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

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HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

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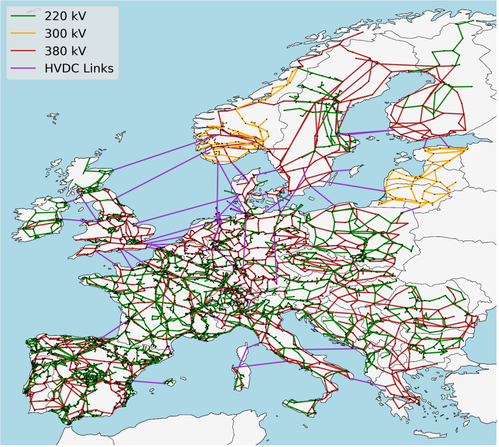
Open Energy System Modelling with PyPSA-Eur



- 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`

Source: Tom Brown

Open Energy System Modelling with PyPSA-Eur

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

$$\textbf{Minimise} \left(\begin{matrix} \textbf{Yearly} \\ \textbf{system costs} \end{matrix} \right) = \sum_{n} \left(\begin{matrix} \textbf{Annualised} \\ \textbf{capital costs} \end{matrix} \right) + \sum_{n,t} \left(\begin{matrix} \textbf{Marginal} \\ \textbf{costs} \end{matrix} \right)$$

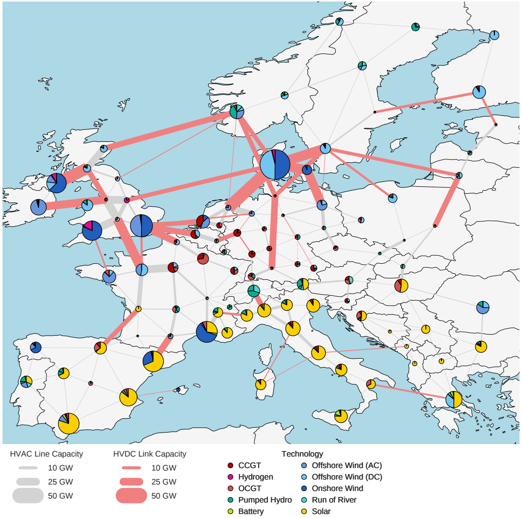
subject to

- 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
- $\mathbf{CO_2}$ **constraint** (e.g. 95% reduction w.r.t. 1990 emission levels)
- **Dispatchability** from gas plants, battery storage, hydrogen storage, HVDC links

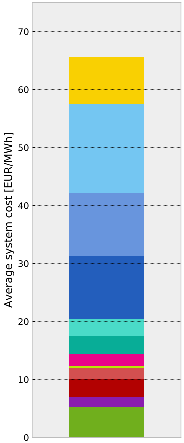
Source: Tom Brown

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

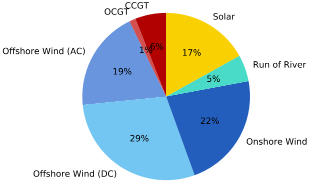
Distribution of generation and transmission **expansion**

