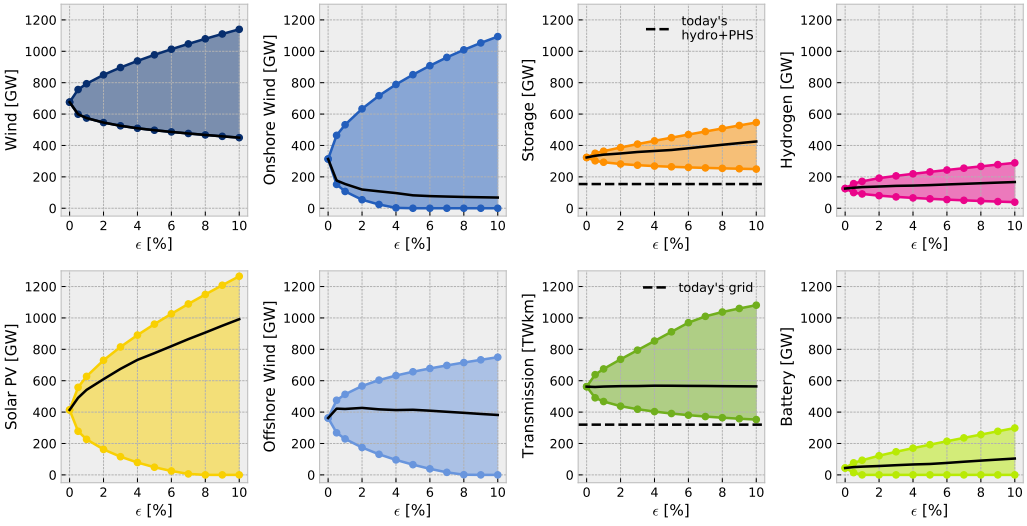


Distributional Equity: Lorenz Curves and Gini Coefficients






Wind [GW]
Onshore Wind [GW]
Storage [GW]
today's hydro+PHS
Hydrogen [GW]
Solar PV [GW]
Offshore Wind [GW]
Transmission [TWkm]
today's grid
Battery [GW]
ϵ [%]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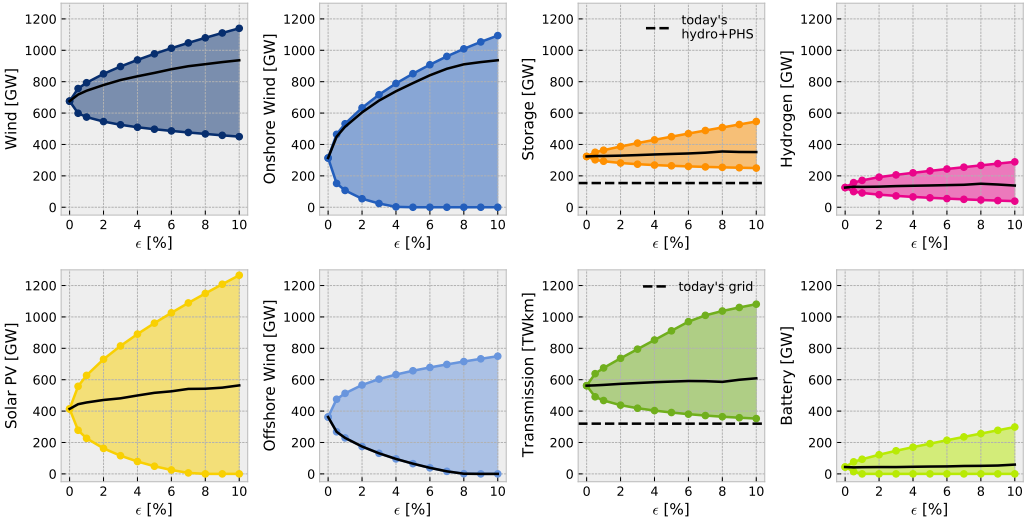
