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

Fabian Neumann, Tom Brown

fabian.neumann@kit.edu
Institute for Automation and Applied Informatics
Karlsruhe Institute of Technology (KIT)

Strommarkttreffen PhD Seminar, Hertie School, Berlin
November 28, 2019

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

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

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

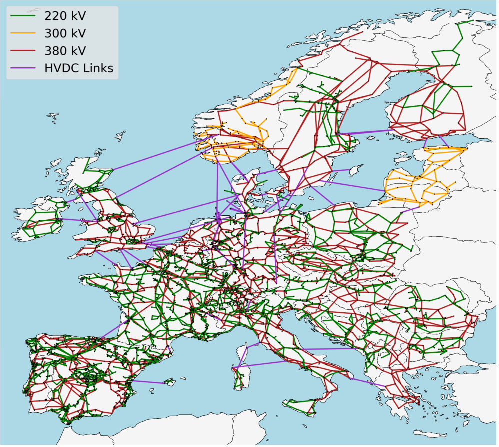
subject to

- 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
- fulfilling CO_2 emission reduction targets
- Flexibility from gas turbines, battery/hydrogen storage, HVDC links

Source: Tom Brown

Karlsruhe Institute of Technology

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 using *k*-means algorithm

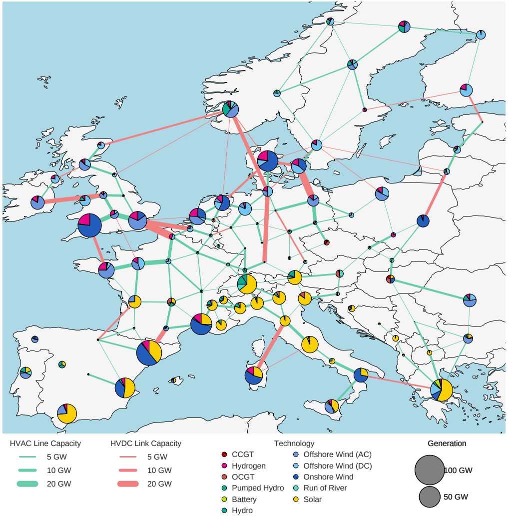
Code and Documentation

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

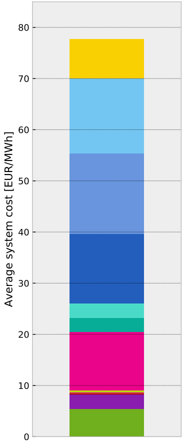
Source: Tom Brown

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

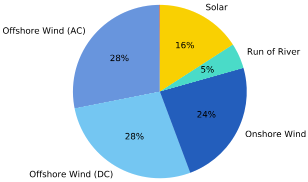
Distribution of generation and transmission expansion



Relative total annual system costs

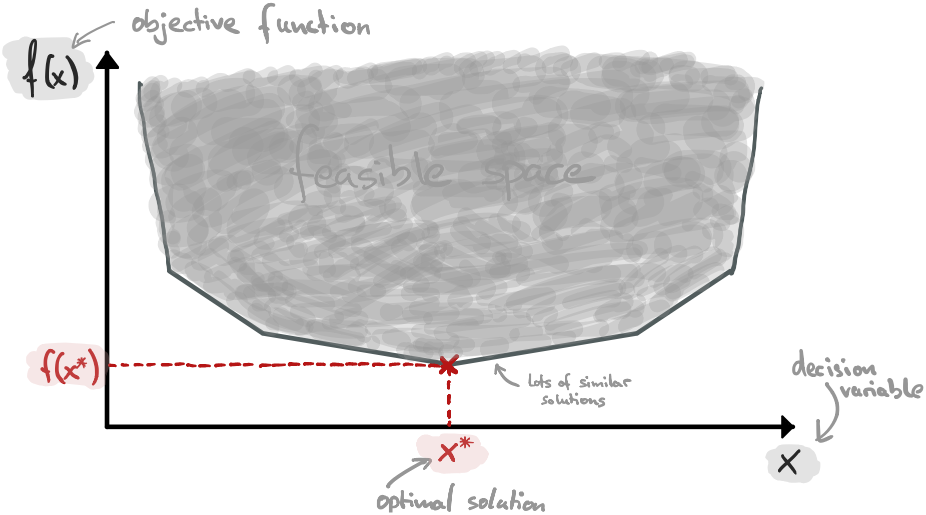


Energy generated by technology

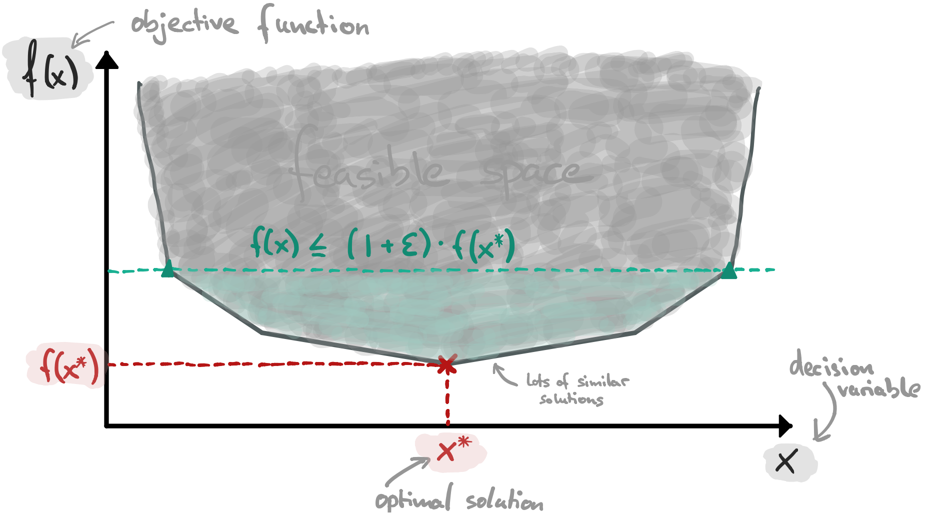


- power sector only
- 100 nodes
- 4380 snapshots (2-hourly resolution for 1 year)
- greenfield (except grid)