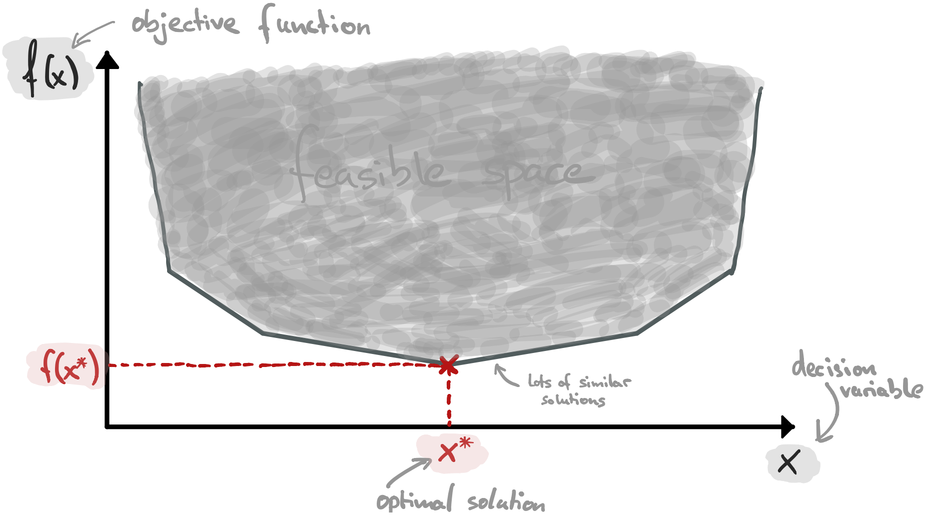


Relative total annual system costs



Energy generated by technology





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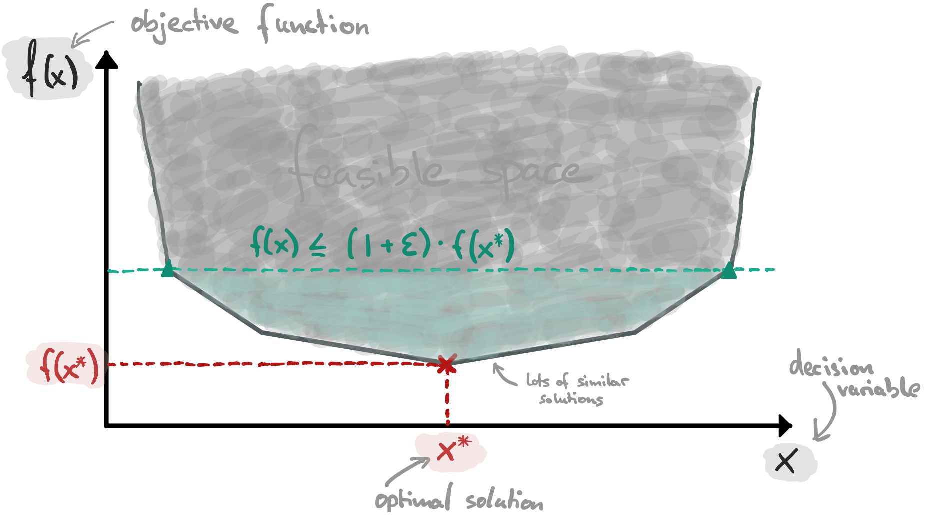
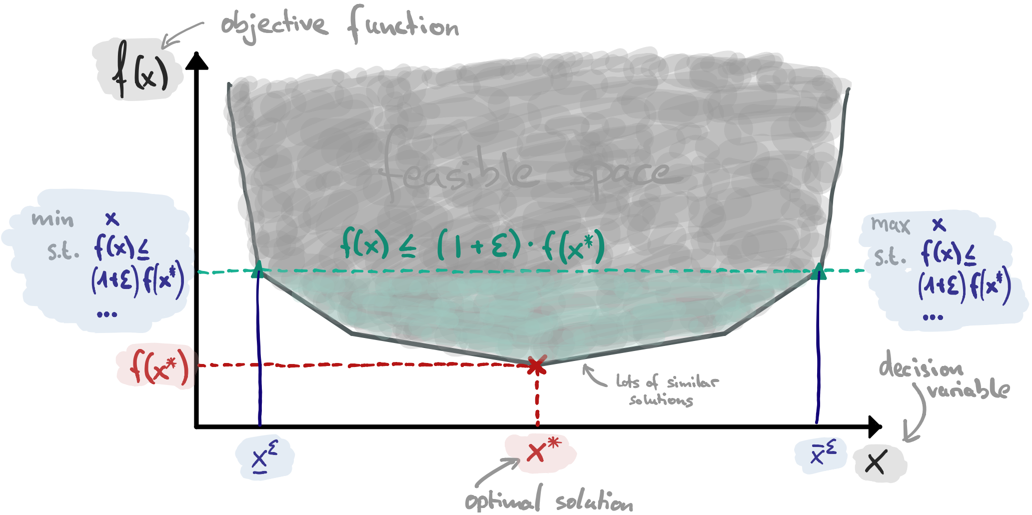

objective function
f(x)
feasible space
f(x) ≤ (1 + ε) · f(x*)
f(x*)
lots of similar solutions
decision variable
x
x*
optimal solution


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
x̲ε
x*
x̄ε
x
optimal solution

Experimental Setup

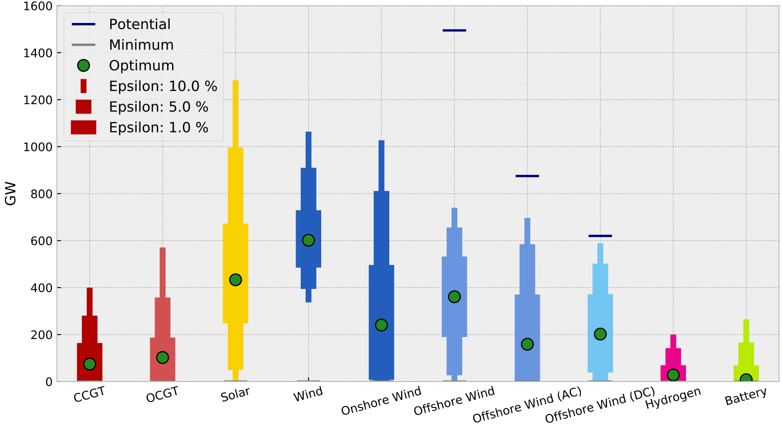
1. Find the **long-term cost-optimal energy system** targeting a greenhouse gas emissions reduction by 95% w.r.t 1990 levels and its total annual system costs.
2. For each $\varepsilon \in \{1, 5, 10\}\%$ **minimise** and **maximise**
   a. generation technologies (wind, onshore wind, offshore wind [AC/DC], solar, OCGT, CCGT),
   b. storage technologies (hydrogen, batteries) and
   c. transmission volume (HVAC lines, HVDC links)

