Power Transmission Bottlenecks: A Deal-Breaker for a Renewable World?

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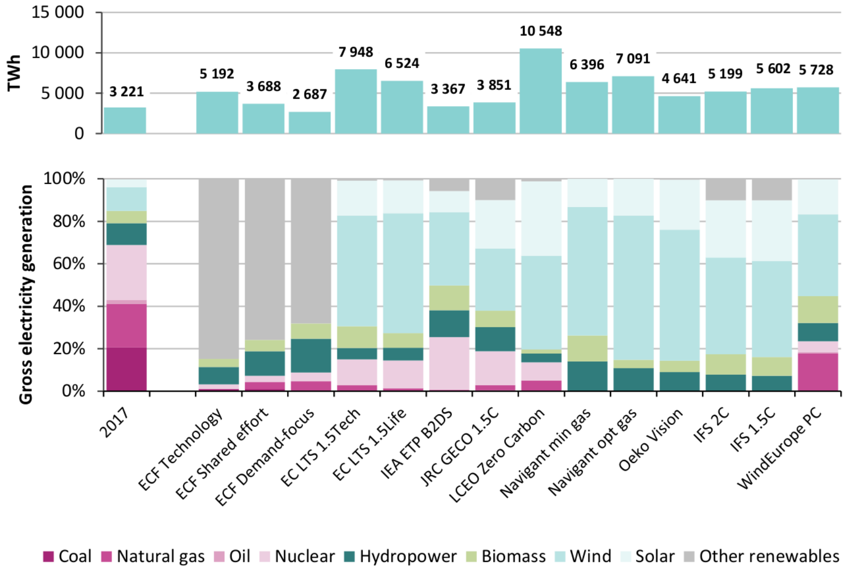
Motivation

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



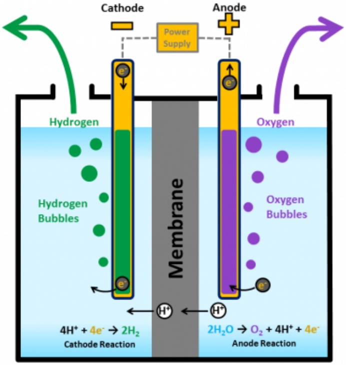
Source: JRC, 2020

Problem: collides with low acceptance for power grid expansion...

...and low acceptance for onshore wind

Can electrolytic hydrogen and a hydrogen network help?

Can we substitute for power grid by producing **electrolytic hydrogen** (here or abroad) and transporting it through a new and/or re-purposed **hydrogen pipeline network** to demand?



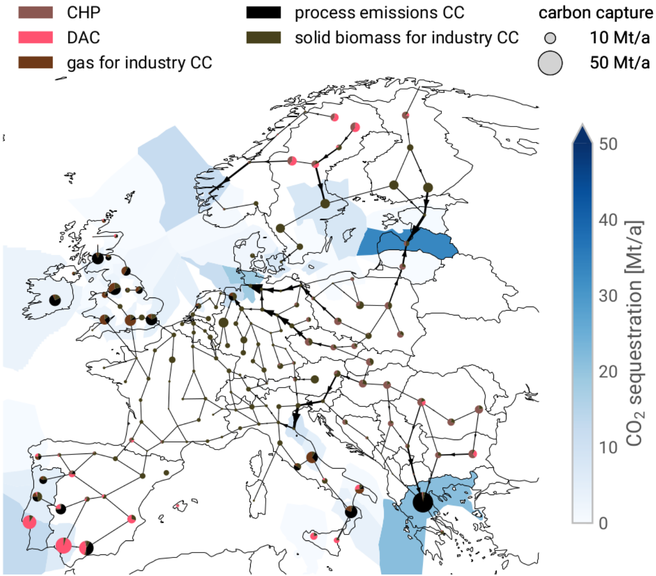
Which hydrogen demand sectors really need a hydrogen network?

For other potential hydrogen demand sectors, they need a hydrogen network if low cost H_2 is not locally available. But for each sector there are **alternatives to transporting hydrogen**.

sector	alternatives if hydrogen not available
backup power & district heat	use derivative fuels (e-methane, e-methanol)
process heat	electrify/use derivative fuels
heavy duty trucks	use battery electric vehicles
iron direct reduction	industry relocates to cluster/abroad
ammonia	industry relocates to cluster/abroad
high value chemicals	transport derivative precursors instead
shipping	transport derivative fuels instead
aviation	transport derivative fuels instead

$\Rightarrow$ There is **no strict need** for a hydrogen network, but it may be easier/cost-optimal.

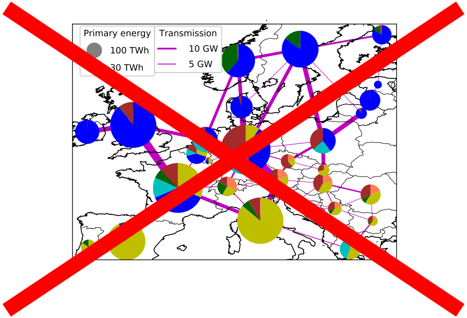
How do we capture, utilise, transport and sequester carbon?



- Hydrogen economy is also linked to **carbon dioxide management**
- Need CCS for process emissions, CCU for synfuels and basic chemicals, CDR for unabatable and negative emissions
- For synthetic hydrocarbons, do we transport hydrogen to carbon sources, or carbon to hydrogen sources?
- Can we avoid hydrogen grid altogether and transport only CO_2, CH_4 and MeOH?

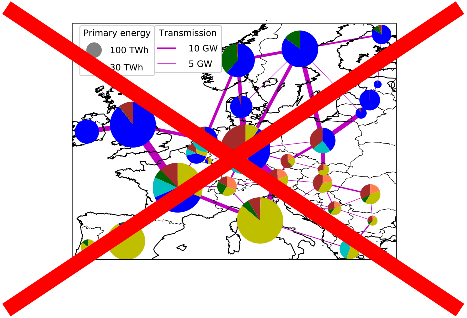
Source: F. Neumann, C. Tries, F. Hofmann, 2023

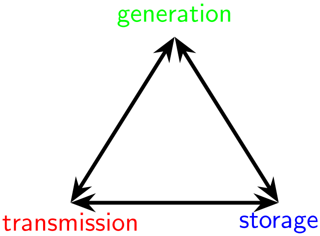
Challenge 1: Need spatial resolution to see grid bottlenecks & infrastructure trade-offs.
$\Rightarrow$ One node per country won't work.



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 generation.
⇒ Optimising separately is inefficient.

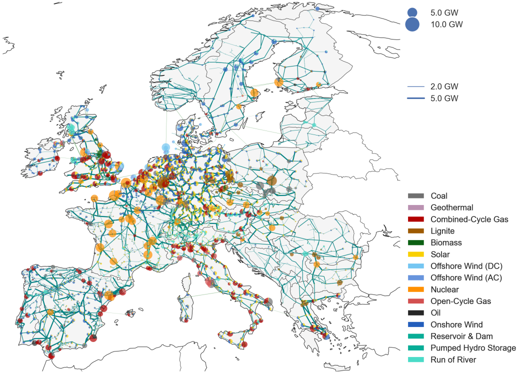




⇒ Need **very large** models, big data and methods for complexity management

European Sector-Coupled Model PyPSA-Eur-Sec

- **Open source** tool for modelling energy systems at **high resolution**.
- Fills missing gap between **power flow software** (e.g. PowerFactory, MATPOWER) and **energy system simulation software** (e.g. PLEXOS, TIMES, OSeMOSYS).
- Good grid modelling is increasingly important, for integration of **renewables** and **electrification** of transport, heating and industry.



PyPSA is available on [GitHub](). It is [used worldwide]() by researchers, consultants, TSOs and NGOs.

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

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

subject to

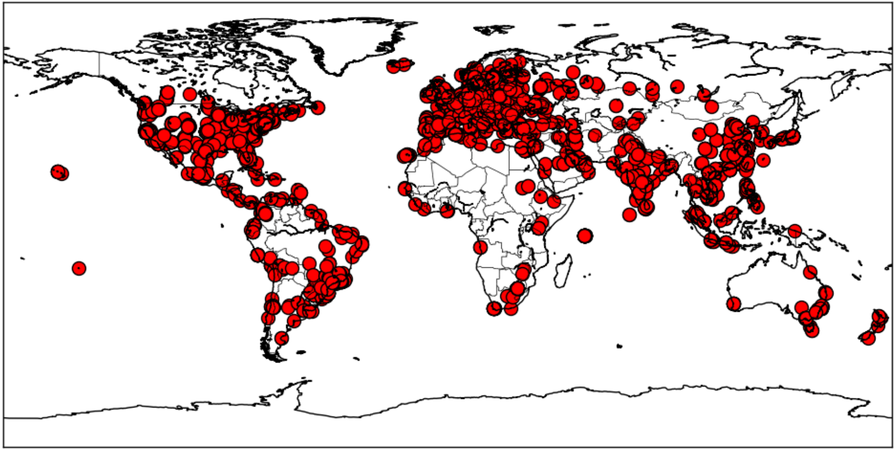
- meeting **energy demand** at each node n (e.g. region) and time t (e.g. hour of year)
- wind, solar, hydro (variable renewables) **availability time series** $\forall\, n, t$
- **transmission constraints** between nodes, **linearised power flow**
- (installed capacity) $\leq$ (**geographical potentials** for renewables)
- **CO_2 constraint** (e.g. reduction compared to 1990)

In short: mostly-greenfield investment optimisation, multi-period with linear power flow.

