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:

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

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 "DC") power flow
- wind, solar, hydro (variable renewables) **availability time series** $\forall\ n, t$
- installed capacity $\leq$ **geographical potentials** for renewables
- **CO_2 constraint** (e.g. 95% reduction w.r.t. 1990 emission levels)
- **Flexibility** from gas plants, battery storage, hydrogen storage, HVDC links

Source: Tom Brown

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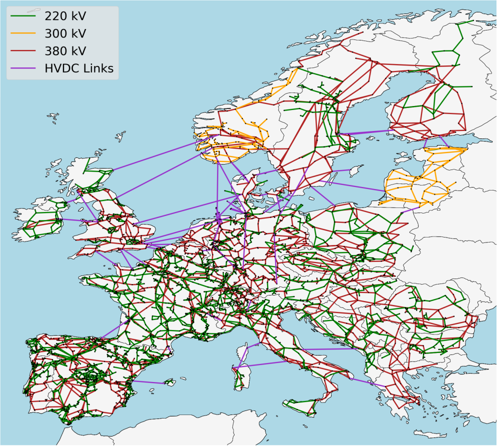
Open Energy System Modelling with **PyPSA-Eur**



- Grid data based on 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 using *k*-means algorithm

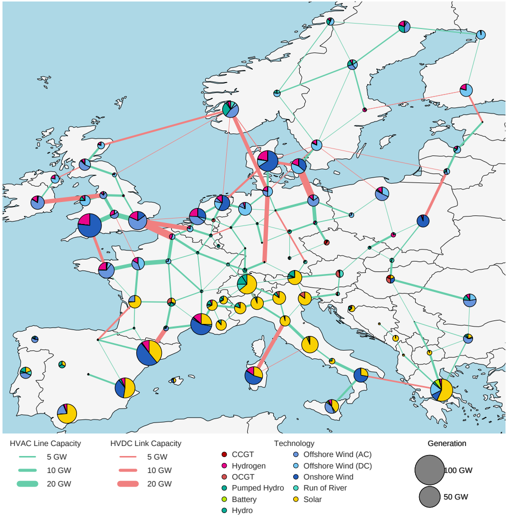
Code and Documentation

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

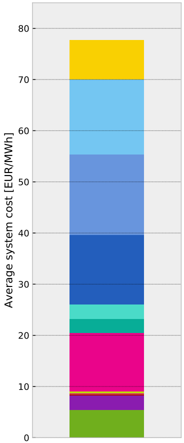
Source: Tom Brown

Optimal System Layout for a 100% emission reduction (w.r.t. 1990 levels)

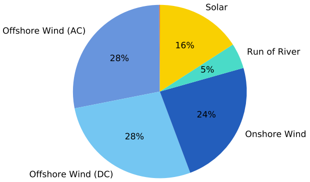
Distribution of generation and transmission expansion

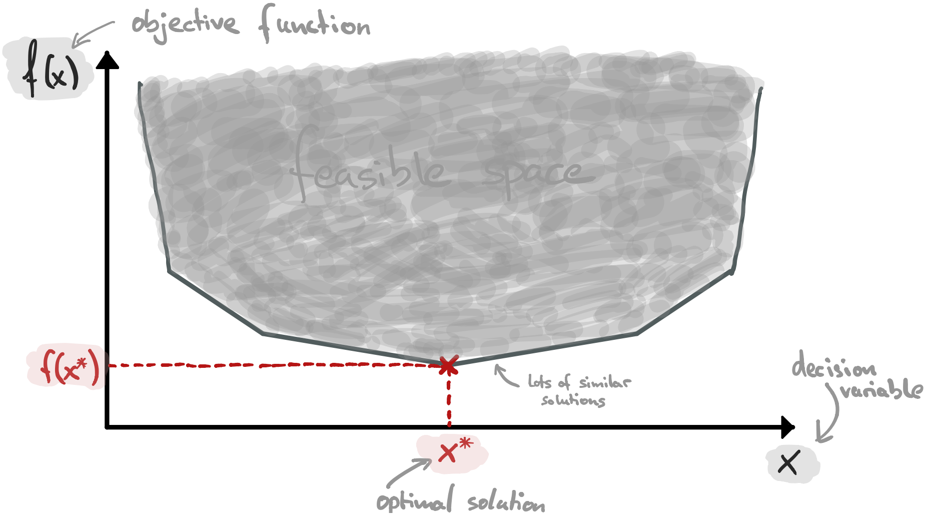


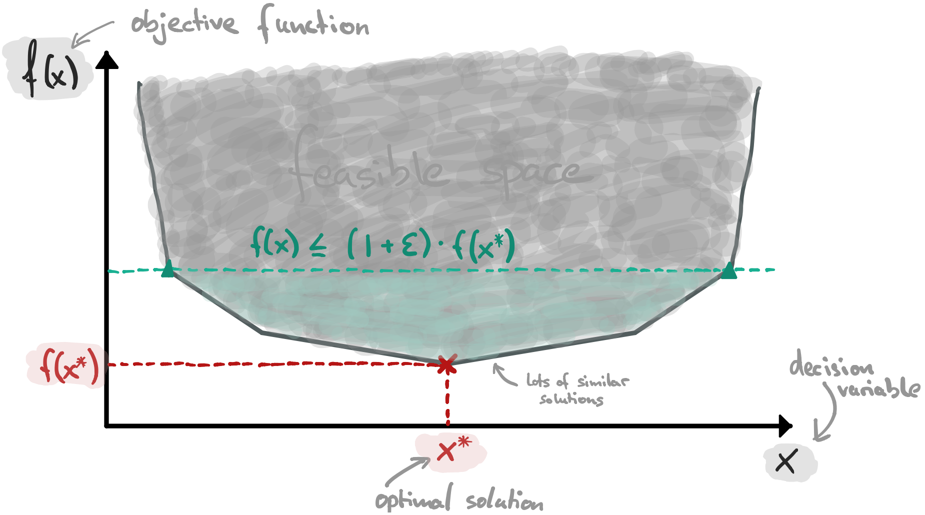
Relative total annual system costs



Energy generated by technology




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



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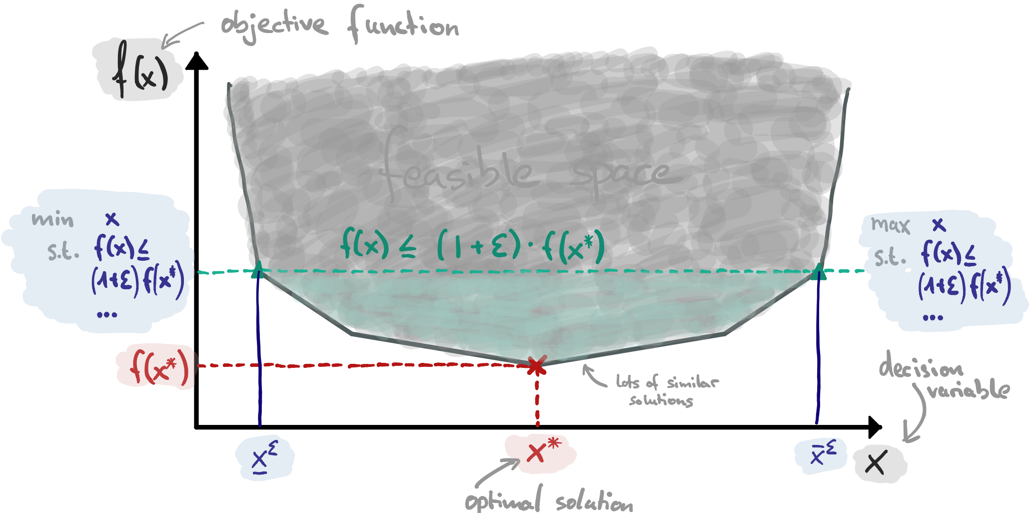