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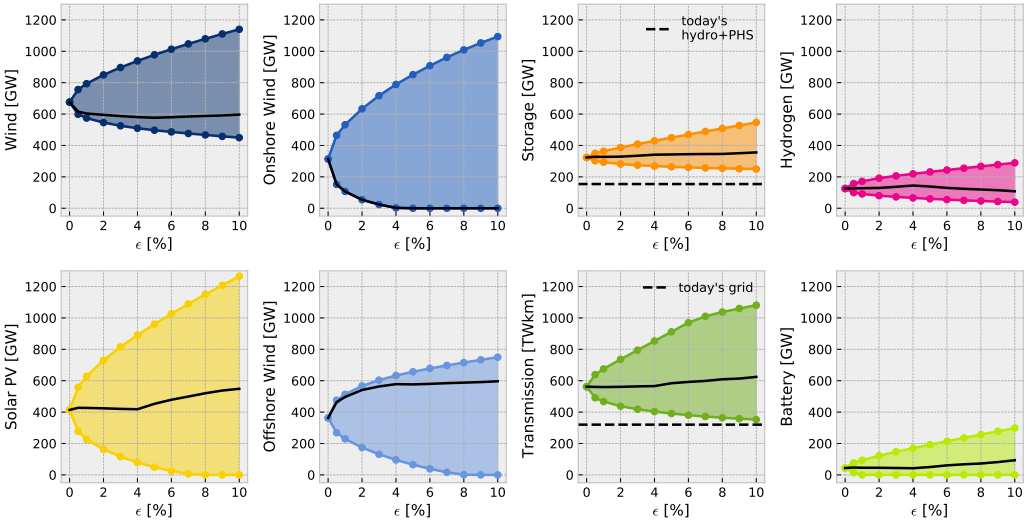
ϵ [%]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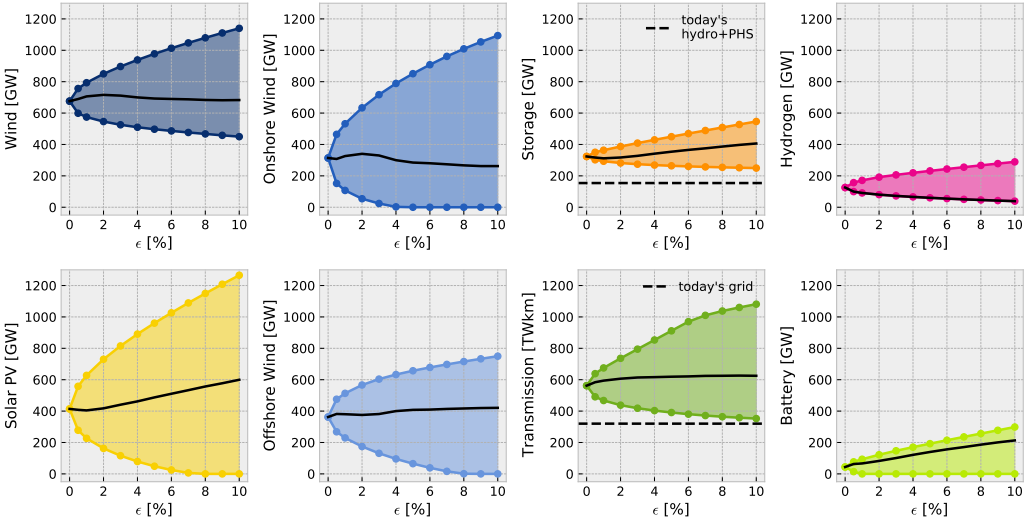
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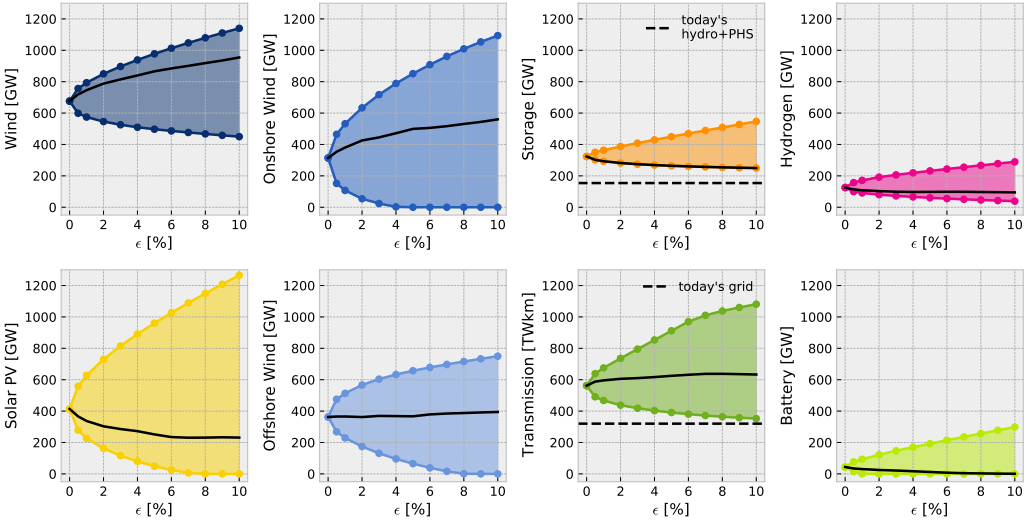
Battery [GW]
ϵ [%]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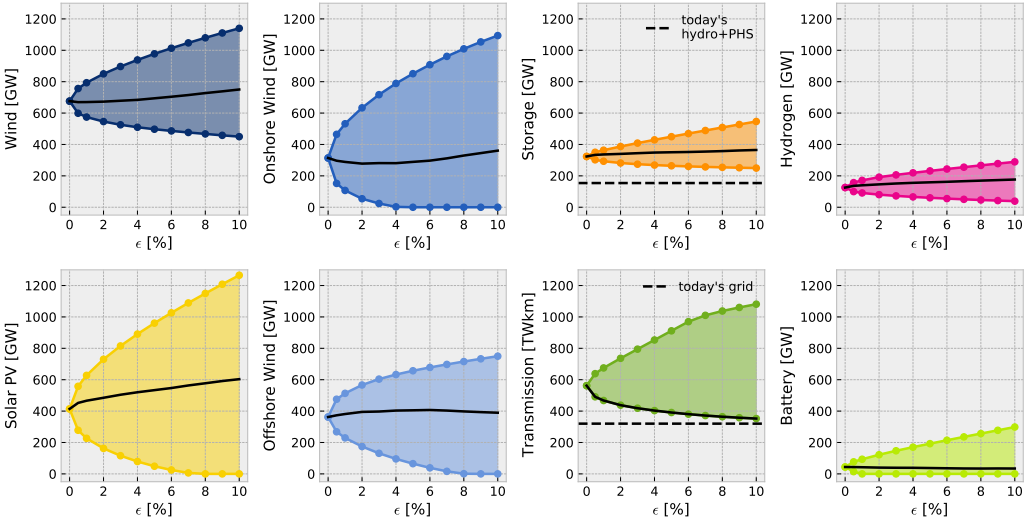
