Can a hydrogen network replace electricity grid expansion in a carbon-neutral scenario for the European energy system?

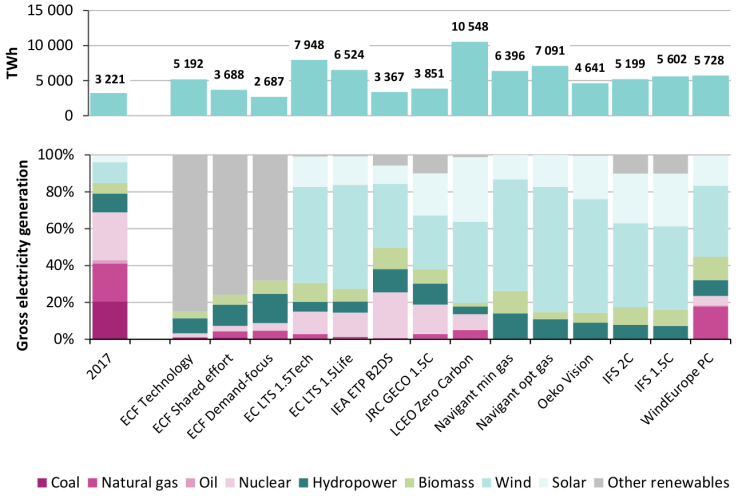
Fabian Neumann, Elisabeth Zeyen, Marta Victoria, Tom Brown

f.neumann@tu-berlin.de
Department of Digital Transformation in Energy Systems
Technical University of Berlin, Germany

IES Seminar, University of Edinburgh

April 26, 2022

2050 scenarios for Europe: power demand doubles, mostly met by VRE



Source: JRC, 2020,
https://ec.europa.eu/jrc/en/publication/towards-net-zero-emissions-eu-energy-system-2050

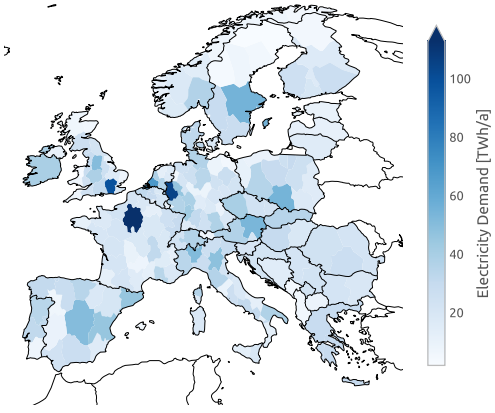
Technische Universität Berlin

Problem: collides with low acceptance for power grid and onshore wind

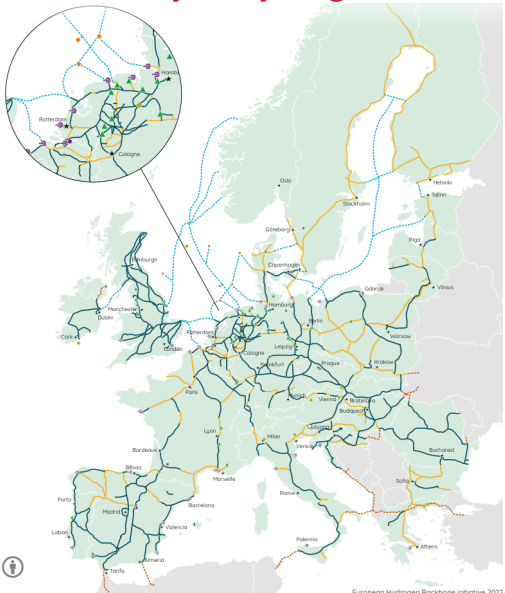
Technische Universität Berlin

Is offshore wind the answer?

Offshore wind can certainly help, but you still need to get the electricity to loads inland.



Can electrolytic hydrogen and a hydrogen pipeline network help?



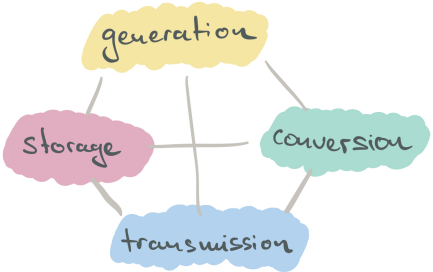
Can we substitute for power grid expansion by producing **electrolytic hydrogen** near high yield generation sites and transporting it through a new or repurposed **hydrogen pipeline network**?

Source: European Hydrogen Backbone (2022), https://gasforclimate2050.eu/wp-content/uploads/2022/04/EHB-A-European-hydrogen-infrastructure-vision-covering-28-countries-pdf

Modelling challenges: spatial resolution and sectoral co-optimisation

Challenge 1: Need spatial resolution to see grid bottlenecks & infrastructure trade-offs.
→ One node per country won't work.

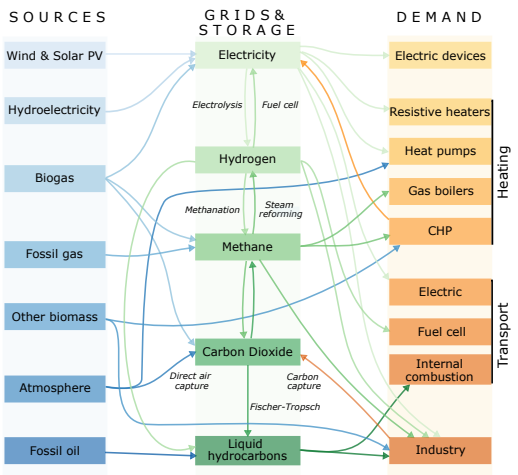
Challenge 2: Need to co-optimise balancing solutions with spatio-temporal variability.
→ Optimising separately won't work.



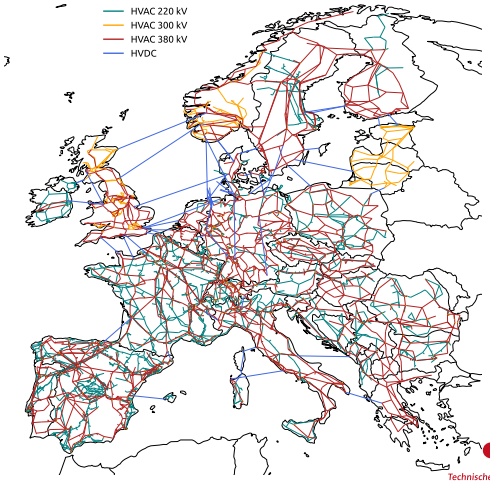
Need **very large** models, lots of data, and methods for complexity management.

What is PyPSA-Eur-Sec? - Open Sector-Coupled Model of Europe

Model for Europe with all energy flows...



and bottlenecks in energy networks.



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

Find **most cost-effective** combination of generation, converison, storage and transmission:

$$\textbf{Min}\left[\begin{array}{c}\textbf{Yearly}\\ \textbf{system costs}\end{array}\right] = \textbf{Min}\left[\sum_{r}\left(\begin{array}{c}\textbf{Annualised}\\ \textbf{capital costs}\end{array}\right)+\sum_{r,t}\left(\begin{array}{c}\textbf{Operating}\\ \textbf{costs}\end{array}\right)\right]$$

subject to

- meeting energy demand in each region r and time t for each carrier
- transmission constraints between regions and (linearised) power flow
- wind, solar, hydro availability time series $\forall\, r, t$
- geographical potentials for renewables
- emission reduction targets

In short: **mostly-greenfield** investment optimisation, multi-period (storage) with LPF.

Optimise transmission, generation, conversion and storage **jointly** $\rightarrow$ strongly interacting.

