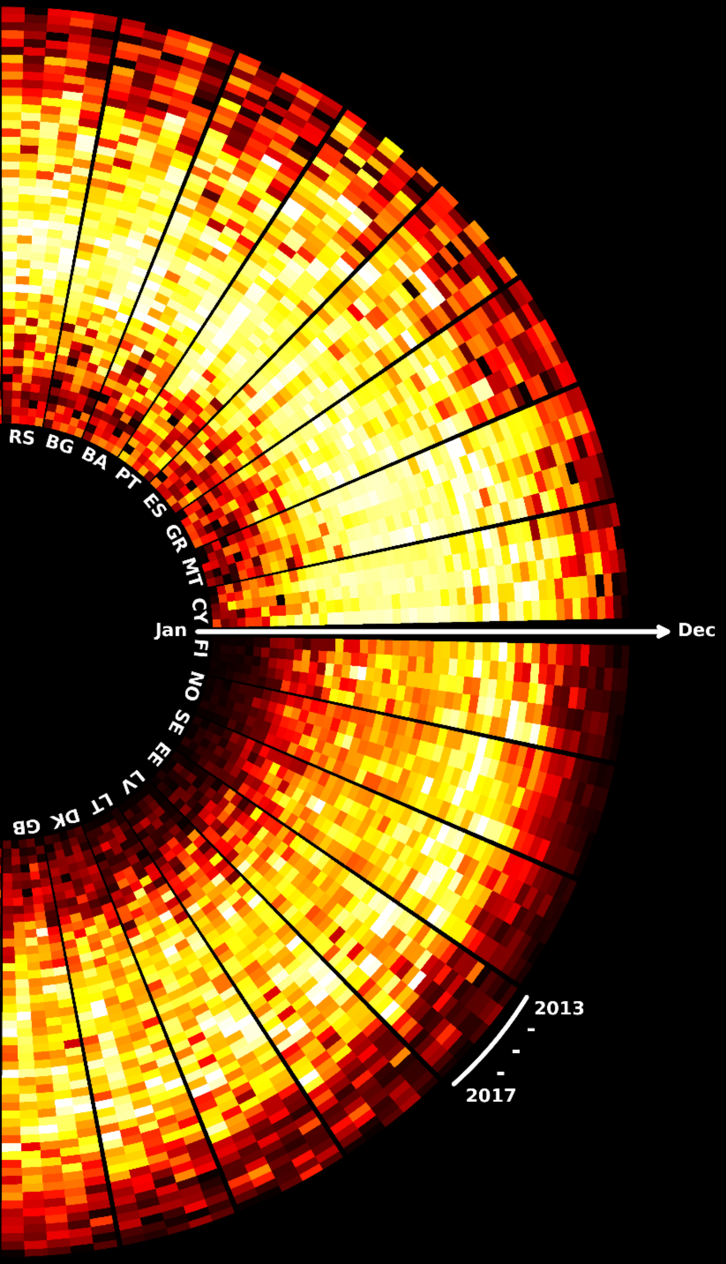


November 2024

Marta Victoria

Modern PyPSA applications

DTU

AARHUS UNIVERSITY

Methodology

Economic optimization subject to constraints

$$\min \left(\sum_{n} \mathit{generation\ costs} + \mathit{storage\ costs} + \mathit{transmission\ costs} + \sum_{n,t} \mathit{variable\ costs} \right)$$

Subject to constraints :

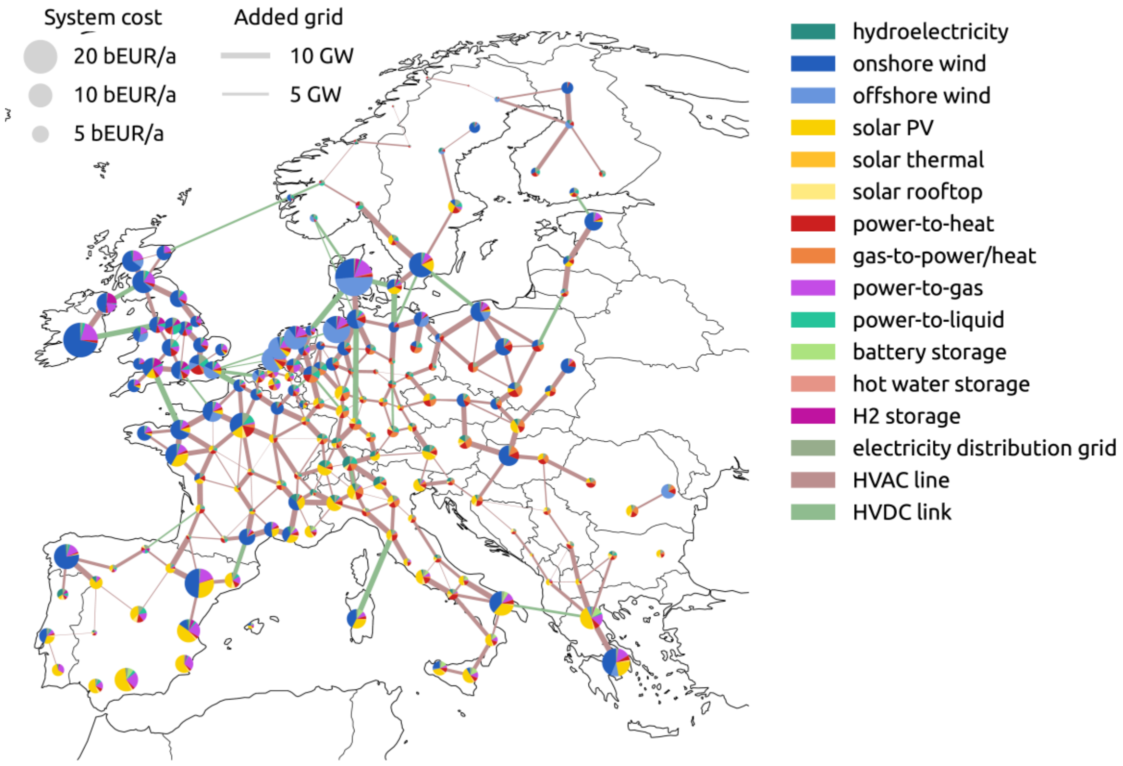
$$\mathit{generation} + \mathit{balance} = \mathit{demand} \quad \leftrightarrow \quad \lambda_{n,t} \qquad \forall n, t$$

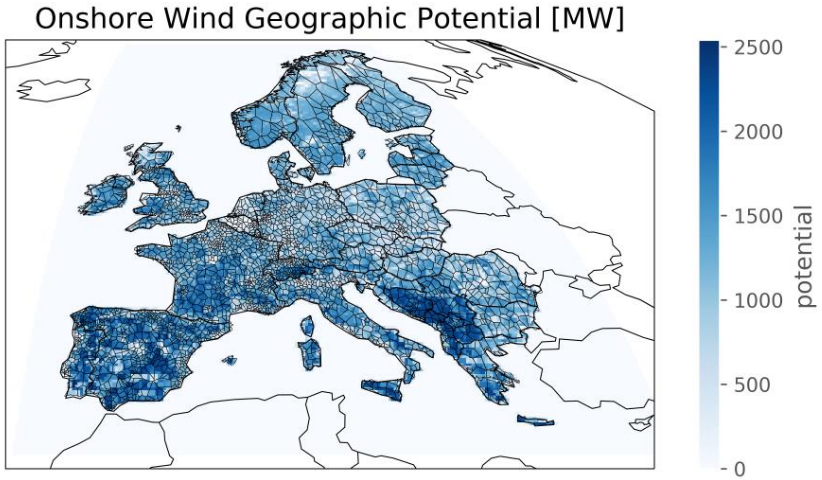
$$\sum \mathit{emissions} \leq CAP_{CO2} \quad \leftrightarrow \quad \mu_{CO2}$$

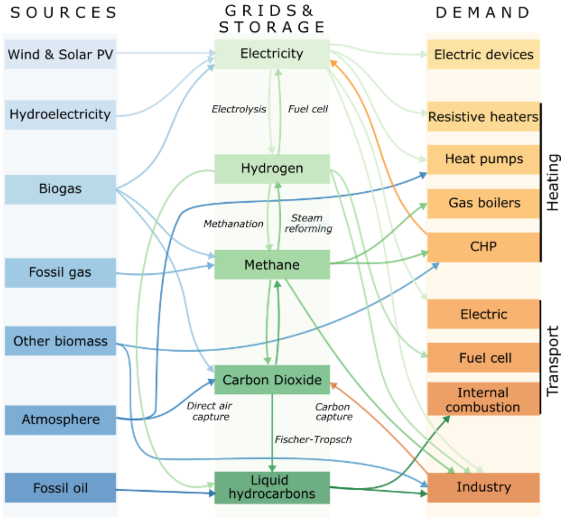
Perfect competition and foresight, long-term market equilibrium

PyPSA-Eur Highlights

- Linear capacity and dispatch optimization
- Simplifies ENTSO-E network topology by k-means clustering, linearized power flow
- Time series for wind, solar, hydro for Voronoi cells
- Includes electricity, heating, transport, industry, and carbon management
- Geo-located database with industrial and power generation facilities in Europe
- Open-license python-based model highly configurable
- Used by many research institutions and companies worldwide
- Lead by TUBerlin, AU group implemented industrial sector, myopic transition paths, repository for costs and technology data based on DEA







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

PyPSA

Outline of today

- Spatial and temporal resolution

- Research example 1: The role of H2 in net-zero emissions scenarios: demand, production, transport and cost

  Neuman, Zeyen, Victoria, Brown, Joule, 2023 https://doi.org/10.1016/j.joule.2023.06.016

- Validation: https://pypsa-eur.readthedocs.io/en/latest/validation.html

- Research example 2: Designing robust energy systems

  Gøtske, Andresen, Neumann, Victoria, Nature Comm. (to be published) 2024 https://arxiv.org/abs/2404.12178

- Research example 3: Technology learning

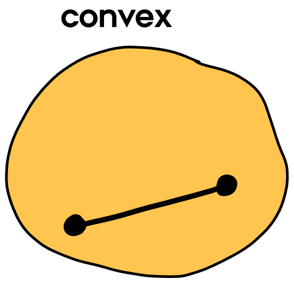
  Zeyen, Victoria, and Brown, Nature Commun. 2023 https://doi.org/10.1038/s41467-023-39397-2

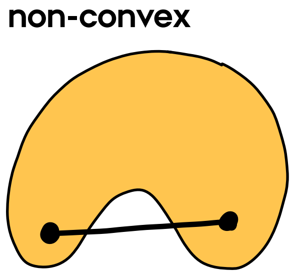
- Research example 4: Exploring near-optimal solution space

  Pedersen, Victoria, Rasmussen, Andresen, Energy, 2021
  Pedersen, Andersen, Victoria, and Andresen, iScience, 2023

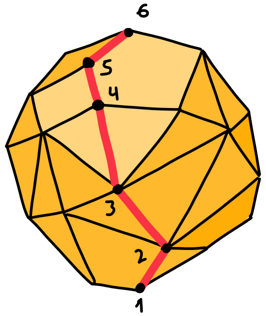
Optimization algorithms and computational challenges

Typically, we work with linear optimization problems. The feasible space is convex, and the solution can be found (without getting trapped in local minima).

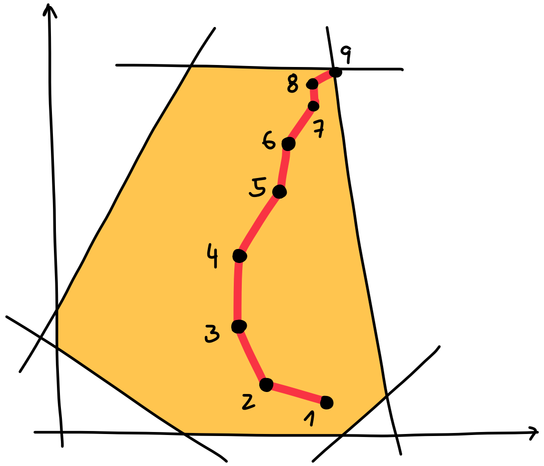




The feasible space is a polyhedron. The optimum always occurs at one of the vertices. We can check all the vertices (simplex algorithm)



We use interior-point methods which converge faster. The objective is to iteratively approach the optimal solution from the interior of the feasible space.
A barrier term is added to the objective function that penalizes solutions that come close to the boundary.



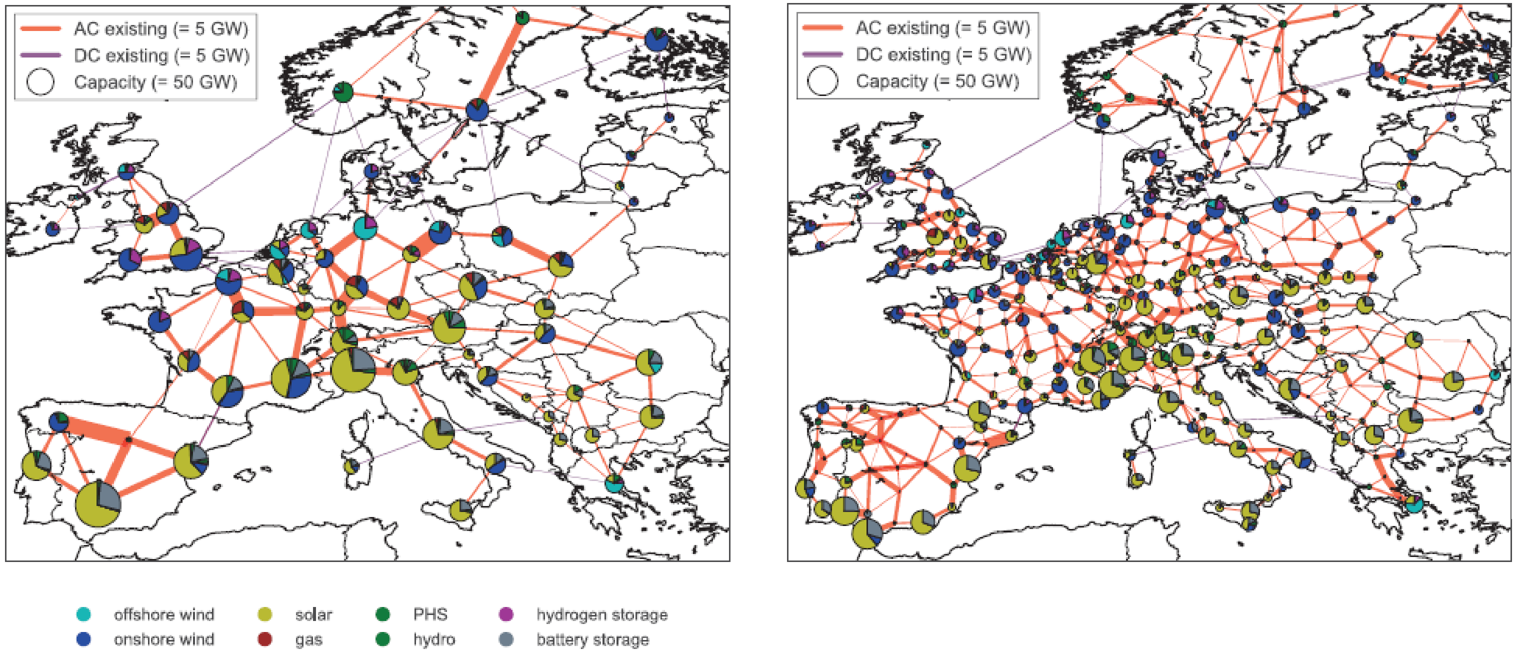
Ideally, we want high resolution in time, space and technologies: Where is the trade-off for space and time resolution?

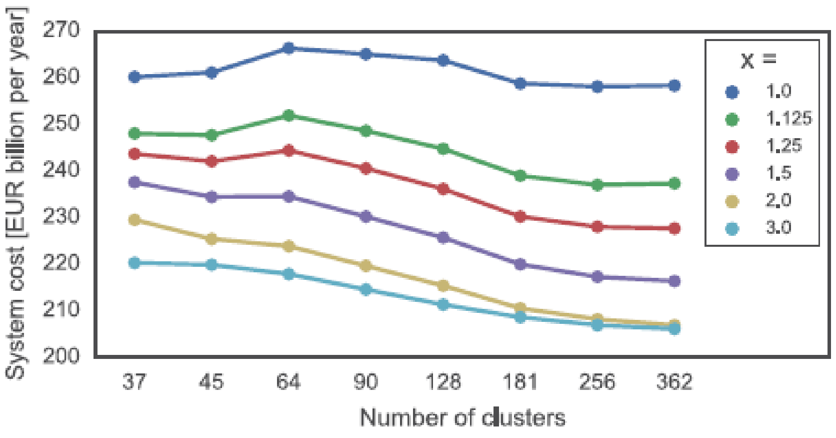
Which spatial resolution is good enough?