today's grid
Battery [GW]
ϵ [%]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Onshore Wind [GW]
Storage [GW]
today's hydro+PHS
Hydrogen [GW]
Solar PV [GW]
Offshore Wind [GW]
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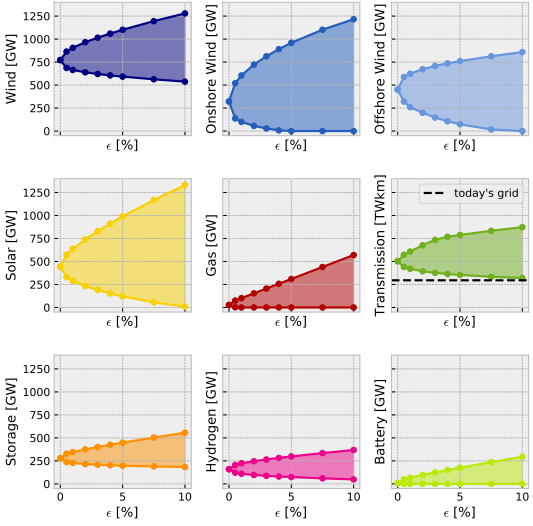
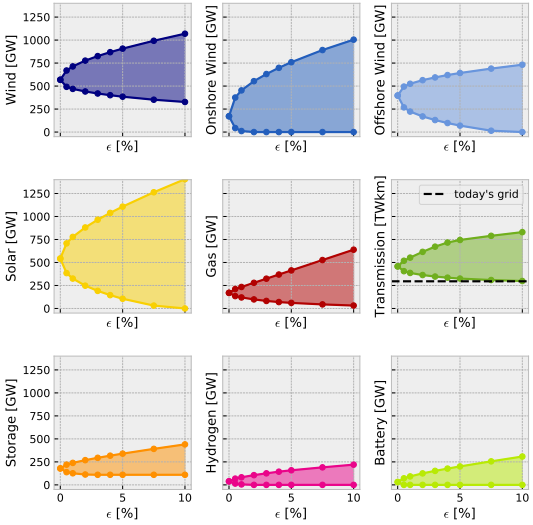
today's grid
Battery [GW]
ϵ [%]