objective function
f(x)
feasible space
f(x) ≤ (1+ε)·f(x*)
min x
s.t. f(x) ≤
(1+ε) f(x*)
...
max x
s.t. f(x) ≤
(1+ε) f(x*)
...
f(x*)
lots of similar solutions
decision variable
x
optimal solution

Experiments

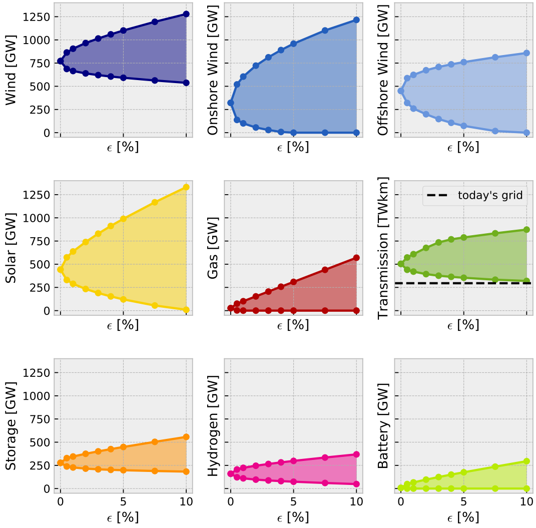
1. Find the **long-term cost-optimal energy system** targeting a greenhouse gas emissions reduction by $\{80, 95, 100\}$ % w.r.t 1990 levels and its total annual system costs.
2. For each $\varepsilon \in \{0.5, 1, \ldots, 5, \ldots, 10\}\%$ **minimise** and **maximise**
   - a. generation technologies (onshore and/or offshore wind [AC and/or DC], solar, gas turbines),
   - b. storage technologies (hydrogen, batteries, or total storage) and
   - c. transmission volume (HVAC lines and 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**.

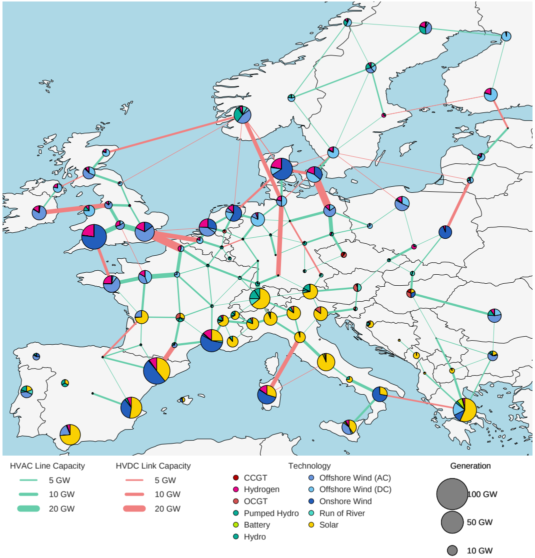
Near-optimal total system capacity ranges for varying ε



Starting from the optimal solution, ...

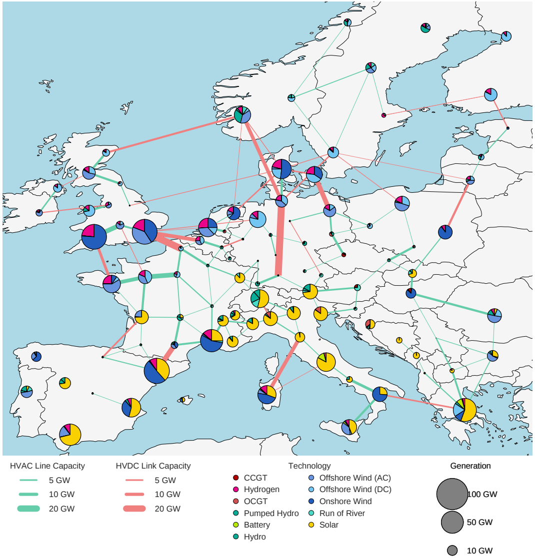
Optimal
Transmission
Volume
Epsilon:
0.0%

This is the optimal solution from earlier!



... seek the minimum transmission volume. ($\varepsilon = 0.5\%$)

Minimise
Transmission
Volume
Epsilon:
0.5%



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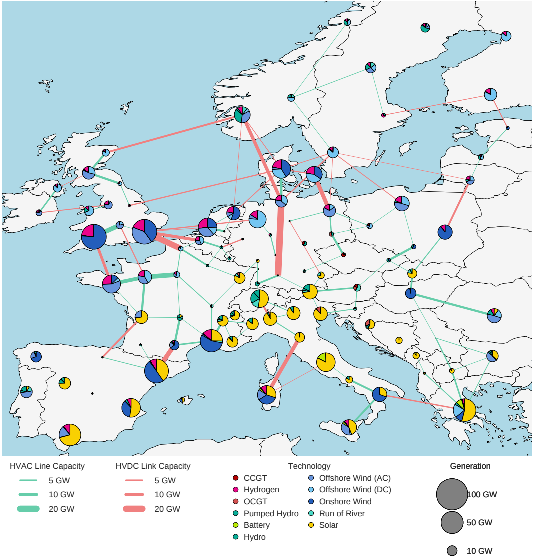
… seek the minimum transmission volume. ($\varepsilon = 1.0\%$)

Minimise
Transmission
Volume
Epsilon:
1.0%



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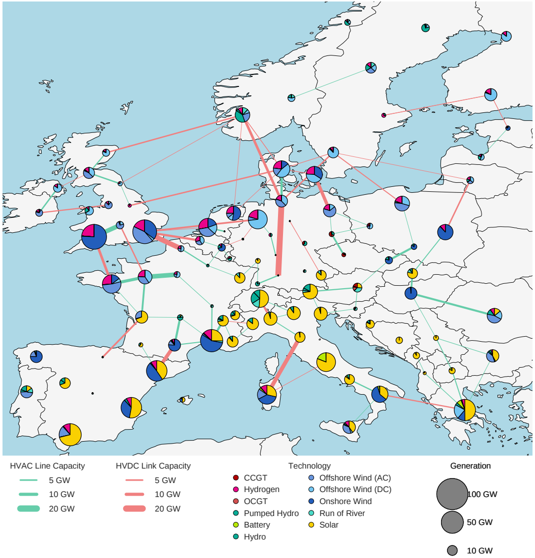
... seek the minimum transmission volume. ($\varepsilon = 2.0\%$)