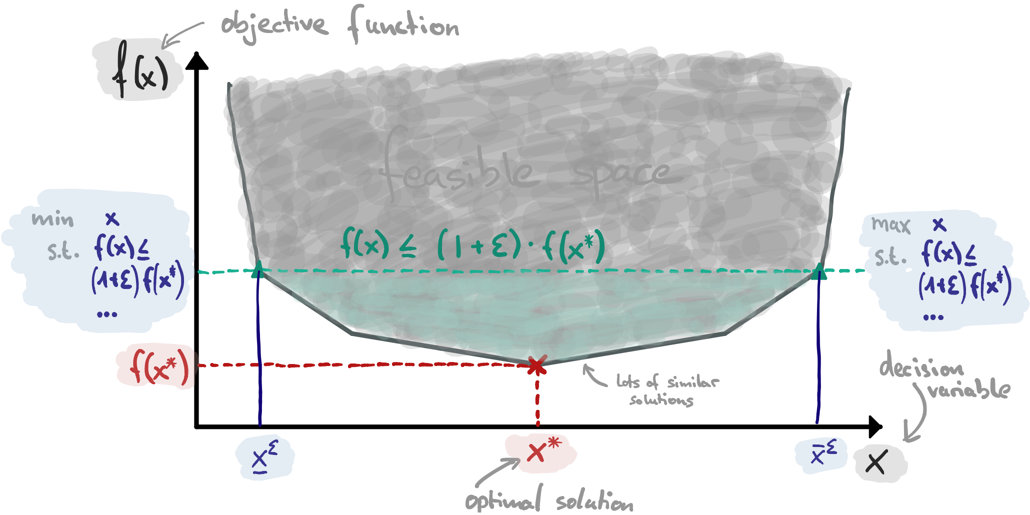
Karlsruhe Institute of Technology



Karlsruhe Institute of Technology



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



Karlsruhe Institute of Technology

Experiments

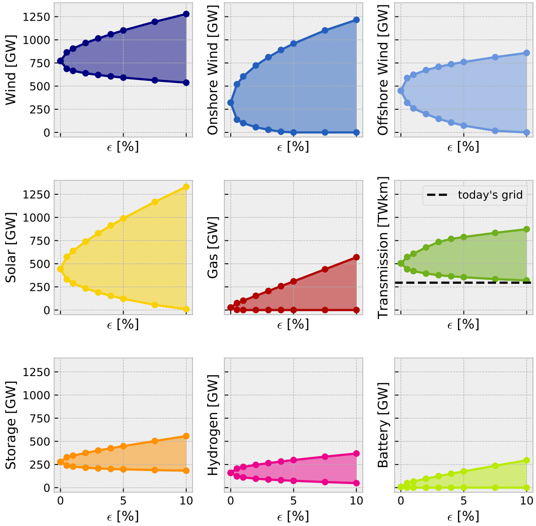
1. Find the **long-term cost-optimal energy system** targeting a greenhouse gas emissions reduction by $\{80, 95, 100\}$ % w.r.t 1990 levels and its total annual system costs.
2. For each $\varepsilon \in \{0.5, 1, \ldots, 5, \ldots, 10\}\%$ **minimise** and **maximise**
   a. generation technologies (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

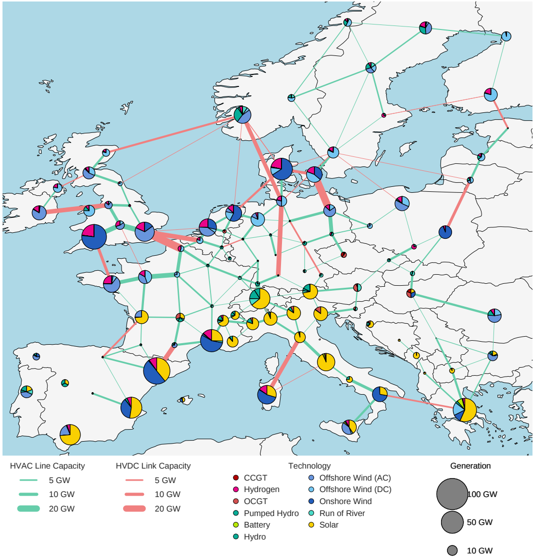


Karlsruhe Institute of Technology

Starting from the optimal solution, ...

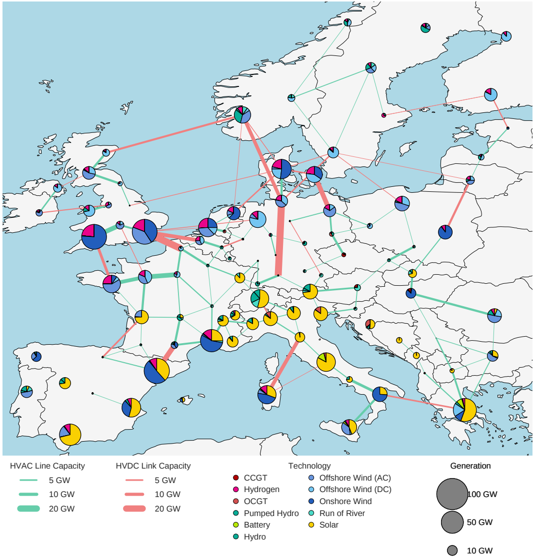
Optimal
Transmission
Volume
Epsilon:
0.0%

This is the optimal solution from earlier!



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

Minimise
Transmission
Volume
Epsilon:
0.5%

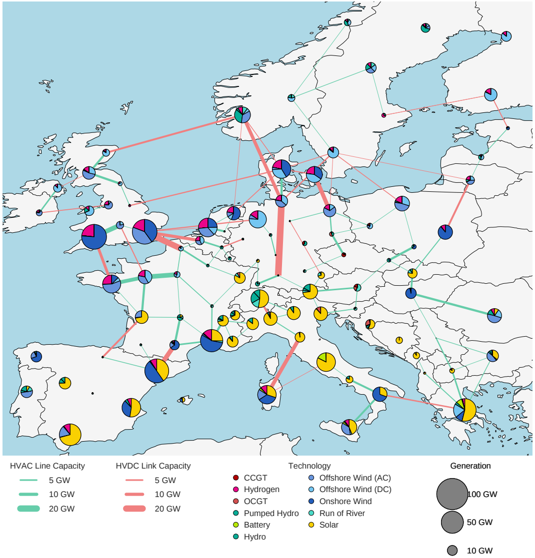


... seek the minimum transmission volume. ($\varepsilon = 1.0\%$)

Minimise Transmission Volume

Epsilon:

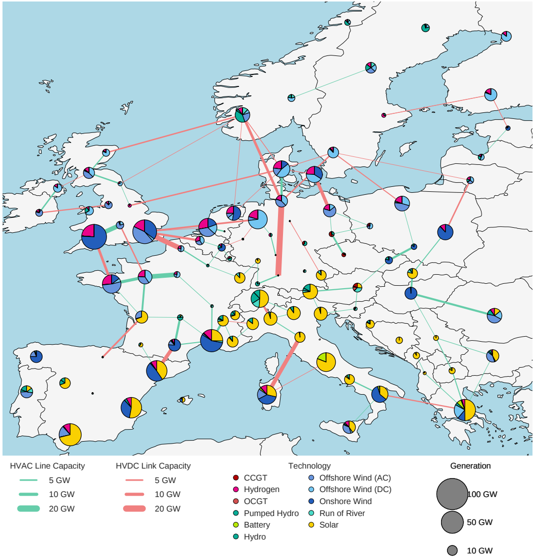
1.0%



Karlsruhe Institute of Technology

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

Minimise
Transmission
Volume
Epsilon:
2.0%



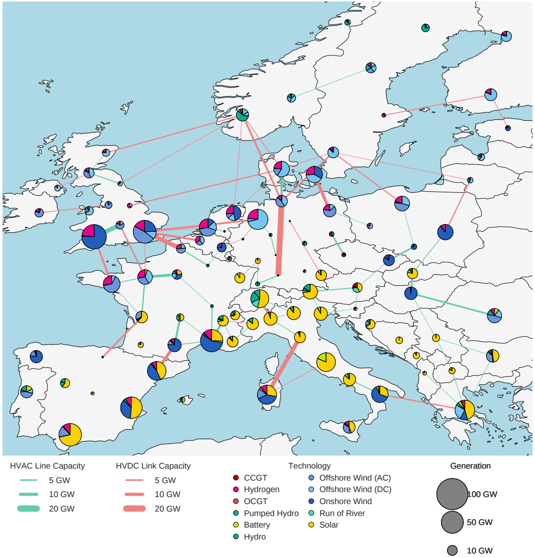
Karlsruhe Institute of Technology

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

Minimise Transmission Volume

Epsilon:

3.0%

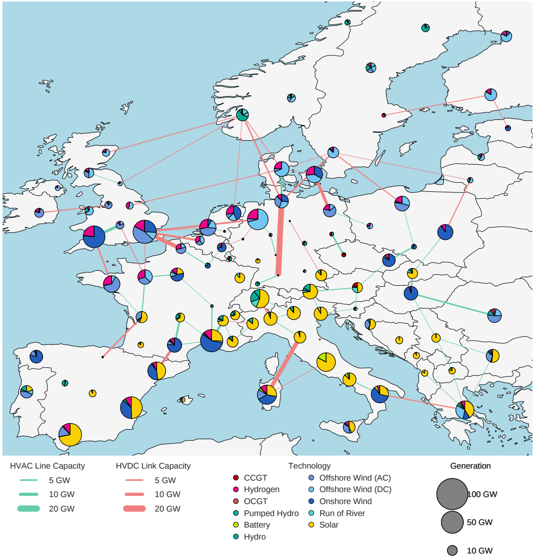


Karlsruhe Institute of Technology

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

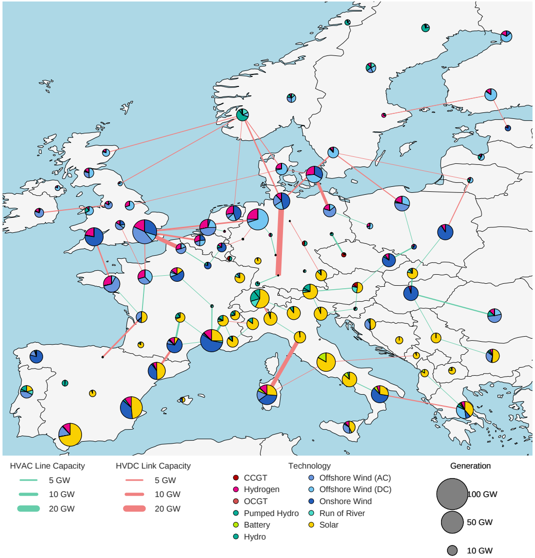
Minimise
Transmission
Volume

Epsilon:
4.0%



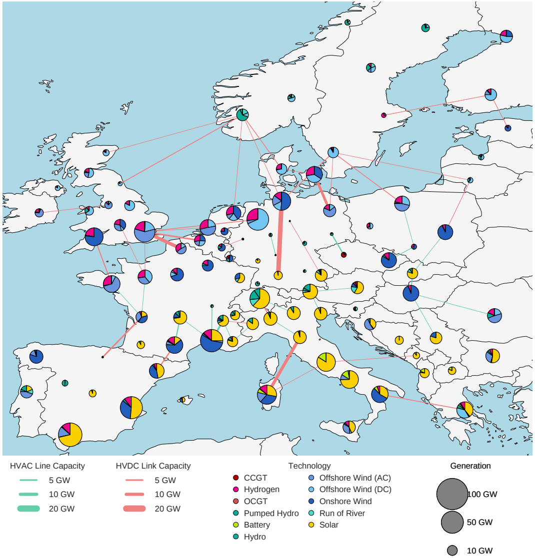
… seek the minimum transmission volume. ($\varepsilon = 5.0\%$)

Minimise
Transmission
Volume
Epsilon:
5.0%



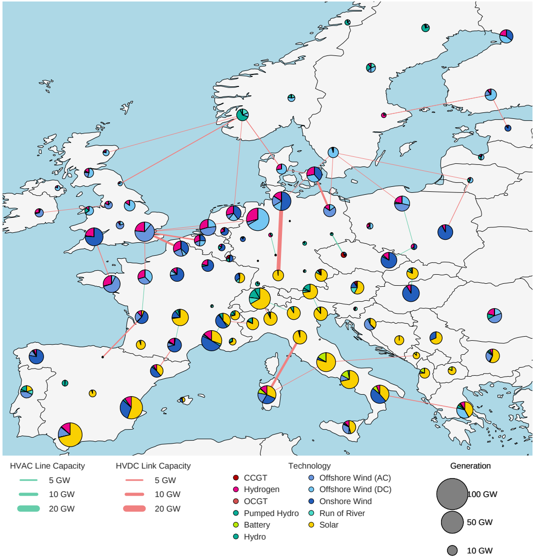
… seek the minimum transmission volume. ($\varepsilon = 7.5\%$)

Minimise
Transmission
Volume
Epsilon:
7.5%

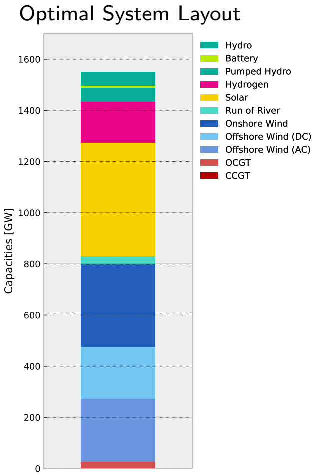


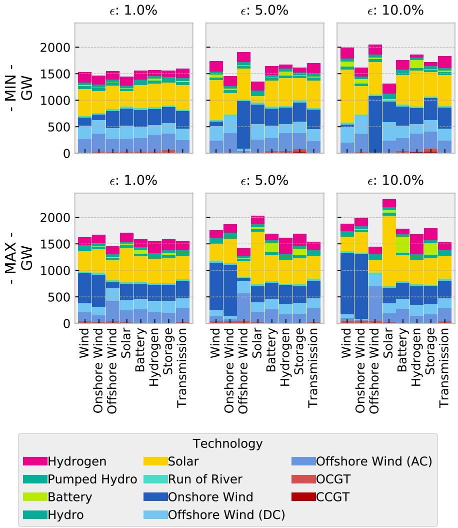
… seek the minimum transmission volume. ($\varepsilon = 10.0\%$)

Minimise
Transmission
Volume
Epsilon:
10.0%



Dependencies: Extremes cannot be achieved simultaneously.