When increasing the number of nodes, the system cost remains roughly constant due to the counterbalancing of two effects:

(a) sites with high capacity factors for wind and solar are available for a more finely resolved network,

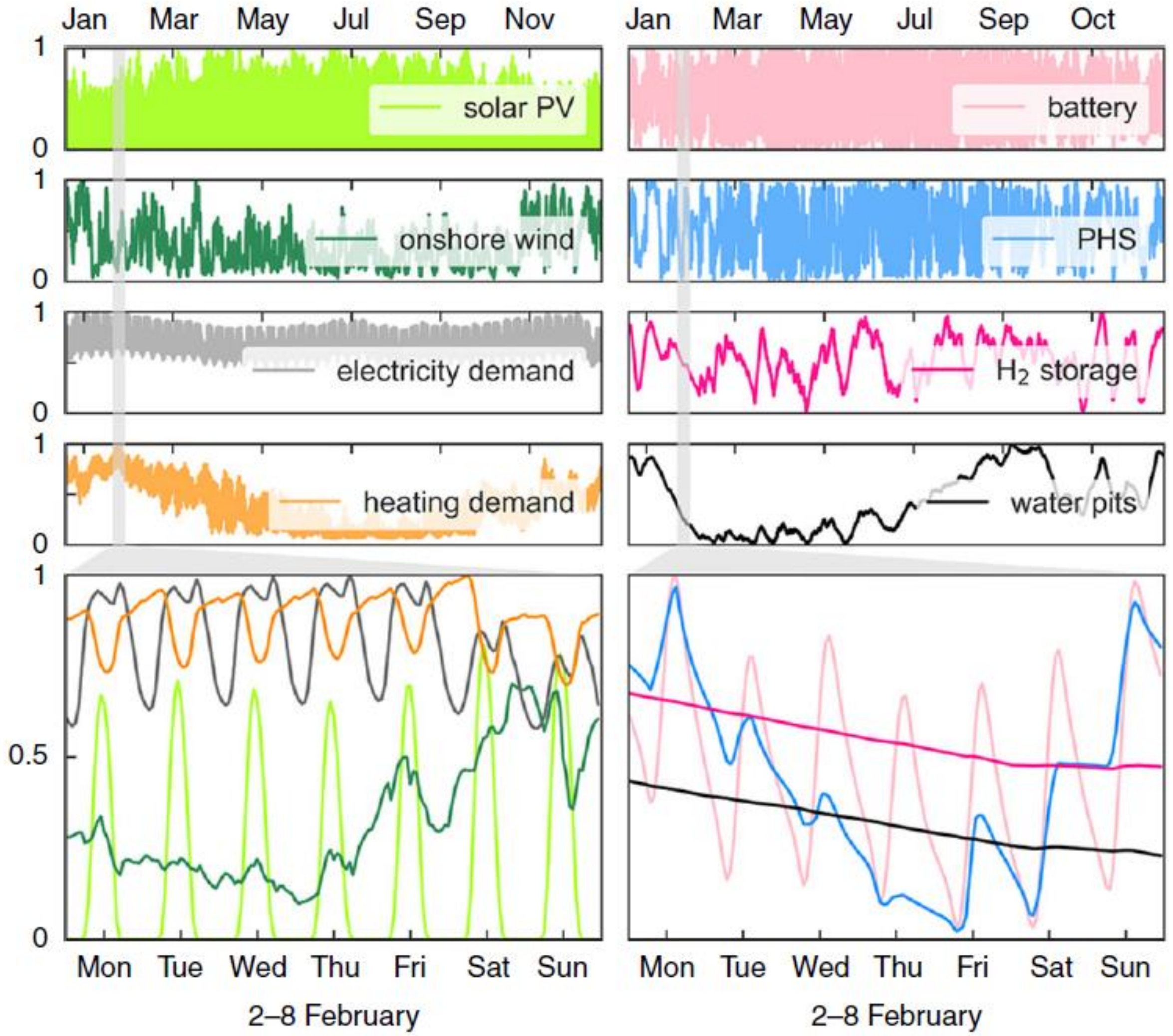
(b) but the emergence of bottlenecks inside countries prevents the use wind energy generated at exterior nodes





Hörsch and Brown, IEEE (2017)

Which time resolution is good enough?



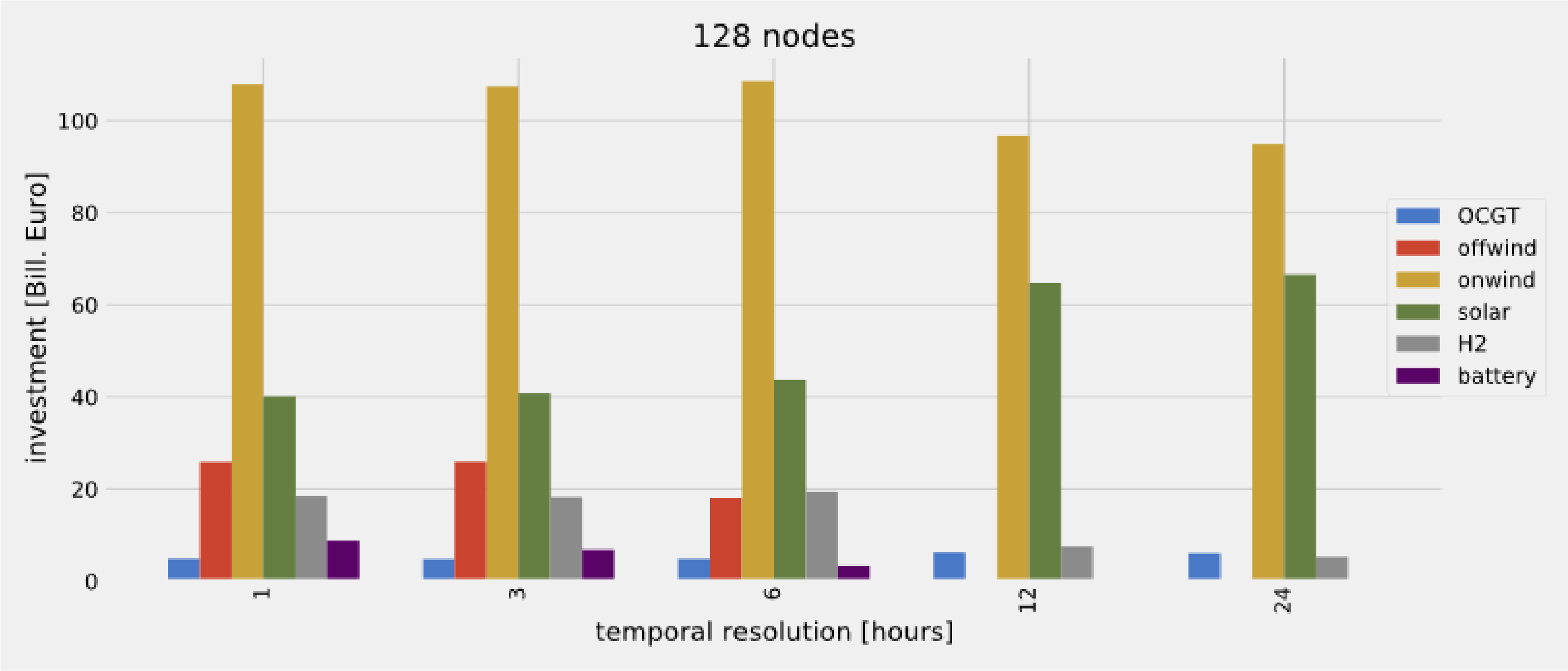
Victoria et al., Nature Commun. (2020)

We need **uninterrupted hourly time stepping** to capture the main fluctuations:

- solar and wind power generation smoothed by the grid and storage
- the role of long-term storage
- system operation during dark doldrums (i.e., periods with low wind and solar generation)

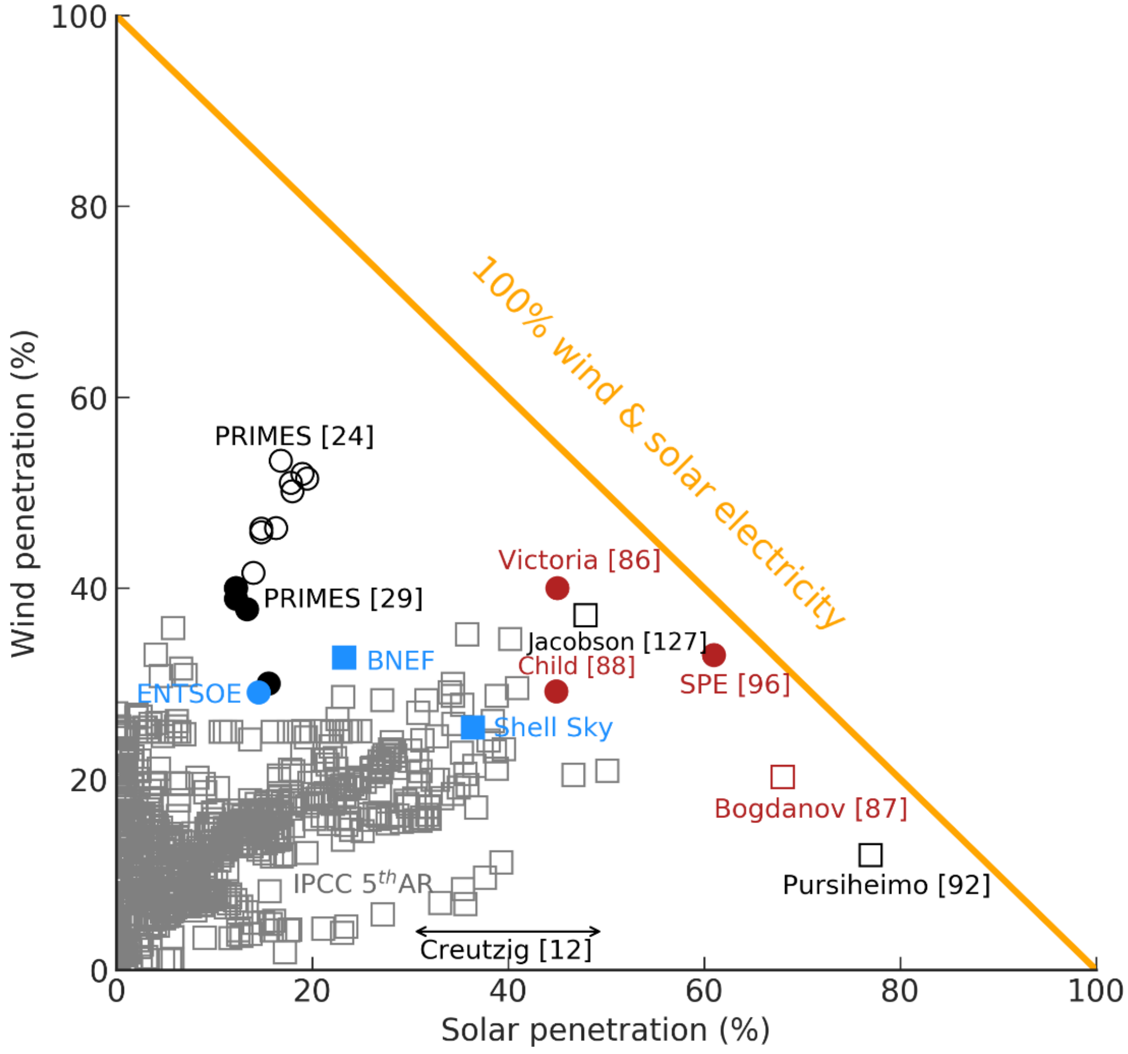
Which time resolution is good enough?

Resolution coarser than 3 hours get a solar balance “for free” and does not need batteries



Schyska et al., Joule. (2021)

High temporal and spatial modelling is paramount for renewables !



Victoria et al., Joule (2021)

Poor modelling of balancing strategies (incorrect time resolution, not including network or sector coupling) penalizes wind and solar.

Research example 1:
The role of H_2 in net-zero emissions scenarios: demand, production, transport and cost

Article

The potential role of a hydrogen network in Europe

Fabian Neumann,[1,4,*] Elisabeth Zeyen,[1] Marta Victoria,[2,3] and Tom Brown[1]

SUMMARY

Europe's electricity transmission expansion suffers many delays, despite its significance for integrating renewable electricity. A hydrogen network reusing the existing gas network could not only help to supply the demand for low-emission fuels but could also balance variations in wind and solar energies across the continent and thus avoid power grid expansion. Our investigation varies the allowed expansion of electricity and hydrogen grids in net-zero CO_2 scenarios for a sector-coupled European energy system, capturing transmission bottlenecks, renewable supply and demand variability, and pipeline retrofitting and geological storage potentials. We find that a hydrogen network connecting regions with low-cost and abundant renewable potentials to demand centers, electrofuel production, and cavern storage sites reduces system costs by up to 26 bn€/a (3.4%). Although expanding both networks together can achieve the largest cost reductions, by 9.9%, the expansion of neither is essential for a net-zero system as long as higher costs can be accepted and flexibility options allow managing transmission bottlenecks.

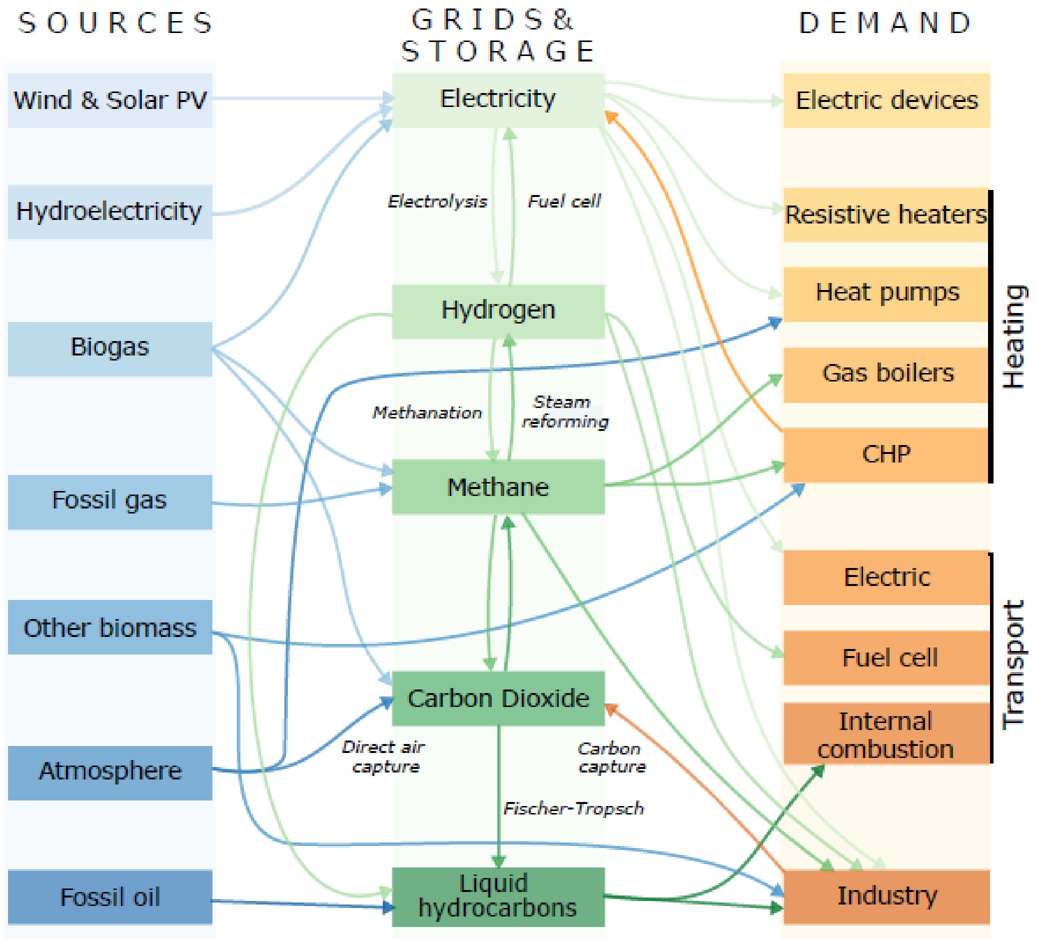
CONTEXT & SCALE

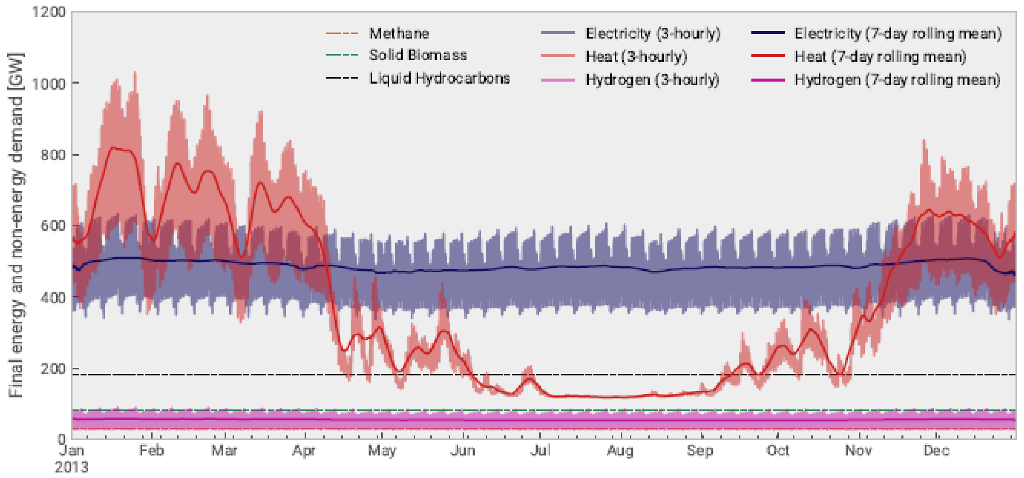
Many different combinations of infrastructure could make Europe carbon neutral by mid-century, but not all solutions meet the same level of acceptance. For example, power grid reinforcements have faced many delays, despite their value for integrating renewables. A hydrogen network reusing gas pipelines could substitute for moving cheap but remote renewables across the continent to where demand is.