Optimise transmission, generation and storage **jointly**, since they're strongly interacting.

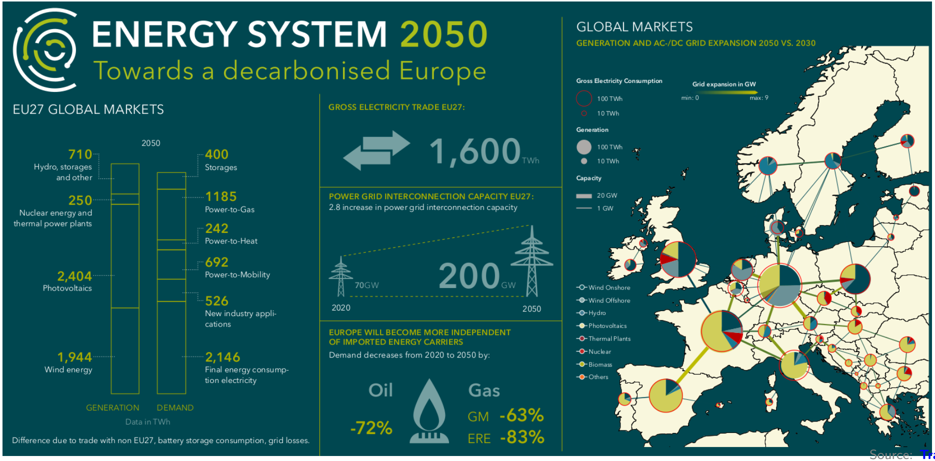
Python for Power System Analysis: Worldwide Usage

PyPSA is used worldwide by **dozens of research institutes and companies** (TU Delft, KIT, Shell, TSO TransnetBW, TSO APG, TERI, Agora Energiewende, RMI, Ember, Instrat, Fraunhofer ISE, Climate Analytics, CLIMACT, DLR, FZJ, RLI, Saudi Aramco, Edison Energy, spire, etc.).



PyPSA example: TransnetBW used PyPSA-Eur-Sec

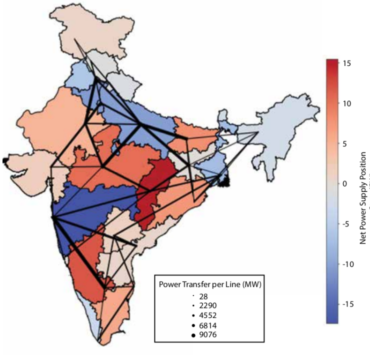
German **Transmission System Operator (TSO) TransnetBW** used an open model (PyPSA-Eur-Sec) to model the European energy system in 2050. Why? Easier to build on an existing model than reinvent the wheel.

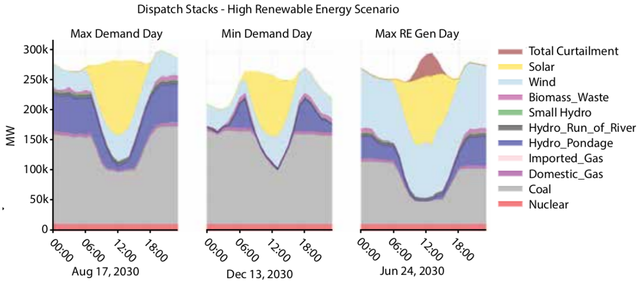


Source: TransnetBW, 2022

PyPSA example: TERI in India

For a government-backed study of India's power system in 2030, The Energy and Resources Institute (TERI) in New Delhi used open framework PyPSA. Why? **Easy to customize**, lower cost than commercial alternatives like PLEXOS, good for building up skills and reproducible by other stakeholders.

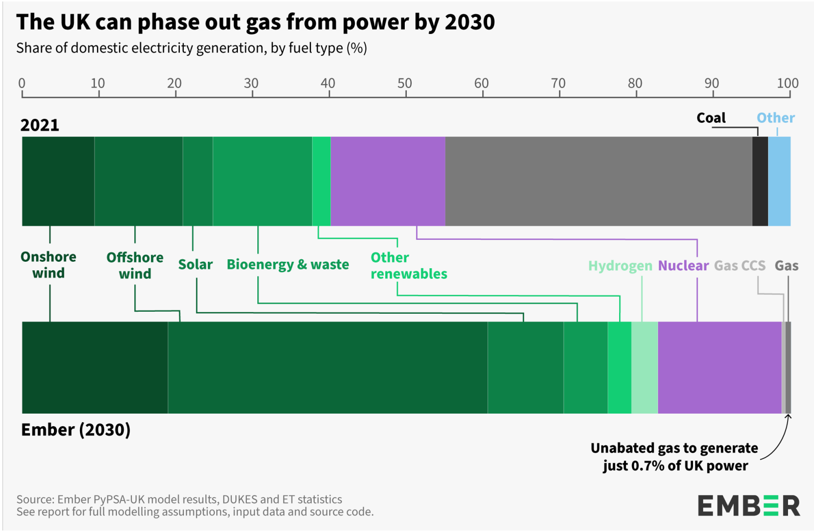




Source: TERI

PyPSA example: NGO Ember in United Kingdom

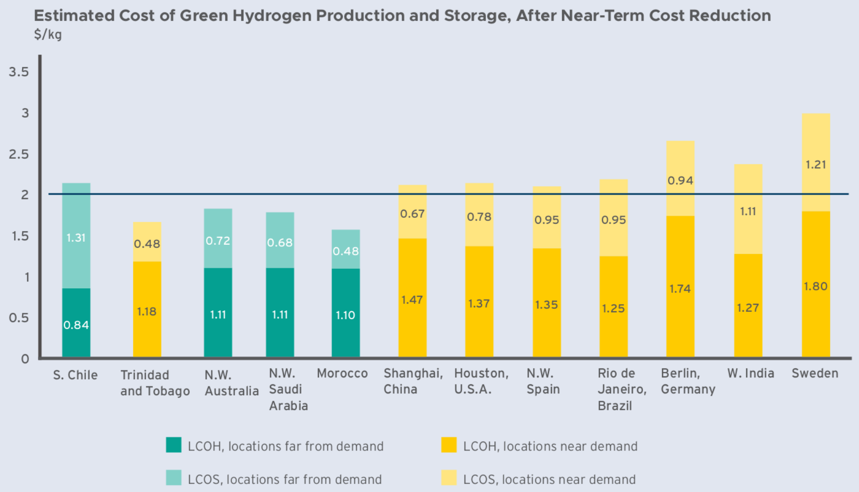
NGO Ember used PyPSA to model a gas phase out in the UK by 2030, releasing all code on github.



Source: Ember, 2022

PyPSA example: RMI in United States

The Rocky Mountain Institute (RMI) in Boulder, Colorado used PyPSA to model hydrogen production costs around the world, since PyPSA had a track record for such calculations.



Source: RMI, 2021

What is PyPSA-Eur-Sec?

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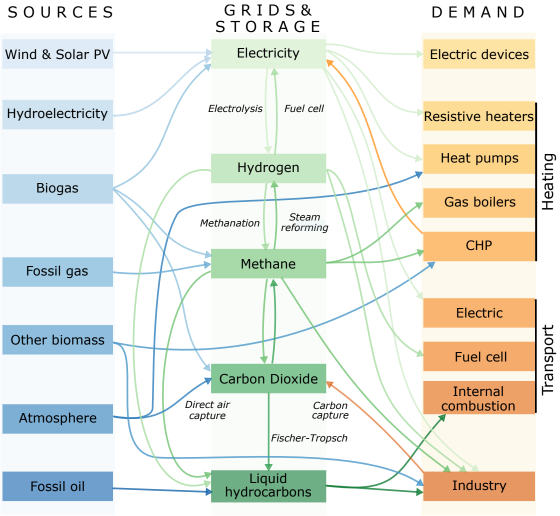
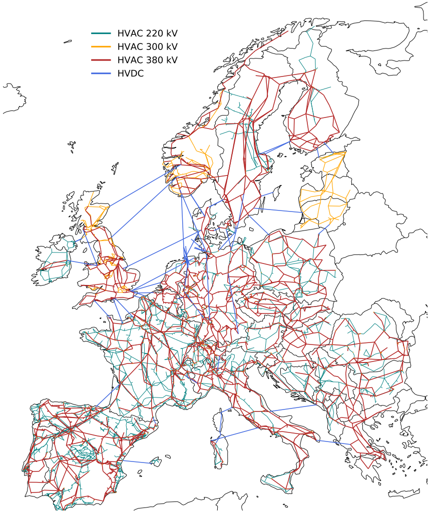
Model for Europe with all energy flows... and bottlenecks in energy networks.





Data-driven energy modelling

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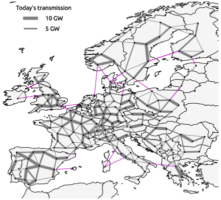
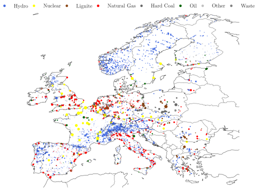
Lots of different types of data and process knowledge come together for the modelling.

Full pipeline of data processing from raw data to results is managed in an **open workflow**.