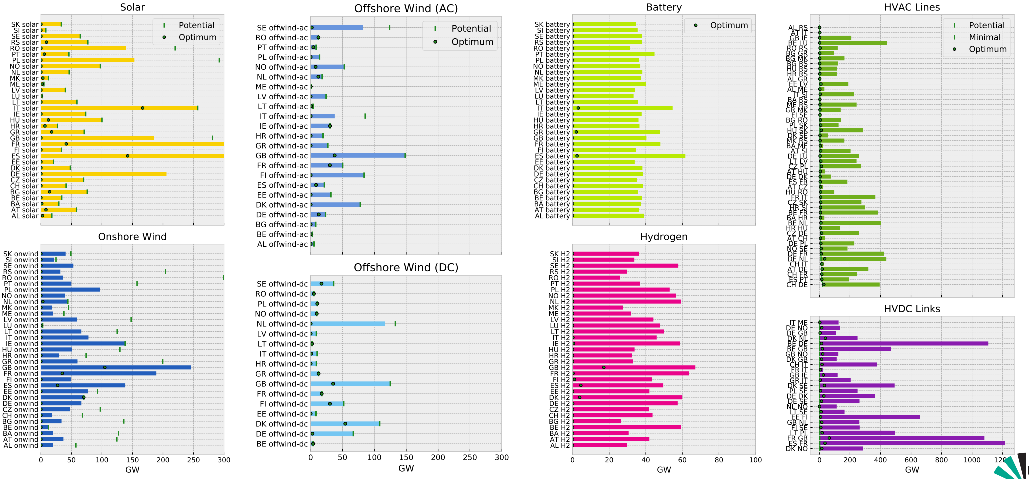




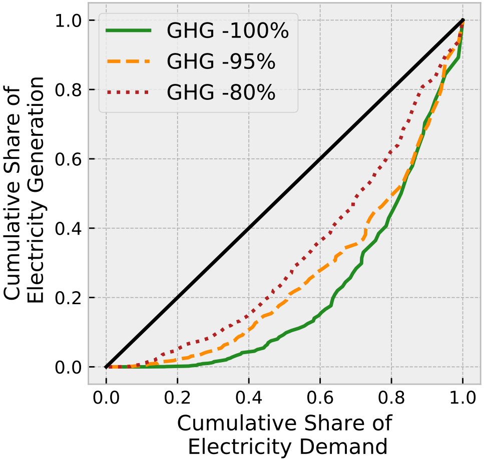
Karlsruhe Institute of Technology

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

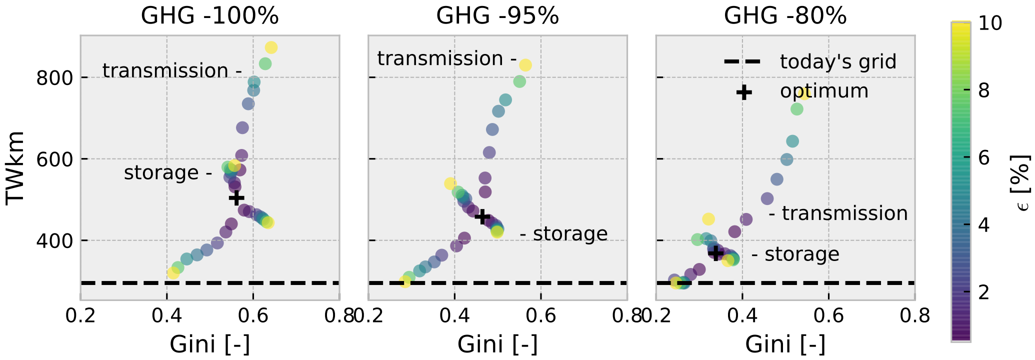
... with an **emission reduction target** of 95% and an **epsilon** of 1.0%



Distributional Equity: Lorenz Curve and Gini Coefficient



Distributional Equity: Storage and Transmission



Karlsruhe Institute of Technology

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 (“fuzzy” boundaries)

Preprint on arXiv.org

Physics > Physics and Society

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)

Submission history

From: Fabian Neumann [view email]

[v1] Fri, 4 Oct 2019 12:12:00 UTC (2,291 KB)

https://arxiv.org/abs/1910.01891

Resources and Copyright

Find the slides:

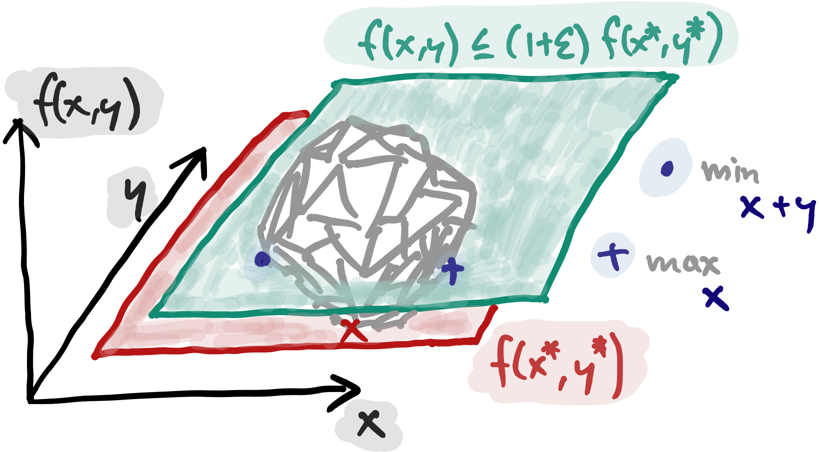
https://neumann.fyi/assets/strommarkttreffen-phd-2019-mga.pdf