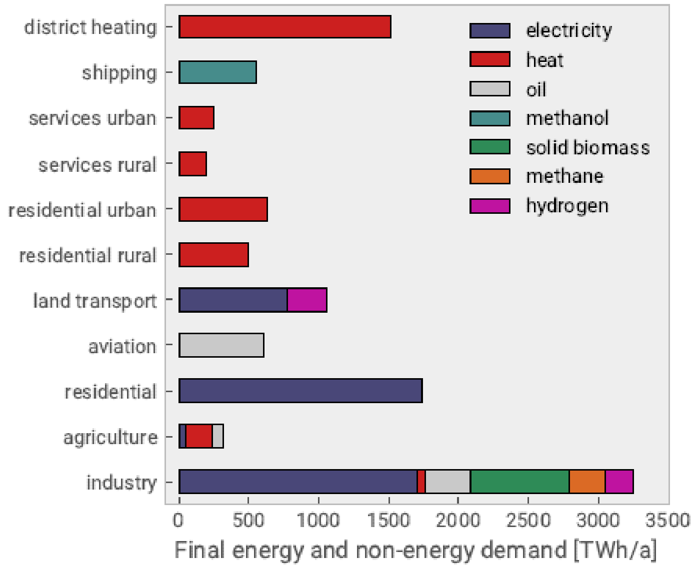
We study trade-offs between new transmission lines and a hydrogen network in the European energy system with net-zero CO_2

Methods

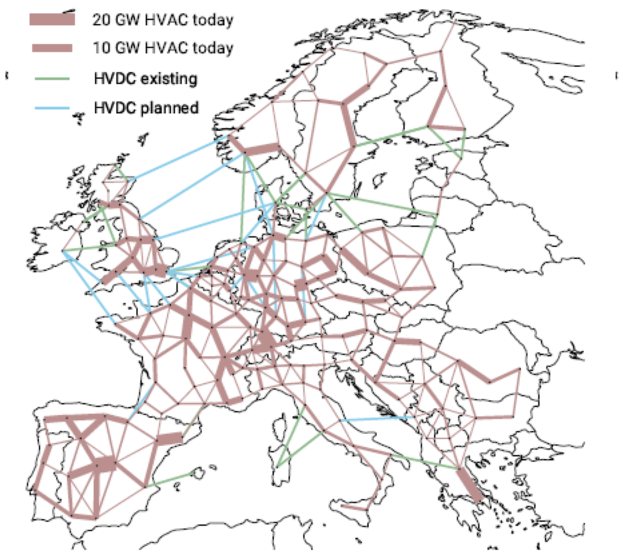
Our open model includes detailed representation of networked sector-coupled Europe: Electricity, Heating, Transport, Industry and feedstock, carbon management

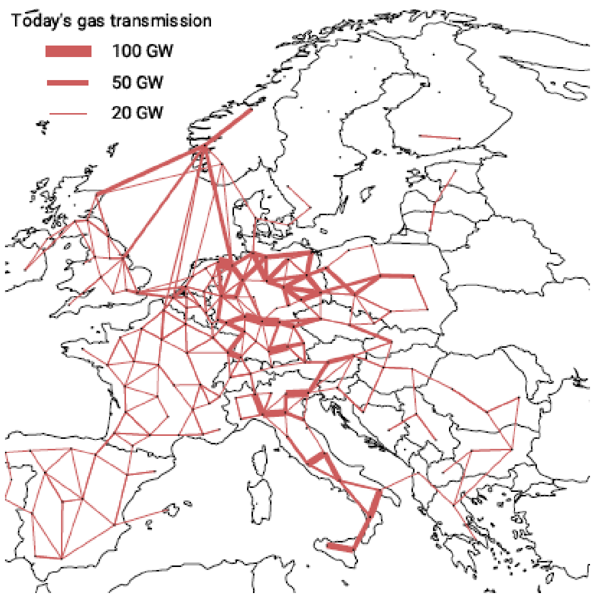






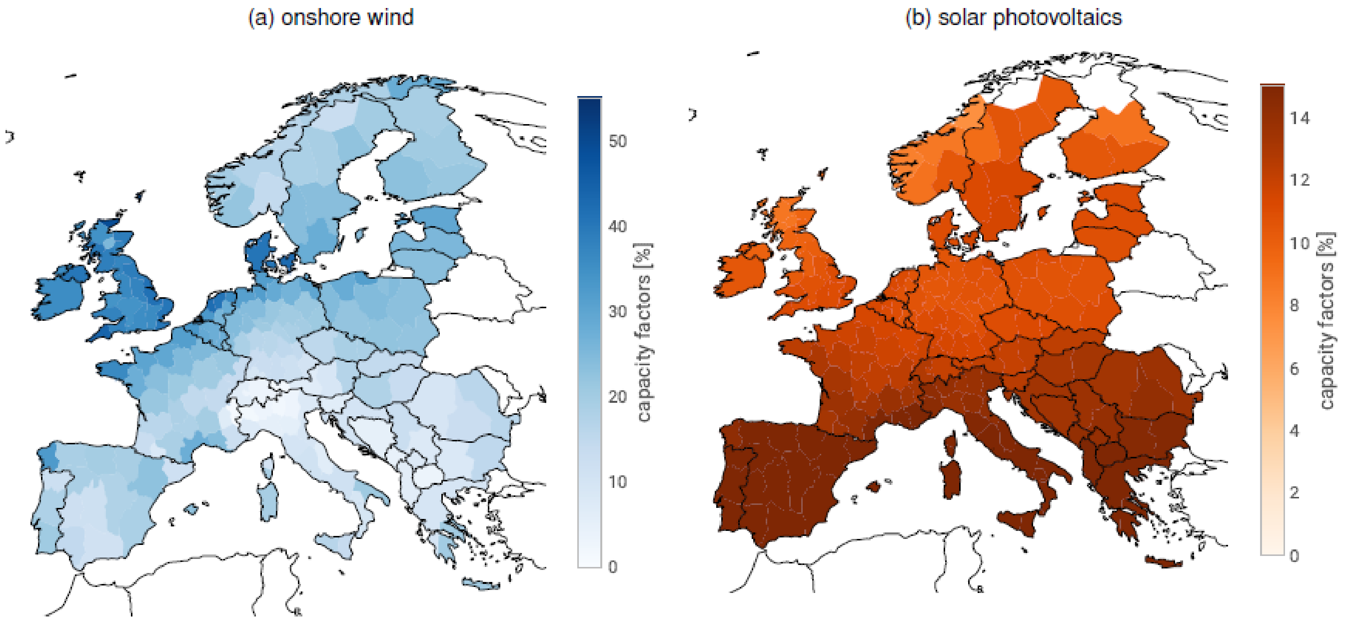
Methods





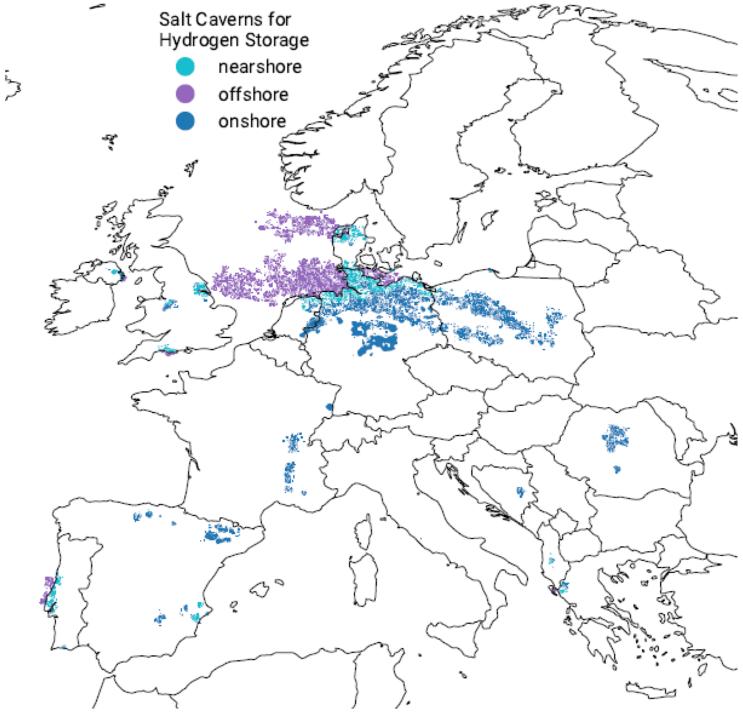
Existing infrastructure for electricity transmission and gas networks included.

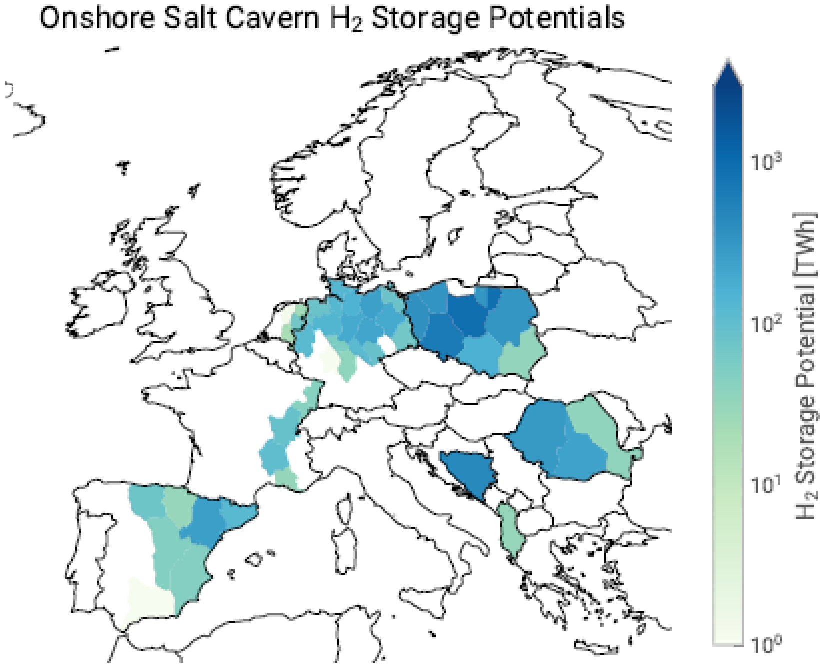
- 3-h resolution and 181 nodes
- Costs from DEA
- Net-zero emissions scenarios
- H2 pipelines can be build from scratch or repurposed