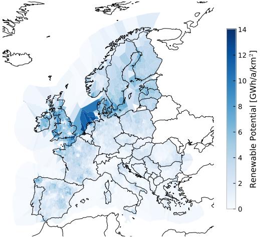
clustered network model



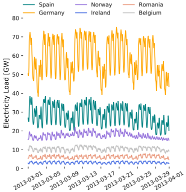
power plants and technology assumptions



renewable potentials and hourly time series for each region



demand projections time series



Final energy and non-energy demand for net-zero scenario

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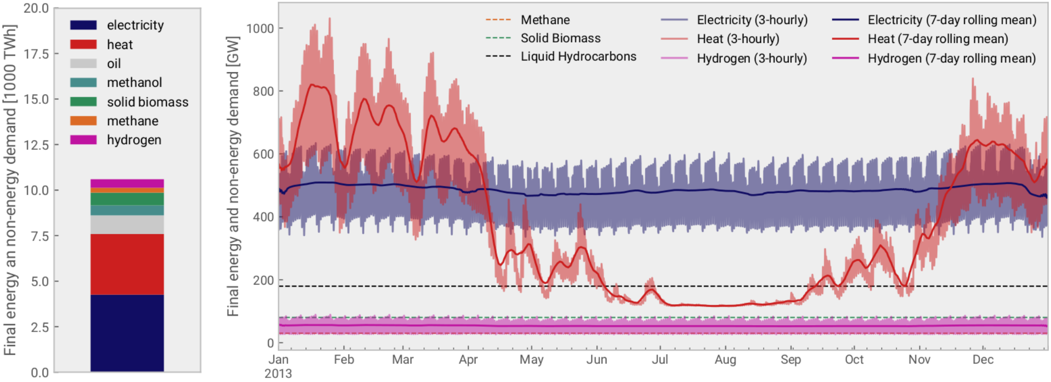
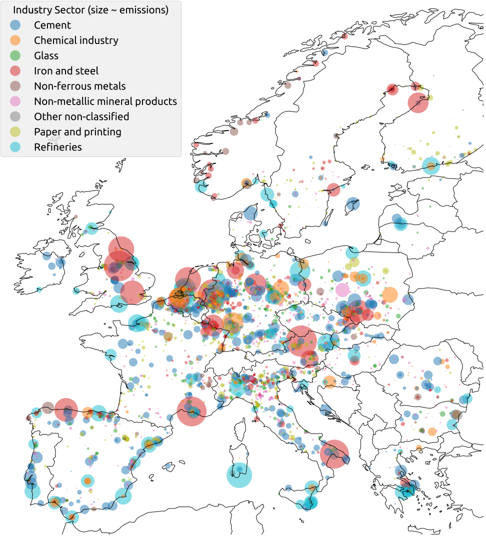


Source: **Neumann et al, 2023**

HotMaps open database of industry from Fraunhofer ISI



- Includes cement, basic chemicals, glass, iron & steel, non-ferrous metals, non-metallic minerals, paper, refineries
- Enables regional analyses, calculation of site-specific energy demand, waste heat potentials, emissions, market shares, process-specific evaluations

Source: Fraunhofer ISI

Process- and fuel-switching in industry, aviation, shipping

Iron & Steel	70% from scrap, rest from direct reduction with 1.7 $MWhH_2/tSteel$ + electric arc (process emissions 0.03 $tCO_2/tSteel$)
Aluminium	80% recycling, for rest: methane for high-enthalpy heat (bauxite to alumina) followed by electrolysis (process emissions 1.5 tCO_2/tAl)
Cement	Waste, solid biomass, methane; capture of CO_2 emissions
Ceramics & other NMM	Electrification
Ammonia	Clean hydrogen
Plastics	Recycling and synthetic naphtha for primary production
Other industry	Electrification; process heat from biomass
Shipping	Methanol; ammonia and LH_2 also possible
Aviation	Kerosene from Fischer-Tropsch

Carbon is tracked through system: up to 90% of industrial emissions can be captured; direct air capture (DAC); synthetic methane and liquid hydrocarbons; transport and sequestration 20 €/tCO_2; yearly sequestration limited to 200 $MtCO_2/a$

Technology Choices: Exogenous Versus Endogenous

Exogenous assumptions (modeller chooses):

- energy services demand
- energy carrier for road transport (2050: BEV for light-duty, BEV or FCEV for heavy-duty)
- kerosene for aviation
- energy carrier for shipping (2050: MeOH)
- steel production 2050: DRI with hydrogen, then electric arc (could compete with BF+CCS)
- electrification & recycling in industry

Endogenous (model optimizes):

- electricity generation fleet
- electricity, gas, hydrogen and carbon networks
- space and water heating technologies (including insulation)
- all P2G/L/H/C
- supply of process heat for industry
- carbon management (CCUTS)

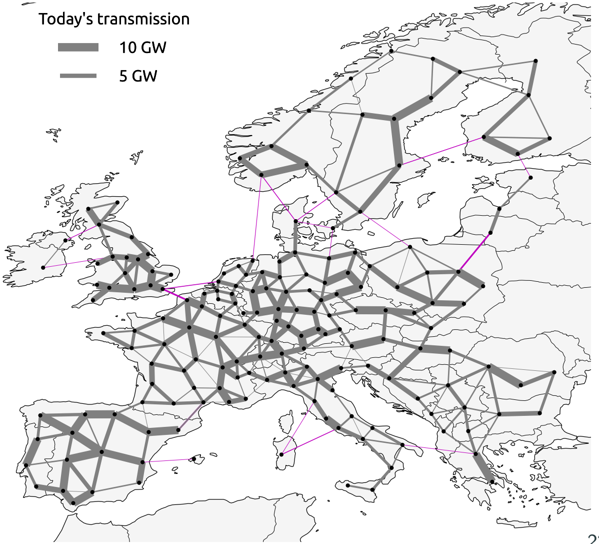
Modelling Results

Results for 181-node model of European energy system

- Couple **all energy sectors** (power, heat, transport, industry)
- Reduce net CO_2 emissions **to zero**
- Assume **energy autarky**
- Assume 181 **smaller bidding zones**
- **Conservative** technology assumptions (for 2030 from Danish Energy Agency)

Examine effects of:

- **power grid expansion**
- **new hydrogen grid**
- **e-fuel imports**



Daily average of hourly electricity balance

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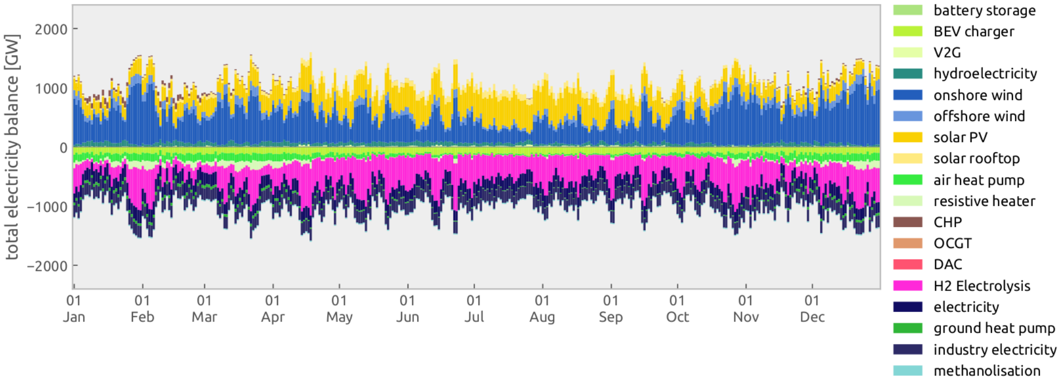
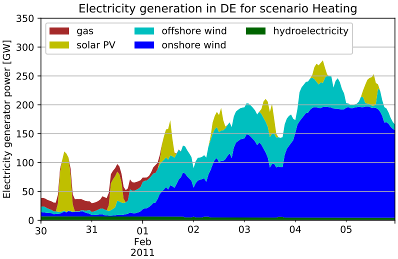
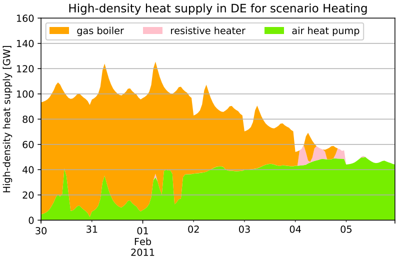
Demand (negative values) is higher in winter thanks to power-to-space-heat; complemented by winter wind; electrolysers have capacity factors in 40-60% range.



