What infrastructure gets us to climate neutrality – without breaking the bank?

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Energy Innovation Summit, Berlin, 24th June 2025

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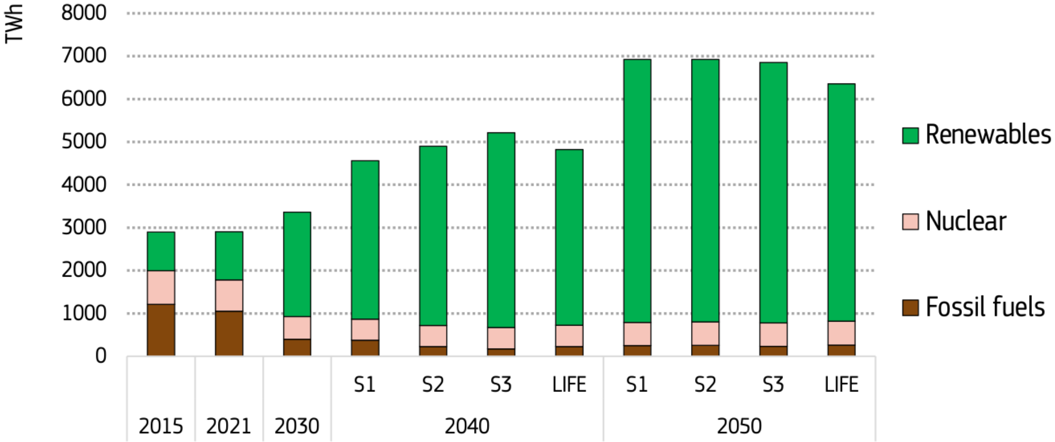
Big Picture

2050 scenarios for EU: electricity doubles, renewables dominate



Source: [EU COM 2040 Impact Assessment, 2040]

Challenge: variability of wind & solar in time...

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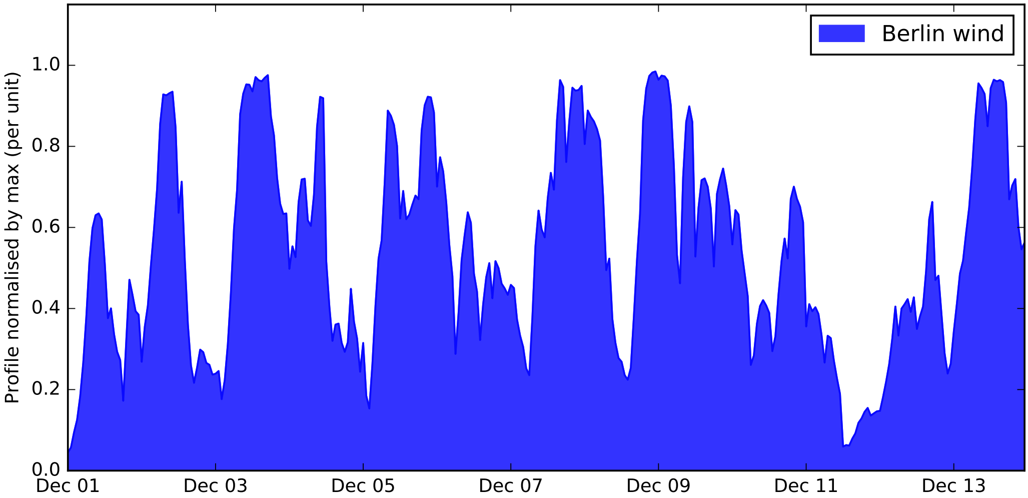
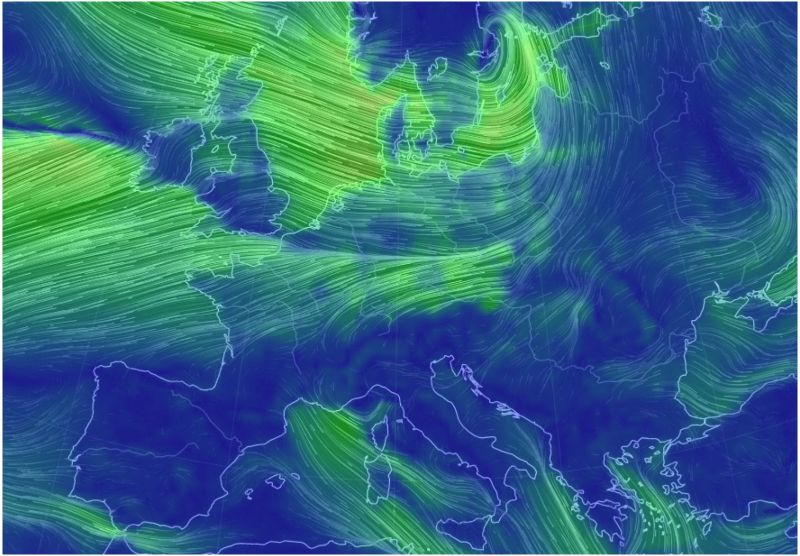