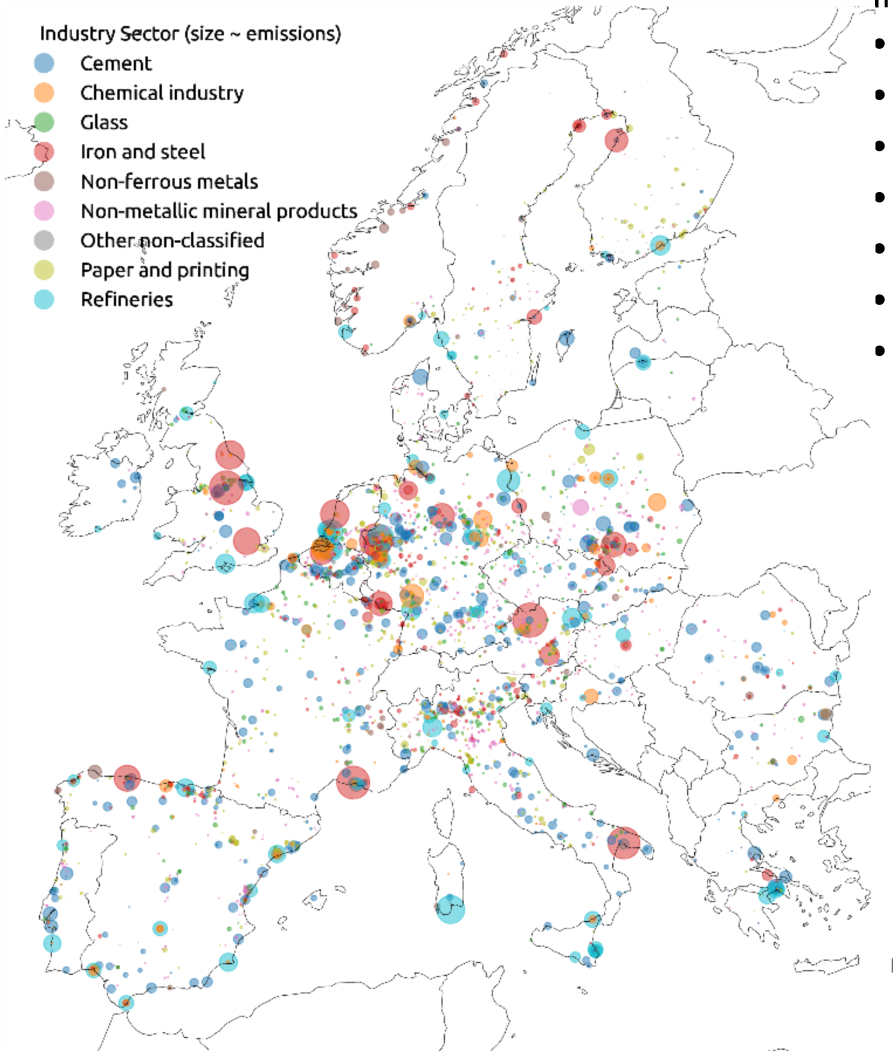
Methods

H2 can be stored overground on steel tanks or underground on salt caverns



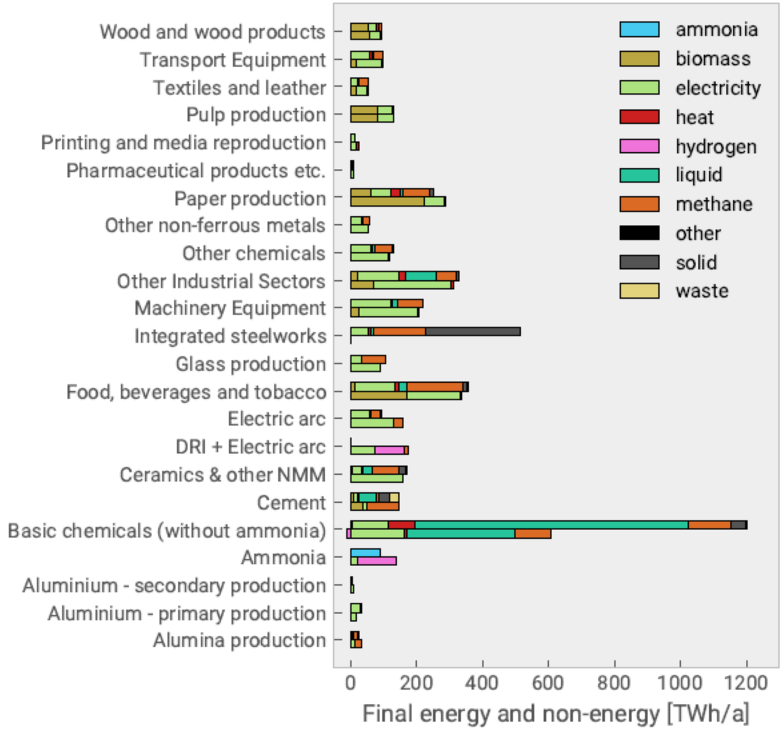


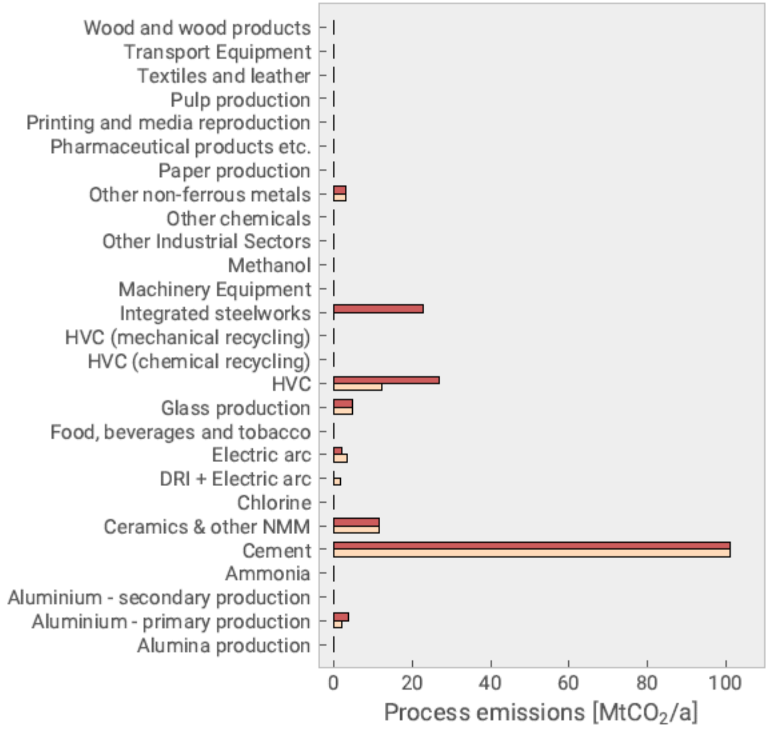
Methods: industrial transformation



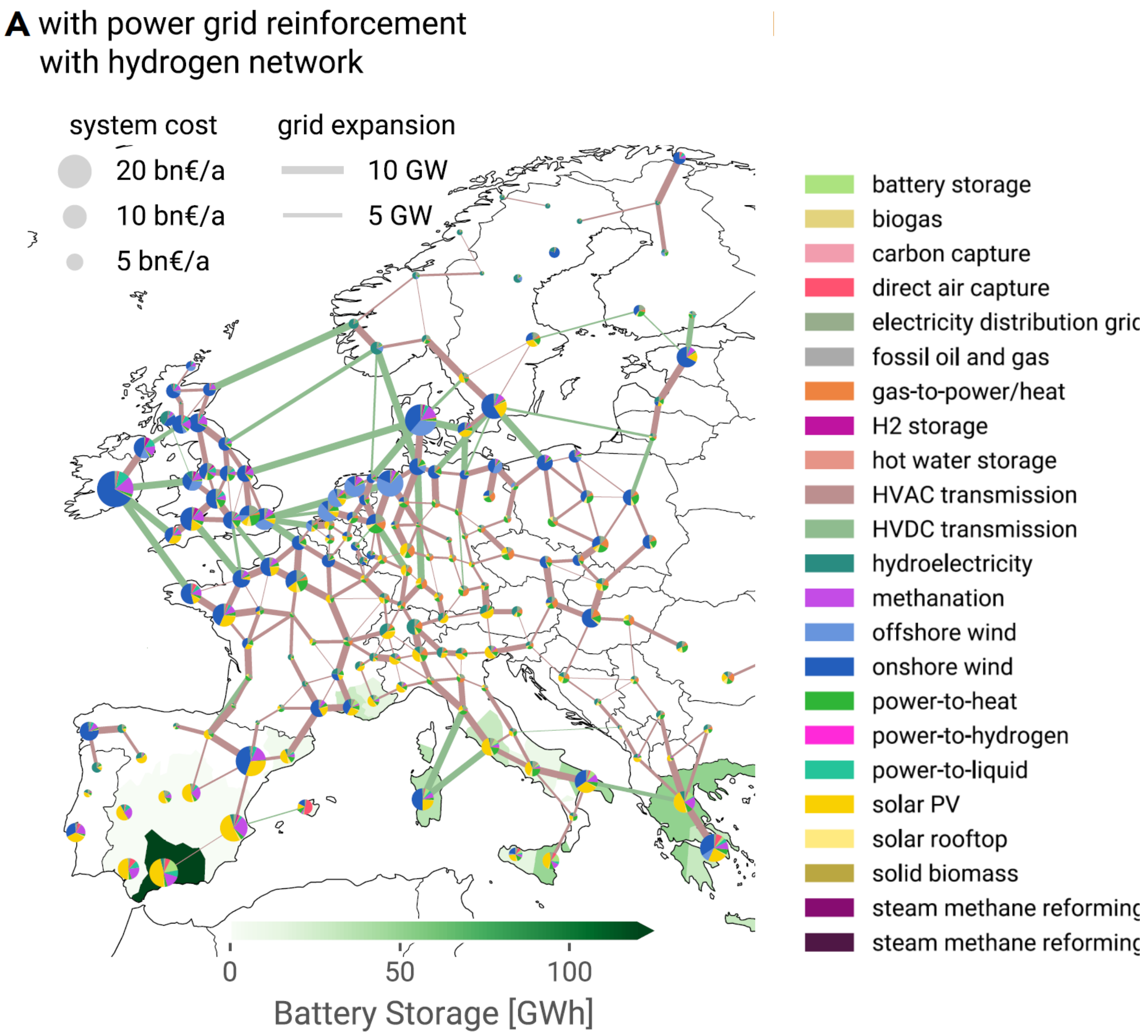
Industrial transformations:

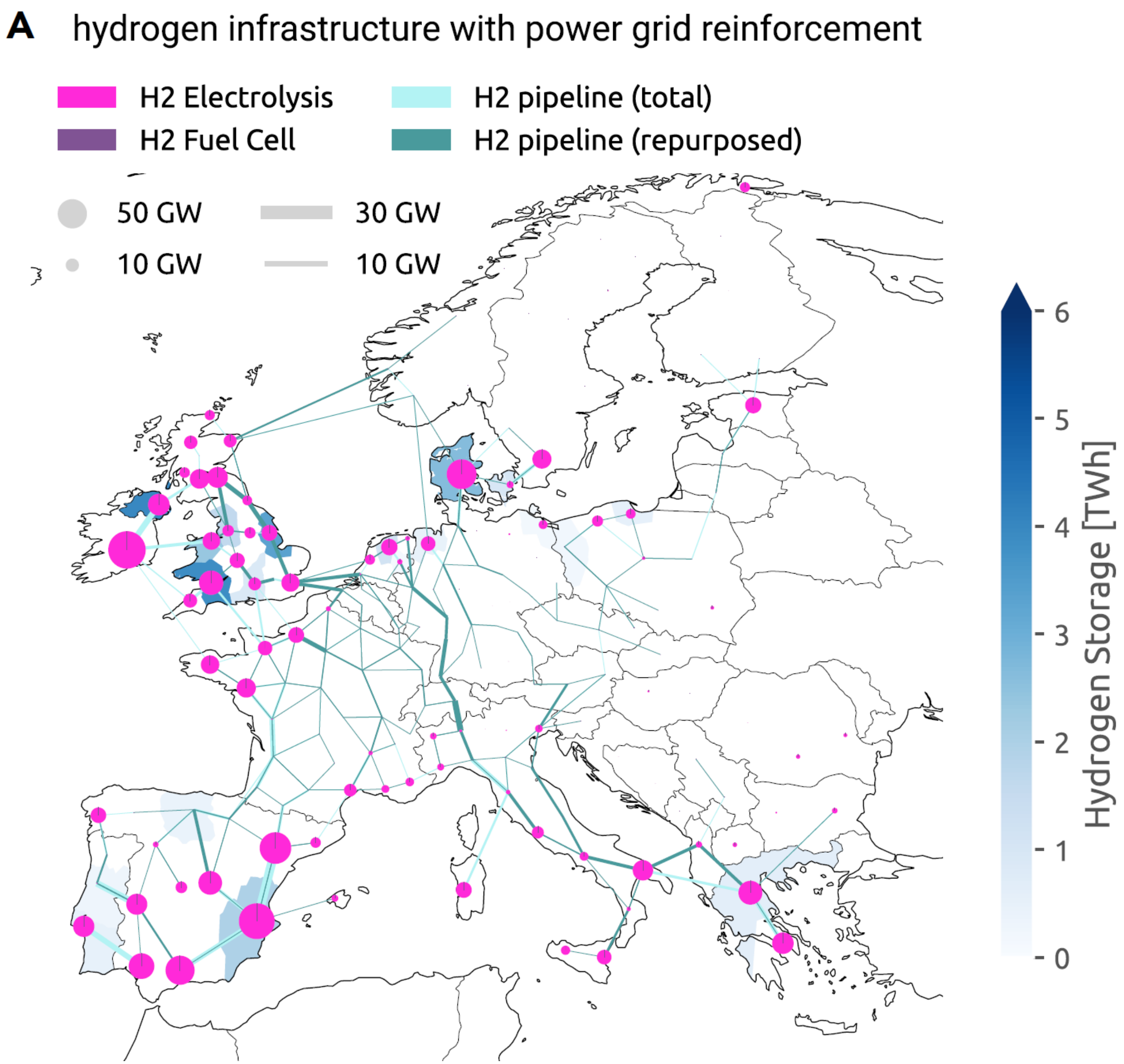
- Materials production remains constant in 2050
- Steel: 70% scrap + H2 from Direct Reduced Iron + EAF
- Aluminum: 80% recycled + methane for high-temperature heat
- Cement: solid biomass for high-temperature, capture process emissions
- Ammonia: H2
- Plastic: 55% recycling and synthetic naphtha
- Others: electrified when possible, methane and biomass for high-temperature heat



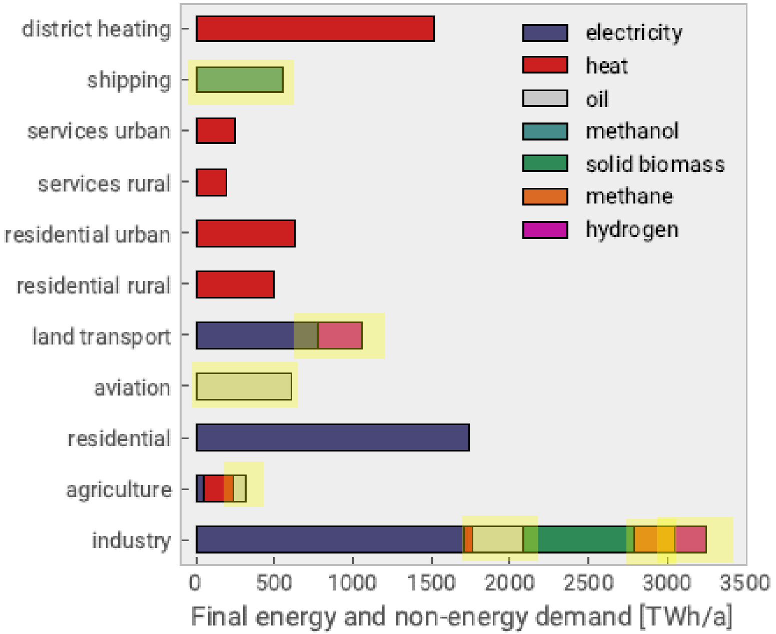


Results: Capacities layouts



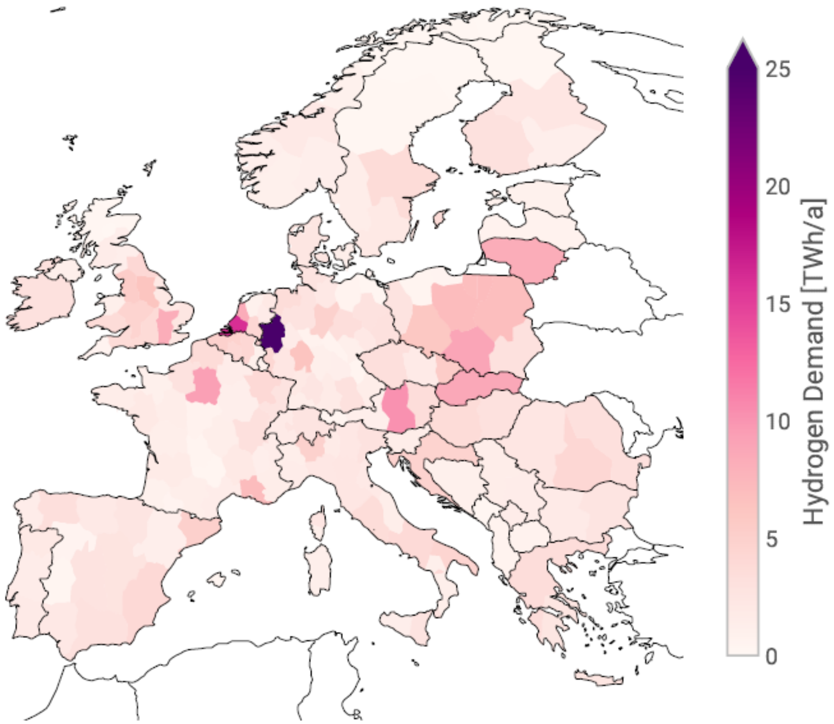


Results: H2 demand



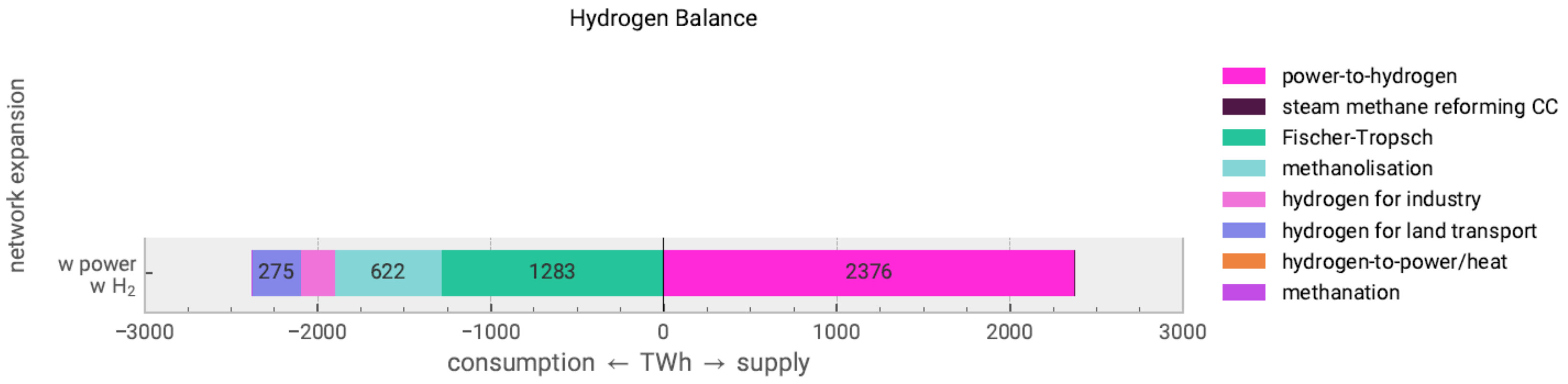
H2 demand:

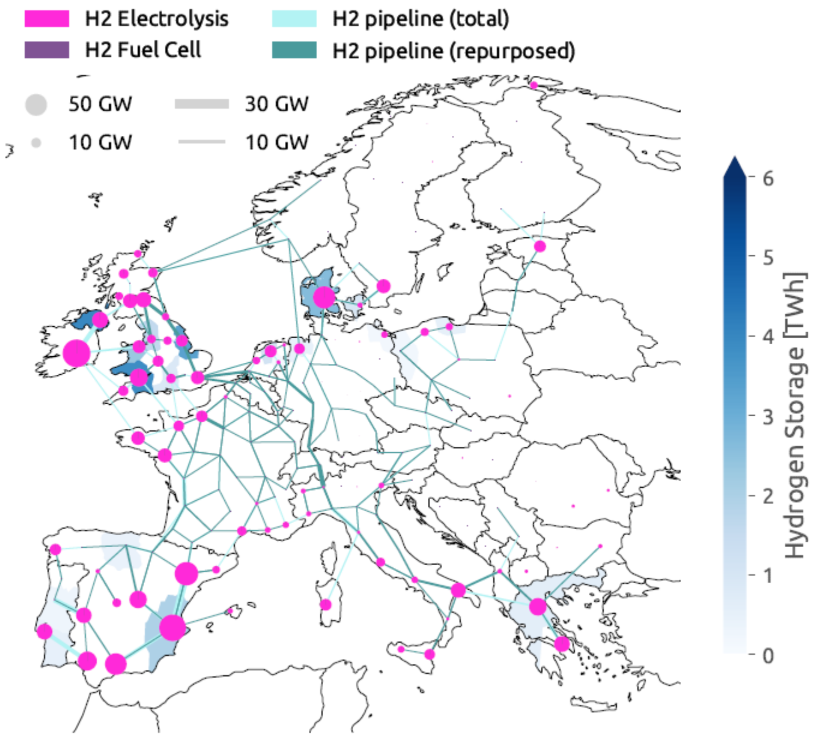
- Land-transport
- Industry
- To produce methanol
- To produce carbon-neutral liquid hydrocarbons
- To produce methane



Results: H2 production

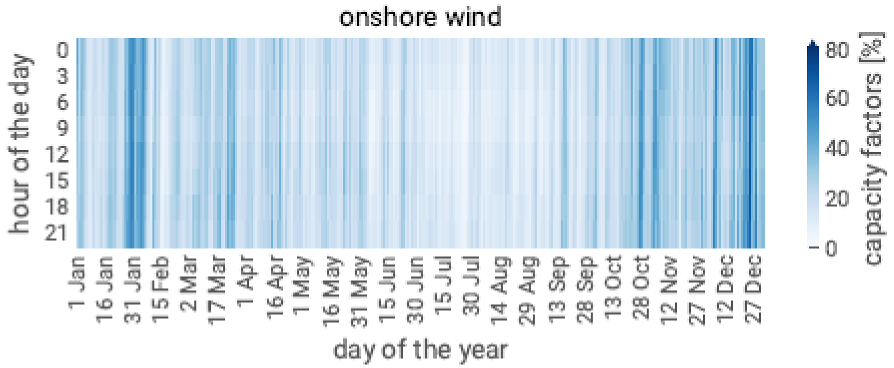
H2 produced electrolytically using wind and solar power

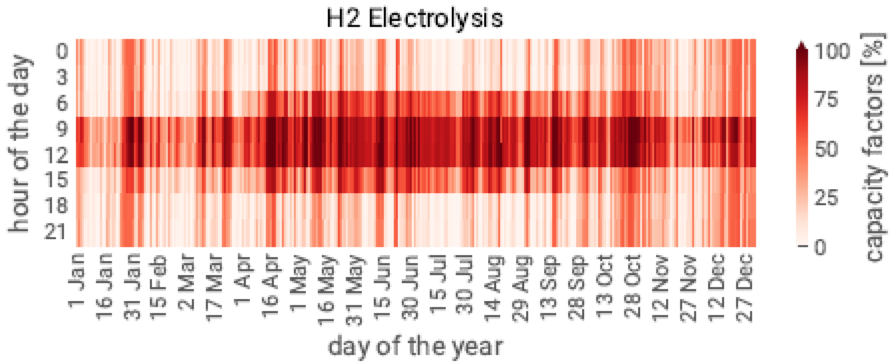


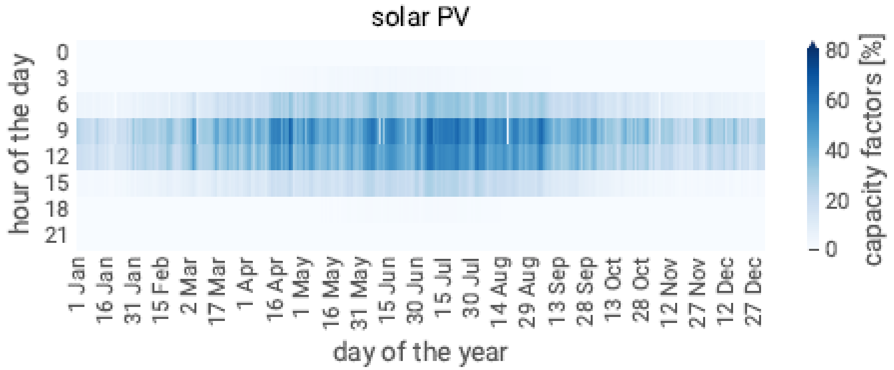


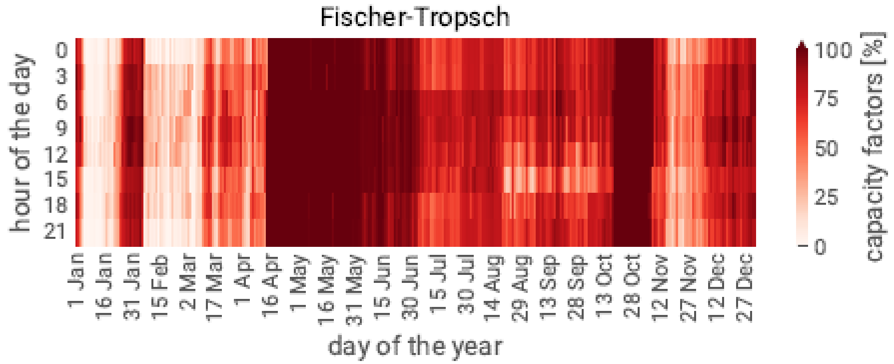
Results: H2 production

H2 smooths out variable renewable generation to other more stable power-to-X processes.



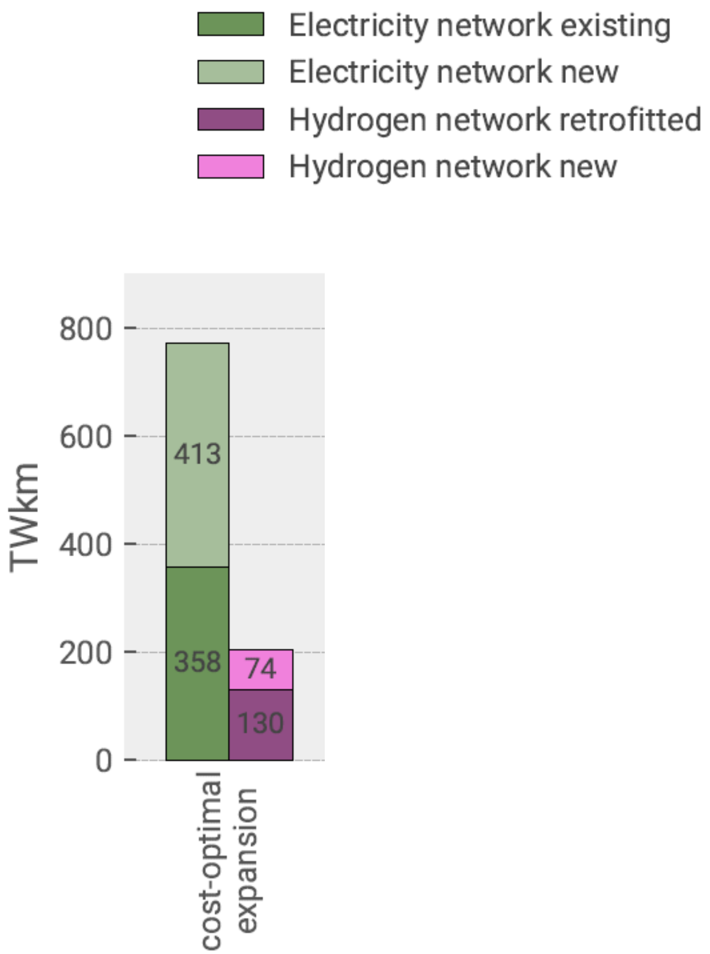




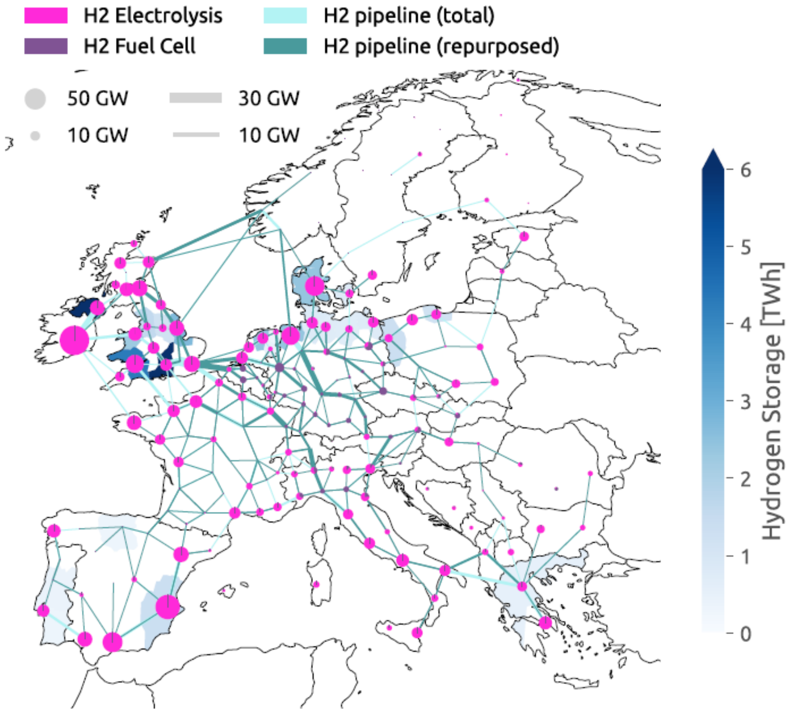


Results: H2 transport

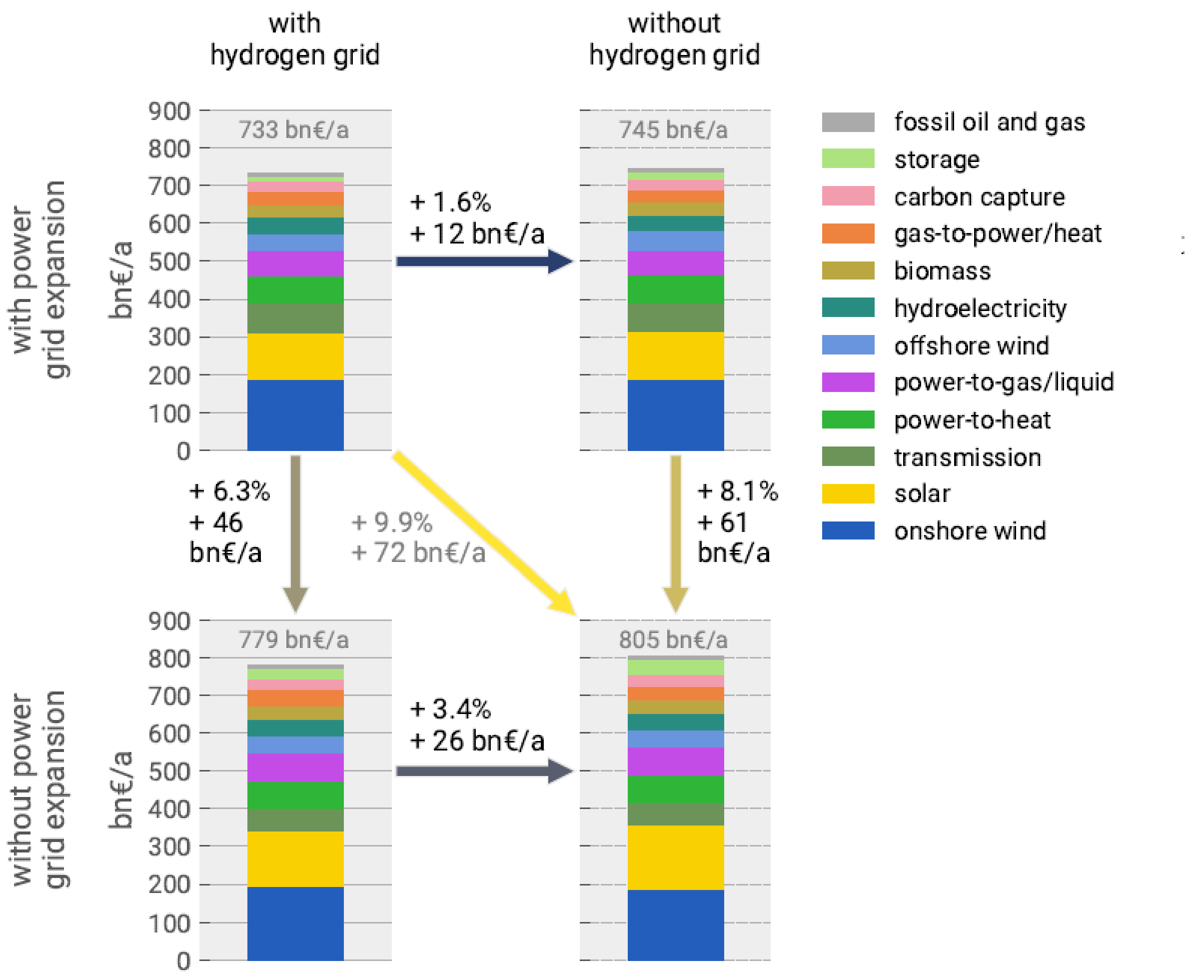
Electricity transmission grid duplicates its capacity, H2 network mostly repurposed from gas network



Results: Is a H2 grid cost-effective for Europe?



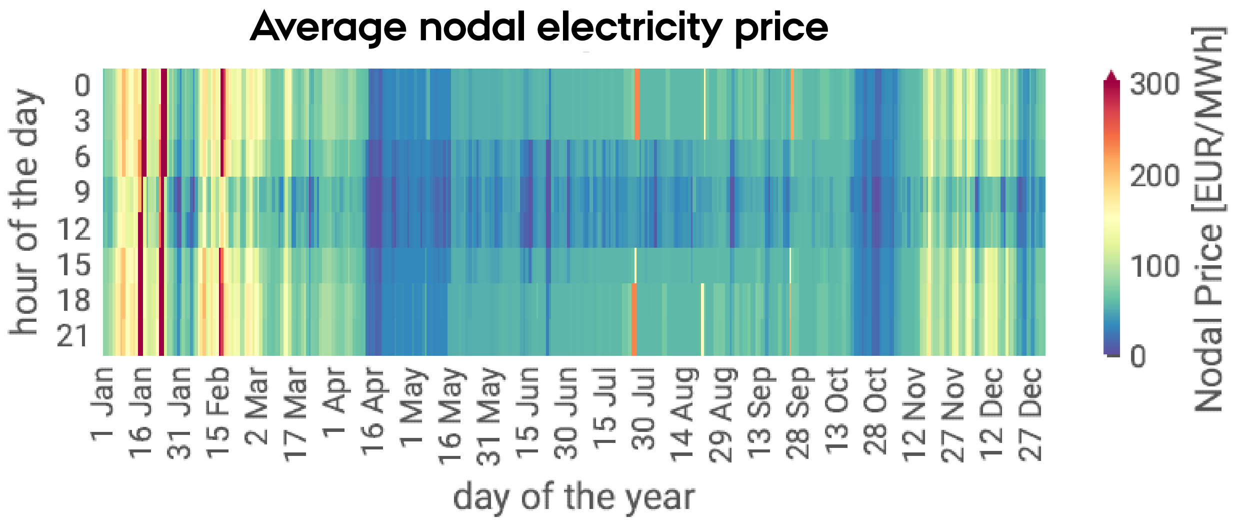
[Neuman, Zeyen, Victoria, Brown, Joule, 2023](#)
[Zeyen, Victoria, and Brown, Nature Commun. 2023](#)