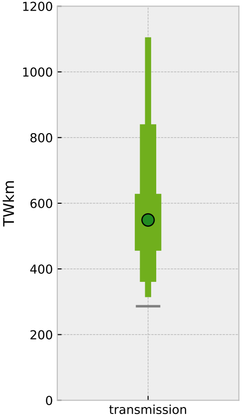
   for each country individually as well as for the total continental system

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

   to obtain a **near-optimal solution**.

Near-optimal total system capacity ranges for varying ε





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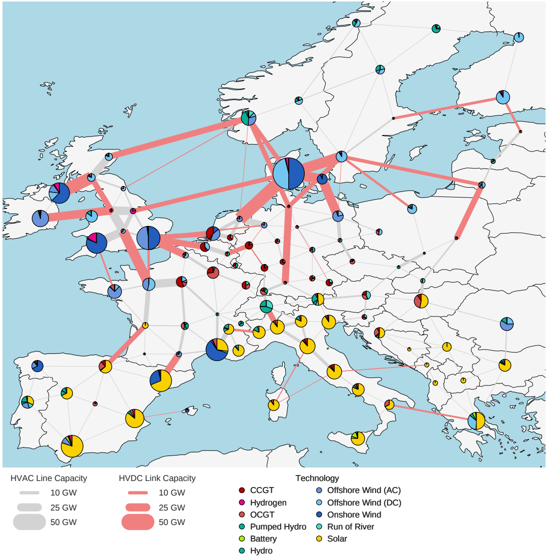
Starting from the optimal solution, ...

Optimal
Transmission
Volume
Epsilon:
0.0%

This is the optimal solution from earlier!



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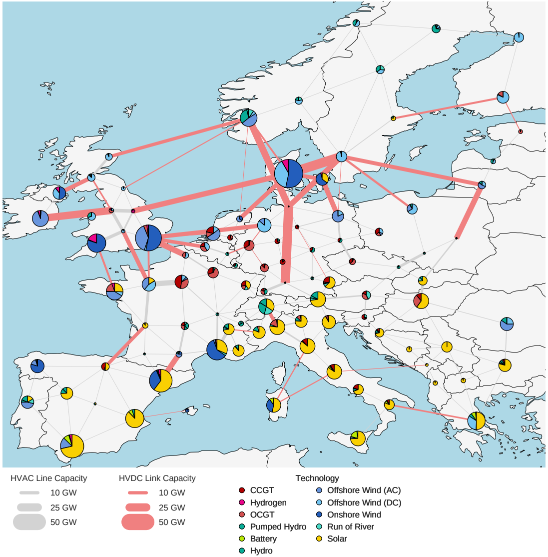
... seek the minimum transmission volume. ($\varepsilon = 1.0\%$)

Minimise
Transmission
Volume
Epsilon:
1.0%



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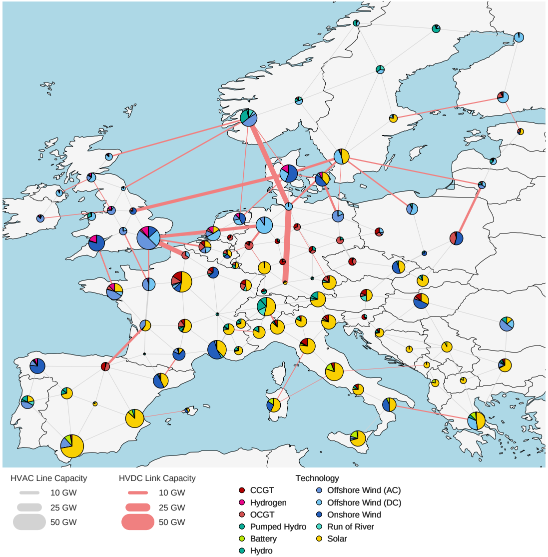
… seek the minimum transmission volume. ($\varepsilon = 5.0\%$)