Minimise
Transmission
Volume
Epsilon:
2.0%

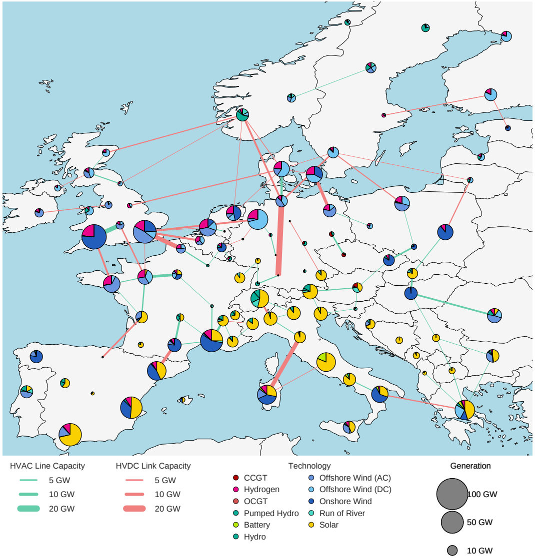


… seek the minimum transmission volume. ($\varepsilon = 3.0\%$)

Minimise Transmission Volume

Epsilon:

3.0%



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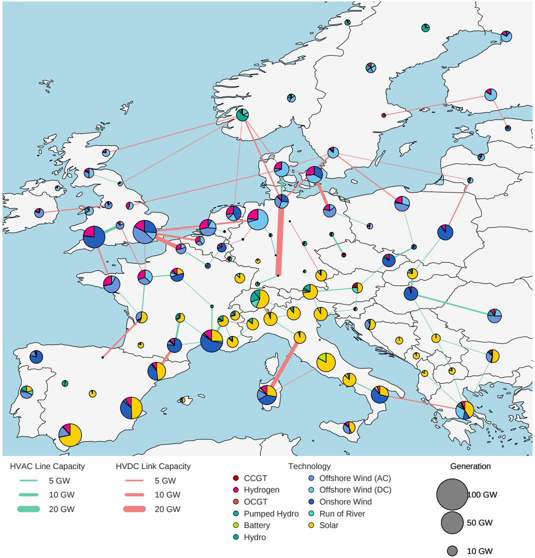
... seek the minimum transmission volume. ($\varepsilon = 4.0\%$)

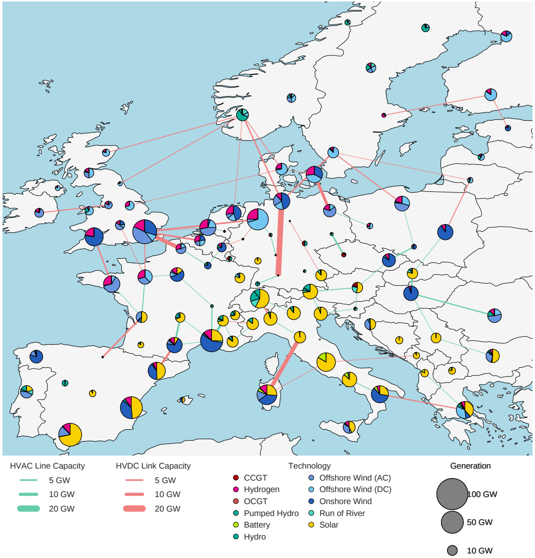
Minimise
Transmission
Volume

Epsilon:
4.0%



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

Minimise
Transmission
Volume
Epsilon:
5.0%



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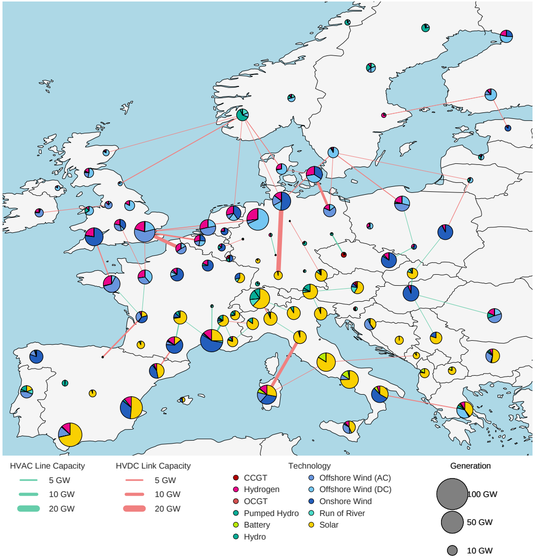
… seek the minimum transmission volume. ($\varepsilon = 7.5\%$)

Minimise Transmission Volume

Epsilon:

7.5%



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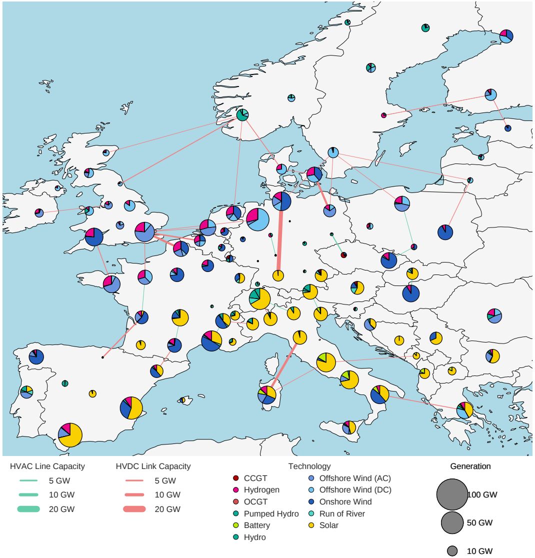
… seek the minimum transmission volume. ($\varepsilon = 10.0\%$)

