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

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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:

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

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

- HVAC Line Capacity: 2 GW, 5 GW, 10 GW
- HVDC Link Capacity: 2 GW, 5 GW, 10 GW
- Technology:
  - Onshore Wind
  - Offshore Wind (AC)
  - Offshore Wind (DC)
  - Solar
  - Pumped Hydro Storage
  - Reservoir & Dam
  - Run of River
  - Hydro Reservoirs
  - Battery
  - Hydrogen
  - HVDC Links
  - HVAC Lines
- Average system cost [EUR/MWh]:
- Offshore Wind (DC): 29%
- Offshore Wind (AC): 16%
- Onshore Wind: 25%
- Solar PV: 14%
- Run of River: 4%
- Hydro Reservoirs: 11%

- power sector only
- ≤900 200 nodes
- 4380 snapshots (2-hourly resolution for 1 year)
- greenfield (except grid, hydro, run of river)
Long-Term Power System Investment Planning

Obtaining Feasible Near-Optimal Solutions

Results

Conclusion & Outlook

Backup

**Objective Function**

\( f(x) \)

**Feasible Space**

**Decision Variables**

Lots of similar solutions

**Optimal Solution**
The objective function is $f(x)$, and the feasible space is defined as $f(x) \leq (1 + \varepsilon) \cdot f(x^*)$.

The optimal solution $x^*$ lies within the feasible space, and there are lots of similar solutions nearby. The decision variable is plotted on the x-axis.
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 $\varepsilon$**.

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**

**Transmit**

**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 $\varepsilon$
Correlations when minimising transmission extension
Correlations when minimising offshore wind

- Wind [GW]
- Onshore Wind [GW]
- Storage [GW]
- Hydrogen [GW]
- Solar PV [GW]
- Offshore Wind [GW]
- Transmission [TWkm]
- Battery [GW]

The diagrams illustrate the correlations between different energy sources and transmission capacity for varying epsilon [ε] percentages, indicating feasible near-optimal solutions for long-term power system investment planning.
Correlations when minimizing $H_2$ 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 H₂-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

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

Send an email:
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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://pypsa-eur.readthedocs.io)
- [https://github.com/PyPSA/pypsa-eur](https://github.com/PyPSA/pypsa-eur)

Source: Tom Brown, and documentation at pypsa-eur.readthedocs.io and pypsa.readthedocs.io
Let's consider the objective function $f(x, y)$ and the feasible space $\mathbb{F}$. The goal is to obtain a feasible near-optimal solution $f(x^*, y^*)$. The constraint is $f(x, y) \leq (1+\varepsilon)f(x^*, y^*)$. The decision variables are $x$ and $y$. The optimal solution is marked by a dot, while the max and min values are indicated by plus and minus signs, respectively.
Isoline $f(x) = f(x^*)$

Isoline $f(x) = (1 + \varepsilon) \cdot f(x^*)$

Optimum $x^* = \arg\min_x f(x)$

$\min \{x_1 : f(x) \leq (1 + \varepsilon) \cdot f(x^*)\}$

$\max \{x_1 : f(x) \leq (1 + \varepsilon) \cdot f(x^*)\}$

feasible space
Dependencies: Extremes cannot be achieved simultaneously.
Correlations of Investment in Technologies
Distributional Equity: Lorenz Curves and Gini Coefficients

![Graph showing cumulative share of electricity demand and generation with Lorenz curves and Gini coefficients.](image-url)
Long-Term Power System Investment Planning

Results

Conclusion & Outlook

Backup
Near-optimal total systems for varying $\varepsilon$ (100% reduction)
Near-optimal total systems for varying $\epsilon$ (95% reduction)
Near-optimal total systems for varying $\varepsilon$ (80% reduction)
Near-optimal total system capacity ranges for varying $\varepsilon$ (100 nodes)
Near-optimal total system capacity ranges for varying $\epsilon$ (200 nodes)