Source: Neumann et al, 2023

Example problem with balancing: Cold week in winter





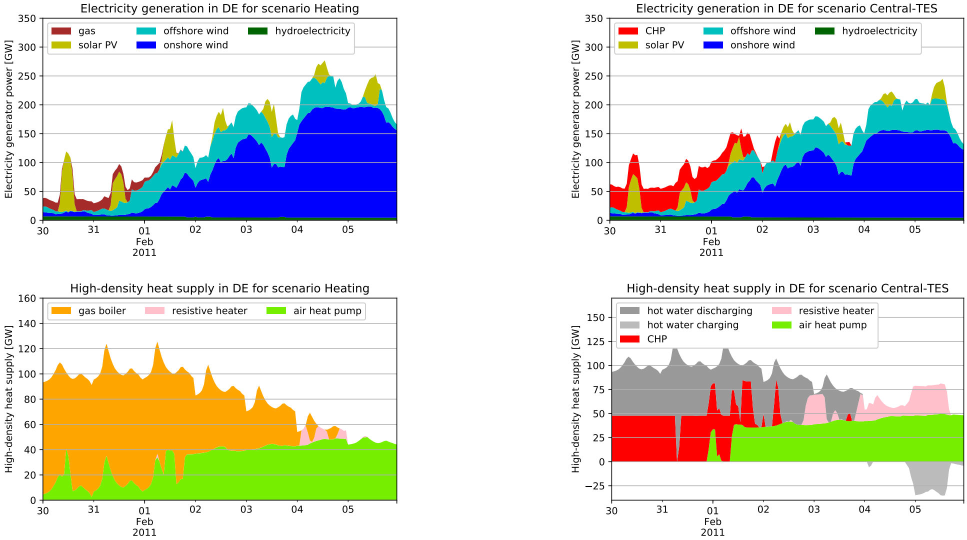
There are difficult periods in winter with:

- **Low** wind and solar ($\Rightarrow$ high prices)
- **High** space heating demand
- **Low** air temperatures, which are bad for air-sourced heat pump performance

Less-smart solution: **backup gas boilers** burning either natural gas, or synthetic methane.

Smart solution: **building retrofitting**, **long-term thermal energy storage** in **district heating networks** and efficient **combined-heat-and-power plants**.

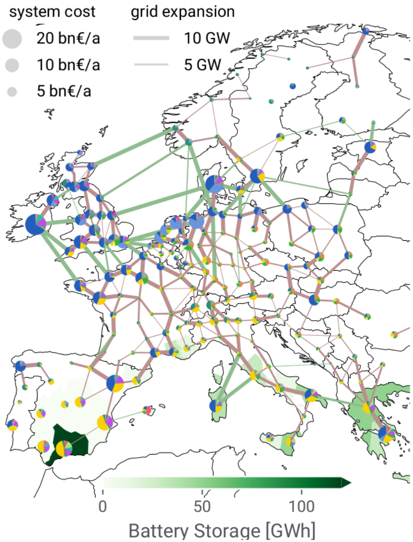
Cold week in winter: inflexible (left); smart (right)



Source: Brown et al, "Synergies of sector coupling," 2018

Distribution of technologies: double today's power grid volume

Electricity grid expansion of 413 TWkm...



Source: **Neumann et al, 2023**

Distribution of technologies: double today's power grid volume

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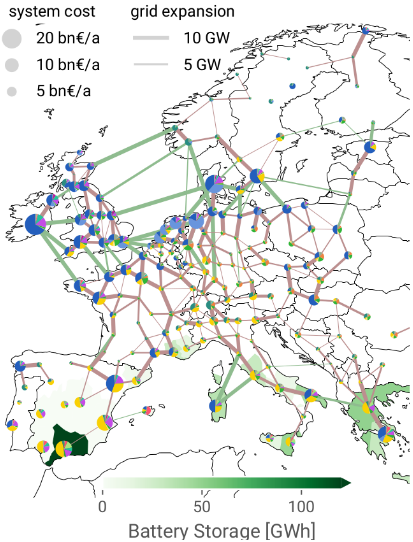
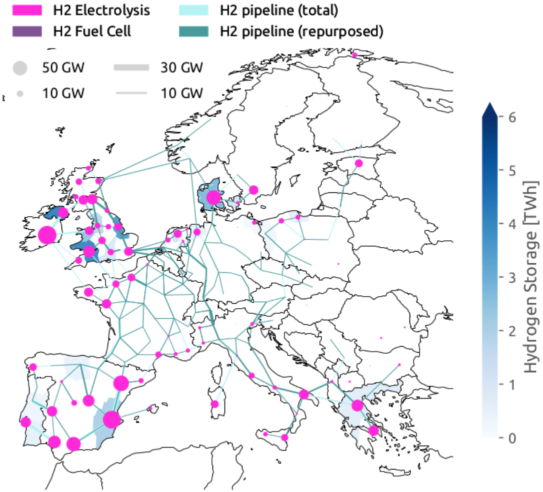
Electricity grid expansion of 413 TWkm...



...and new hydrogen grid of 204 TWkm.



Source: Neumann et al, 2023

Distribution of technologies: 50% more power grid volume

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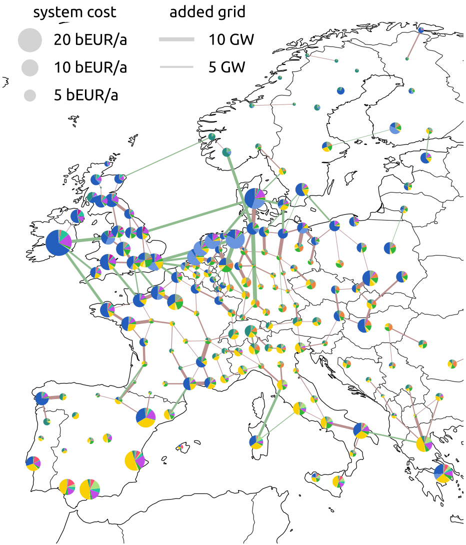
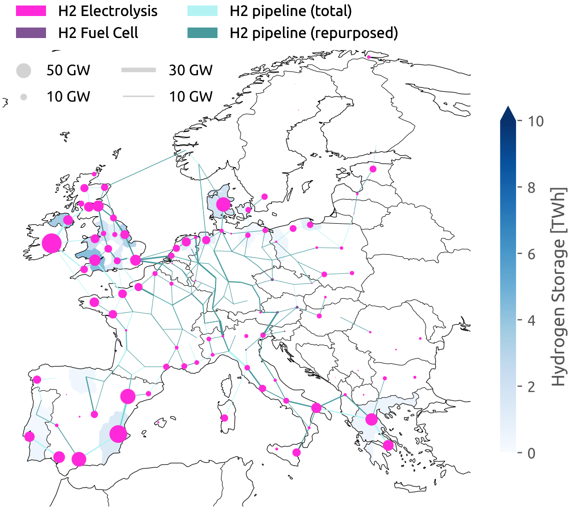
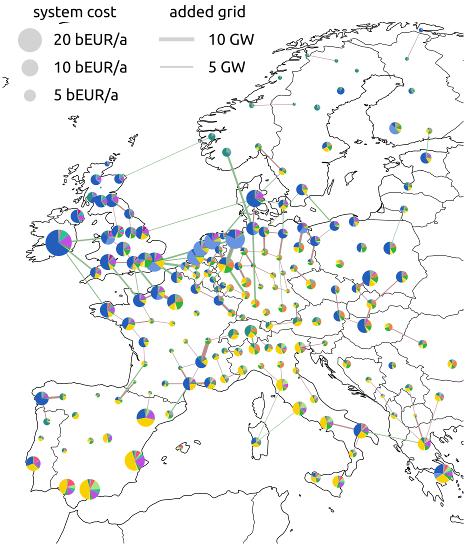
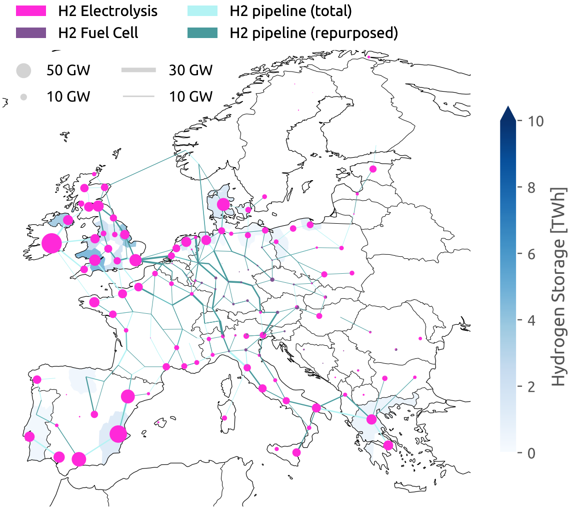




Source: **Neumann et al, 2023**

Distribution of technologies: 25% more power grid volume

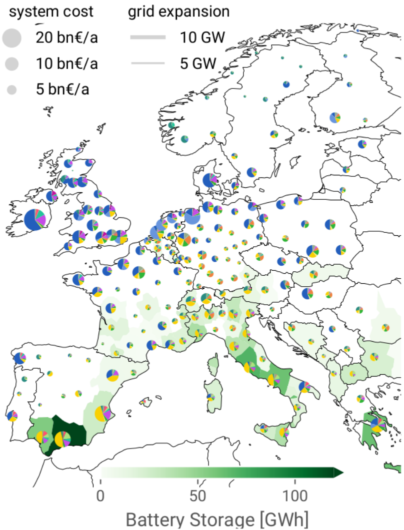




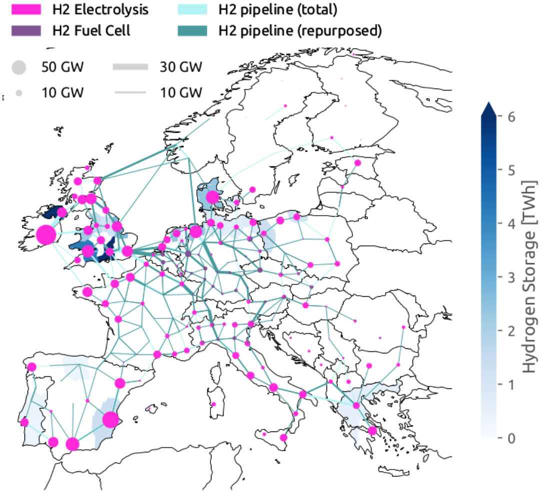
Source: **Neumann et al, 2023**

Distribution of technologies: no power grid expansion

No electricity grid expansion...