Minimise
Transmission
Volume
Epsilon:
5.0%



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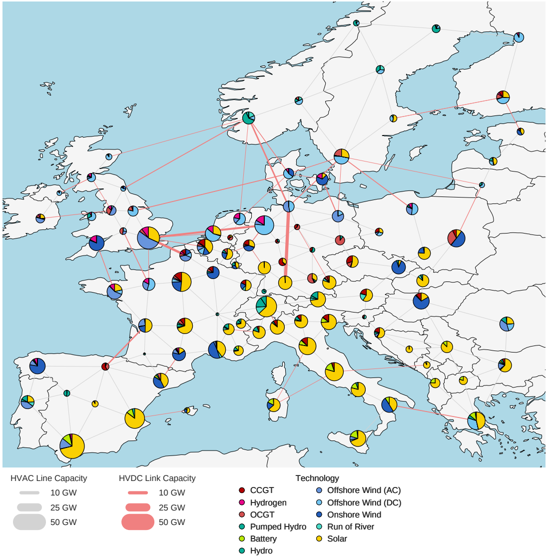
… seek the minimum transmission volume. ($\varepsilon = 10.0\%$)

Minimise Transmission Volume

Epsilon:

10.0%



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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:

https://neumann.fyi/assets/es2050-seminar-mga.pdf

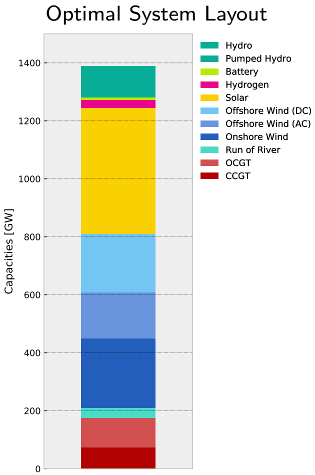
Send an email:

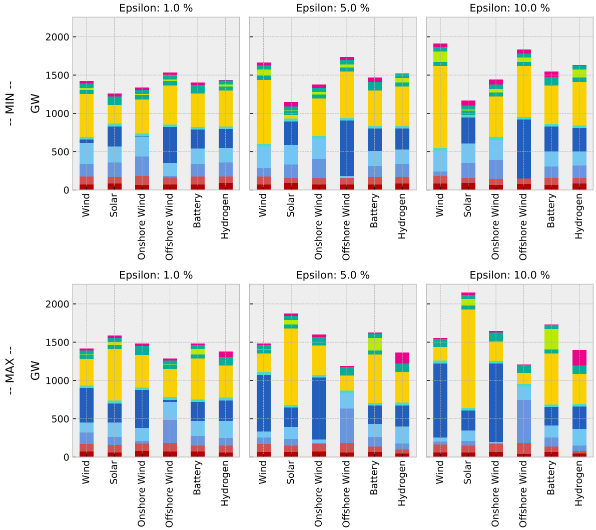
fabian.neumann@kit.edu

Find the energy system model:

https://github.com/pypsa/pypsa-eur

Capacities for near-optimal solutions vary notably.