Source: See also https://pypsa.readthedocs.io/en/latest/optimal_power_flow.html

Technology Choices: Exogenous versus Endogenous

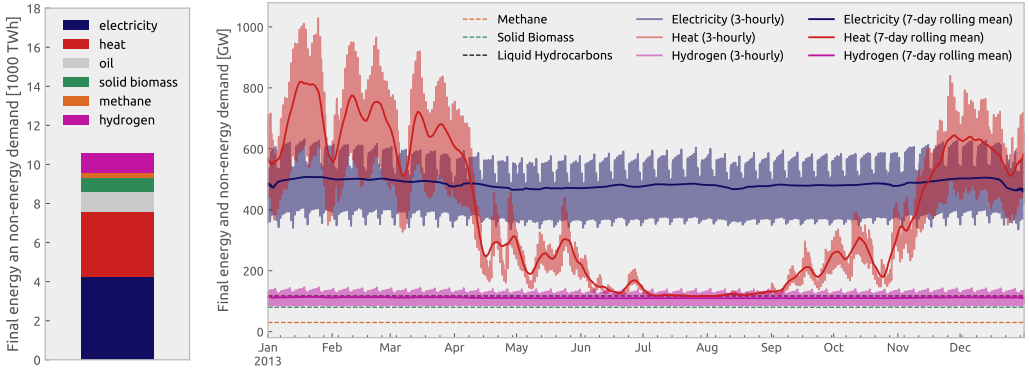
Exogenous assumptions (modeller chooses):

- energy services demand
- electricity for road transport
- kerosene for aviation
- hydrogen for shipping
- steel production in 2050: H_2-DRI + EAF
- electrification & recycling in industry
- district heating shares

Endogenous assumptions (model optimises):

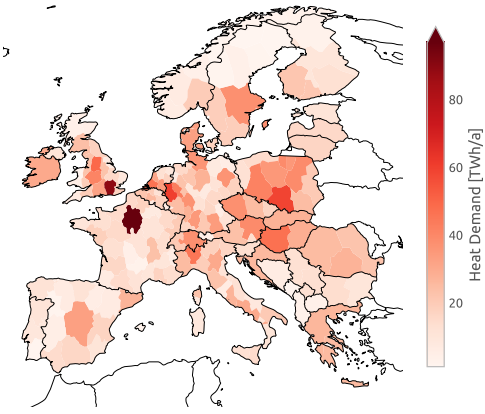
- electricity generation fleet
- transmission reinforcement
- space and water heating technologies
- all P2X infrastructure
- V2G and other demand-side management
- supply of process heat for industry
- carbon capture

Heat demand is strongly seasonally peaked! Need seasonal storage.



There are difficult periods in winter with **low** wind and solar, **high** space heating demand **low** air temperatures, which are bad for air-sourced heat pump performance

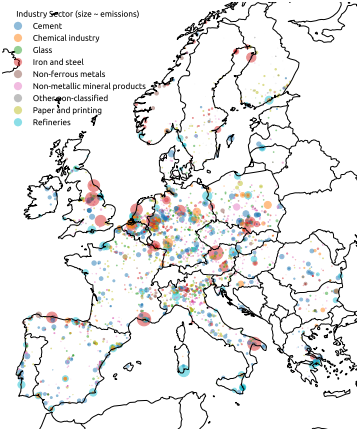
Heating Sector: Individual and District Heating



Various heat supply options are **co-optimised** depending on whether rural or urban region:

- ground-/air-sourced heat pumps
- district heating networks
- combined-heat-and-power (CHP)
- long-term thermal energy storage
- building retrofitting
- gas boilers
- solar thermal
- resistive heating

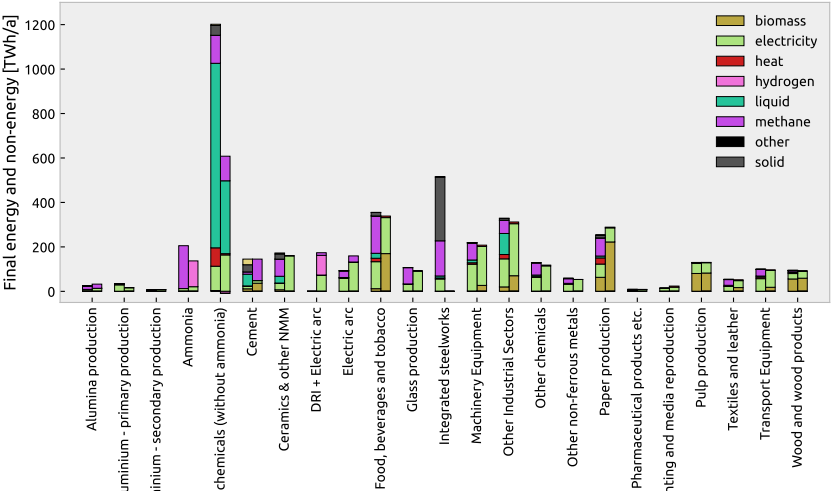
Industry Decarbonisation: Process and Fuel Switching



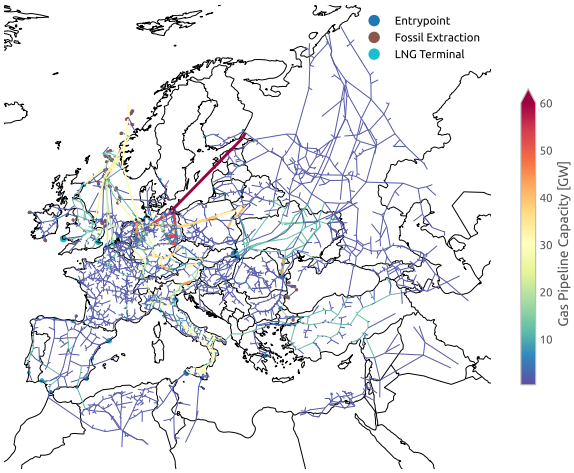
Iron & Steel	70% from scrap, rest from H_2-DRI + EAF
Aluminium	80% recycling; methane for high-enthalpy heat
Cement	Solid biomass; capture of CO_2 emissions
Ceramics	Electrification
Ammonia	Clean hydrogen
Plastics	55% recycling and synthetic naphtha
Other industry	Electrification; process heat from biomass
Shipping	Liquid hydrogen
Aviation	Kerosene from Fischer-Tropsch

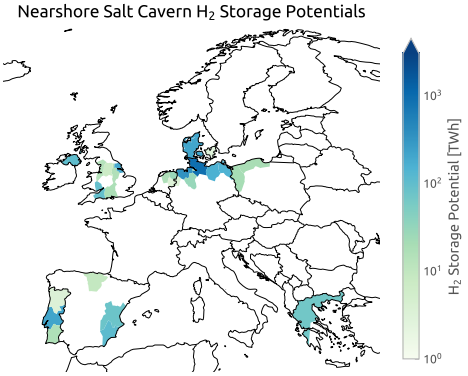
Carbon is tracked through system: up to 90% of industrial emissions can be captured; direct air capture (DAC); yearly sequestration limited to 200 $MtCO_2/a$

Overview of Industry Transformation by Industry Subsector



Gas network with H_2 retrofitting option and cavern storage potentials



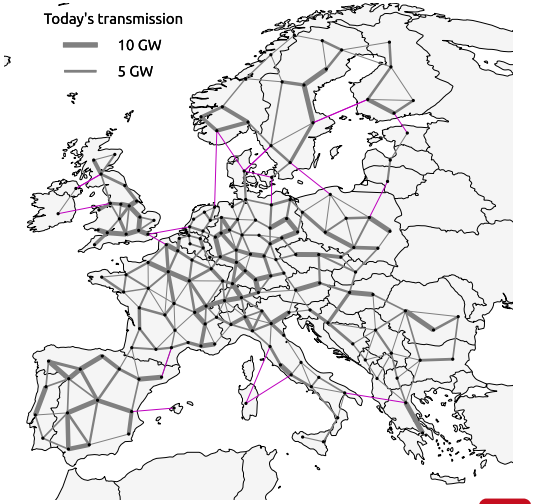


Technische Universität Berlin

Results from a 181-node model of European energy system

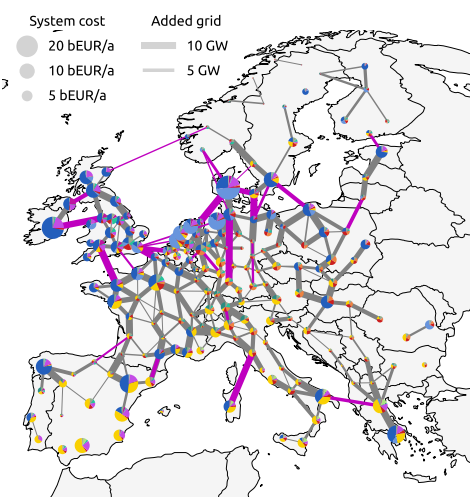
Model set-up:

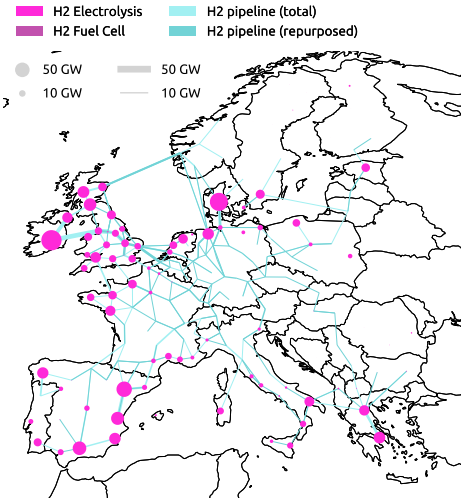
- Couple **all energy sectors** (power, heat, transport, industry)
- Reduce net CO_2 emissions **to zero**
- **Conservative** technology assumptions (for 2030 from Danish Energy Agency)
- Europe is energy **self-sufficient**
- **Carbon sequestration** limited to 200 $MtCO_2/a$
- Results in large LP **optimisation problem**



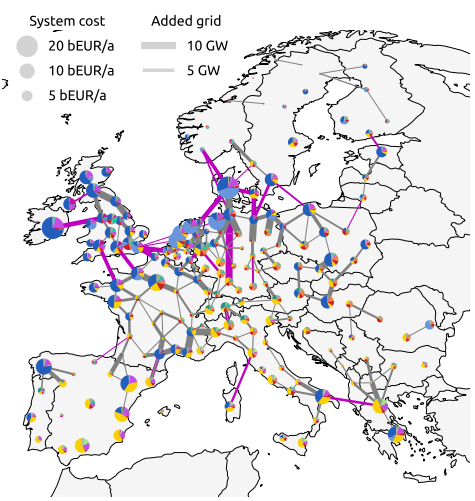
Technische Universität Berlin

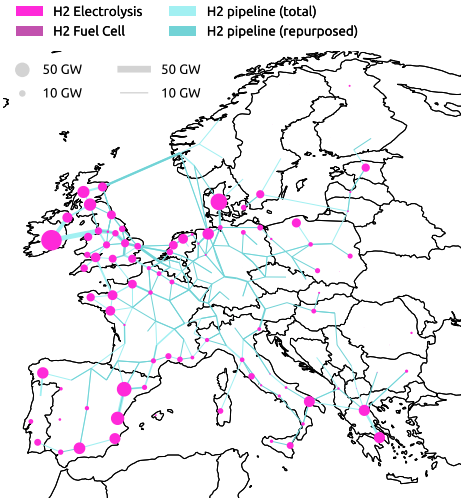
Distribution of technologies: doubled power grid volume



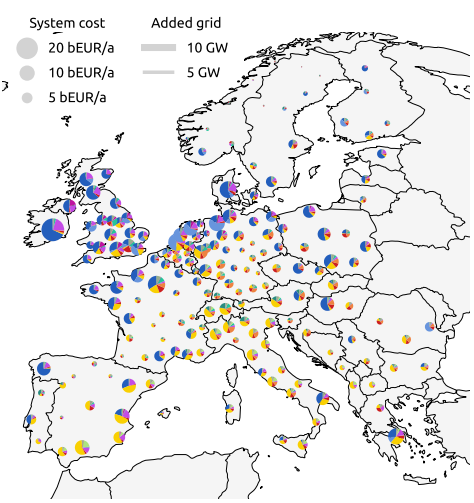


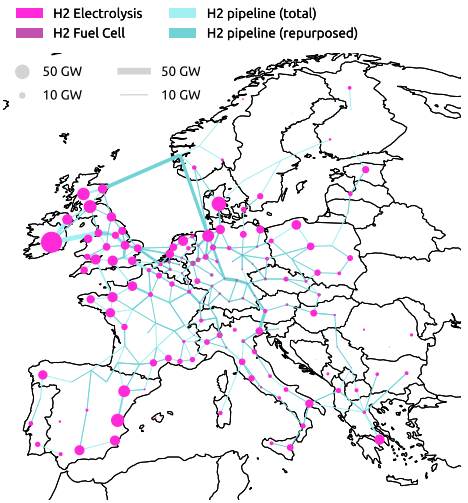
Distribution of technologies: 50% more power grid volume



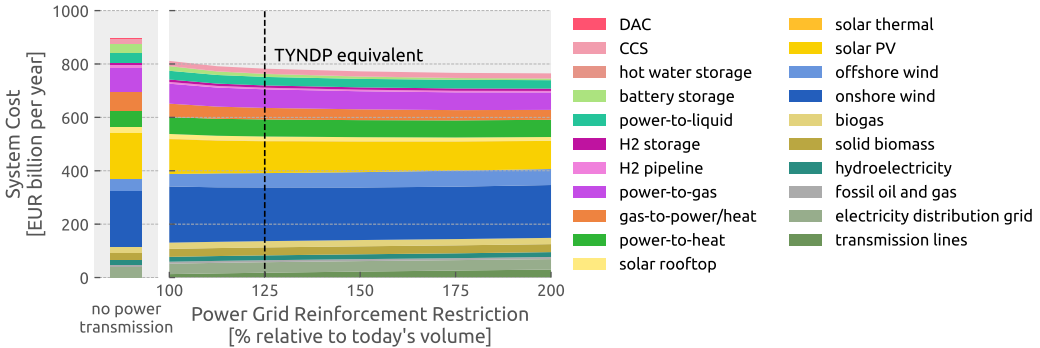


Distribution of technologies: no power grid expansion



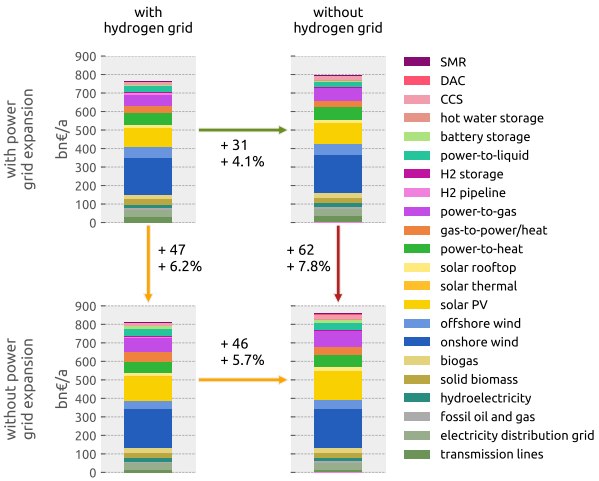


Benefit of power grid expansion for sector-coupled system



- Systems **without grid expansion** are feasible, but more costly
- Total cost benefit of extra grid: $\approx$ €47 billion per year ($\leq$5%)
- Over half of the benefit available at 25% grid expansion (like TYNDP)

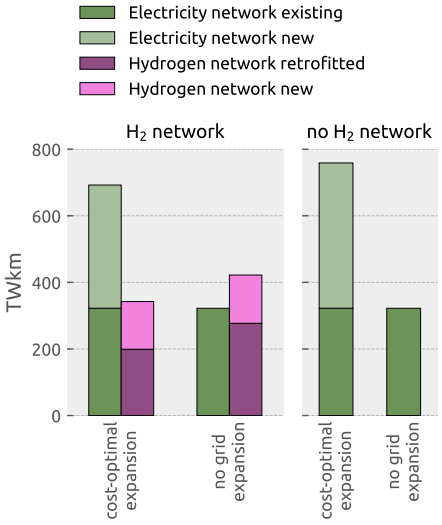
Benefit of hydrogen network infrastructure



- **Cost** of hydrogen network: €6-8 billion per year
- **Net benefit** is much higher: €31-46 billion per year
- Benefit is strongest when there is no power grid expansion
- Both are important for costs, but **power grid expansion brings more benefit**
- hydrogen network can **partially substitute** transmission expansion