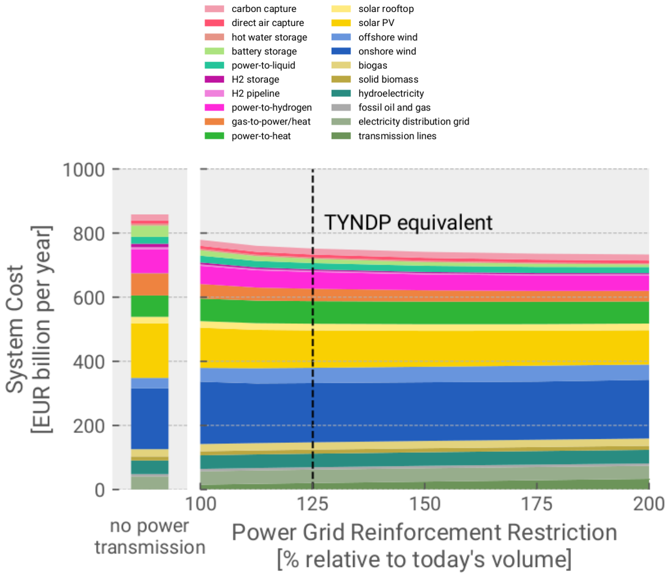


...and new hydrogen grid of 307 TWkm.



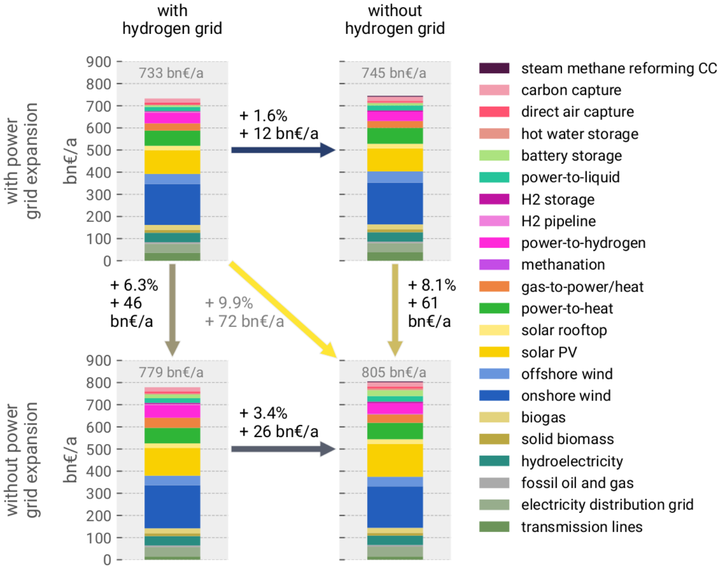
Source: Neumann et al, 2023

Benefit of power grid expansion for sector-coupled system



- Direct system costs **bit higher than today's system** (€ 700 billion per year with same assumptions)
- Systems **without grid expansion** are feasible, but more costly
- As grid is expanded, **costs reduce** from solar, power-to-gas and H_2 network; more offshore wind
- Total cost benefit of extra grid: $\sim$ € 50 billion per year
- **Over half of benefit available at 25% expansion** (like TYNDP)

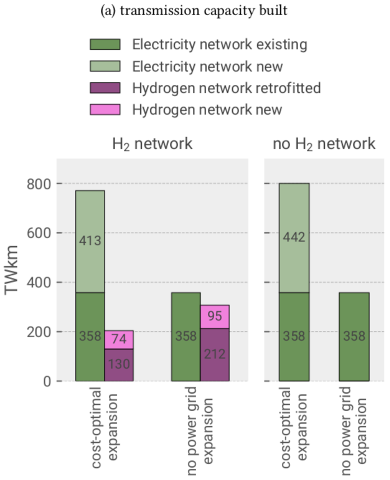
With and without hydrogen network

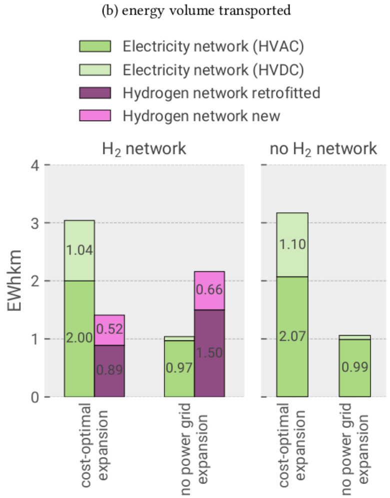


- **Cost** of hydrogen network: € 6-8 billion per year
- **Net benefit** is higher: € 12-26 billion per year (1.6-3.4% of total)
- Hydrogen network brings **robust benefit** if you assume energy autarky
- Benefit is strongest without power grid expansion
- Power grid expansion is better if you have to choose

Source: Neumann et al, 2023

Energy grid in different cases

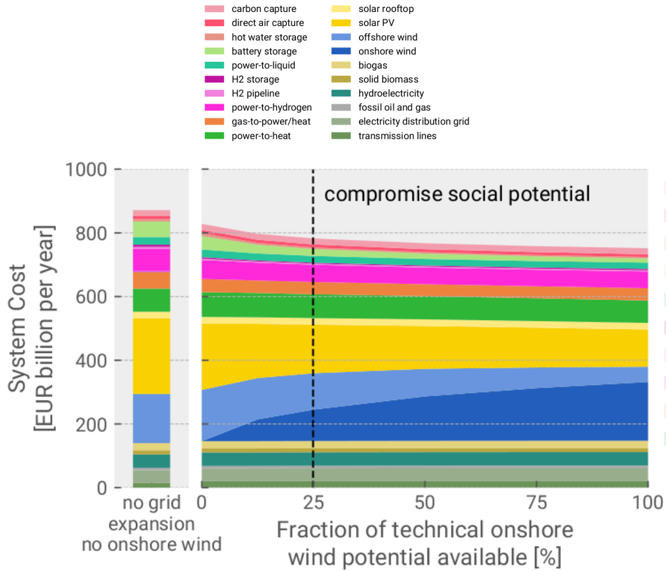




- More hydrogen grid with less power grid
- Without power expansion, hydrogen transports more energy
- Hydrogen grid is not perfect substitute
- Two-thirds of hydrogen grid can re-use methane pipes

Source: Neumann et al, 2023

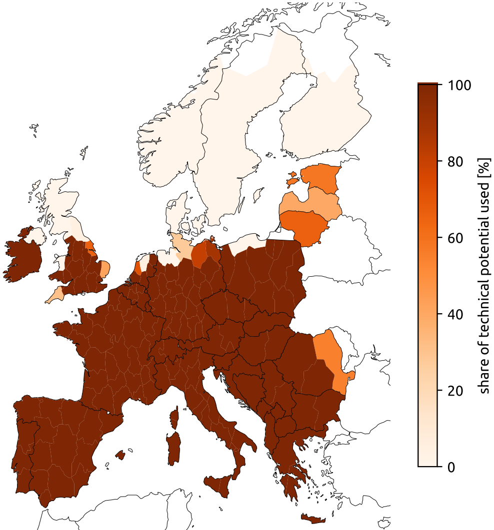
Benefit of full onshore wind potentials

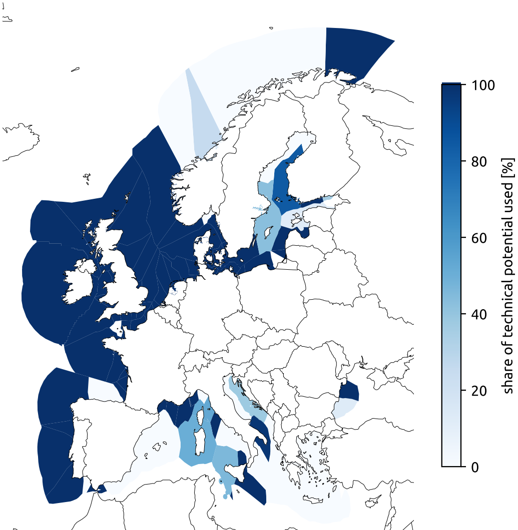


- **Technical potentials** for onshore wind respect land usage
- However, they do not represent the **socially-acceptable potentials**
- Technical potential of ∼ 480 GW in Germany is **unlikely to be built**
- Costs rise by ∼ € 77 billion per year as we **eliminate onshore wind** (with no grid expansion)
- Rise is only half if we **allow a quarter of technical potential** (∼ 120 GW for Germany)

Without onshore: solar rooftop and offshore potentials maxxed out

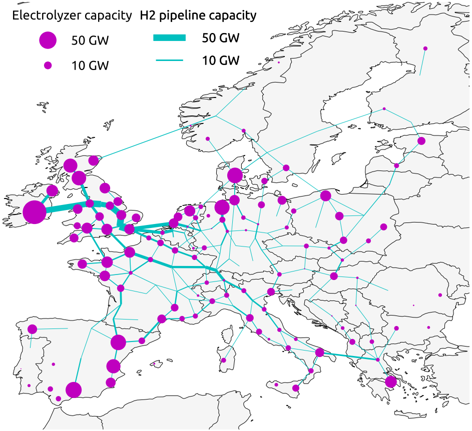
If all sectors included and Europe self-sufficient, effect of **installable potentials** is critical.