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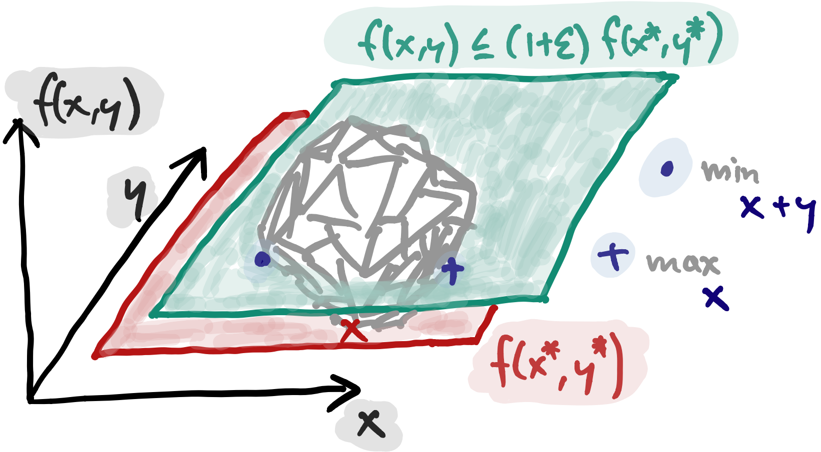
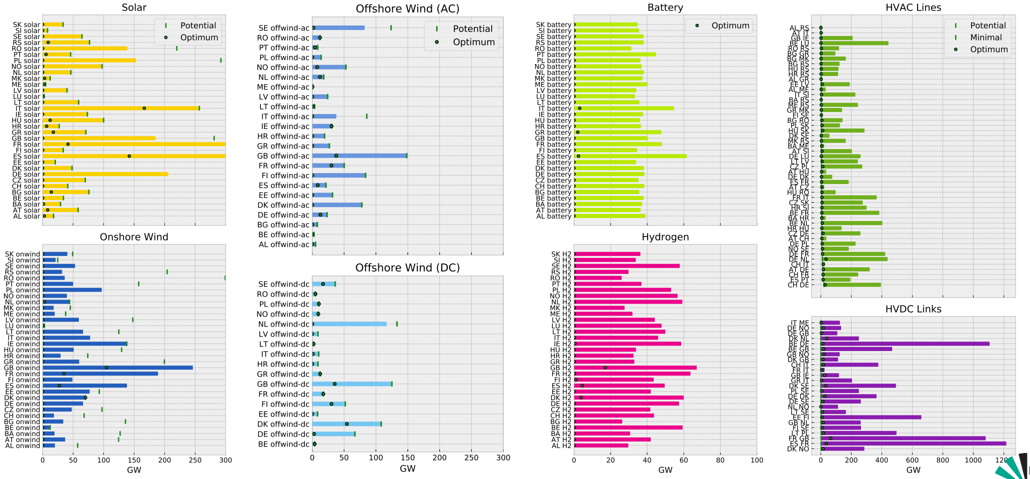


$f(x,y) \leq (1+\varepsilon)\, f(x^*,y^*)$
$f(x,y)$
y
x
min
$x+y$
max
x
$f(x^*,y^*)$

Any country can give up on one carrier completely...

... with an **emission reduction target** of 95% and an **epsilon** of 1.0%



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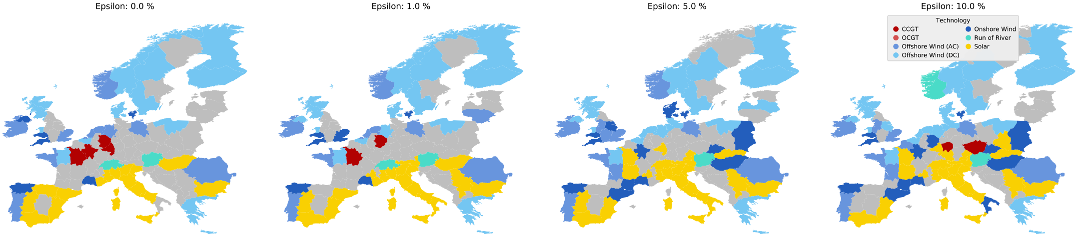
Dominant Carrier by Energy Generated