Technische Universität Berlin

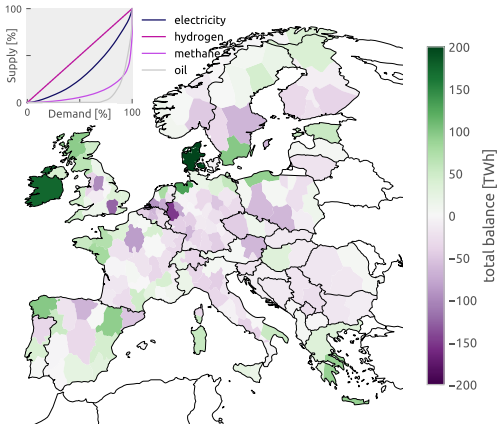
Electricity and hydrogen grid expansion and level of retrofitting



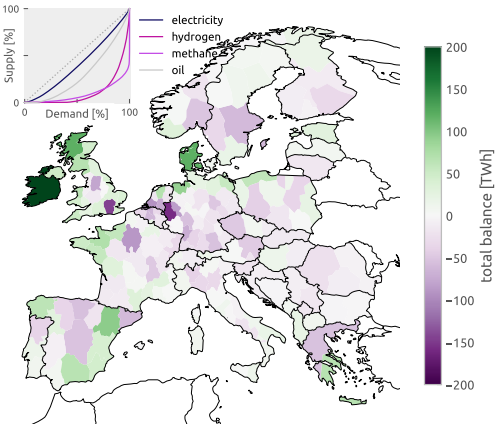
- Optimal hydrogen grid capacity rises as grid expansion is restricted
- Hydrogen grid is not a perfect substitute
- Around two-thirds of hydrogen grid can re-purpose existing methane network
- If grid expansion is forbidden, hydrogen grid transmits 3x more energy than electricity grid

Both cases: strong regional imbalance between generation and demand

only power grid expansion

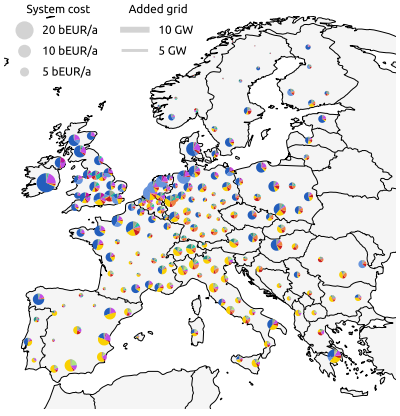


only hydrogen network expansion

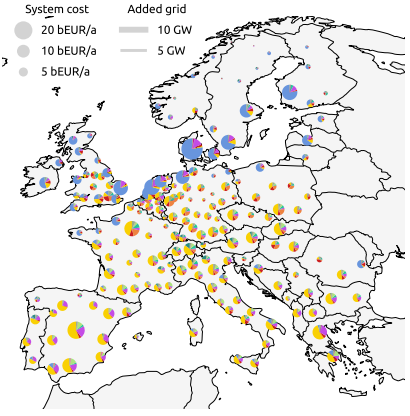


What about restricting onshore wind potentials?

With onshore wind



Without onshore wind

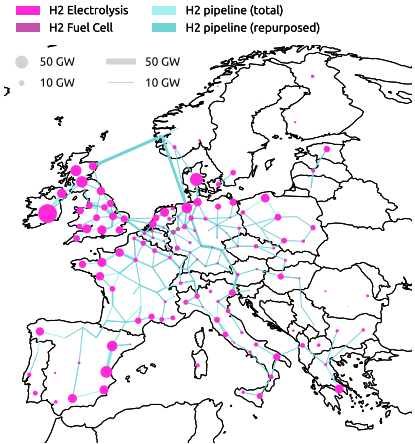


- hydroelectricity
- offshore wind
- solar
- power-to-heat
- gas-to-power/heat
- power-to-gas
- power-to-liquid
- battery storage
- hot water storage
- DAC
- H2 storage
- electricity distribution grid
- HVAC line
- HVDC link

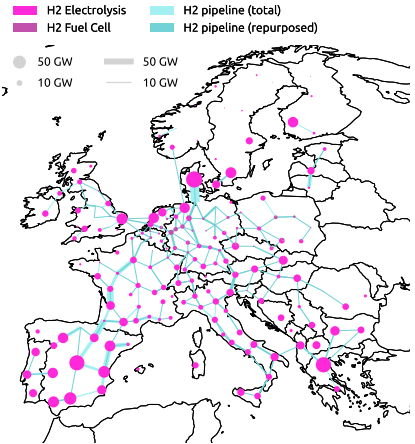
Technische Universität Berlin

Effect of onshore wind potentials on hydrogen network

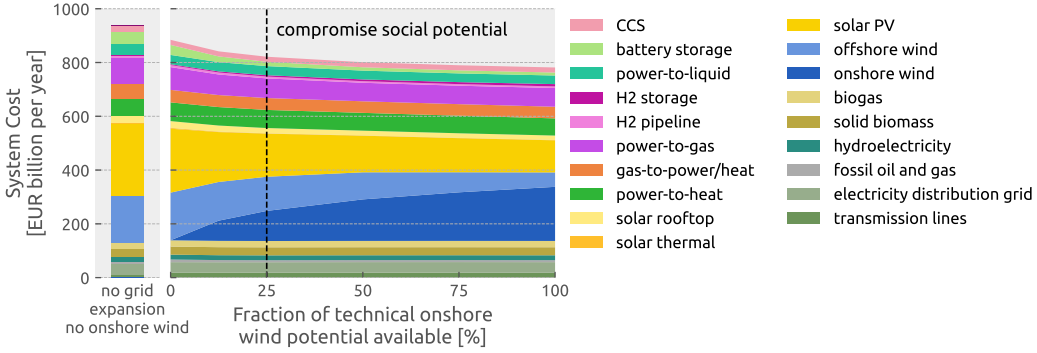
With onshore: British Isles and North Sea dominate hydrogen production



Without onshore: Southern Europe becomes much larger exporter of hydrogen



Benefit of high onshore wind potentials



- costs rise by $\approx$ €104 bn/a (12%) as we **eliminate onshore wind** (25% grid expansion)
- rise drops to $\approx$ €64 bn/a (7%) if we allow **a quarter of the technical potential**

Future work

- Consider **pathway** of investments now-2050 (with **technological learning**)
- Compare local production with import of **synfuels from outside Europe**
- Extend offshore wind potentials with **floating wind** and **wake effects**
- Cost-benefit of more **energy sufficiency**
- spatial optimisation of CO_2 transport and sequestration infrastructure
- more endogenous model decisions for **fuel and process switching** in industry
- cost impact of more **regionally balanced** solutions

Conclusion

- **Cross-sectoral** approaches are important to reduce CO_2 emissions **and** for flexibility
- There are many **trade-offs** between unpopular infrastructure and system cost
- In our model, limiting power grid expansion **costs $\sim$ €40-50 billion per year more**
- **Hydrogen networks** can partially substitute for power grid expansion, but system costs are 3-5% higher; can also get away with neither power grid expansion nor H_2 network
- All results depend strongly on assumptions and modelling approach - therefore **openness and transparency are critical**, guaranteed by open licences for data and code

Meta

Find the slides:
https://neumann.fyi/files/neumann-edinburgh-seminar.pdf

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

Find the open modelling framework:
https://github.com/pypsa/pypsa

Send an email:
mailto:f.neumann@tu-berlin.de

Technische Universität Berlin

Notes and Sketches

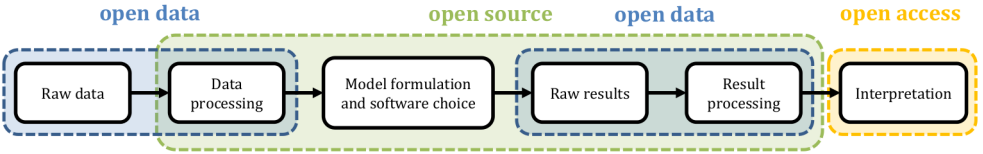
What is open modelling?

Open energy modelling means modelling with open software, open data and open publishing.

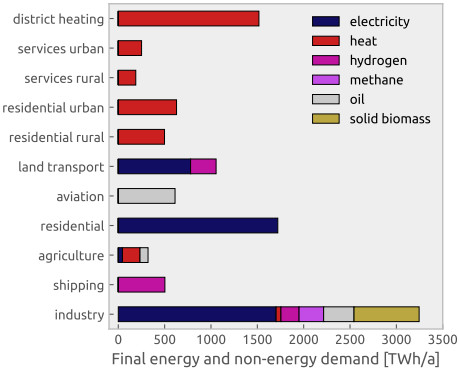
Open means that anybody is free to download the software/data/publications, inspect it, machine process it, share it with others, modify it, and redistribute the changes.