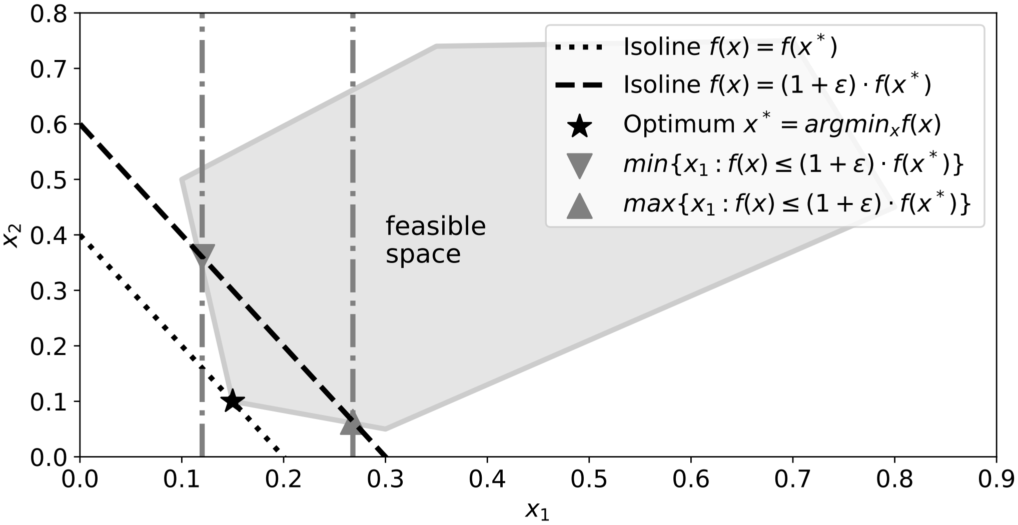
Send an email:

fabian.neumann@kit.edu

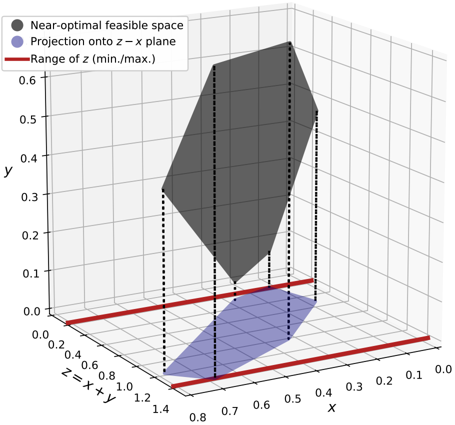
Find the energy system model:

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


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



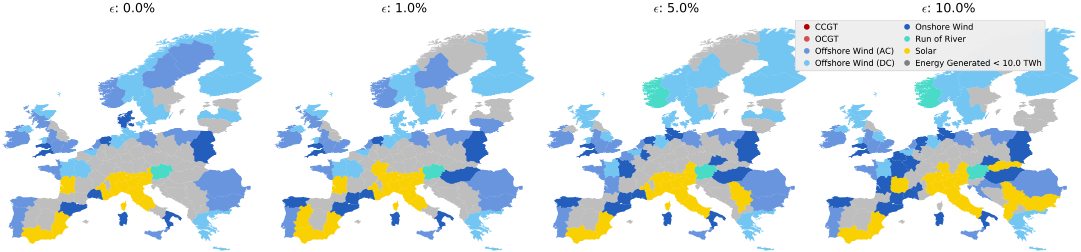
Isoline $f(x) = f(x^*)$
Isoline $f(x) = (1+\varepsilon) \cdot f(x^*)$
Optimum $x^* = argmin_x f(x)$
$min\{x_1 : f(x) \leq (1+\varepsilon) \cdot f(x^*)\}$
$max\{x_1 : f(x) \leq (1+\varepsilon) \cdot f(x^*)\}$
feasible space
x_1
x_2
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9