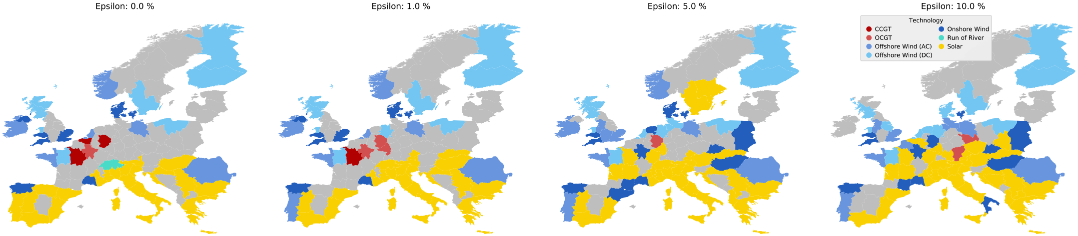
Minimise
Power Transmission Volume



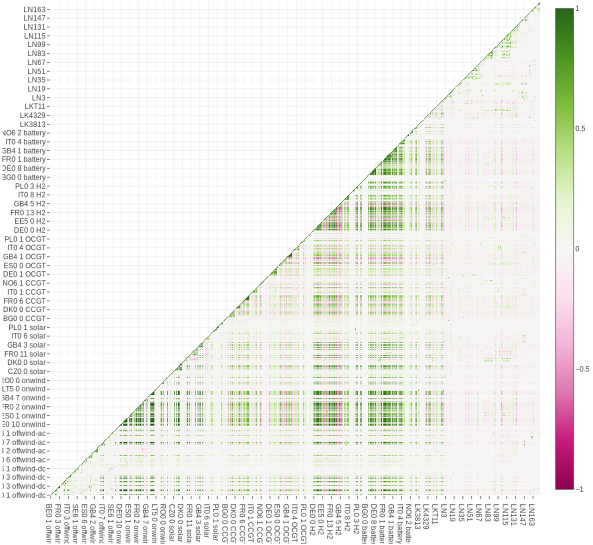
Dominant Carrier by Capacity

Minimise

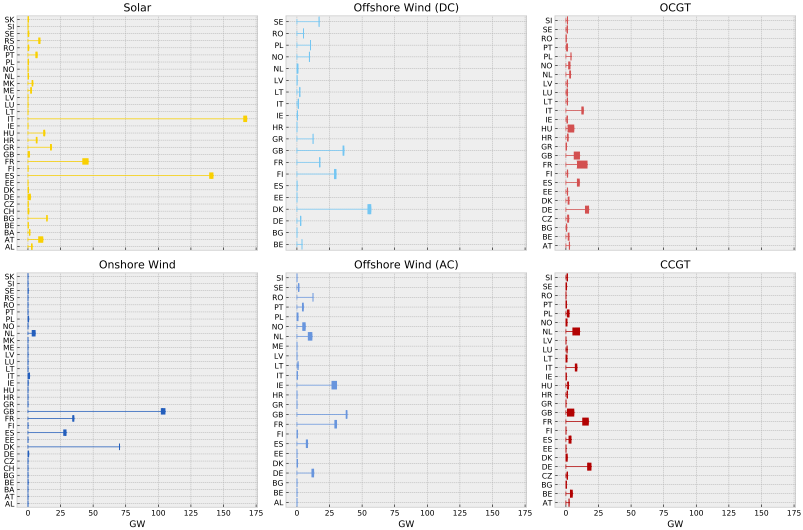
Power Transmission Volume



Correlations of Investment Variables



Distribution of Individual Investment Variables



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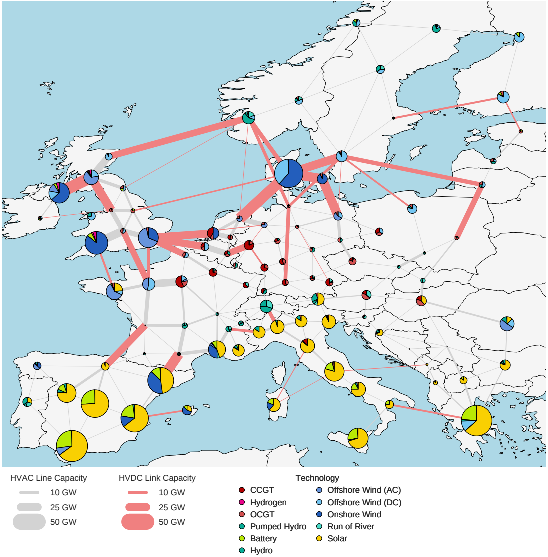
A near-optimal feasile solution

Maximise
Battery
Storage
Epsilon:
5.0%



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A near-optimal feasile solution

Minimise
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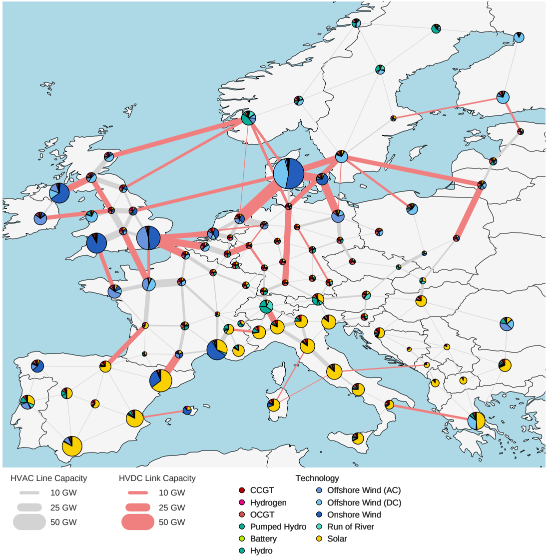
Epsilon:
5.0%