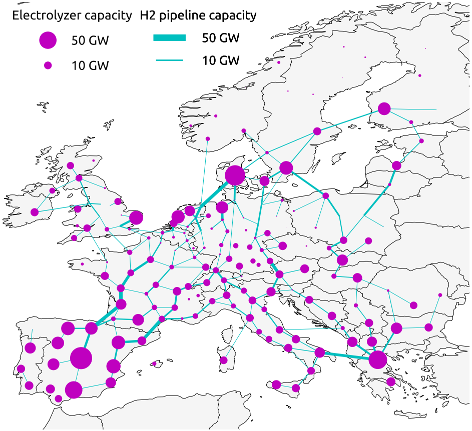


Effect of onshore wind potentials on hydrogen network

With onshore: British Isles and North Sea dominate hydrogen production.

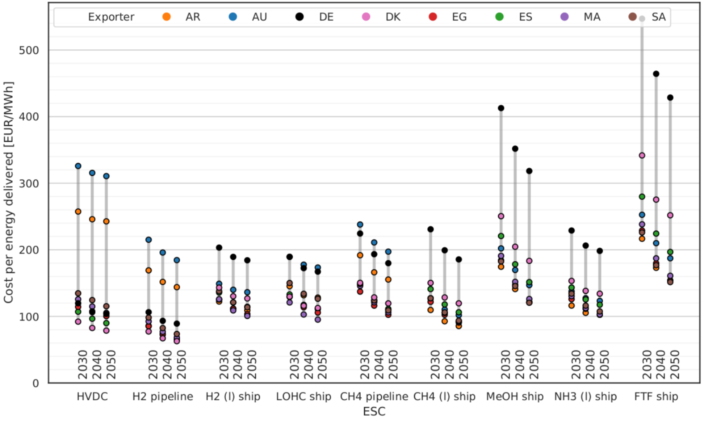


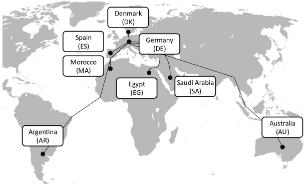
Without onshore: Southern Europe becomes much larger exporter of hydrogen.



Synthetic fuels from outside Europe?

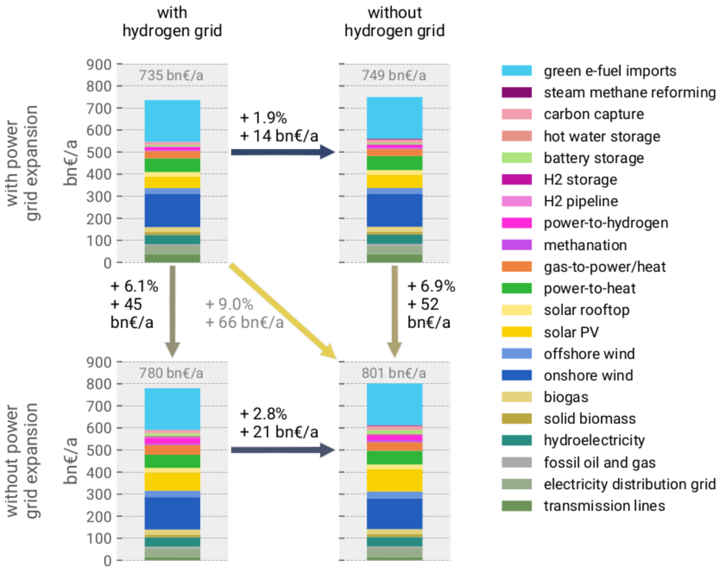
Green hydrogen with pipeline transport costs around ~ 80 €/MWh in model. Shipping green hydrogen from **outside Europe** in liquid, LOHC or NH_3 form may not compete on cost (depends e.g. on WACC), but scarce land in Europe may still drive adoption.





Source: **Hampp et al, 2021**

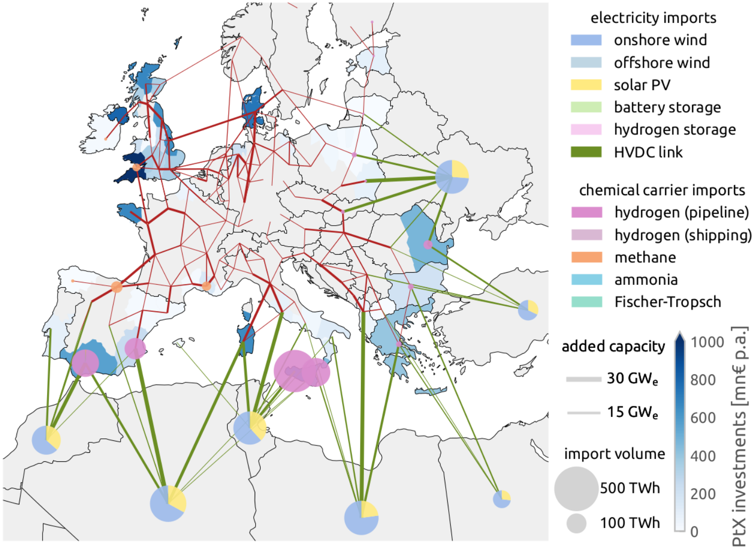
Synthetic fuels from outside Europe?



- Do the results change if we import e-fuels from outside Europe? Not really
- Hydrogen network is still used to transport hydrogen to spatially-fixed demands in industry, heavy trucks, backup power and heat
- Costs are similar, since need DAC for carbon outside of Europe; in Europe point sources of CO_2 suffice

Source: Neumann et al, 2023

With e-fuel, hydrogen and electricity imports instead of autarky

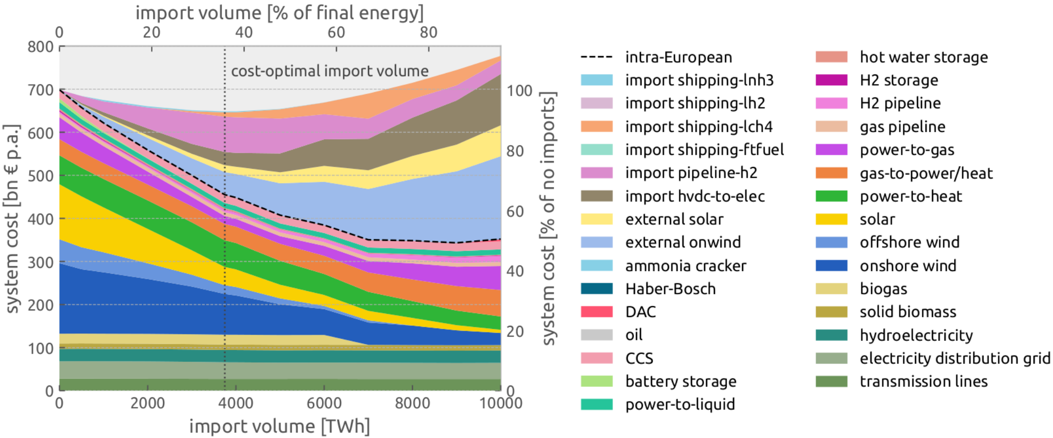


- Allowing imports of electricity, green hydrogen, e-fuels, **changes infrastructure needs completely**
- PtX out-sourced from Europe
- Electricity imported too, providing seasonal balancing

Source: Hampp, Brown, Neumann; 2022/3

E-fuel imports reduce costs, but not completely

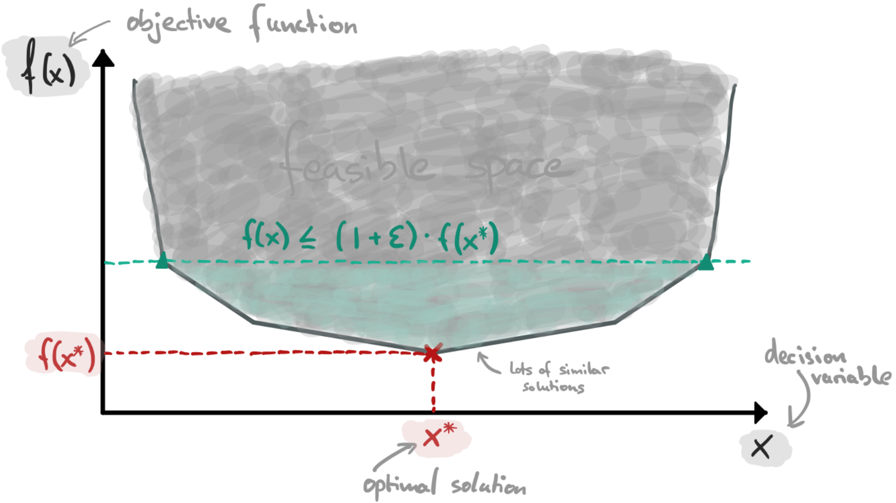
Cost-optimal import volume of 3750 TWh, reducing costs by 7% versus autarky.



Source: Hampp, Brown, Neumann; 2022/3

Large Space of Near-Optimal Energy Systems

There is a **large degeneracy** of different possible energy systems close to the optimum.