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

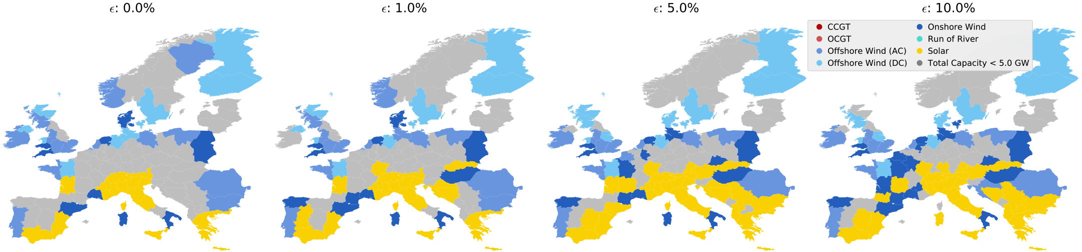
Dominant Carrier by Energy Generated

Minimise
Power Transmission Volume



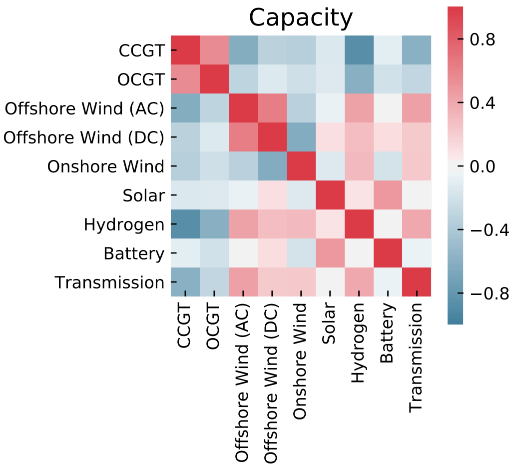
Dominant Carrier by Capacity

Minimise
Power Transmission Volume

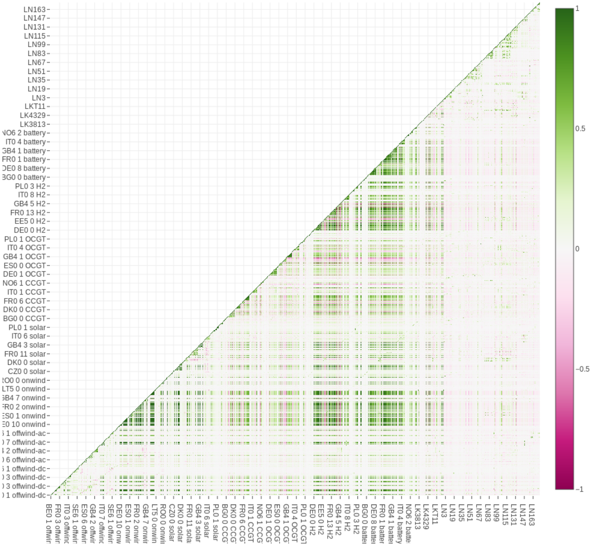


Karlsruhe Institute of Technology

Correlations of Investment Variable Groups

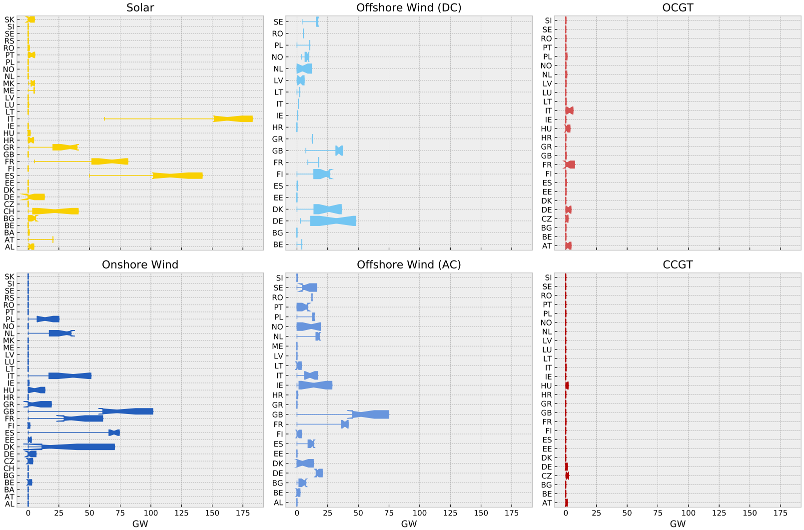


Correlations of Individual Investment Variables



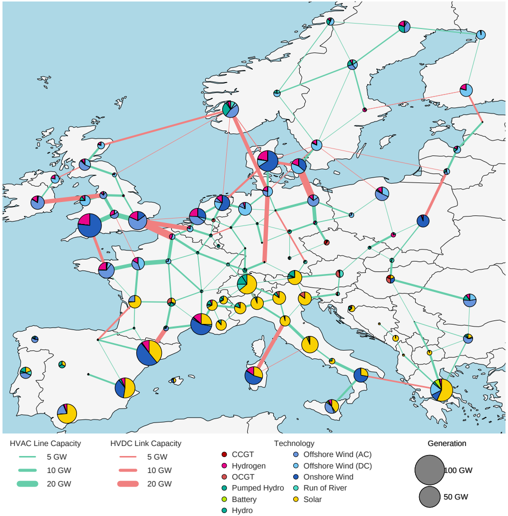
Karlsruhe Institute of Technology

Distribution of Individual Investment Variables

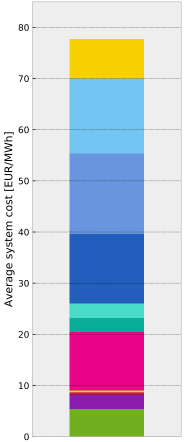


Optimal System Layout for a 100% emission reduction (w.r.t. 1990 levels)

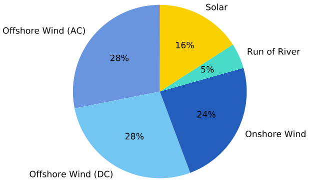
Distribution of generation and transmission **expansion**



Relative total annual system costs



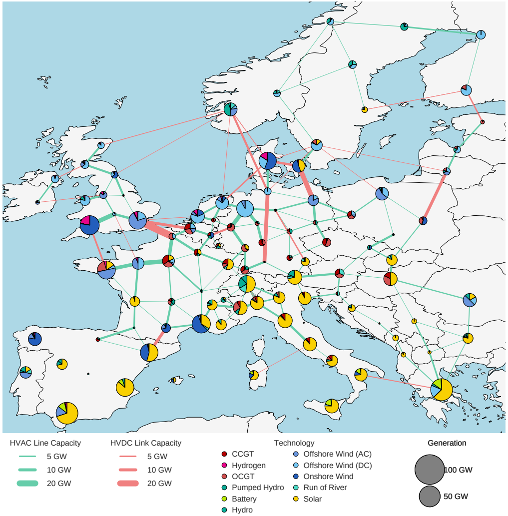
Energy generated by technology



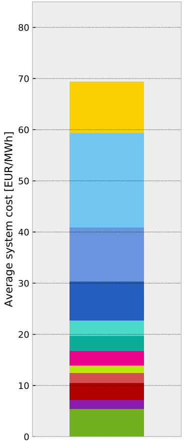
Karlsruhe Institute of Technology

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

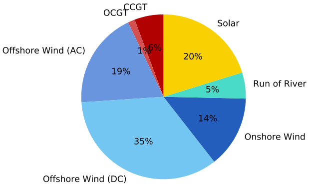
Distribution of generation and transmission expansion



Relative total annual system costs



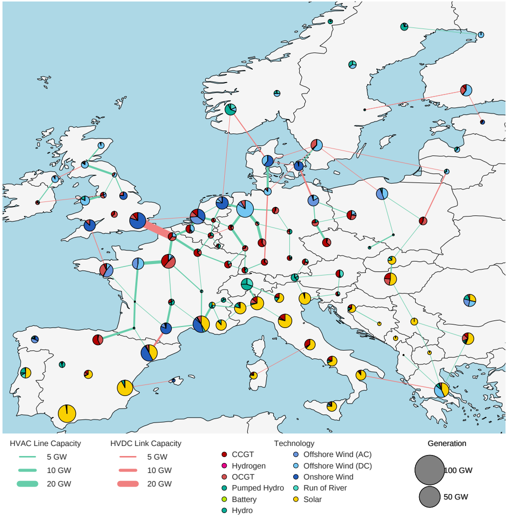
Energy generated by technology



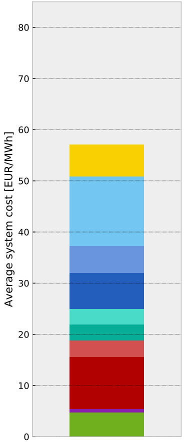
Karlsruhe Institute of Technology

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

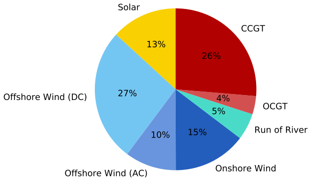
Distribution of generation and transmission **expansion**