… and space



Also strong variability from electrified heating and transport demand

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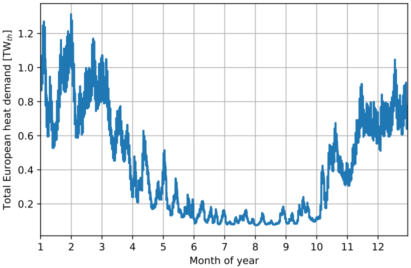
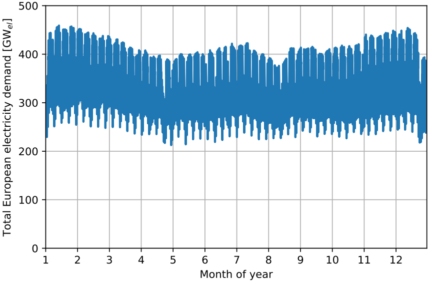
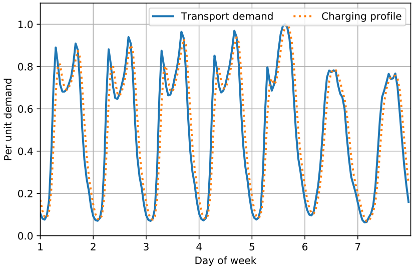
Compared to electricity, heating and transport are **strongly peaked**.

- Heating is strongly seasonal, but also with weekly variations.
- Transport has strong daily periodicity.



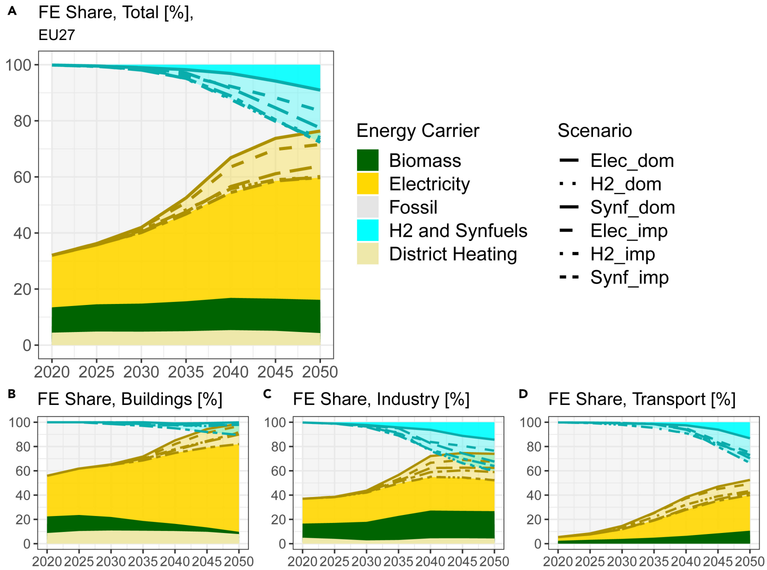




First Conclusion

Electricity variability needs infrastructure for balancing, including storage, demand-management and grids.

Final energy: electricity doubles, hydrogen/biomass/CCS for rest



Source: Schreyer et al, 2024

Energy scenarios: consensus versus uncertainty

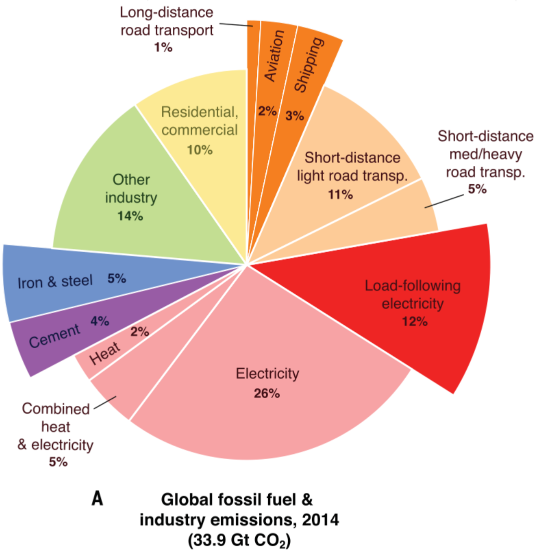
Consensus that first ~80% of energy emissions can be addressed at low cost by:

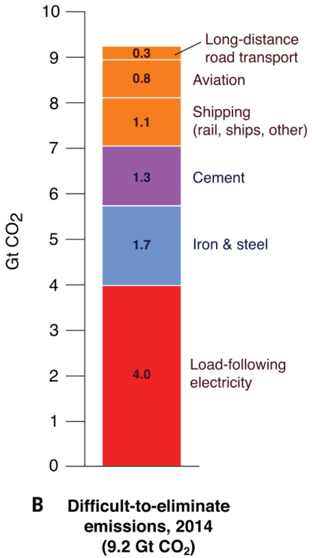
- **Decarbonisation of bulk of electricity** by 2035, mostly by renewables, requiring storage and grid expansion
- **Electrification of demand**, e.g. land transport, building heating, medium-temperature process heat, domestic shipping, short-hop aviation