Minimise
Transmission
Volume
Epsilon:
10.0%



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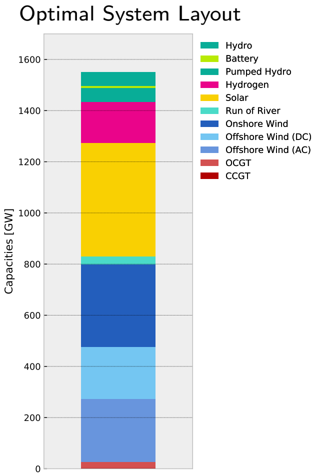
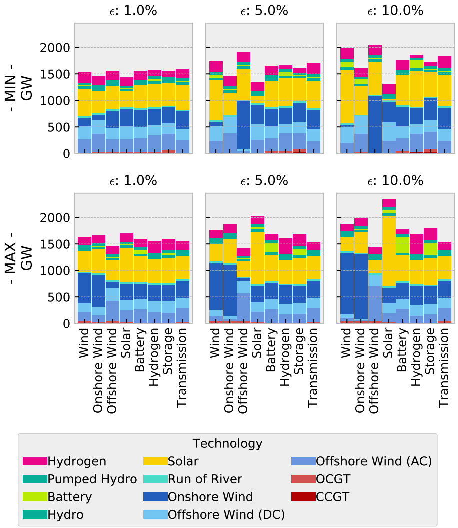
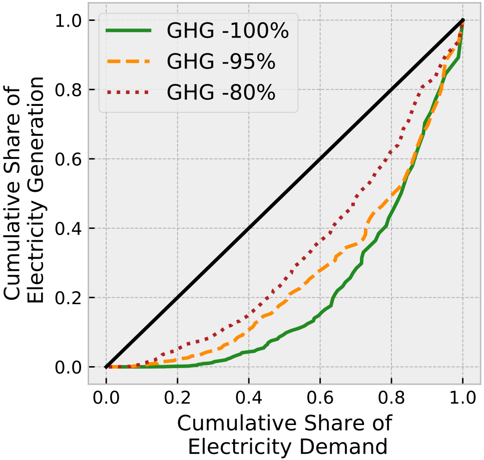
Dependencies: Extremes cannot be achieved simultaneously.

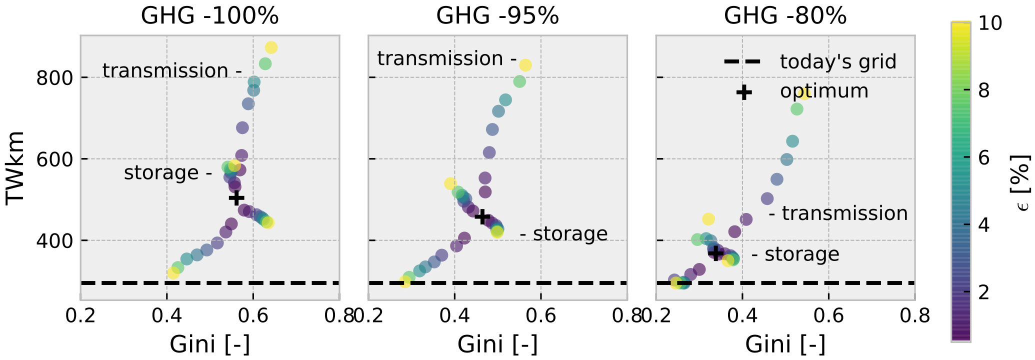




Distributional Equity: Lorenz Curve and Gini Coefficient



Distributional Equity: Storage and Transmission



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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

- repeat with coupling between multiple energy sectors
- include parametric uncertainty of cost assumptions

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

Fabian Neumann, Tom Brown

(Submitted on 4 Oct 2019)

Models for long-term investment planning of the power system typically return a single optimal solution per set of cost assumptions. However, typically there are many near-optimal alternatives that stand out due to other attractive properties like social acceptance. Understanding features that persist across many cost-efficient alternatives enhances policy advice and acknowledges structural model uncertainties. We apply the modeling-to-generate-alternatives (MGA) methodology to systematically explore the near-optimal feasible space of a completely renewable European electricity system model. While accounting for complex spatio-temporal patterns, we allow simultaneous capacity expansion of generation, storage and transmission infrastructure subject to linearized multi-period optimal power flow. Many similarly costly, but technologically diverse solutions exist. Already a cost deviation of 0.5% offers a large range of possible investments. However, either offshore or onshore wind energy along with some hydrogen storage and transmission network reinforcement are essential to keep costs within 10% of the optimum.

Comments: Submitted to the 21st Power Systems Computation Conference (PSCC 2020); 8 pages, 8 figures, 3 tables
Subjects: **Physics and Society (physics.soc-ph)**; Systems and Control (eess.SY)
Cite as: arXiv:1910.01891 [physics.soc-ph]
(or arXiv:1910.01891v1 [physics.soc-ph] for this version)

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Which authors of this paper are endorsers? | Disable MathJax (What is MathJax?)

https://arxiv.org/abs/1910.01891

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Resources and Copyright

Find the slides:

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

Send an email:

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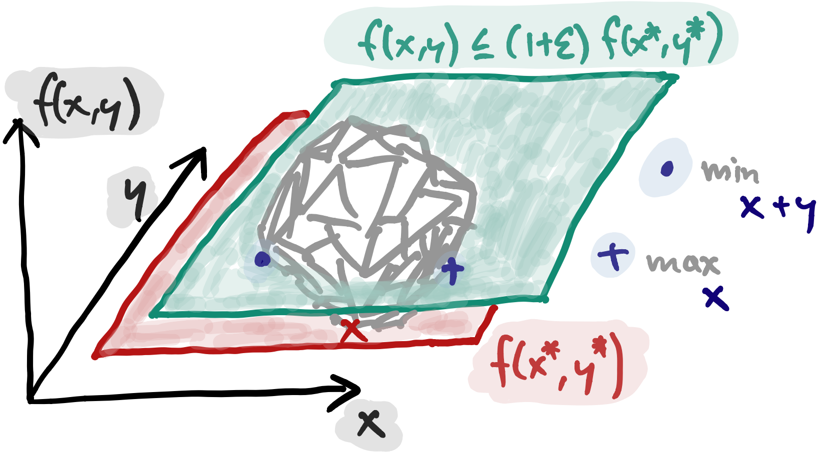
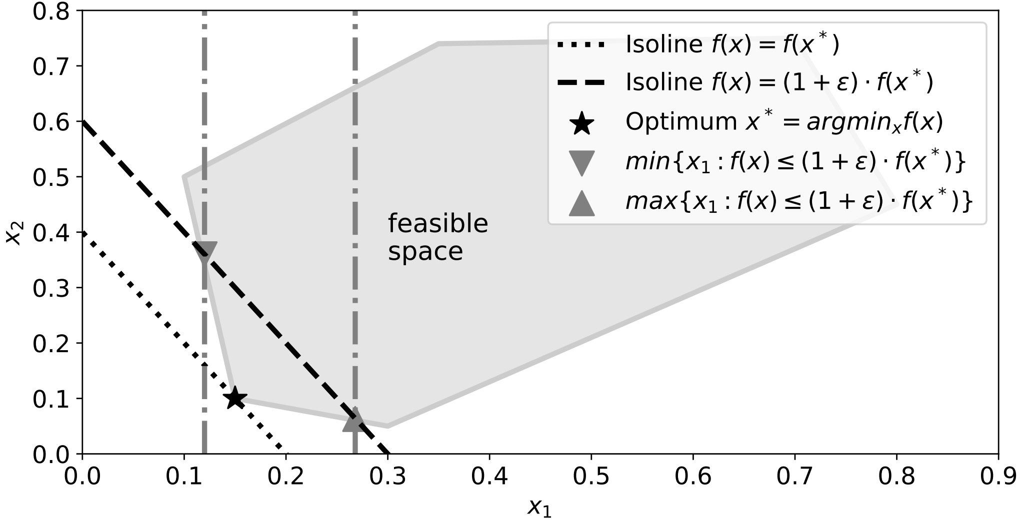
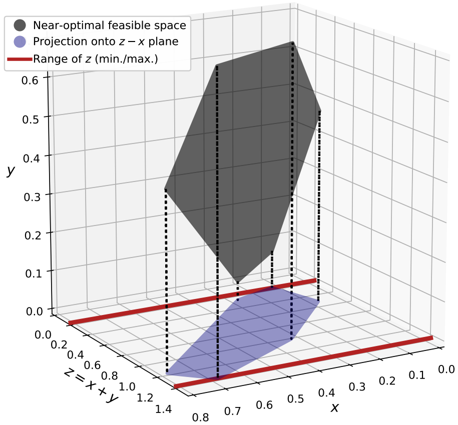
Find the energy system model:

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

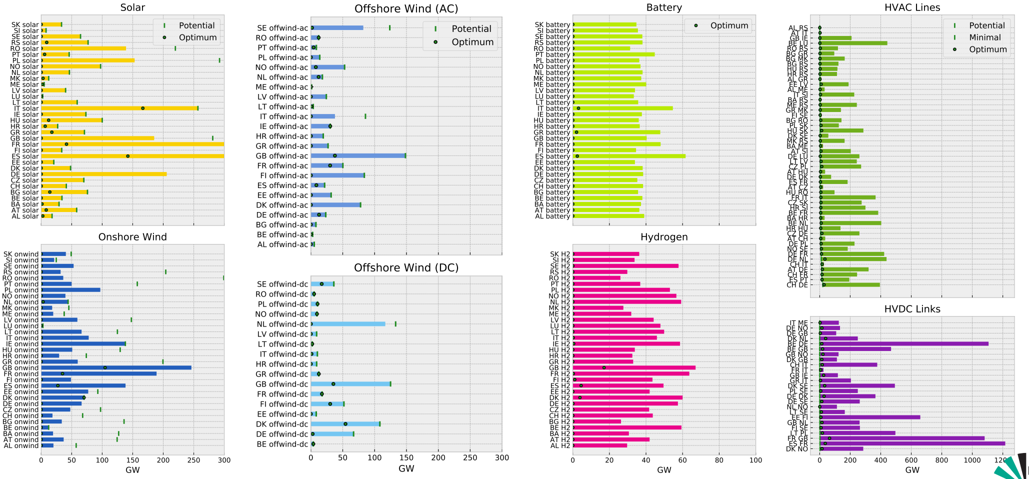

f(x,y) ≤ (1+ε) f(x*,y*)
f(x,y)
y
x
f(x*,y*)
min
x+y
max
x


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
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8


Near-optimal feasible space
Projection onto $z-x$ plane
Range of z (min./max.)
y
0.0
0.1
0.2
0.3
0.4
0.5
0.6
$z=x+y$
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
x
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0

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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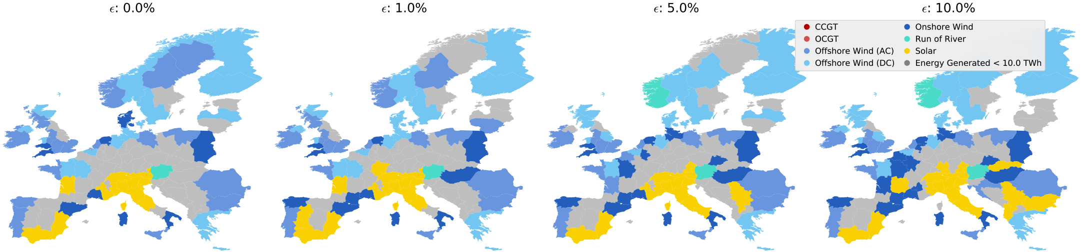
Dominant Carrier by Energy Generated