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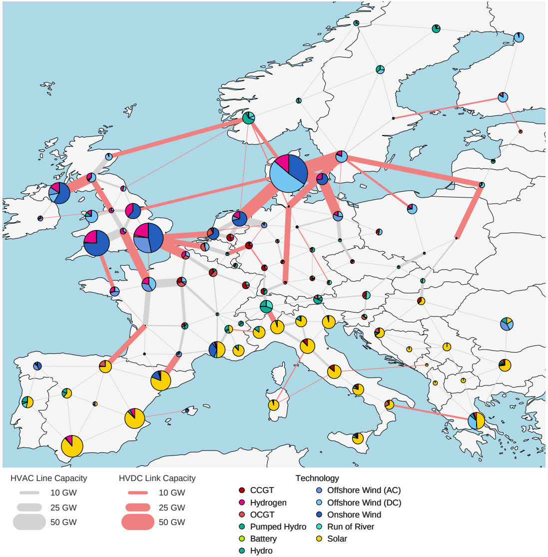
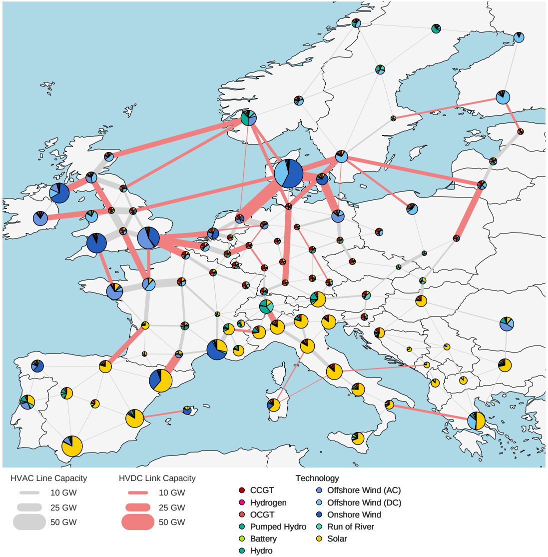
A near-optimal feasile solution

Maximise
Hydrogen
Storage
Epsilon:
5.0%



A near-optimal feasile solution

Minimise
Hydrogen
Storage
Epsilon:
5.0%



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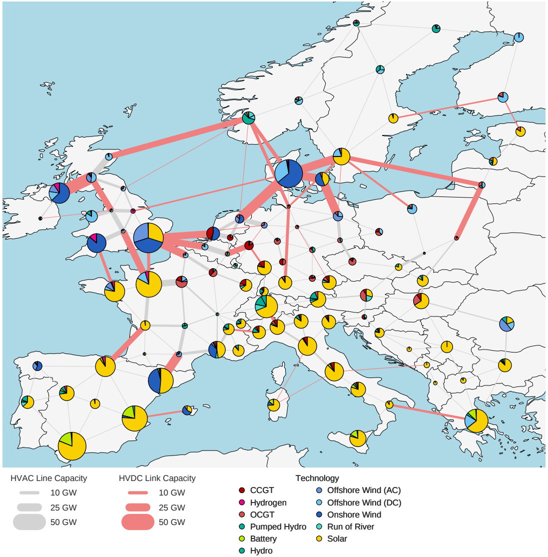
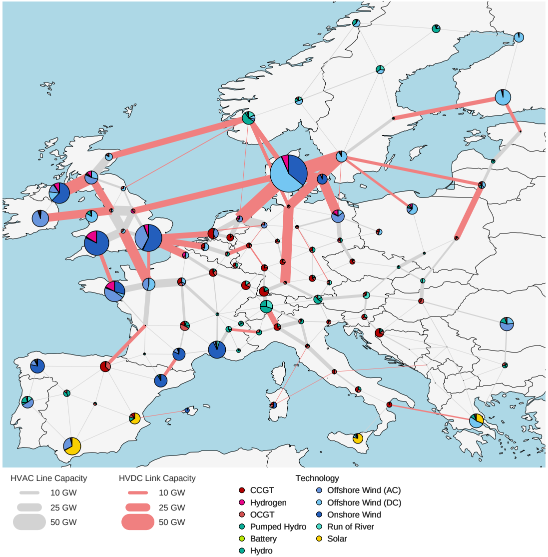
A near-optimal feasile solution

