Analysing the Near-Optimal Feasible Space of Low-Emission Energy System Models (WIP)

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Open Energy System Modelling with PyPSA-Eur

- Grid data based on GridKit extraction of ENTSO-E interactive map
- `powerplantmatching` tool combines open databases using matching algorithms
- Renewable energy time series from atlite tool
- Geographic potentials for RE from land use databases processed with glaes
- Optionally, time series aggregation with tsam
- Network clustering using $k$-means algorithm

Code and Documentation

- https://pypsa-eur.readthedocs.io
- https://github.com/PyPSA/pypsa-eur
Open Energy System Modelling with PyPSA-Eur

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

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

subject to

- meeting \textbf{energy demand} at each node \( n \) (e.g. region) and time \( t \) (e.g. hour of year)
- \textbf{transmission constraints} between nodes and (linearised) power flow
- wind, solar, hydro (variable renewables) \textbf{availability time series} \( \forall n, t \)
- installed capacity \( \leq \textbf{geographical potentials} \) for renewables
- \textbf{CO}_2 \textbf{ constraint} (e.g. 95% reduction w.r.t. 1990 emission levels)
- \textbf{Dispatchability} from gas plants, battery storage, hydrogen storage, HVDC links

Source: Tom Brown
Optimal System Layout for a 95% emission reduction (w.r.t. 1990 levels)

Distribution of generation and transmission expansion

Relative total annual system costs

Energy generated by technology

HVAC Line Capacity
- 10 GW
- 25 GW
- 50 GW

HVDC Link Capacity
- 10 GW
- 25 GW
- 50 GW

Technology
- CCGT
- Hydrogen
- OCGT
- Pumped Hydro
- Battery
- Hydro
- Offshore Wind (AC)
- Offshore Wind (DC)
- Onshore Wind
- Run of River
- Solar

Average system cost [EUR/MWh]
- 0
- 10
- 20
- 30
- 40
- 50
- 60
- 70

HVAC Line Capacity
- 10 GW
- 25 GW
- 50 GW

HVDC Link Capacity
- 10 GW
- 25 GW
- 50 GW

Technology
- CCGT
- Hydrogen
- OCGT
- Pumped Hydro
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- Hydro
- Offshore Wind (AC)
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Relative total annual system costs

Energy generated by technology

Distribution of generation and transmission expansion

Relative total annual system costs

Energy generated by technology
The Energy System Modelling Process

Near-Optimal Feasible Solutions: Modelling to Generate Alternatives (MGA)

Preliminary Results

Next Steps

Backup

Objective function

$\mathbf{f}$

Kiara

Feasible space

Decision

Nuts of similar solutions

Er

Optimal solution

Objective function

$\mathbf{f(x)}$

$\mathbf{f(x^*)}$

Decision variable

Lots of similar solutions

Optimal solution

$\mathbf{x}$
The Energy System Modelling Process

Near-Optimal Feasible Solutions: Modelling to Generate Alternatives (MGA)

Preliminary Results

Next Steps

Backup

\[ f(x) \leq (1 + 3) \cdot f(x^*) \]

objectives

feasible space

\[ f(x^*) \]

lots of similar solutions

optimal solution

decision variable

Nuts of similar solutions as optimal solution
The Energy System Modelling Process

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Backup

Objective function $f(x)$

Feasible space $\{x \mid f(x) \leq (1 + 3) \cdot f(x^*)\}$

Optimal solution $x^*$

Decision variable $x$

Min $f(x)$

Max $f(x)$
Experimental Setup

1. Find the **long-term cost-optimal energy system** targeting a greenhouse gas emissions reduction by 95% w.r.t 1990 levels and its total annual system costs.