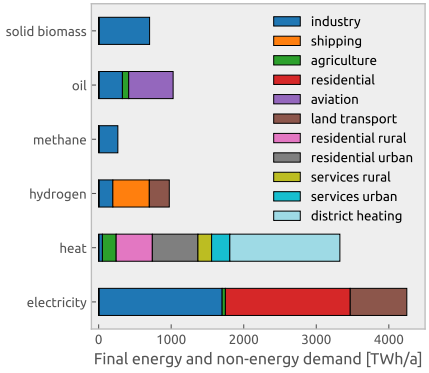
This is typically done by uploading the model to an online platform with an **open licence** telling users what their reuse rights are.

The **whole pipeline** should be open:

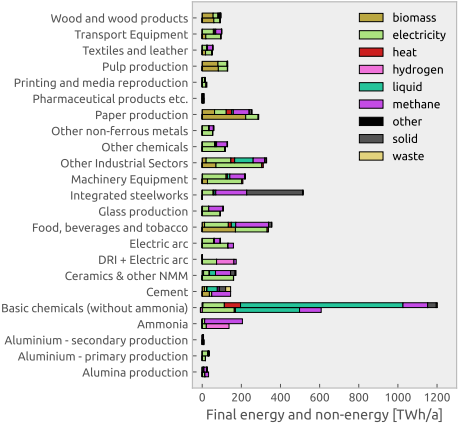


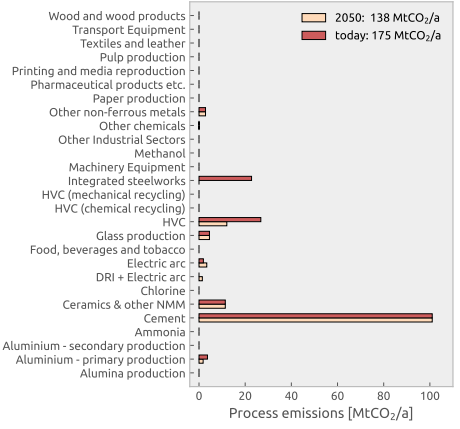
Final Energy Consumption by Carrier





Industry Sector – Demand and Process Emissions

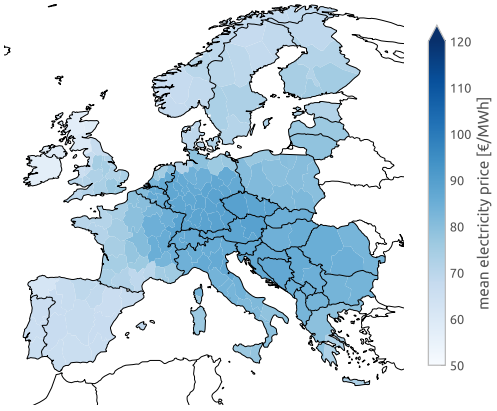




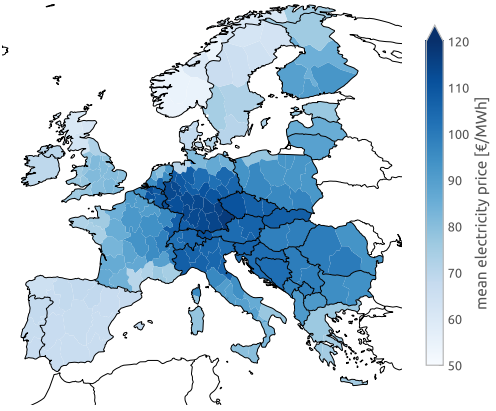
Technische Universität Berlin

Nodal Prices Electricity

only power grid expansion



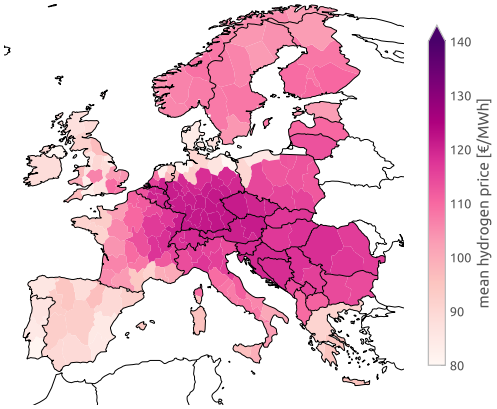
only hydrogen network expansion



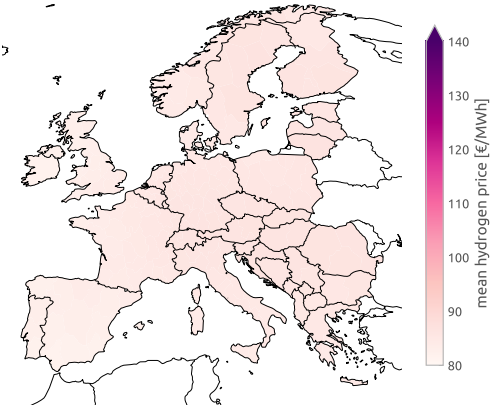
Technische Universität Berlin

Nodal Prices Hydrogen

only power grid expansion

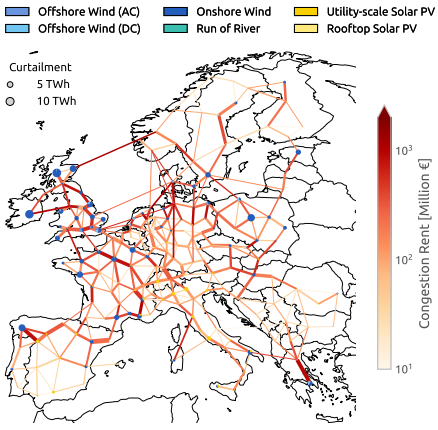


only hydrogen network expansion

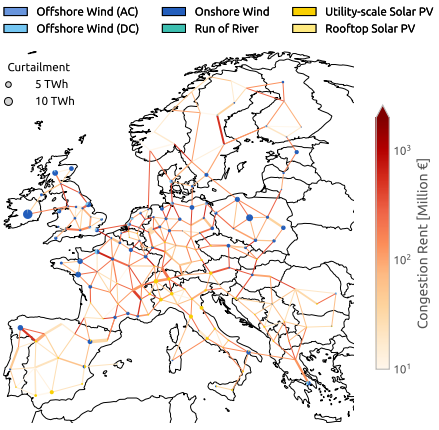


Congestion and Curtailment