Relative total annual system costs

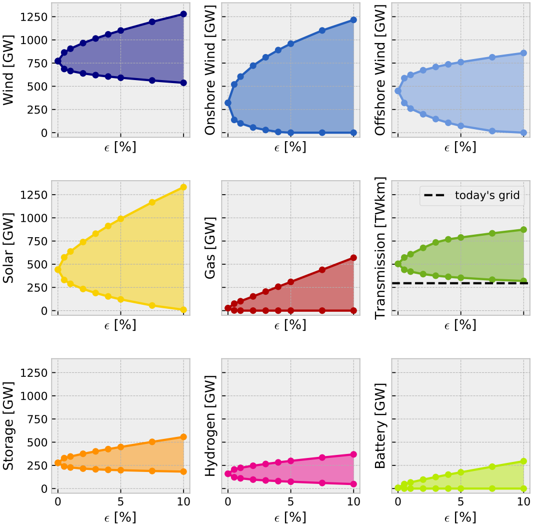


Energy generated by technology



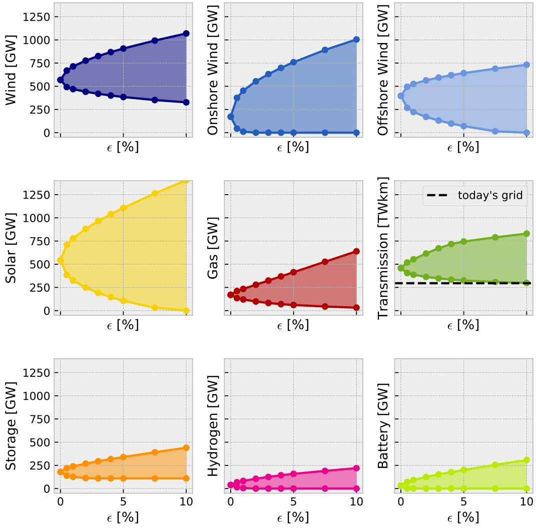
Karlsruhe Institute of Technology

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



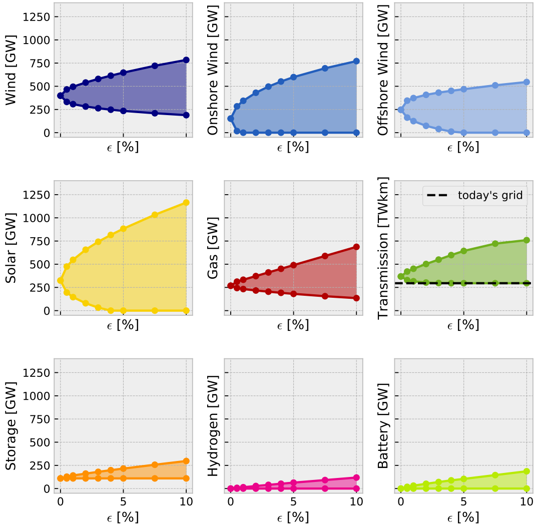
Karlsruhe Institute of Technology

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



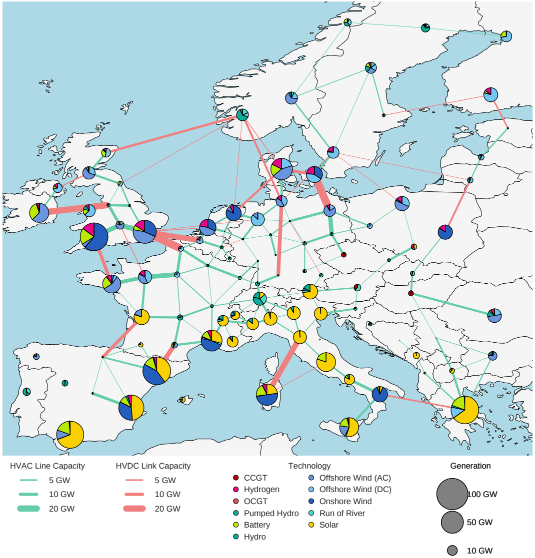
Karlsruhe Institute of Technology

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



A near-optimal feasile solution

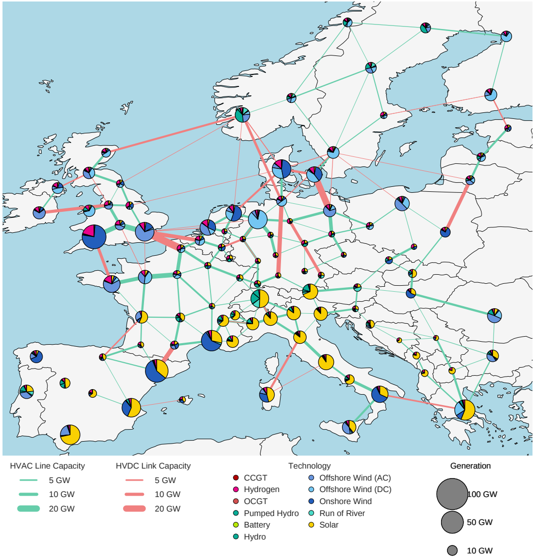
Maximise
Battery
Storage
Epsilon:
5.0%



Karlsruhe Institute of Technology

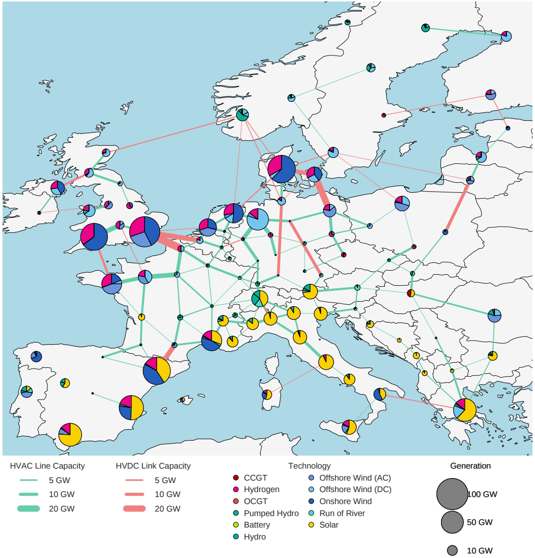
A near-optimal feasile solution

Minimise
Battery
Storage
Epsilon:
5.0%



A near-optimal feasile solution

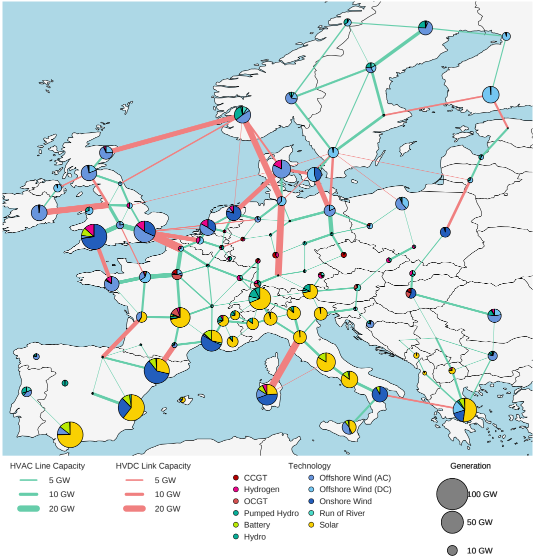
Maximise
Hydrogen
Storage
Epsilon:
5.0%



Karlsruhe Institute of Technology

A near-optimal feasile solution

Minimise
Hydrogen
Storage
Epsilon:
5.0%



Karlsruhe Institute of Technology

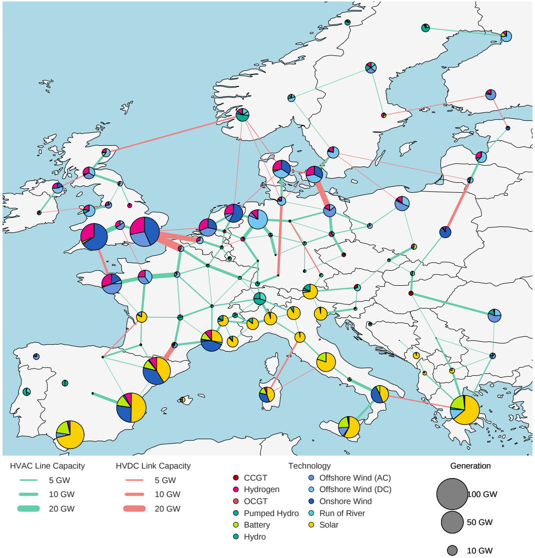
A near-optimal feasile solution

Maximise All

Storage

Epsilon:

5.0%

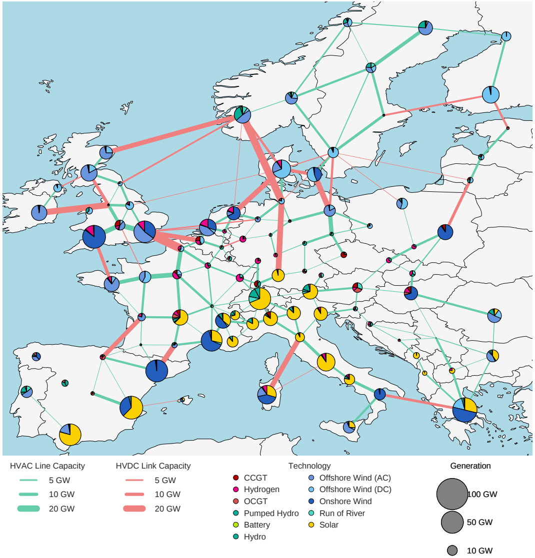


A near-optimal feasile solution

Minimise All Storage

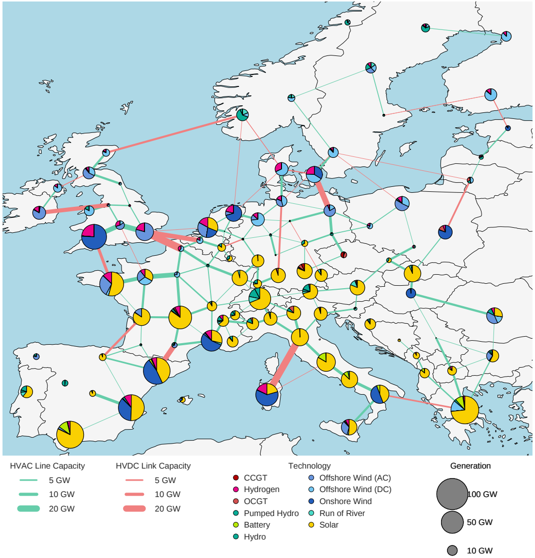
Epsilon:

5.0%



A near-optimal feasile solution

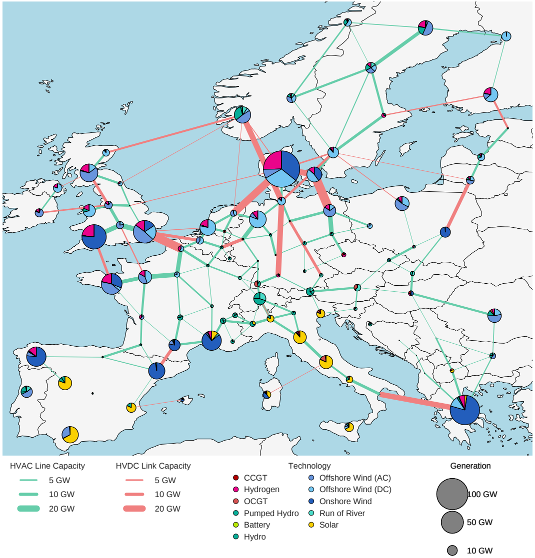
Maximise
Solar
Capacity
Epsilon:
5.0%



Karlsruhe Institute of Technology

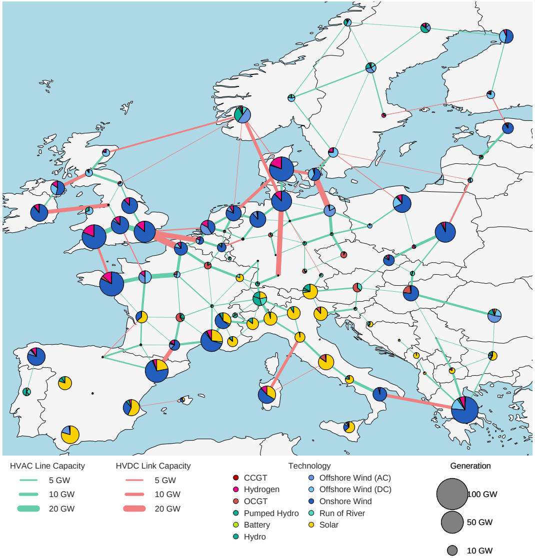
A near-optimal feasile solution

Minimize
Solar
Capacity
Epsilon:
5.0%



A near-optimal feasile solution

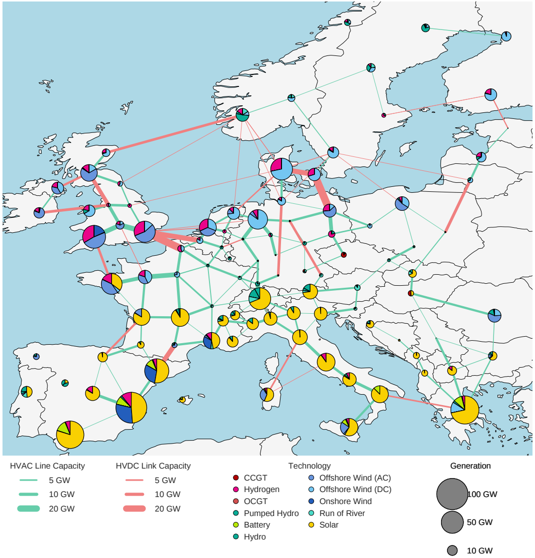
Maximise
Wind
Capacity
Epsilon:
5.0%



Karlsruhe Institute of Technology

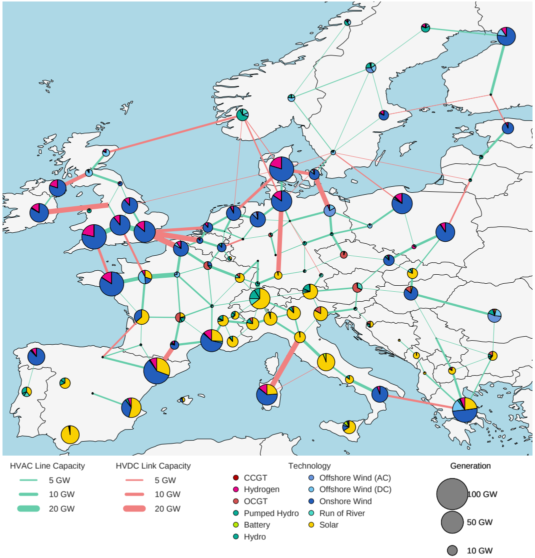
A near-optimal feasile solution

Minimise
Wind
Capacity
Epsilon:
5.0%



A near-optimal feasile solution

Maximise
Onshore
Wind
Capacity
Epsilon:
5.0%



Karlsruhe Institute of Technology

A near-optimal feasile solution

Minimise
Onshore
Wind
Capacity
Epsilon:
5.0%