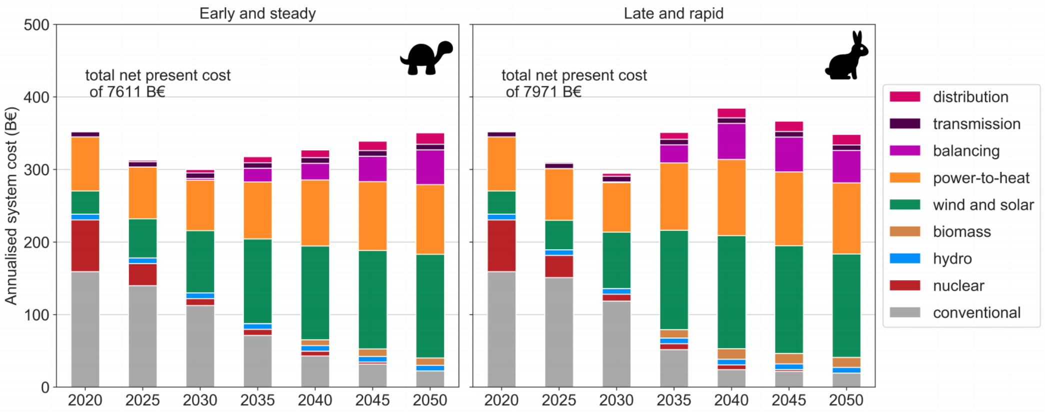


Source: Neumann & Brown, 2020

Pathway for European energy system from now until 2050

For a fixed CO_2 budget, it's more cost-effective to **cut emissions early** than wait.

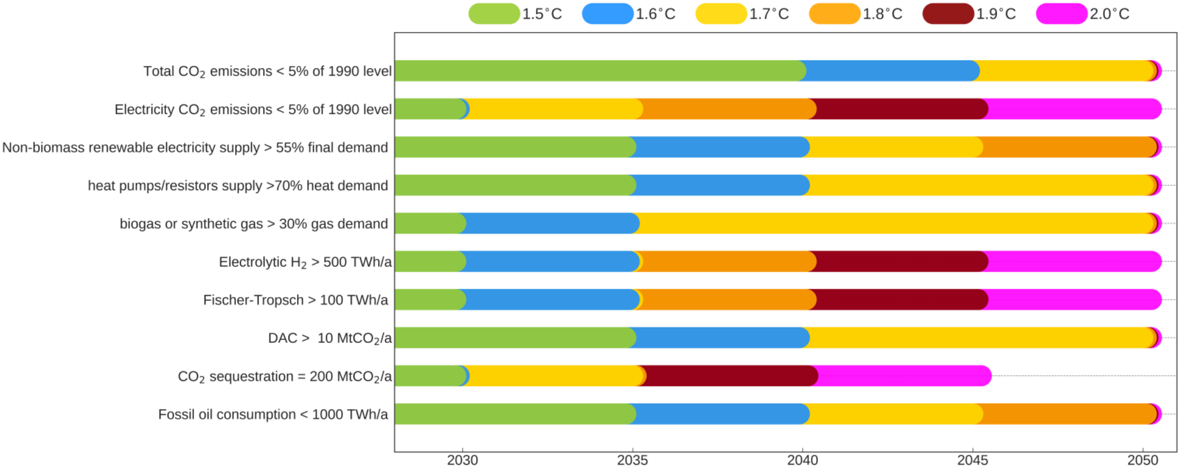
NB: These results only include electricity, heating in buildings and land-based transport.



Source: M. Victoria et al, Nature Communications (2020)

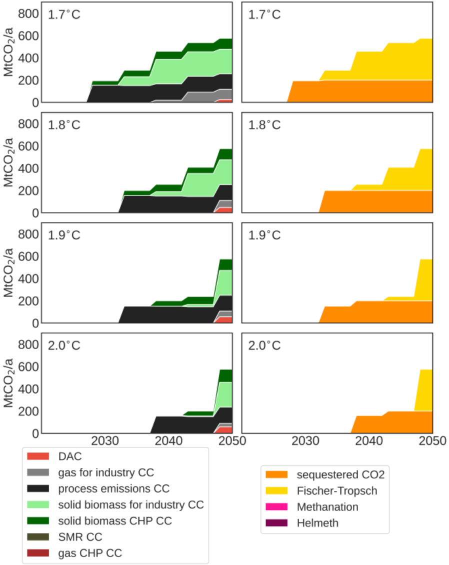
Appearance of technologies until 2050 depends on temperature target

Technische Universität Berlin



Source: M. Victoria et al, 2021

Carbon Management

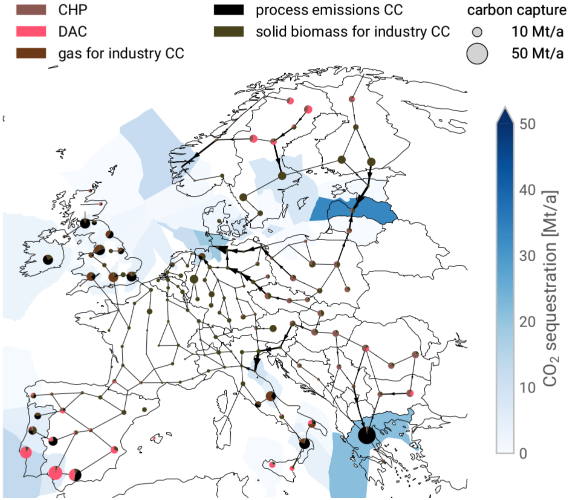


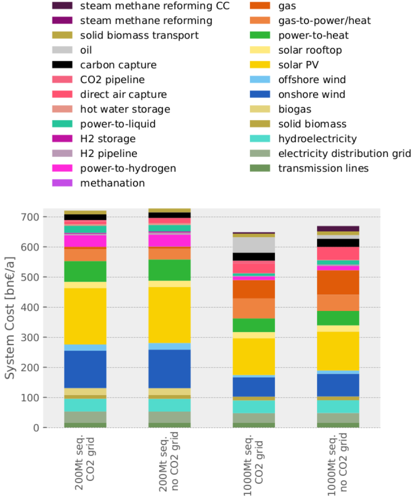
- Carbon capture (left): from process emissions, but also from heat production in industry and for combined-heat-and-power (CHP) plants
- Sequestration limited to 200 $MtCO_2/a$ (enough to cover today's process emissions)
- Further carbon capture is used for Fischer-Tropsch fuels (kerosene and naphtha)
- The tighter the CO_2 budget, the more is captured, and at some point direct air capture (DAC) also plays a role
- If sequestration is relaxed to 1000 $MtCO_2/a$, then CDR compensates unabated emissions elsewhere

Source: M. Victoria et al, 2021

Carbon management: value of CO_2 grid

Pipeline network for liquid carbon dioxide can reduce costs, particularly for large sequestration.



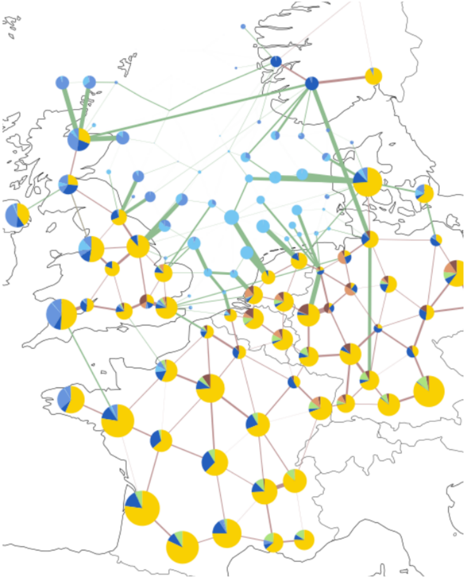


Source: F. Neumann, C. Tries, F. Hofmann, 2023

Future work

- Allow **industry relocation**
- Explore **circular carbon economy**
- Extend offshore wind potentials by including **floating wind** for depths > 50 m
- Examine benefits of offshore **hub-and-spoke grid topology**
- Proper consideration of **wake effects** (currently 11% linear reduction of CF)
- Cost-benefit of **sufficiency**
- Improving **open access** to models

Offshore network topology, floating wind



- How meshed does the offshore network need to be?
- Can offshore hubs and islands reduce costs?
- How do wake effects impact production for dense configurations?
- Should hydrogen be produced offshore on at landing points?
- Do we need floating wind if onshore potentials are limited?