only power grid expansion

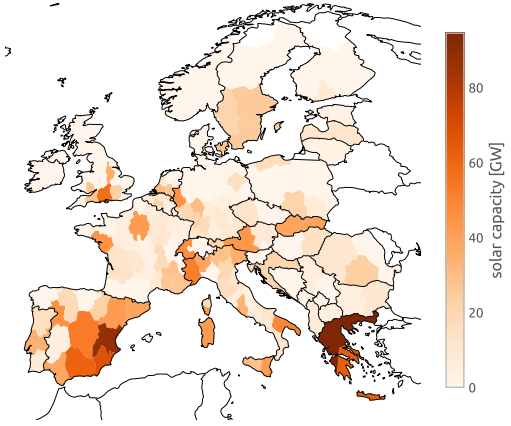


only hydrogen network expansion

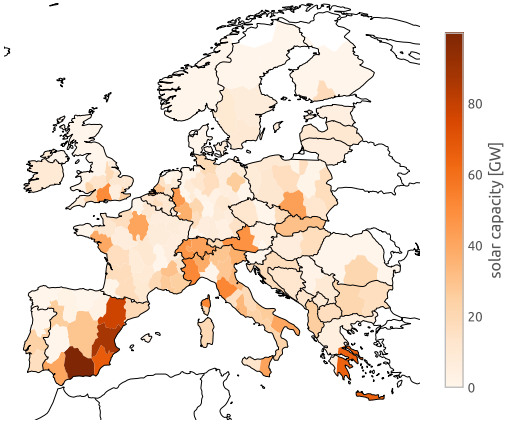


Capacities Built – Solar

only power grid expansion



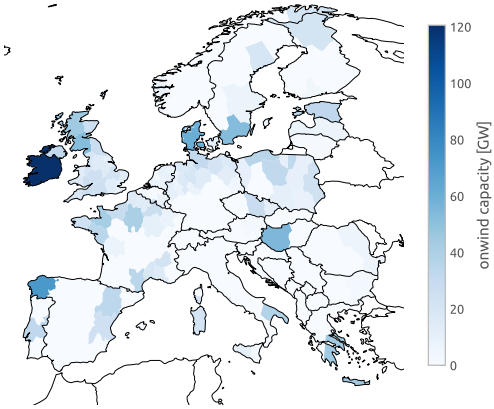
only hydrogen network expansion



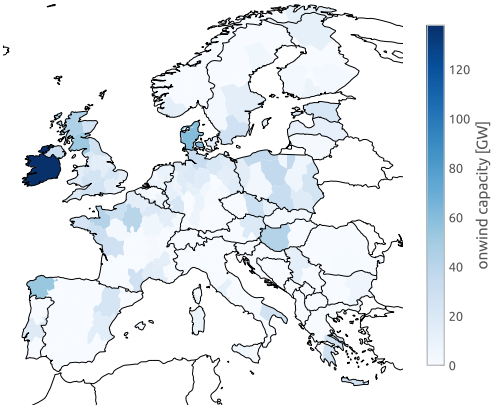
Technische Universität Berlin

Capacities Built – Onshore Wind

only power grid expansion



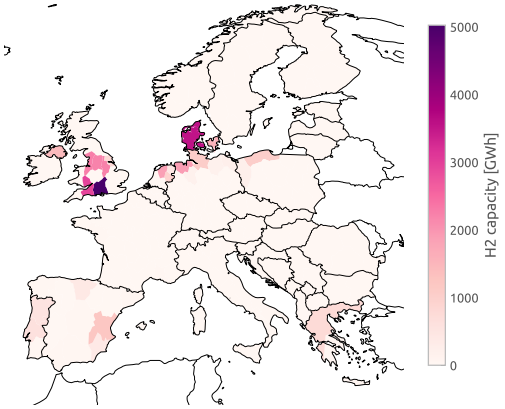
only hydrogen network expansion



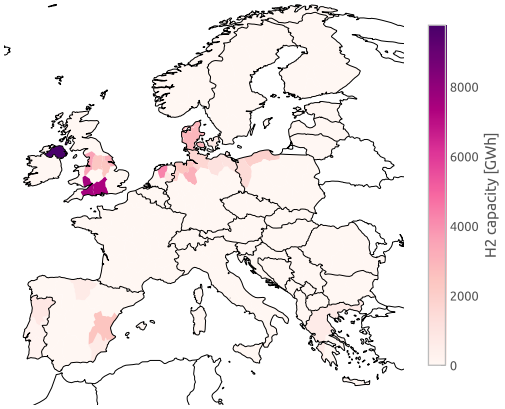
Technische Universität Berlin

Capacities Built – Hydrogen Storage

only power grid expansion

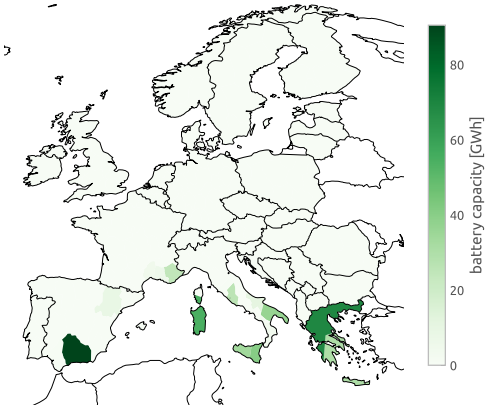


only hydrogen network expansion

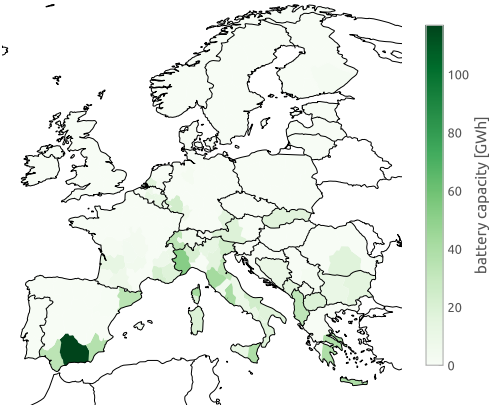


Capacities Built – Battery Storage

only power grid expansion



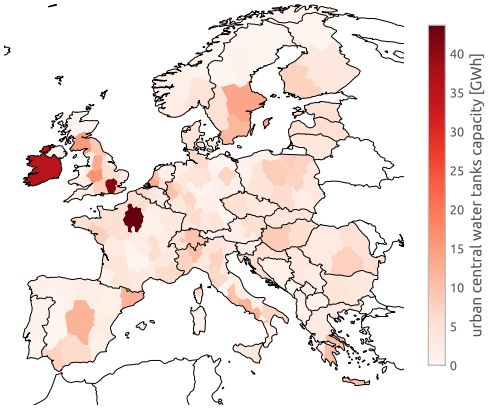
only hydrogen network expansion



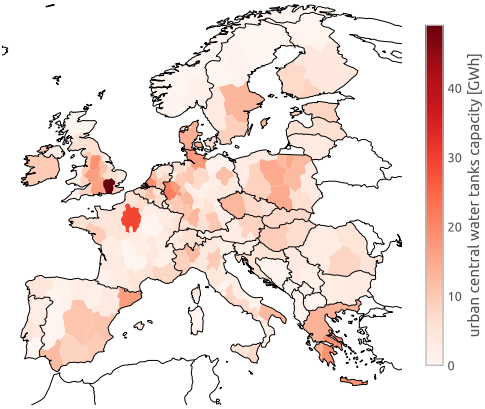