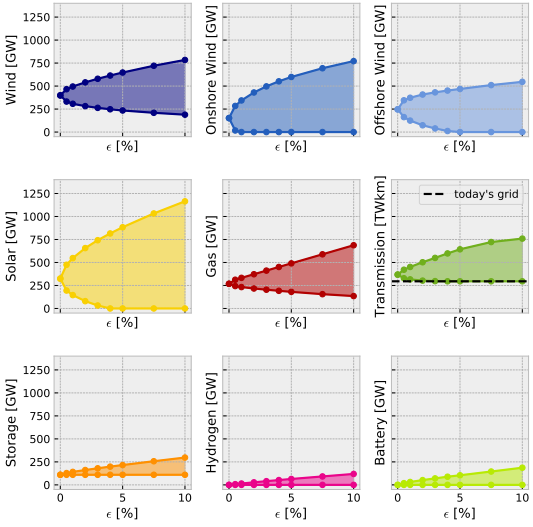
Near-optimal total systems for varying ε (100% reduction)



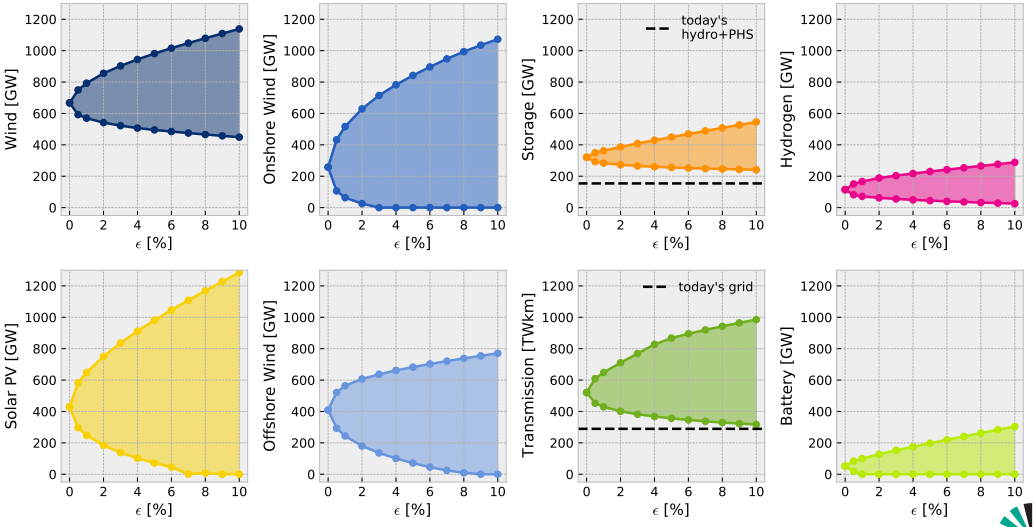
Near-optimal total systems for varying ε (95% reduction)



Near-optimal total systems for varying ε (80% reduction)



Near-optimal total system capacity ranges for varying ε (100 nodes)



Near-optimal total system capacity ranges for varying ε (200 nodes)