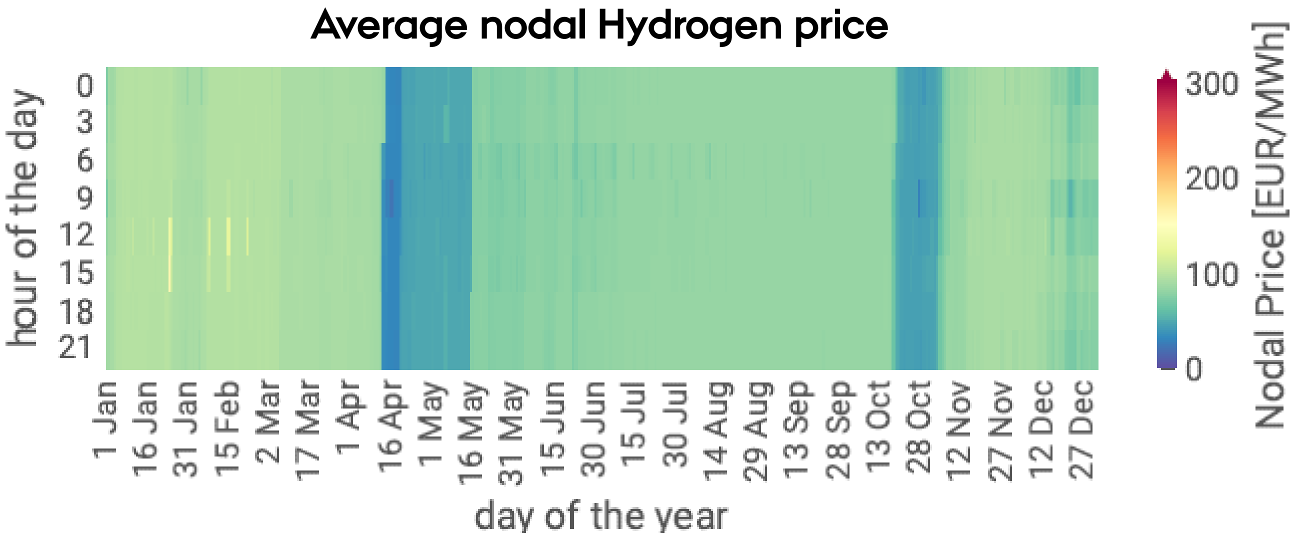


H2 and electricity transmission grid play complementary roles but:

- Not building H2 network increases system cost by 1.6%
- Not expanding electricity transmission grid increases cost by 6.3%

Electricity an H2 prices in a highly renewable system





Electrolytic H2:
90 EUR/MWh
(3 EUR/kg)

Summary

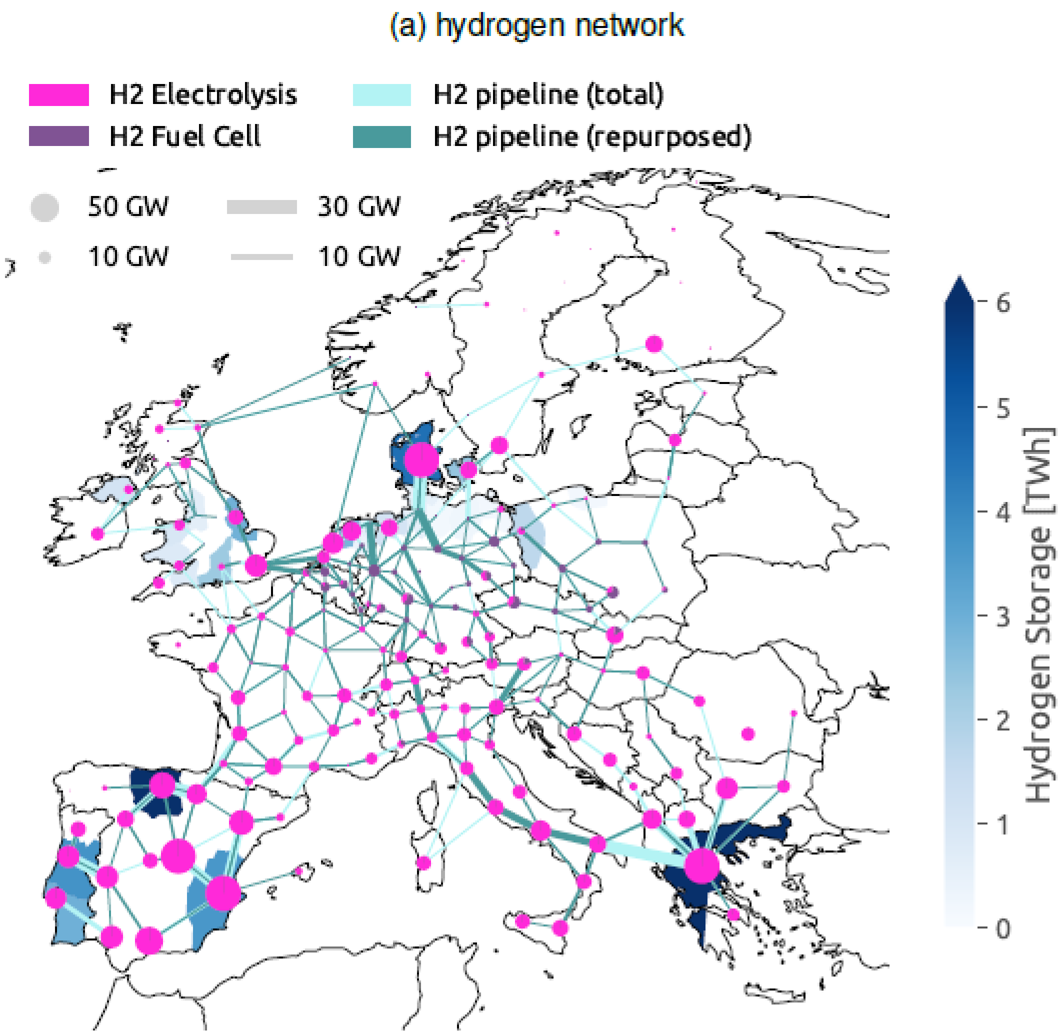
H2 demand: 2400 TWh/a for land-transport, Industry, to produce methanol, carbon-neutral liquid hydrocarbons, to produce methane

H2 production: electrolytic powered by wind and solar

H2 transport: building a H2 network from repurposed methane network helps but it is not indispensable

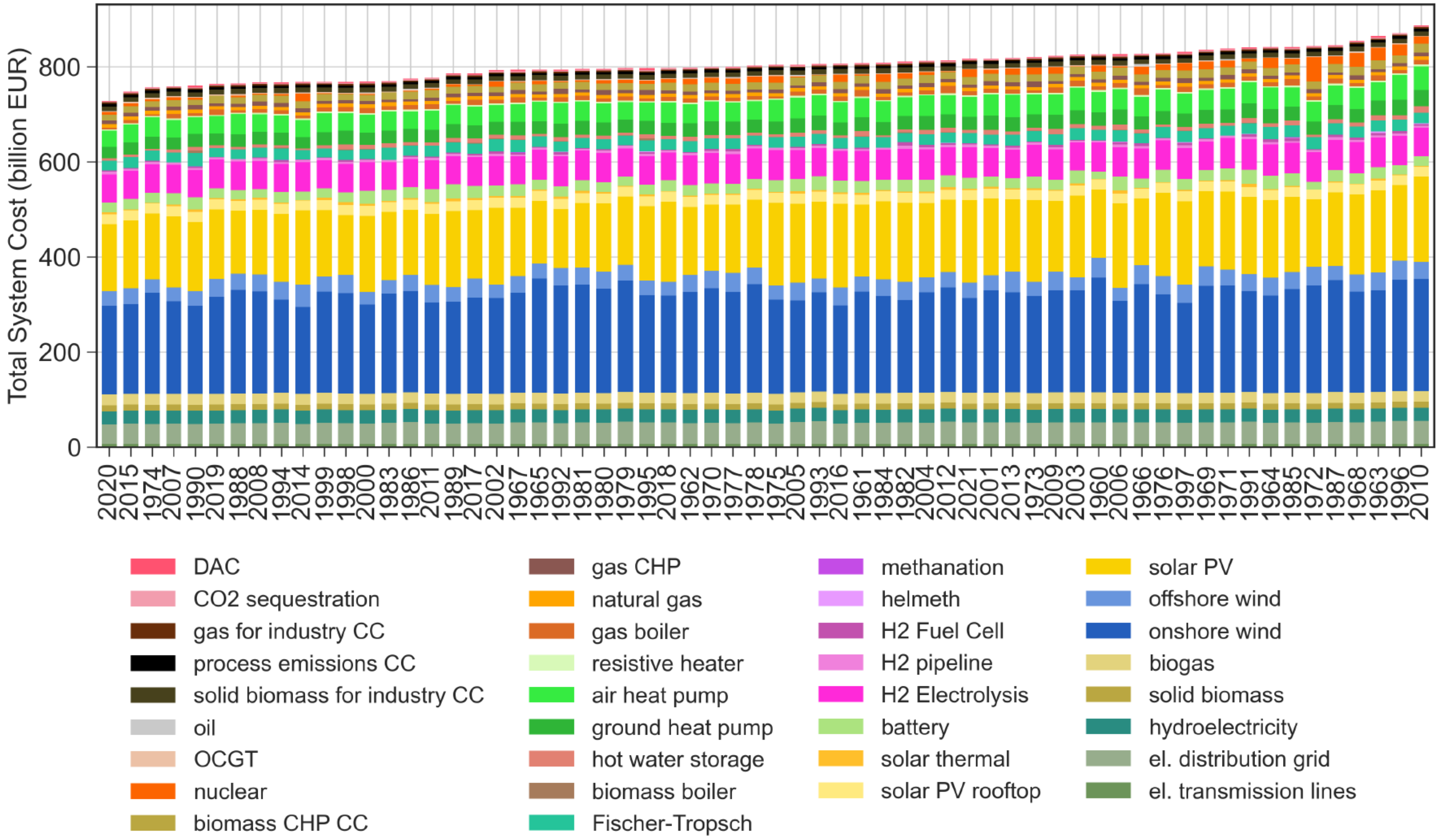
H2 cost: 90 EUR/MWh (3 EUR/kg), hourly fluctuations . H2 network reduces system cost by up to 3.4 %

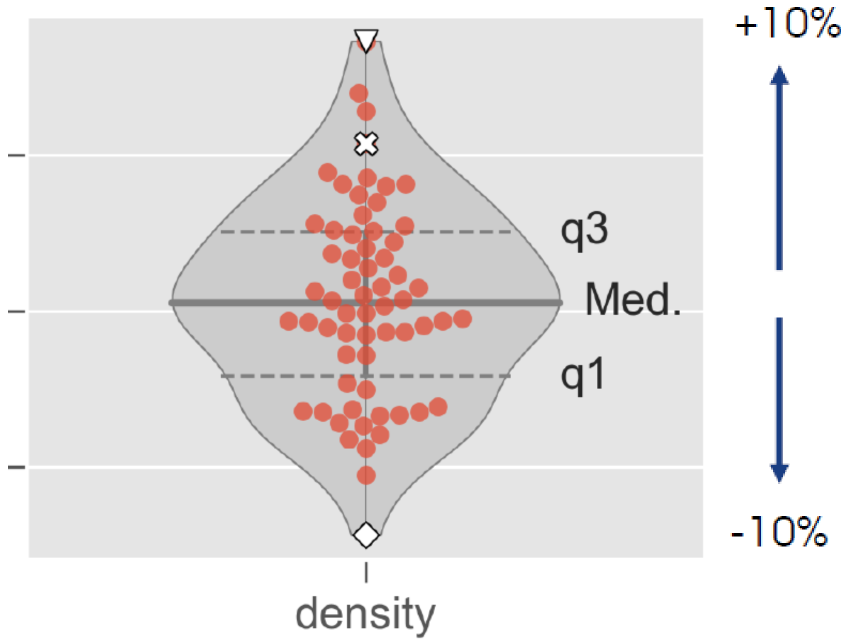
Scenario without onshore wind and power grid expansion



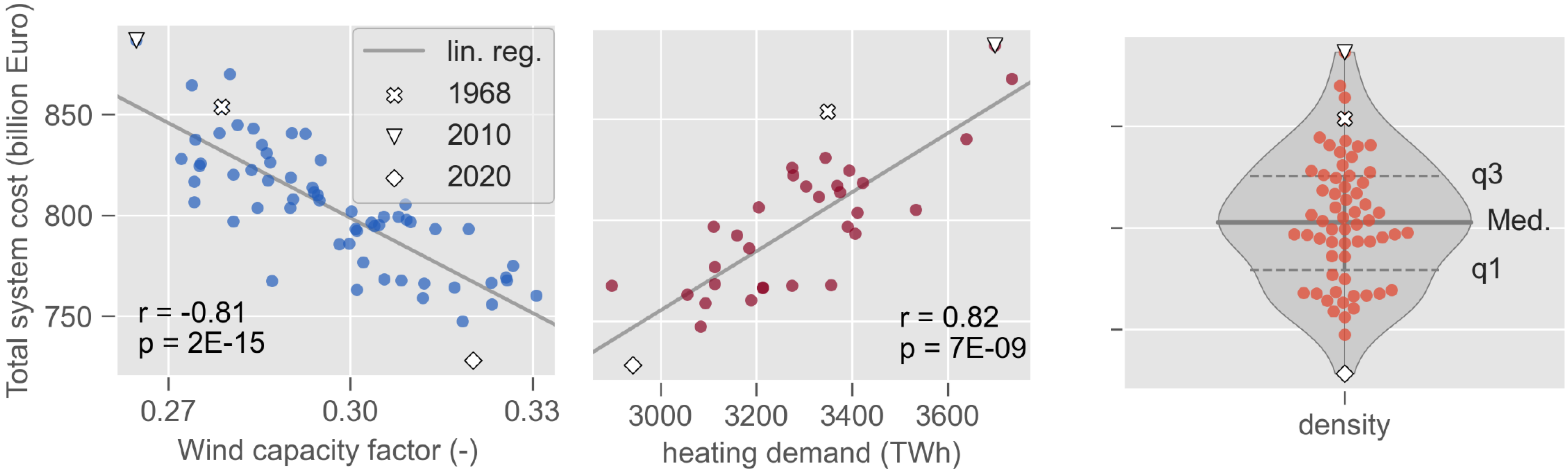
Research example 2:
Designing robust energy systems