Technische Universität Berlin

Capacities Built – Thermal Energy Storage

only power grid expansion



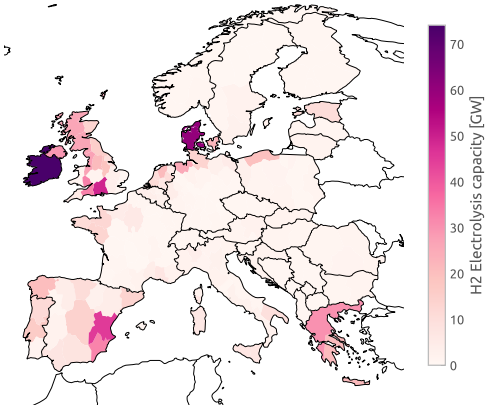
only hydrogen network expansion



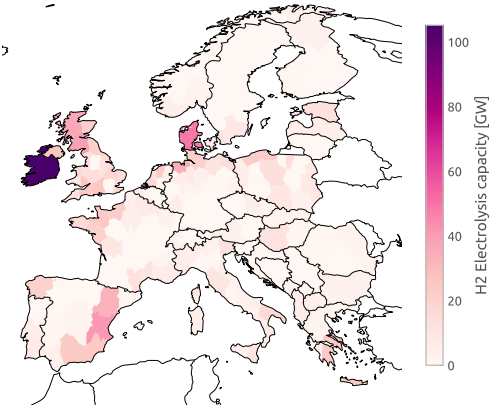
Technische Universität Berlin

Capacities Built – Electrolysis

only power grid expansion



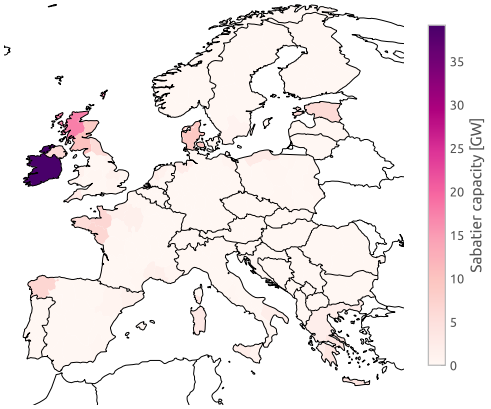
only hydrogen network expansion



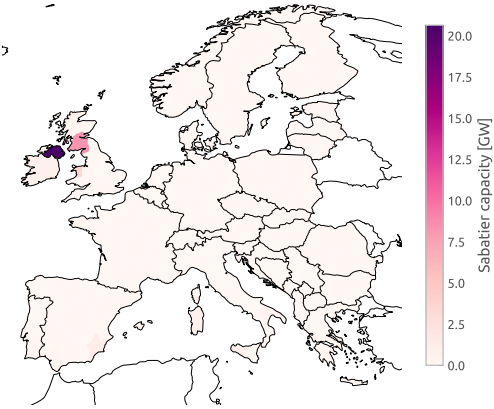
Technische Universität Berlin

Capacities Built – Methanation

only power grid expansion



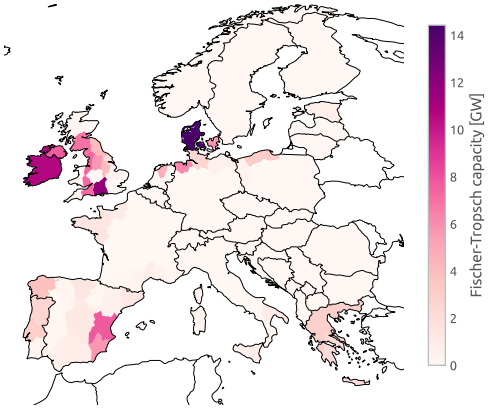
only hydrogen network expansion



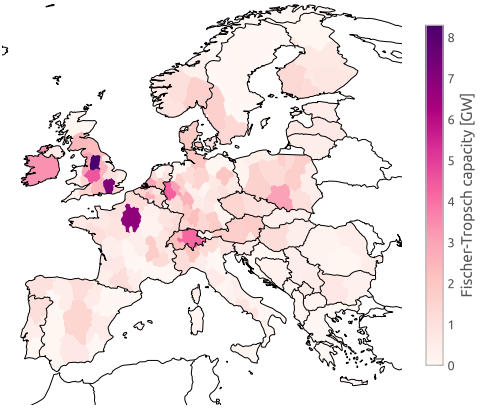
Technische Universität Berlin

Capacities Built – Fischer-Tropsch

only power grid expansion

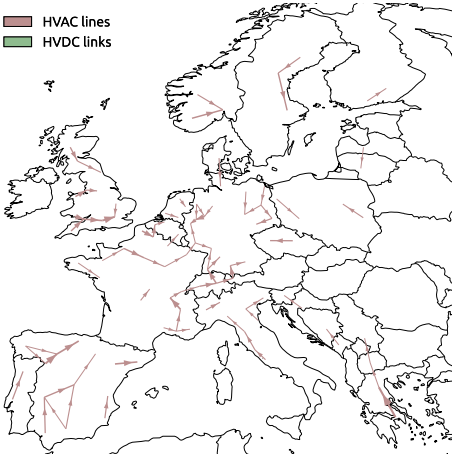


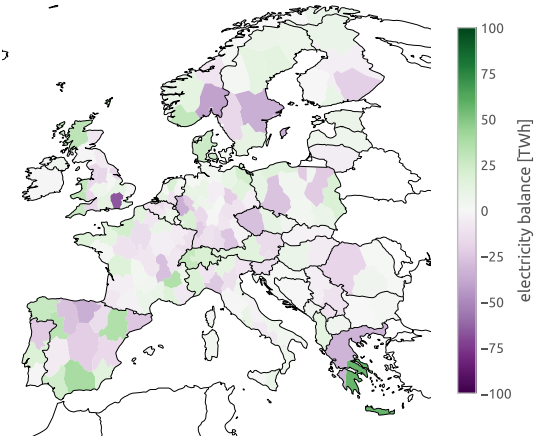
only hydrogen network expansion



Technische Universität Berlin