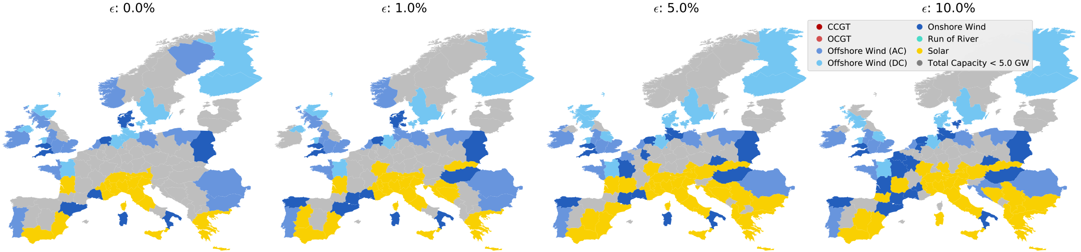
Minimise

Power Transmission Volume

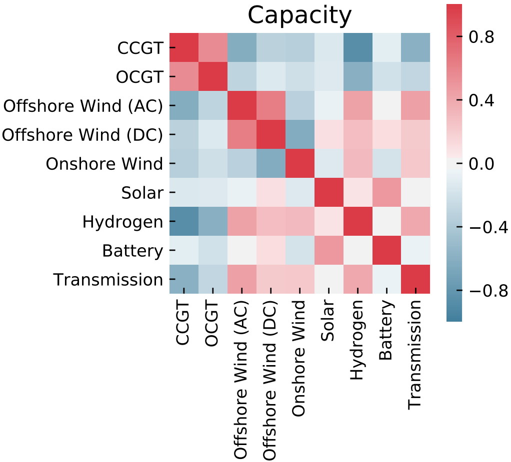


Dominant Carrier by Capacity

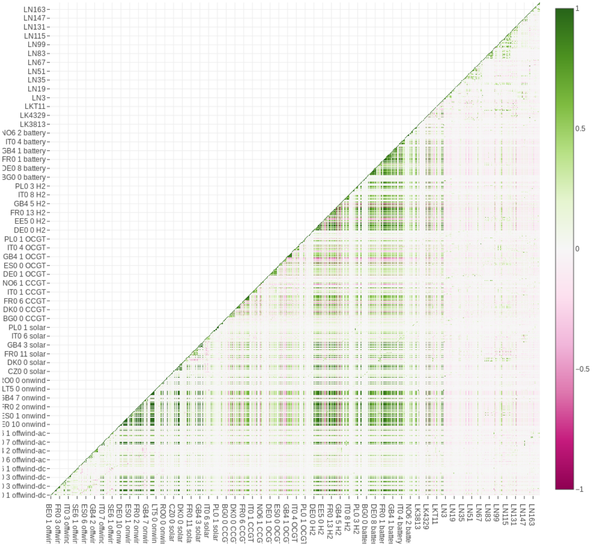
Minimise
Power Transmission Volume



Correlations of Investment Variable Groups



Correlations of Individual Investment Variables



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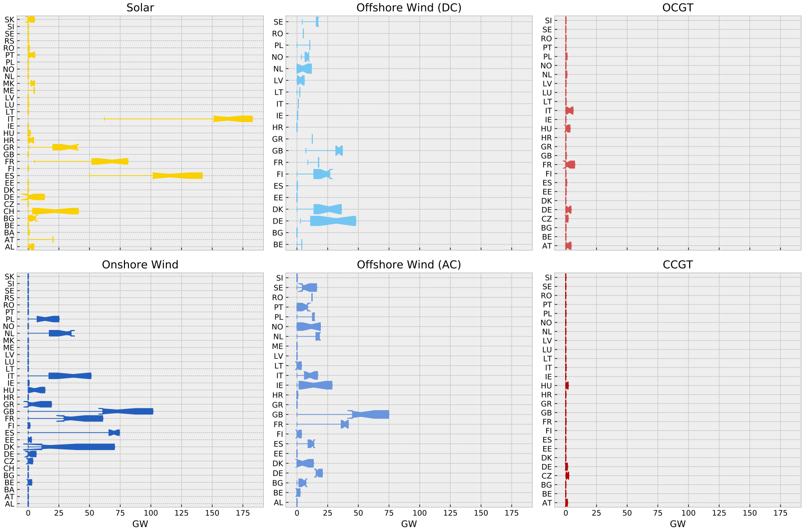
Distribution of Individual Investment Variables



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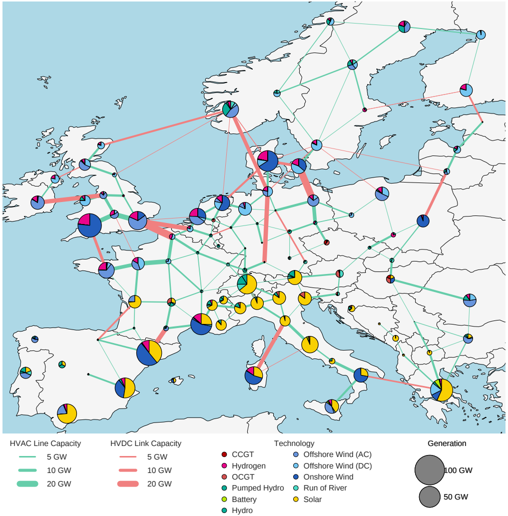
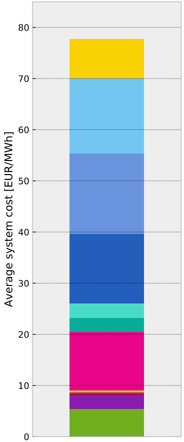
Optimal System Layout for a 100% emission reduction (w.r.t. 1990 levels)

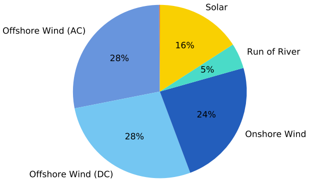
Distribution of generation and transmission **expansion**



Relative total annual system costs



Energy generated by technology



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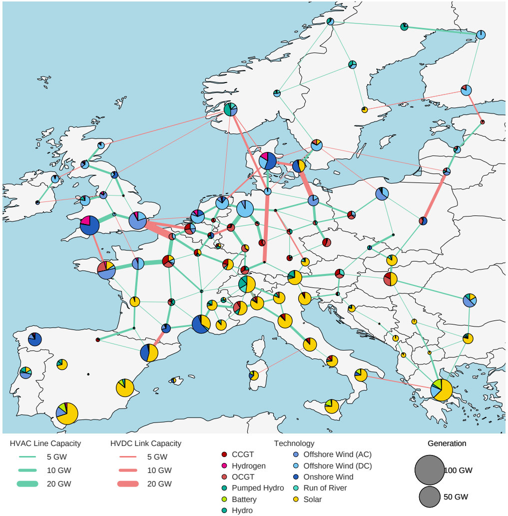
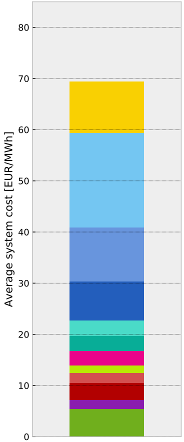
Optimal System Layout for a 95% emission reduction (w.r.t. 1990 levels)

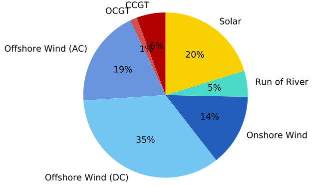
Distribution of generation and transmission **expansion**



Relative total annual system costs

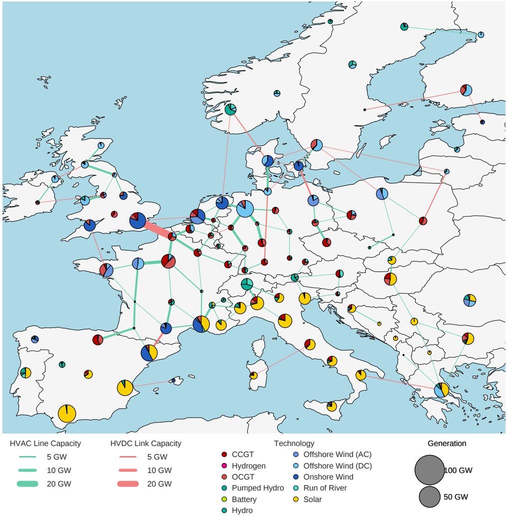


Energy generated by technology

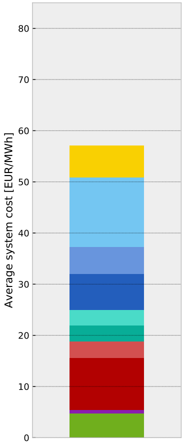


Optimal System Layout for a 80% emission reduction (w.r.t. 1990 levels)

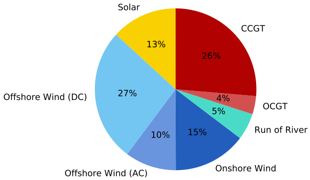
Distribution of generation and transmission **expansion**



Relative total annual system costs



Energy generated by technology



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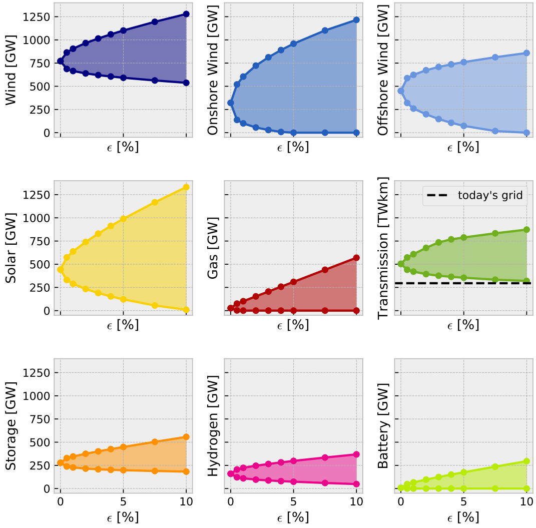
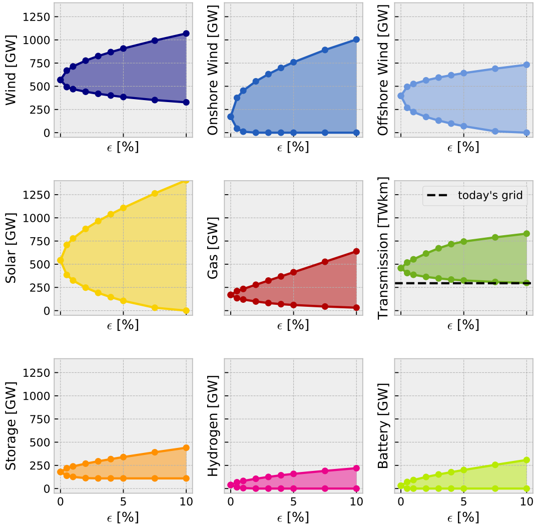
Near-optimal total systems for varying ε (100% reduction)