Maximise
Solar
Capacity
Epsilon:
5.0%



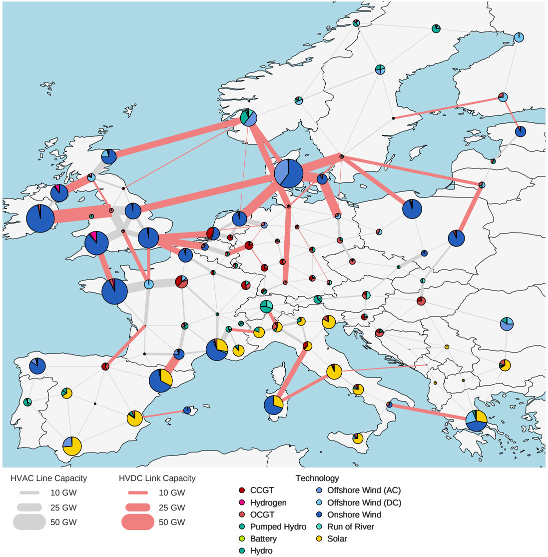
A near-optimal feasile solution

Minimize
Solar
Capacity
Epsilon:
5.0%



A near-optimal feasile solution

Maximise
Wind
Capacity
Epsilon:
5.0%



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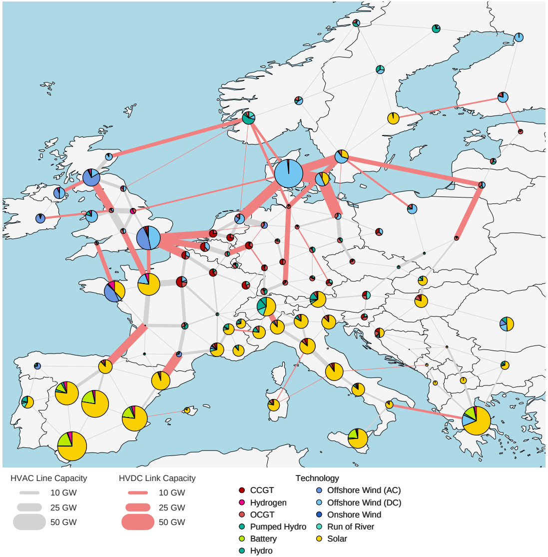
A near-optimal feasile solution

Minimise
Wind
Capacity
Epsilon:
5.0%



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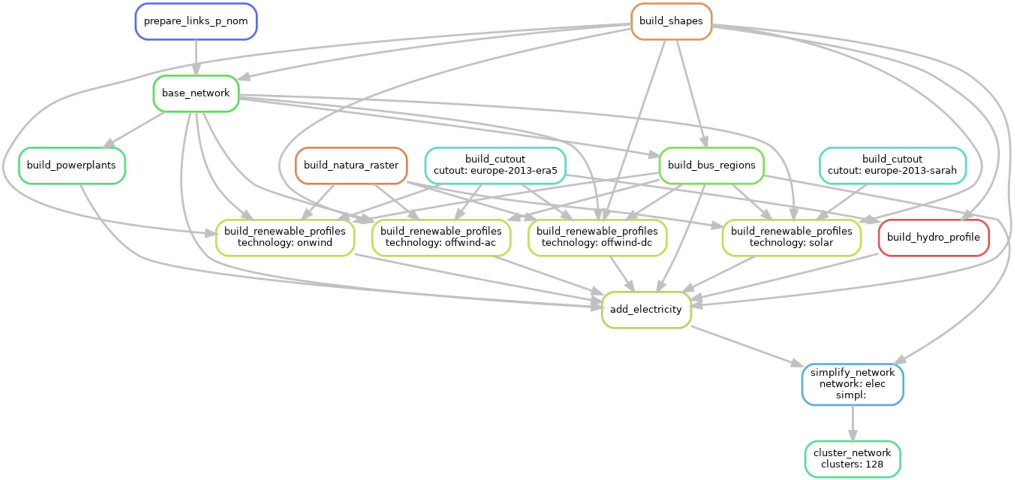
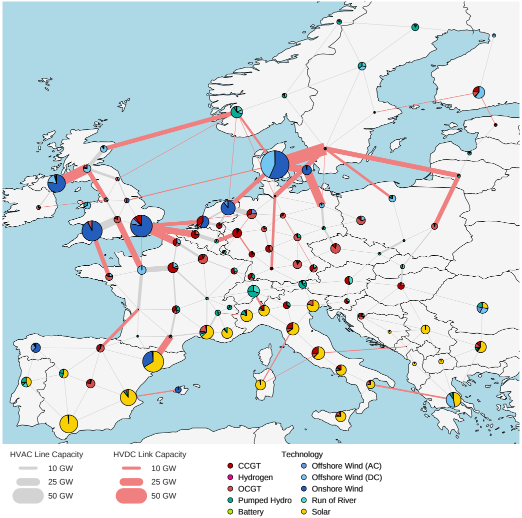
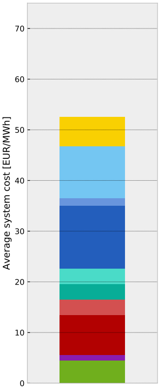
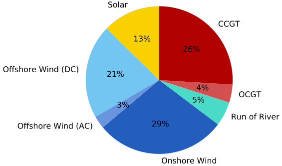
PyPSA-Eur Workflow with Snakemake



Optimal System Layout (80% emission reduction)







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"Must-Haves" and "Must-Avoids" (80% emission reduction)