2. For each $\varepsilon \in \{1, 5, 10\}\%$ **minimise and maximise**
   - generation technologies (wind, onshore wind, offshore wind [AC/DC], solar, OCGT, CCGT),
   - storage technologies (hydrogen, batteries) and
   - transmission volume (HVAC lines, HVDC links)

for each country individually as well as for the total continental system such that the **total annual system costs increase by less than $\varepsilon$**

to obtain a **near-optimal solution**.
Near-optimal total system capacity ranges for varying $\varepsilon$
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%
Minimise
Transmission
Volume
Epsilon:
5.0%

... seek the minimum transmission volume. \( \varepsilon = 5.0\% \)
... seek the minimum transmission volume. ($\varepsilon = 10.0\%$)

Minimise
Transmission
Volume
Epsilon:
10.0\%
Next Steps

The goal is to find...

- a set of rules that must be satisfied to keep costs within a pre-defined range, and
- metrics that quantify the wide array of similarly costly but diverse technology mixes.

- **Repeat** analysis for
  - a 100% and 80% greenhouse-gas emissions reduction,
  - more levels of allowed cost increases ($\varepsilon = \{0.5\%, 3\%, 7.5\%\}$),
  - higher temporal and geographical resolution (e.g. hourly snapshots and 200 nodes), and
- Explore methods to more evenly search the **inside** of the near optimal feasible space.
- Investigate **distributions of** and **correlations between** investment variables
Resources and Copyright

Find the slides:

Send an email:
fabian.neumann@kit.edu

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

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Capacities for near-optimal solutions vary notably.
The Energy System Modelling Process

Near-Optimal Feasible Solutions: Modelling to Generate Alternatives (MGA)

Preliminary Results

Next Steps

Backup

Objective function

\( f(x, y) \)

Feasible space

\( x \), \( y \)

Decision variables

Optimal solution

\( f(x^*, y^*) \)

\( f(x, y) \leq (1 + \epsilon) f(x^*, y^*) \)

\( \min x + y \)

\( \max x \)

\( \epsilon \)

Nuts of similar solutions as optimal solution
Any country can give up on one carrier completely...

... with an **emission reduction target** of 95% and an **epsilon** of 1.0%
Dominant Carrier by Energy Generated

Minimise

Power Transmission Volume

Epsilon: 0.0%
Epsilon: 1.0%
Epsilon: 5.0%
Epsilon: 10.0%
Dominant Carrier by Capacity

Minimise
Power Transmission Volume

Epsilon: 0.0 %

Epsilon: 1.0 %

Epsilon: 5.0 %

Epsilon: 10.0 %

Technology
- CCGT
- OCGT
- Offshore Wind (AC)
- Offshore Wind (DC)
- Onshore Wind
- Run of River
- Solar
Correlations of Investment Variables
Distribution of Individual Investment Variables

- Solar
- Offshore Wind (DC)
- OCGT
- Onshore Wind
- Offshore Wind (AC)
- CCGT

GW

AL
AT
BA
BE
BG
CH
CZ
DE
DK
EE
ES
FI
FR
GB
GR
HR
HU
IE
IT
LT
LU
LV
ME
MK
NL
NO
PL
PT
RO
RS
SE
SI
SK
A near-optimal feasible solution

Maximise
Battery
Storage

Epsilon: 5.0%
A near-optimal feasible solution

Minimise
Battery
Storage

Epsilon:
5.0%
A near-optimal feasible solution

Maximise

Hydrogen Storage

Epsilon: 5.0%
A near-optimal feasible solution

Minimise
Hydrogen Storage
Epsilon:
5.0%
A near-optimal feasible solution

Maximise
Solar
Capacity
Epsilon:
5.0%
A near-optimal feasible solution

Minimize
Solar Capacity
Epsilon:
5.0%
A near-optimal feasible solution

Maximise
Wind Capacity
Epsilon:
5.0%
A near-optimal feasible solution

Minimise

Wind Capacity

Epsilon: 5.0%
PyPSA-Eur Workflow with Snakemake
Optimal System Layout (80% emission reduction)
“Must-Haves” and “Must-Avoids” (80% emission reduction)