Robust system design and extreme weather events

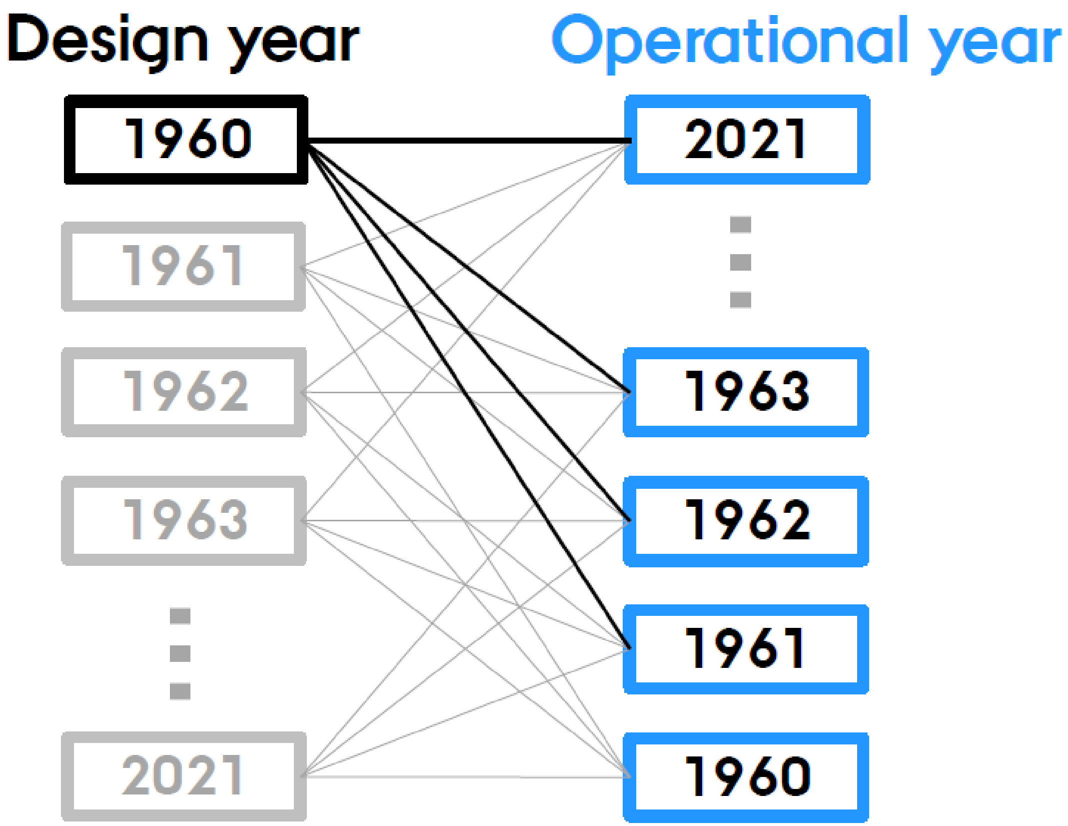




Robust system design and extreme weather events



Robust system design and extreme weather events

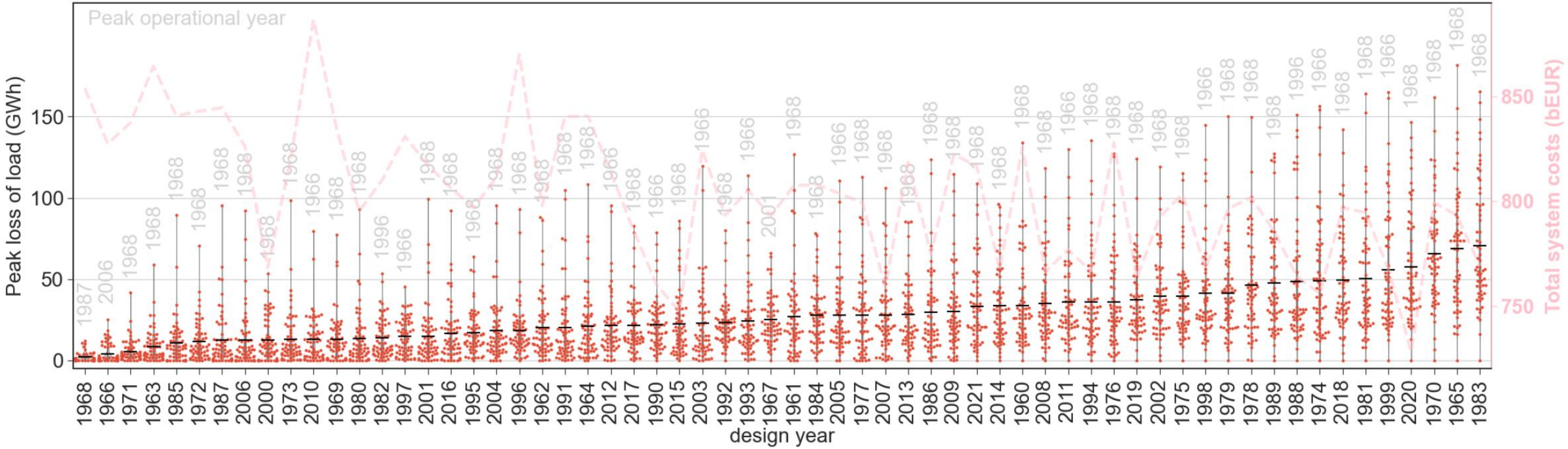


62 x 61 = 3,782 simulations

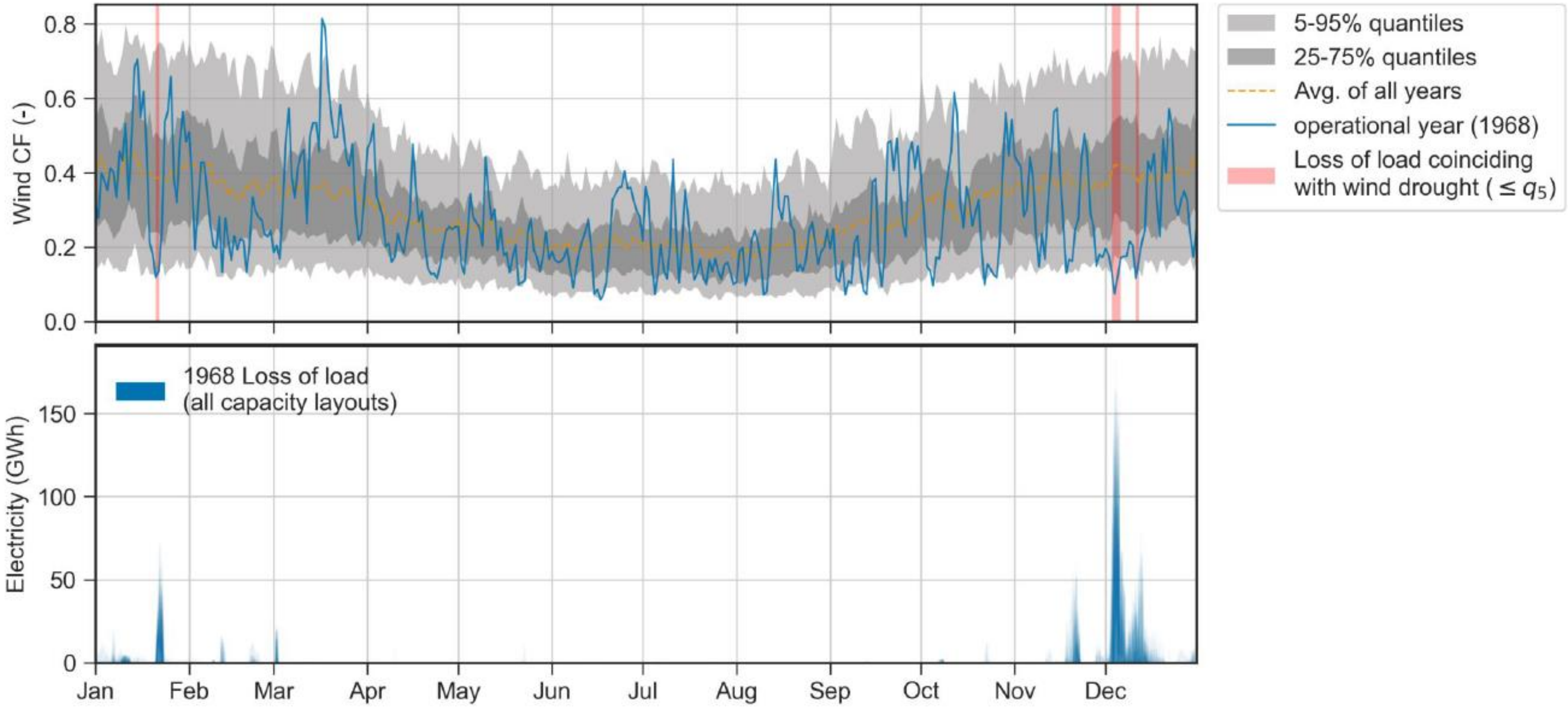
Load shedding (100,000 EUR/MWh) can be activated if needed

Gøtske, Andresen, Neumann, Victoria, ArXiv 2024

Robust system design and extreme weather events



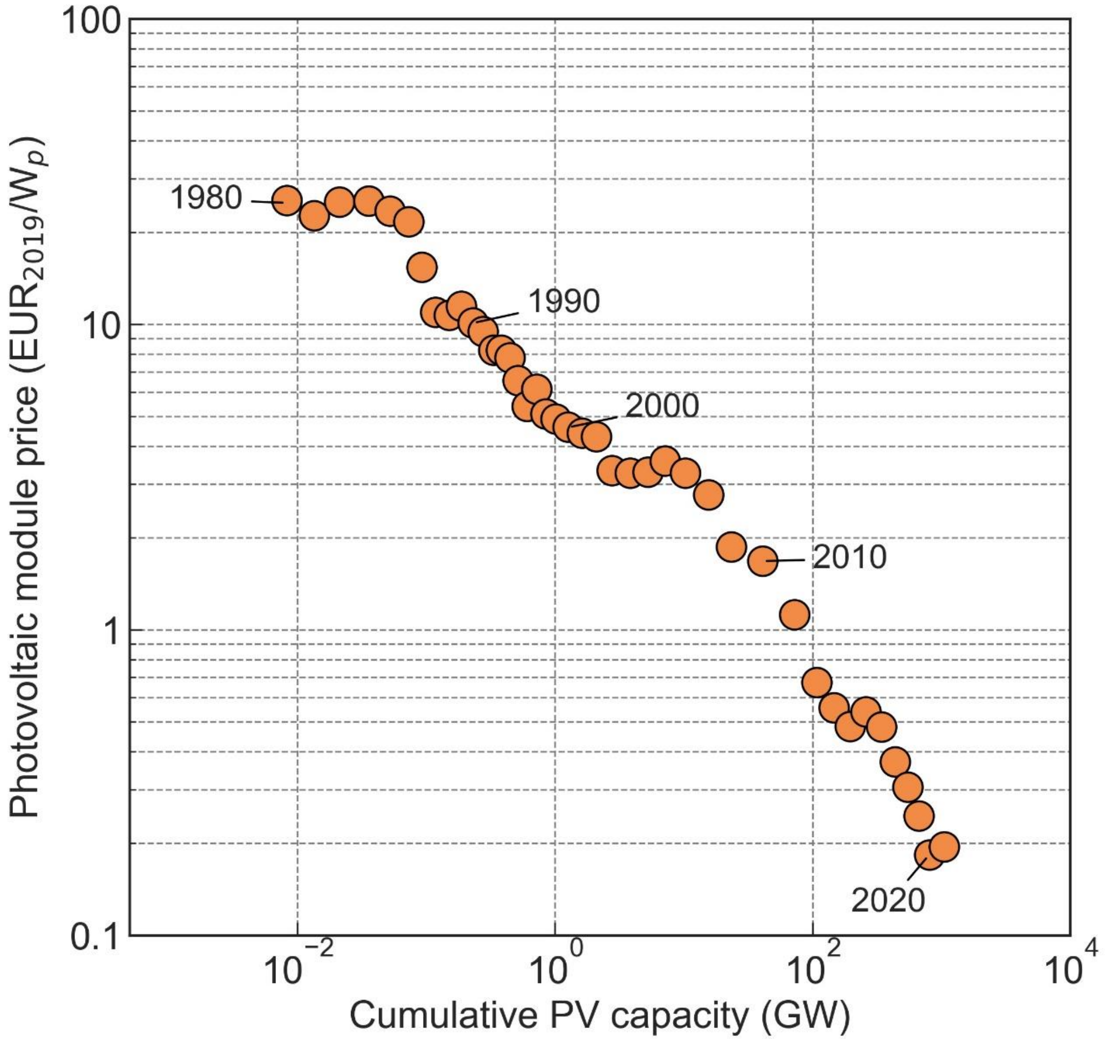
Robust system design and extreme weather events



Gøtske, Andresen, Neumann, Victoria, ArXiv 2024

Research example 3:
Technology learning

How did solar become so cheap so fast?



Learning by doing cost decreases as experience of production increases.

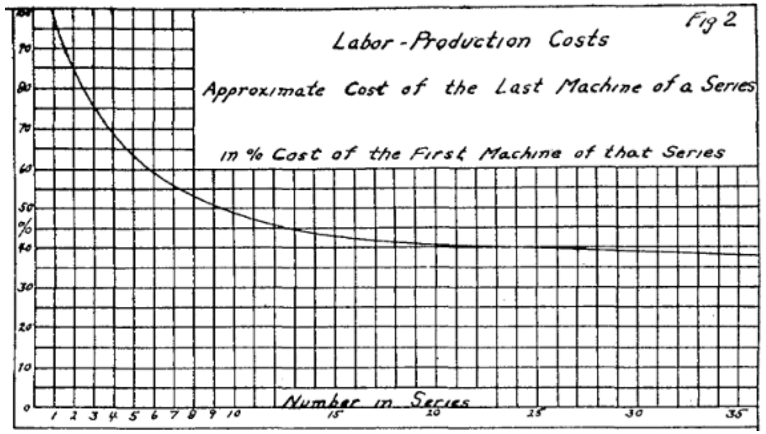
$$\frac{Cost_y}{Cost_{y_0}} = \left(\frac{Cumulative\ capacity_y}{Cumulative\ capacity_{y_0}}\right)^{-b}$$

Learning rate = relative price reduction every time cumulative capacity doubles

$$LR = 1 - 2^{-b}$$

PV module show LR=23% since1980

First-time observed in airplanes

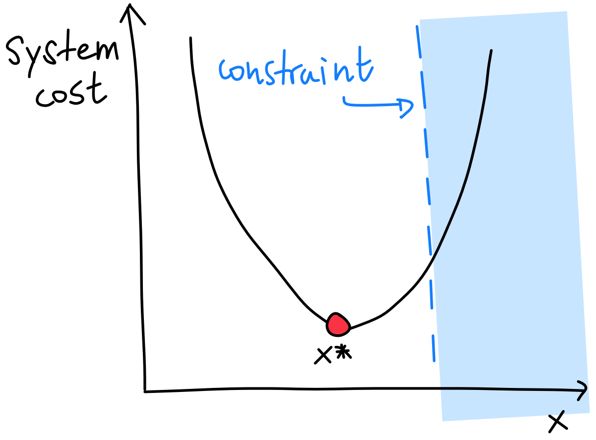


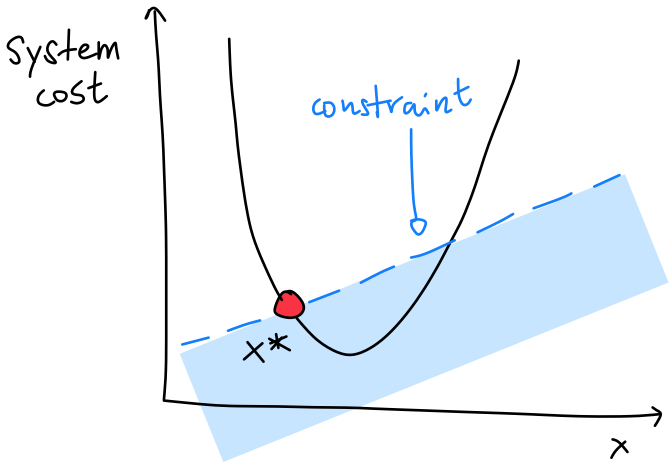
Wright , 1934

Technology learning make the problem non-linear

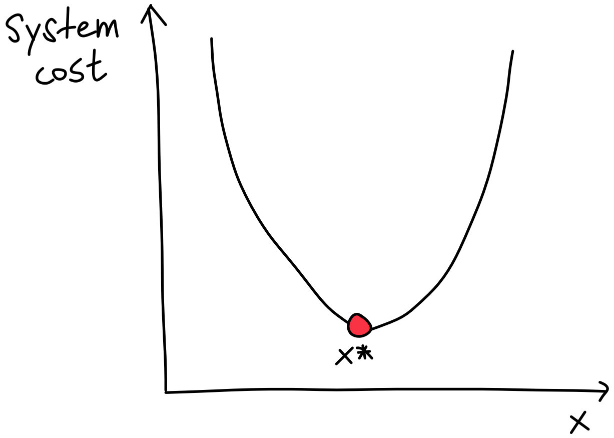
We look for cost-optimal system designs and define constraints to represent physical or societal limitations.