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



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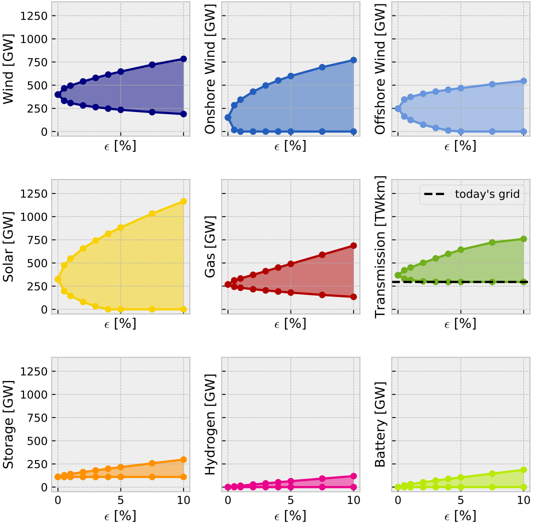
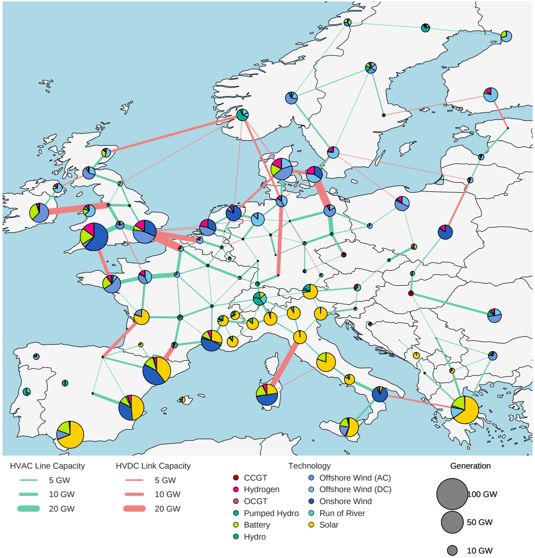
Near-optimal total systems for varying ε (80% reduction)



A near-optimal feasile solution

Maximise
Battery
Storage
Epsilon:
5.0%



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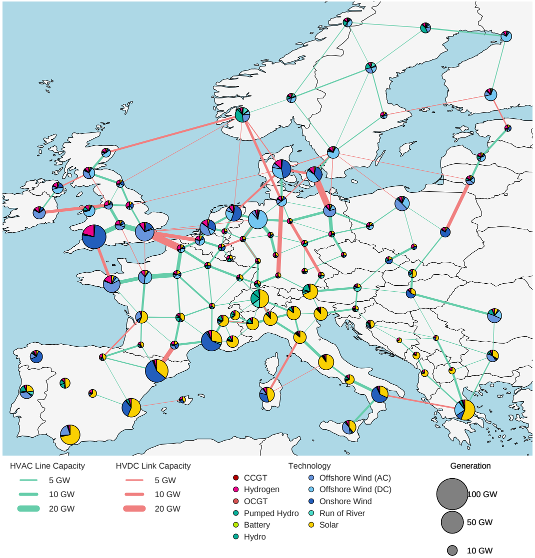
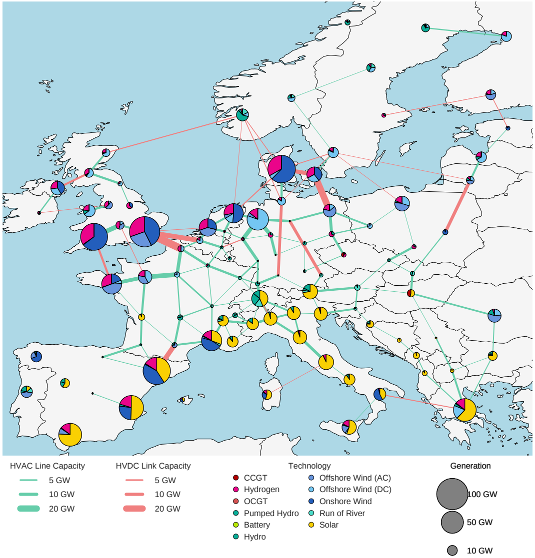
A near-optimal feasile solution

Minimise
Battery
Storage
Epsilon:
5.0%



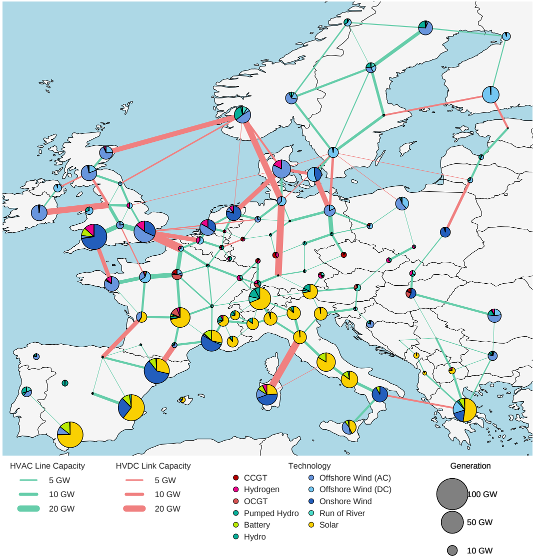
A near-optimal feasile solution

Maximise
Hydrogen
Storage
Epsilon:
5.0%



A near-optimal feasile solution

Minimise
Hydrogen
Storage
Epsilon:
5.0%

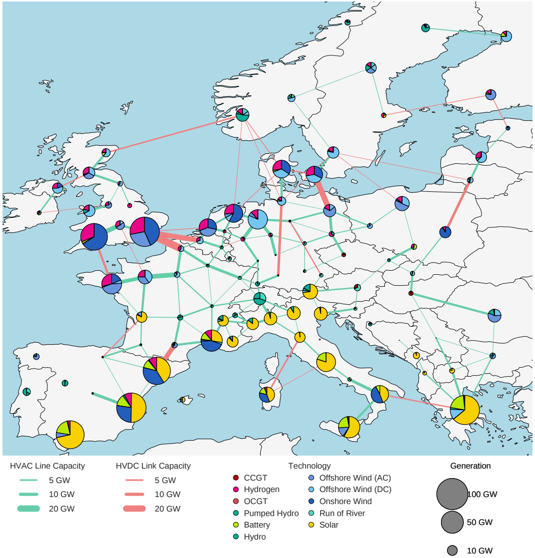


A near-optimal feasile solution

Maximise All Storage

Epsilon:

5.0%



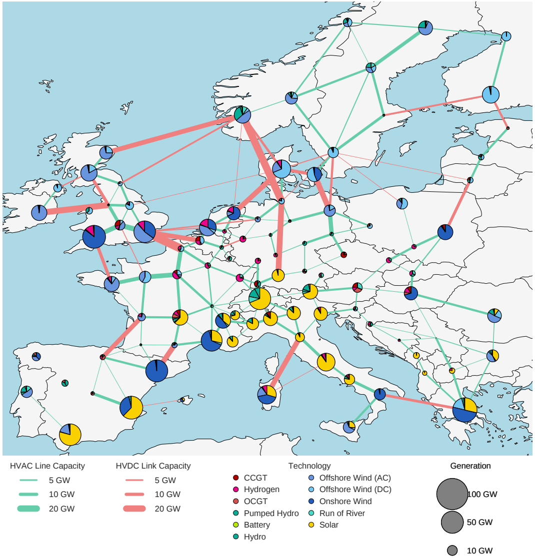
A near-optimal feasile solution

Minimise All

Storage

Epsilon:

5.0%



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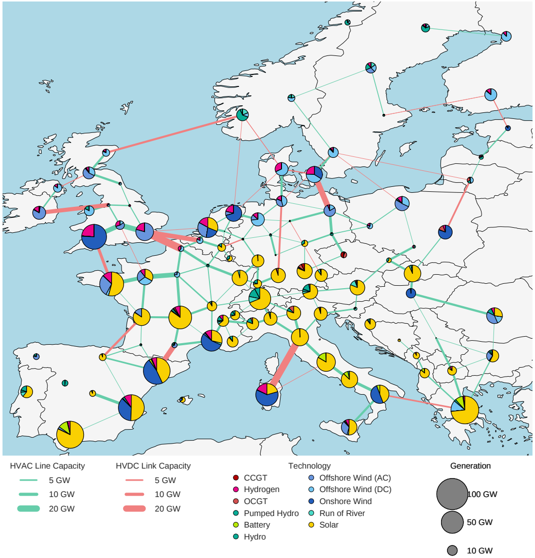
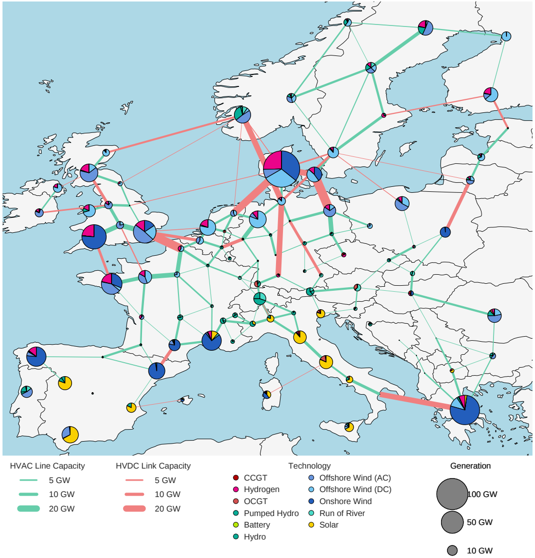
A near-optimal feasile solution

Maximise
Solar
Capacity
Epsilon:
5.0%



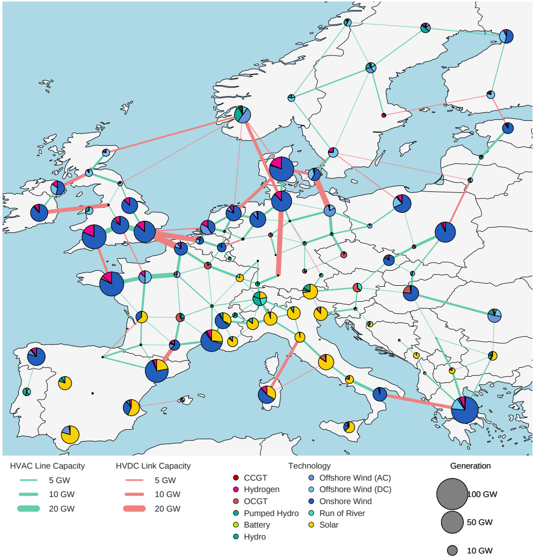
A near-optimal feasile solution

Minimize
Solar
Capacity
Epsilon:
5.0%



A near-optimal feasile solution

Maximise
Wind
Capacity
Epsilon:
5.0%



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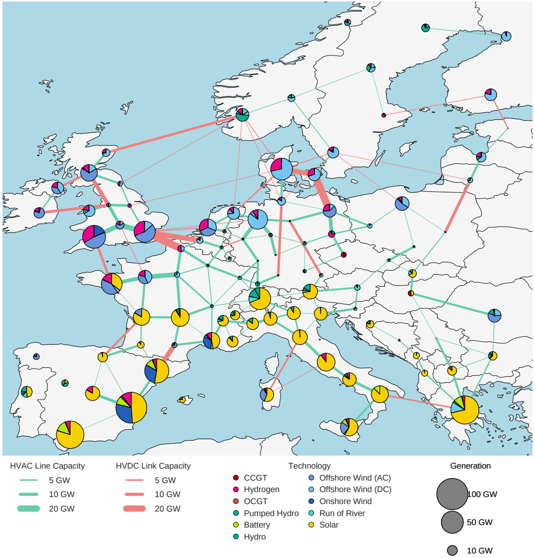
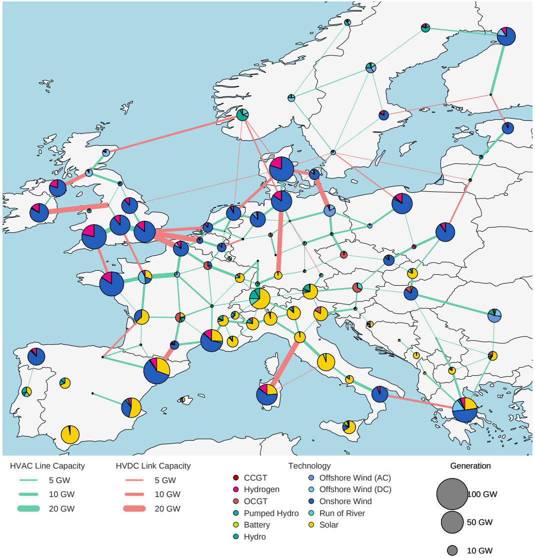
A near-optimal feasile solution

Minimise
Wind
Capacity
Epsilon:
5.0%



A near-optimal feasile solution

Maximise
Onshore
Wind
Capacity
Epsilon:
5.0%



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A near-optimal feasile solution

Minimise
Onshore
Wind
Capacity
Epsilon:
5.0%