Source: Philipp Glaum, 2023

PyPSA-Eur-Sec is **open source**. You can run your it with your own assumptions in a simplified **online version** of the model: **https://model.energy/scenarios/**

Basic scenario settings

Scenario name so you can identify the scenario later

no name

Fraction of 1990 CO2 emissions allowed	0	per unit
Sampling frequency (n-hourly for representative year)	193	integer >= 25

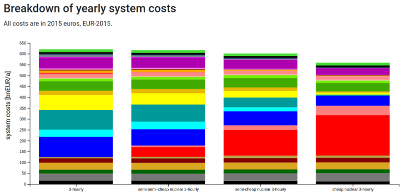
Demand

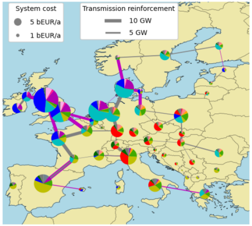
Demand for electricity in residential and services sector compared to today	0.9	per unit
Demand for space heating in buildings compared to today	0.71	per unit
Demand for hot water in buildings demand compared to today	1	per unit
Demand for land transport (road and rail) compared to today	1	per unit
Demand for shipping compared to today	1	per unit
Demand for aviation compared to today	1.2	per unit
Demand in industry compared to today	0.9	per unit

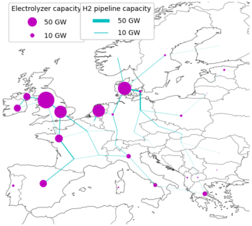
Sector coupling options

Yearly sequestration potential for carbon dioxide	200	MtCO2/a
Share of battery electric vehicles in land transport	0.85	per unit
Share of fuel cell electric vehicles in land transport	0.15	per unit

- [x] Allow battery electric vehicles to perform demand response







Hydrogen network scenario explorer: **https://h2-network.streamlit.app**

Conclusions

Conclusions

- There are **many trade-offs** to be made between cost, unpopular infrastructure, speed of implementation and security; but also many **near-optimal** compromise solutions
- Can work around transmission bottlenecks, but **costly** and needs **tight coordination**
- **Hydrogen networks** reduce system costs, especially if imports and power grid expansion are limited; but can avoid both power grid expansion and H_2 network (for a cost)
- The more restricted we are, the more **policy intervention** is required for joint planning, enabling local price signals, responsive demand and robust carbon pricing
- Many more **tricky topics to come**: e-fuel/material imports, industry relocation, geopolitical risk spreading, carbon transport, use and sequestration
- Need to find solutions which are **robust to uncertainty** $\Rightarrow$ calculate many scenarios
- **Openness and transparency** and critical to ensure **re-usability**, **customisability** and **swift policy response** by diverse actors

More information

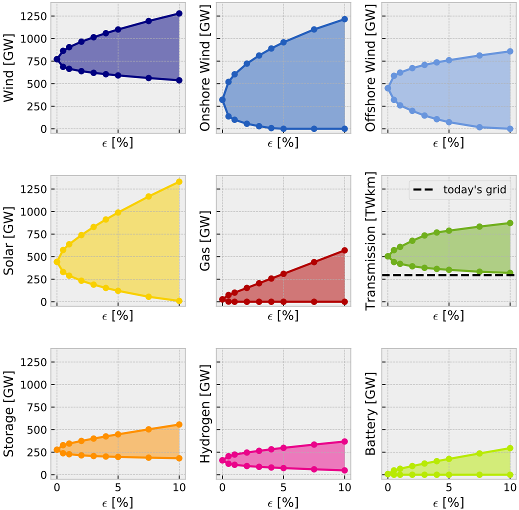
All input data and code for PyPSA-Eur-Sec is open and free to download:

1. `https://github.com/pypsa/pypsa`: The modelling framework
2. `https://github.com/pypsa/pypsa-eur`: The power system model for Europe
3. `https://github.com/pypsa/pypsa-eur-sec`: The full energy system model for Europe

Publications (selection):

1. F. Neumann, E. Zeyen, M. Victoria, T. Brown, *"Benefits of a Hydrogen Network in Europe,"* arXiv preprint (2022), **arXiv**.
2. M. Victoria, K. Zhu, T. Brown, G. B. Andresen, M. Greiner, *"Early decarbonisation of the European energy system pays off,"* Nature Communications (2020), **DOI**, **arXiv**.
3. T. Brown, D. Schlachtberger, A. Kies, S. Schramm, M. Greiner, *"Synergies of sector coupling and transmission reinforcement in a cost-optimised, highly renewable European energy system,"* Energy 160 (2018) 720-739, **DOI**, **arXiv**.
4. J. Hörsch, F. Hofmann, D. Schlachtberger and T. Brown, *"PyPSA-Eur: An open optimization model of the European transmission system,"* Energy Strategy Reviews (2018), **DOI**, **arXiv**
5. T. Brown, J. Hörsch, D. Schlachtberger, *"PyPSA: Python for Power System Analysis,"* Journal of Open Research Software, 6(1), 2018, **DOI**, **arXiv**.
6. D. Schlachtberger, T. Brown, S. Schramm, M. Greiner, *"The Benefits of Cooperation in a Highly Renewable European Electricity System,"* Energy 134 (2017) 469-481, **DOI**, **arXiv**.

Example: 100% renewable electricity system for Europe



Within 10% of the optimum we can:

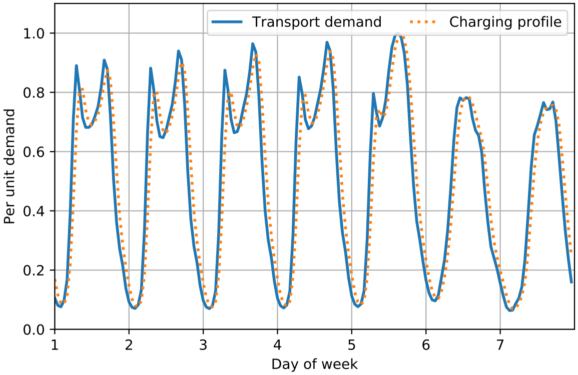
- Eliminate most grid expansion
- Exclude onshore or offshore wind or PV
- Exclude battery or most hydrogen storage

Robust conclusions: wind, some transmission, some storage, preferably hydrogen storage, required for a cost-effective solution.

This gives space to choose solutions with **higher public acceptance**.

Source: Neumann & Brown, 2020

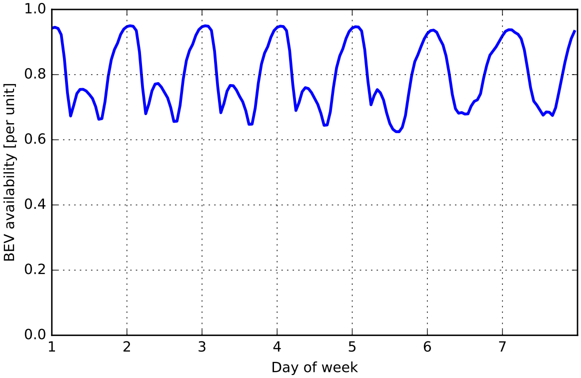
Transport sector: Electrification of Transport



Weekly profile for the transport demand based on statistics gathered by the German Federal Highway Research Institute (BASt).

- Road and rail transport is fully electrified (vehicle costs are not considered)
- Because of higher efficiency of electric motors, final energy consumption 3.5 times lower than today at 1100 TWh_{el}/a for Europe
- In model can replace Battery Electric Vehicles (BEVs) with Fuel Cell Electric Vehicles (FCEVs) consuming hydrogen. Advantage: hydrogen cheap to store. Disadvantage: efficiency of fuel cell only 60%, compared to 90% for battery discharging.

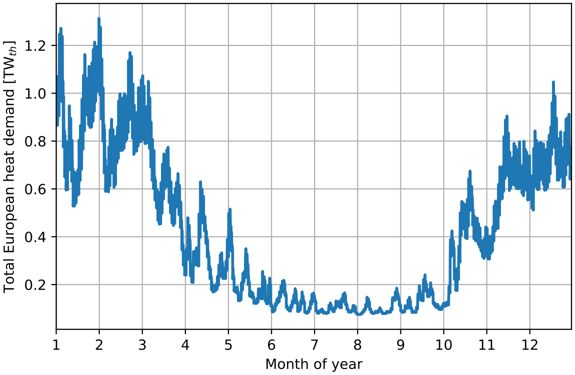
Transport sector: Battery Electric Vehicles



Availability (i.e. fraction of vehicles plugged in) of Battery Electric Vehicles (BEV).

- Passenger cars to Battery Electric Vehicles (BEVs), 50 kWh battery available and 11 kW charging power
- Can participate in DSM and V2G, depending on scenario (state of charge returns to at least 75% every morning)
- All BEVs have time-dependent availability, averaging 80%, max 95% (at night)
- No changes in consumer behaviour assumed (e.g. car-sharing/pooling)
- BEVs are treated as exogenous (capital costs NOT included in calculation)

Heating sector: Many Options with Thermal Energy Storage (TES)



Heat demand profile from 2011 in each region using population-weighted average daily T in each region, degree-day approx. and scaled to Eurostat total heating demand.

- All space and water heating in the residential and services sectors is considered, with no additional efficiency measures (conservative) - total heating demand is 3585 TWh_{th}/a.
- Heating demand can be met by heat pumps, resistive heaters, gas boilers, solar thermal, Combined-Heat-and-Power (CHP) units. No industrial waste heat.
- Thermal Energy Storage (TES) is available to the system as hot water tanks.

We model both fully decentralised heating and cases where up to 45% of heat demand is met with district heating in northern countries. Heating technology options for buildings:

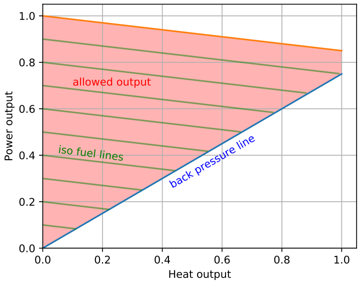
Decentral individual heating can be supplied by:

- Air- or Ground-sourced heat pumps
- Resistive heaters
- Gas boilers
- Small solar thermal
- Water tanks with short time constant $\tau = 3$ days

Central heating can be supplied via district heating networks by:

- Air-sourced heat pumps
- Resistive heaters
- Gas boilers
- Large solar thermal
- Water tanks with long time constant $\tau = 180$ days
- CHPs

CHP feasible dispatch:



Building renovations can be co-optimised to reduce space heating demand.