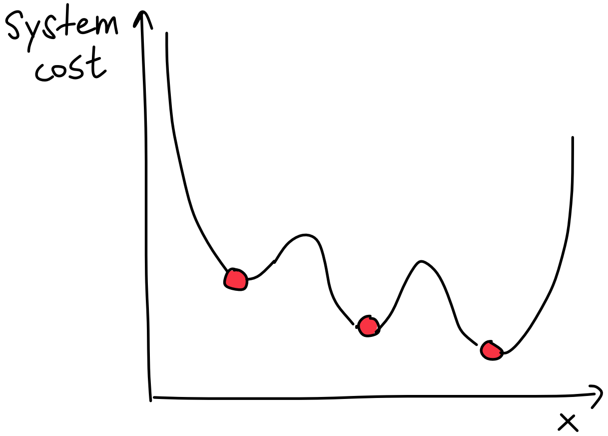
$$
\begin{cases}
\min \left(\sum_{n,s} \begin{matrix} generation \\ costs \end{matrix} + \begin{matrix} storage \\ costs \end{matrix} + \begin{matrix} transmission \\ costs \end{matrix} + \sum_{n,s,t} \begin{matrix} variable \\ costs \end{matrix} \right) \\
subject\ to: \\
\quad \sum_s generation_{s,t,n} + balance_{t,n} = demand_{t,n} \quad \leftrightarrow \quad \lambda_{t,n} \qquad \forall t,n \\
\quad \sum_{s,t} CO_2\ emissions \leq CO_2\ limit \quad \leftrightarrow \quad \mu_{CO2}
\end{cases}
$$





We keep to problem linear to ensure a unique solution.
Learning is not linear, including it in the model makes it non-linear, non-convex and multiple solution exist





Including learning in large-scale systems modelling

nature communications

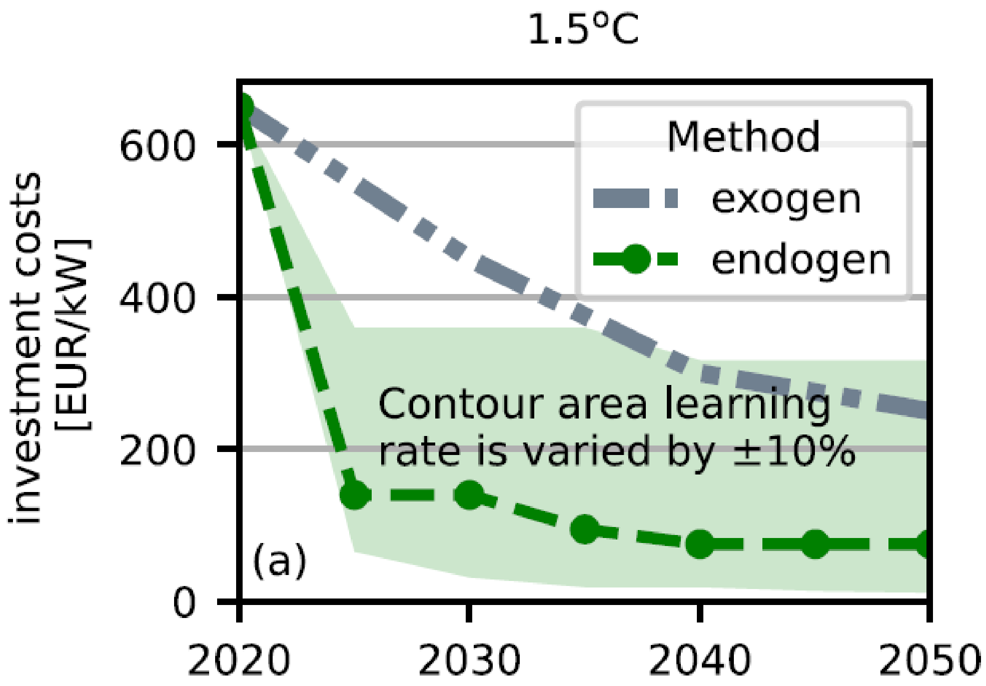
Article

https://doi.org/10.1038/s41467-023-39397-2

Endogenous learning for green hydrogen in a sector-coupled energy model for Europe

Technology	Global capa-city [GW]	European share [%]	Learning rate [%]
Solar PV	707[58]	22[58]	24[31]
Onshore wind	699[58]	26[58]	10[31]
Offshore wind	34[58]	73[58]	10[31]
Electrolysis	1[159]	Local learning	16[9]

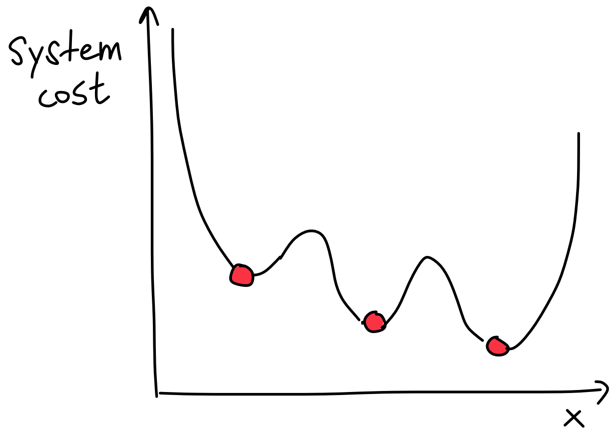
Zeyen, Victoria, and Brown, Nature Communications, 2023

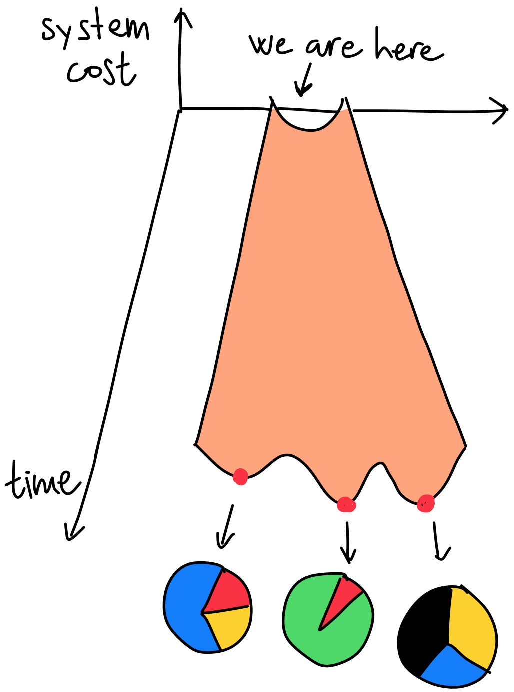


Electrolyzers deployment occurs earlier, and costs are reduced further if we consider endogenous learning

Including learning in large-scale systems modelling

We keep to problem linear to ensure a unique solution.
Learning is not linear, including it in the model makes it non-linear, non-convex and multiple solution exist





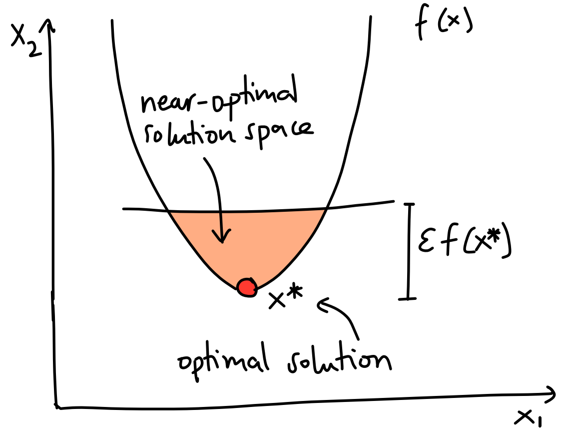
Grub, Planetary Economics, 2014

Research example 3:
Exploring near-optimal solutions

Modeling all alternative solutions for highly renewable energy systems

The optimal solution space is quite flat.

We can search the near-optimal solution space to find solutions slightly more expensive than the optimum, but which brings additional benefits (e.g. higher social acceptance).



Original problem

$$\begin{array}{ll} \text{minimize} & f(\mathbf{x}) = \mathbf{c}\cdot\mathbf{x} \\ \text{subject to} & \mathbf{Cx} \le \mathbf{d} \\ & \mathbf{Ax} = \mathbf{b}; \end{array}$$

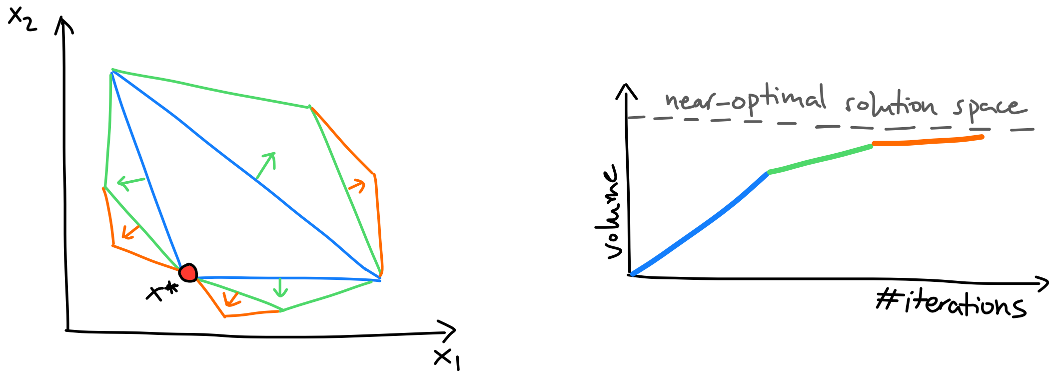
Modified problem

$$X = \{\mathbf{x} \mid \mathbf{Cx} \le \mathbf{d}\ ,\ \mathbf{Ax} = \mathbf{b}\}$$

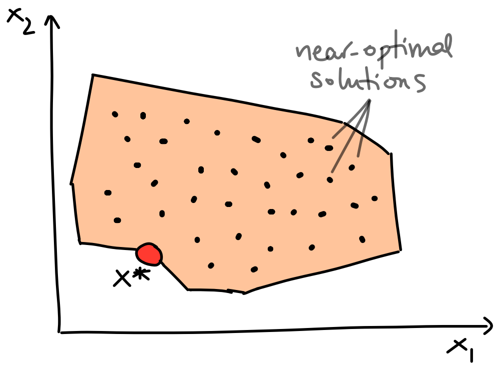
$$W = \{\mathbf{x} | \mathbf{x} \in X\ ,\ f(\mathbf{x}) \le f(\mathbf{x}^*)(1+\varepsilon)\}$$

We need methods to map the near-optimal solutions space (Modelling to Generate Alternatives)

Step 1. Exploring solution boundary



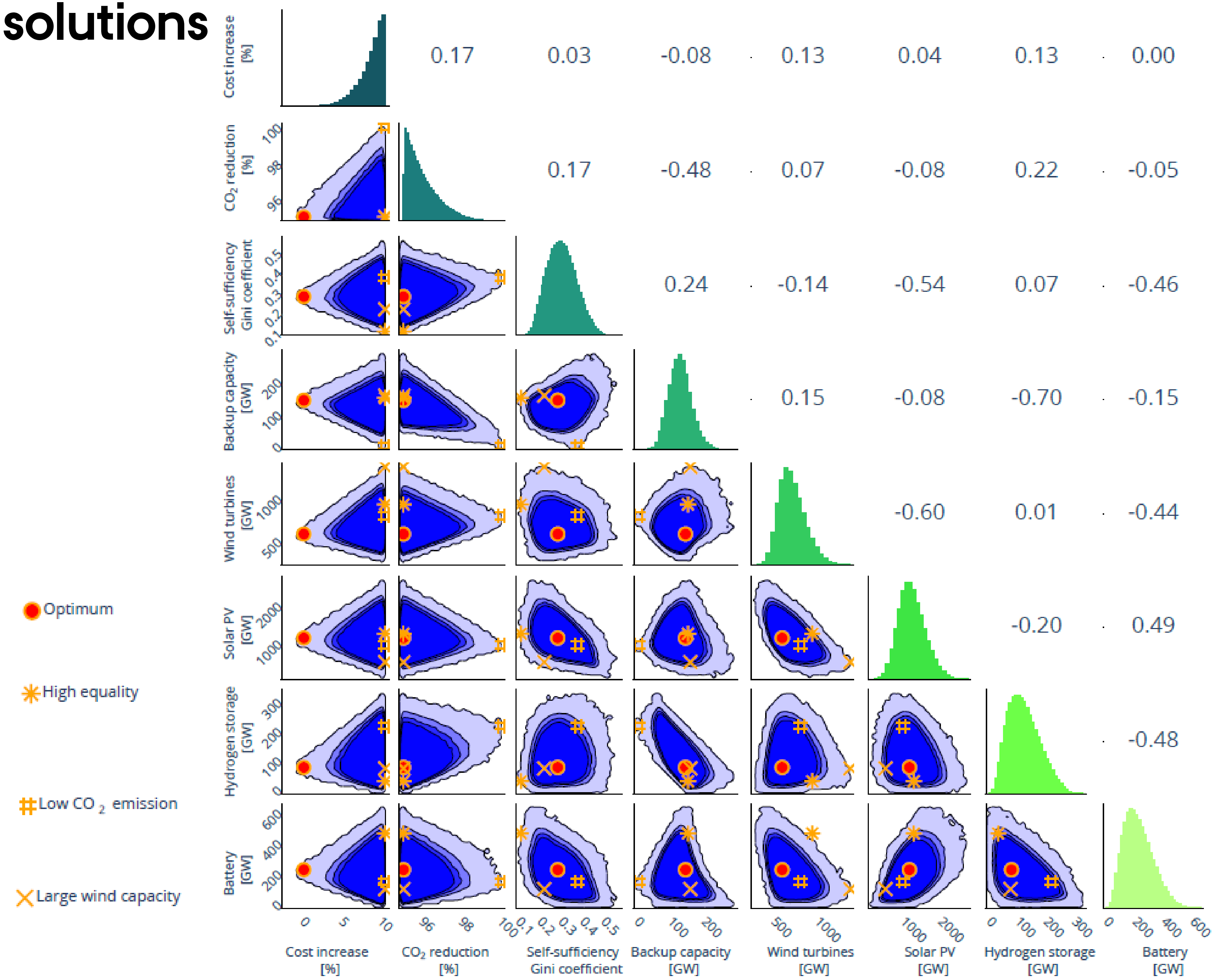
Step2. Population near-solution space



Pedersen, Victoria, Rasmussen, Andresen, Energy, 2021
Pedersen, Andersen, Victoria, and Andresen, iScience, 2023

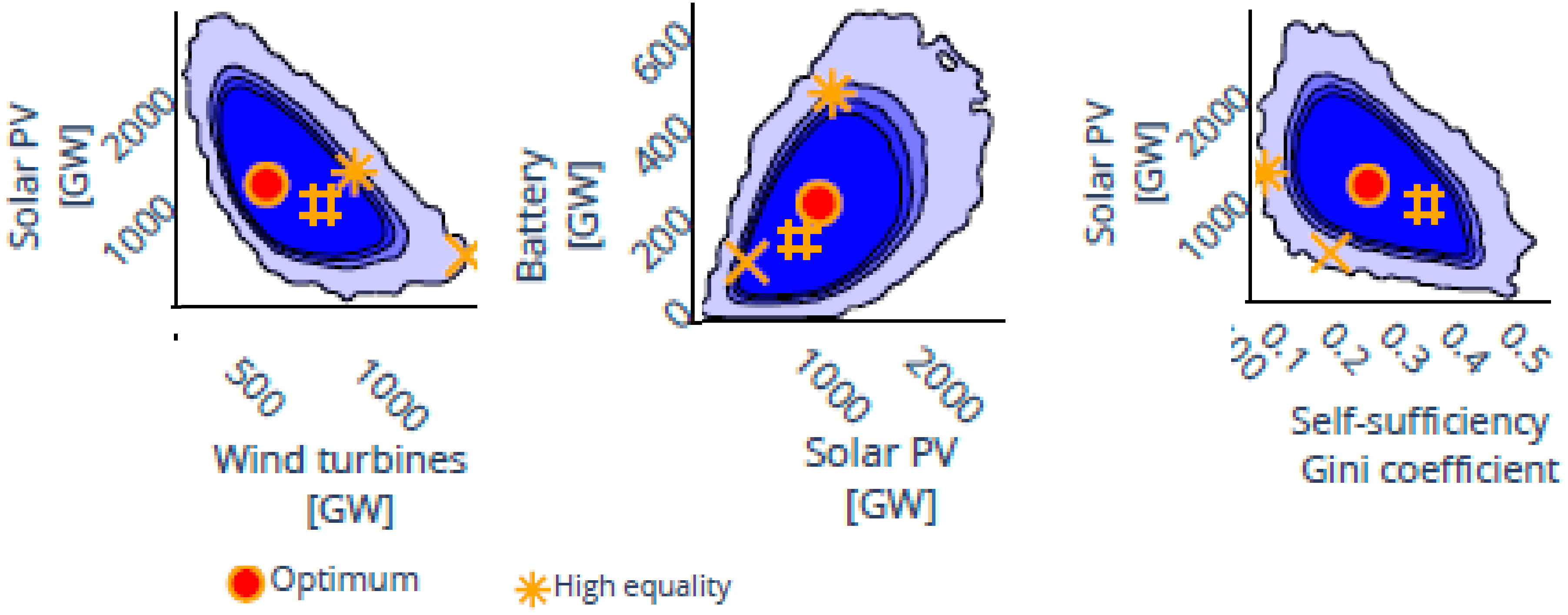
Modeling all alternative solutions

- 10% slack on system cost
- 95% reduction in emissions



Near-optimal solutions to increase social acceptance

Example: Optimal decarbonized European power system with 10% cost slack



Pedersen, Victoria, Rasmussen, Andresen, Energy, 2021
Pedersen, Andersen, Victoria, and Andresen, iScience, 2023

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EUDP

Ørsted

References

To keep learning:

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

Simple tutorial with one-node country model: https://github.com/martavp/MESM_project/blob/master/MESM_project.ipynb

Book Chapter 14 on Macro-Energy Systems Modelling: https://doi.org/10.1016/B978-0-323-96105-9.00014-8

Video explaining how the code structure of PyPSA-Eur: https://www.youtube.com/watch?v=ty47YU1_eeQ

Modelling renewable time series with atlite: https://github.com/PyPSA/atlite

Curated date on technologies costs and efficiencies: https://github.com/PyPSA/technology-data

Geolocated database with existing power plants in Europe: https://github.com/PyPSA/powerplantmatching

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