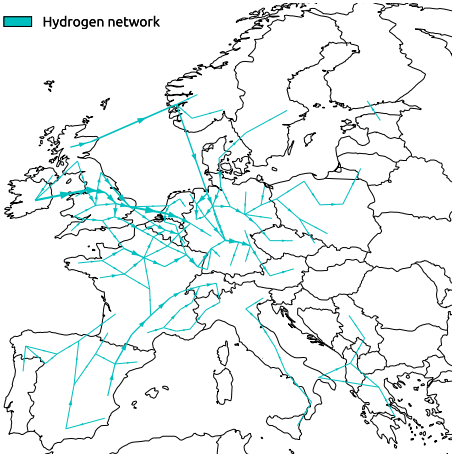
Electricity Net Flows

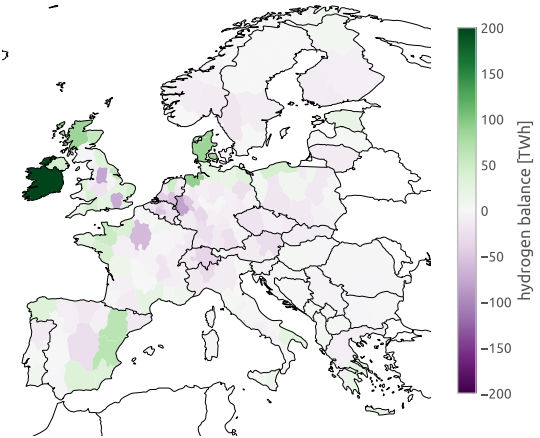




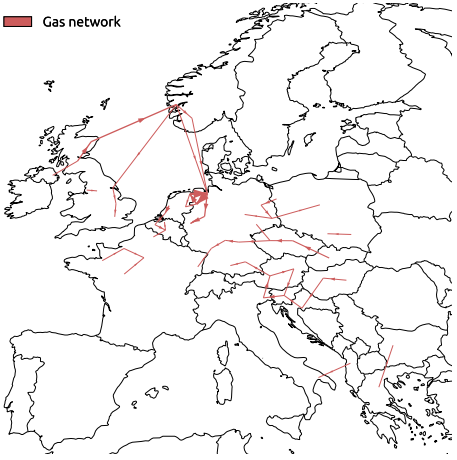
Technische Universität Berlin

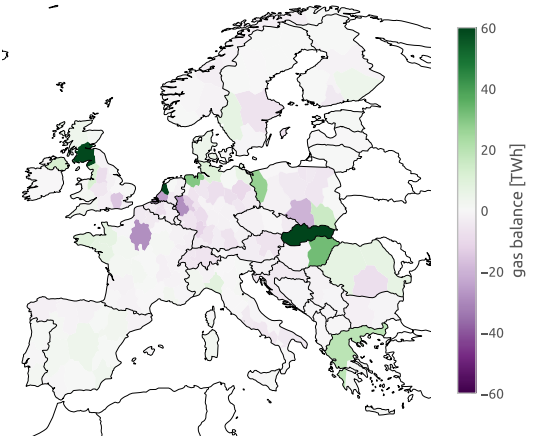
Hydrogen Net Flows





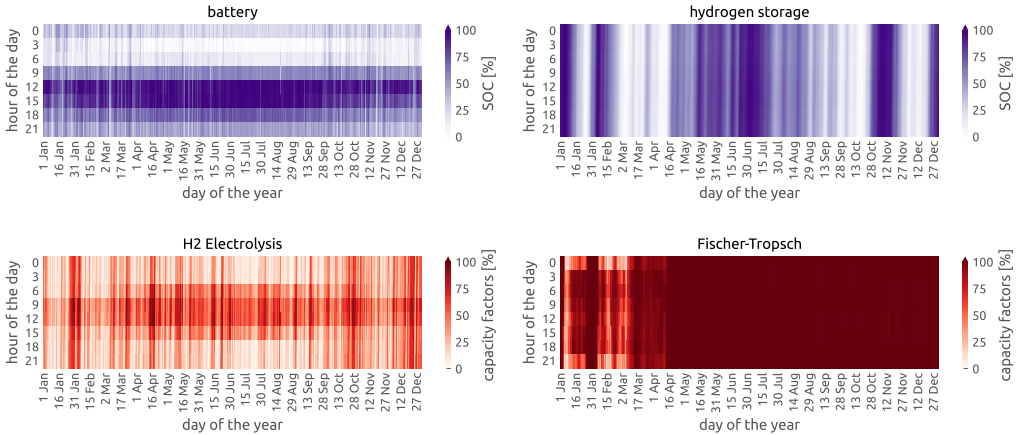
Methane Net Flows



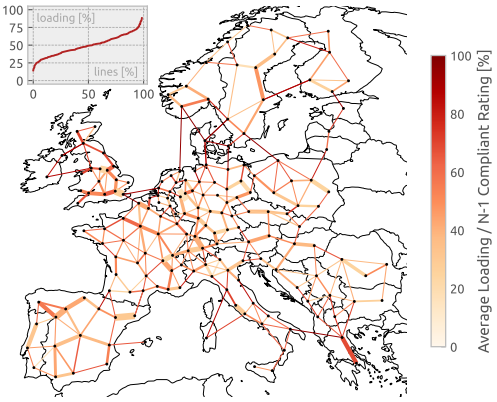


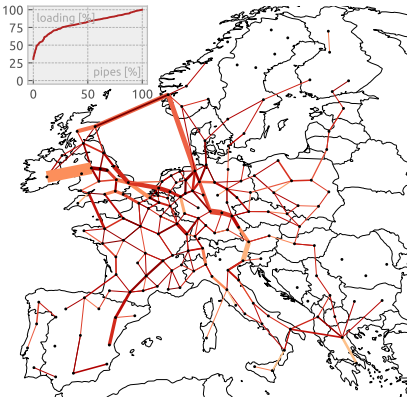
Technische Universität Berlin

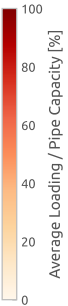
Utilisation Patterns



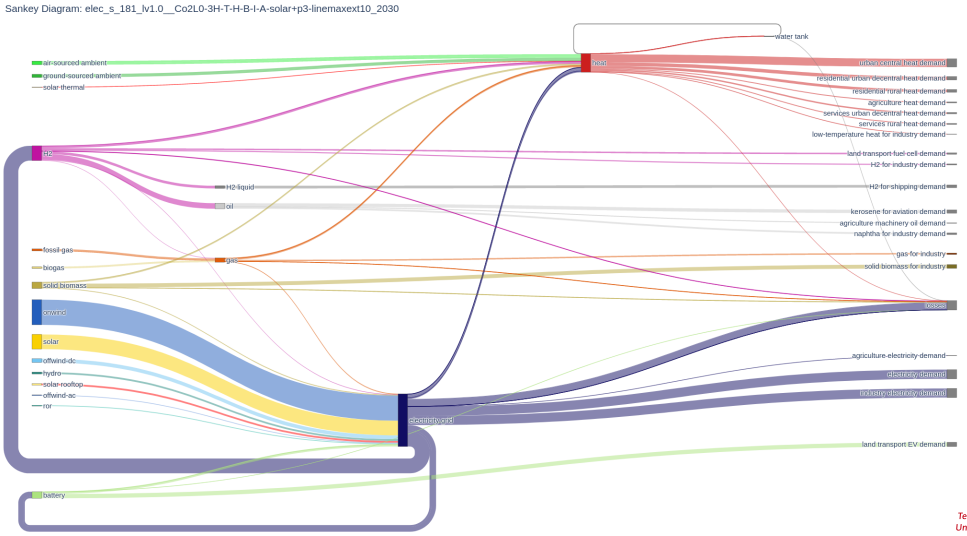
Network Loading



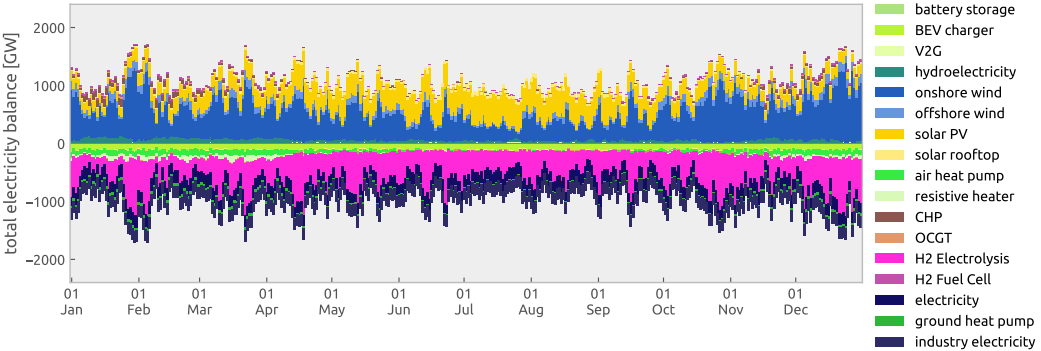




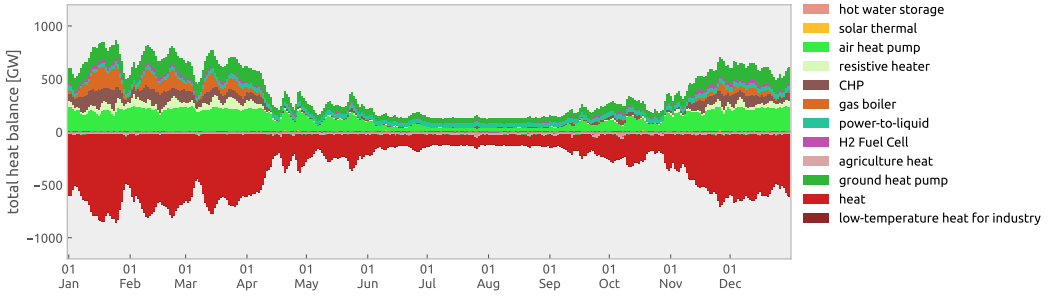
Sankey Diagram



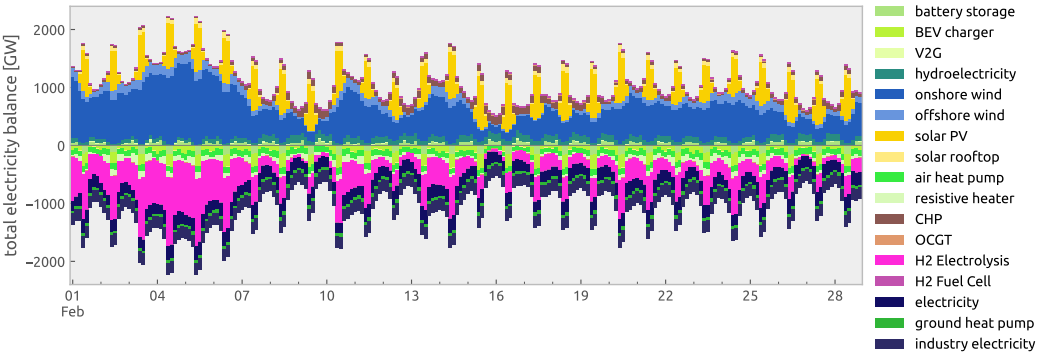
Time Series Electricity Balance



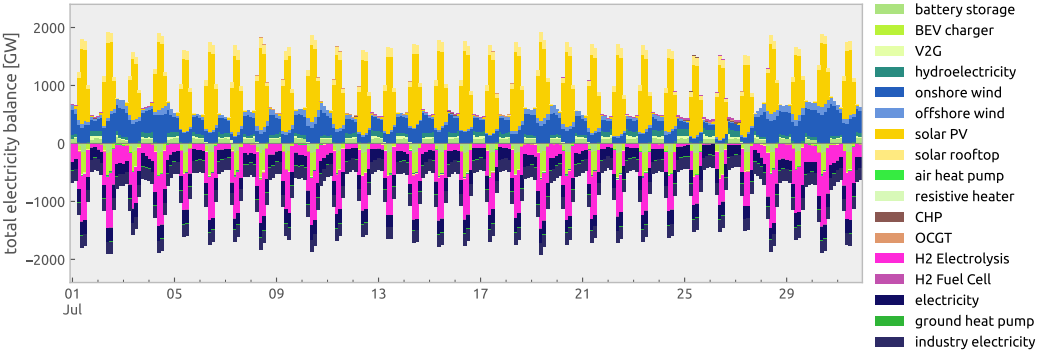
Time Series Heat Balance



Time Series Electricity Balance – February



Time Series Electricity Balance – July



Technische Universität Berlin