Uncertainty on final hard-to-abate ~20% (backup electricity/heat, fuels for longhaul shipping & aviation, steel, chemicals). Several options can meet these demands, none without problems:

- **Hydrogen and its derivatives**, but they are expensive
- **Biomass**, but sustainable sources without additional land use are limited
- **Carbon capture and sequestration (CCS)**, or compensating unabated fossil use with carbon dioxide removal (CDR), but sequestration rate may be limiting

∼20% of hard-to-abate emissions





Source: Davis et al, 2018

What infrastructures do we need?

- **Electricity transport** to connect renewable sites to demand and balance variability
- **Hydrogen transport** where we need hydrogen for non-electrifiable energy/feedstocks (can also be **derivatives** like ammonia, methanol, hydrocarbons)
- **Carbon (dioxide) transport** for fuels, feedstocks and sequestration (can also be **derivatives** like methanol, hydrocarbons)

But what is **strictly necessary** and what are the **trade-offs**?

Second Conclusion

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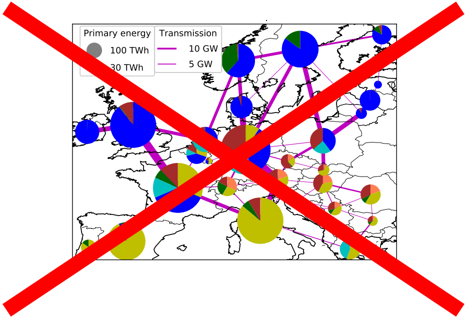
There is considerable uncertainty about the last 20% of emissions, which has strong effects on infrastructure.

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



Challenge 1: Need spatial resolution to see grid bottlenecks & infrastructure trade-offs.
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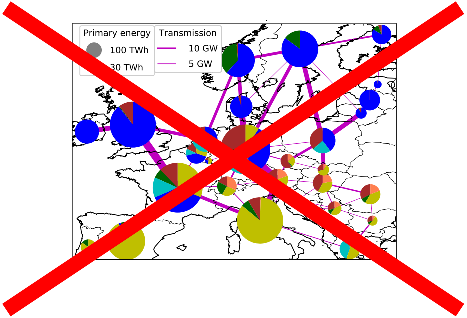
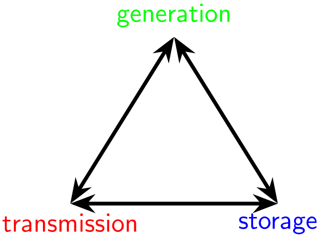


Challenge 2: Need to co-optimise balancing solutions with generation.
⇒ Optimising separately is inefficient.

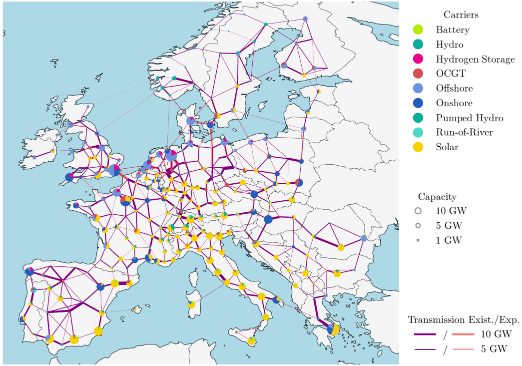


⇒ Need **very large** models, complexity management and **performant optimisation**

PyPSA Framework and PyPSA-Eur Model

Python for Power System Analysis (PyPSA)

- **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.

Python for Power System Analysis (PyPSA)

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Capabilities

- **capacity expansion planning** (linear)
- **market modelling** (linear, quadratic)
- **power flow** (non-linear)

with components for:

- AC and DC **power networks**
- generators with **unit commitment**
- **variable generation** with time series
- **storage** and **conversion**
- **power-to-mobility/heat/gas**

Backend

- PyPSA integrates with **widely-used Python** programming language ecosystem
- all data for components stored in **pandas** DataFrames for easy manipulation
- **optimisation framework linopy** built for large networks and long time series
- interfaces to **major solvers** (Gurobi, CPLEX, Express, cbc, glpk, etc.)
- suitable for **greenfield**, **brownfield** and **pathway** planning
- **no GUI yet** but Jupyter notebooks

Optimisation of annual system costs

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

$$\text{Minimise}\left(\begin{matrix}\textbf{Yearly}\\ \textbf{system costs}\end{matrix}\right) = \sum_{n}\left(\begin{matrix}\textbf{Annualised}\\ \textbf{fixed costs}\end{matrix}\right) + \sum_{n,t}\left(\begin{matrix}\textbf{Variable}\\ \textbf{costs}\end{matrix}\right)$$

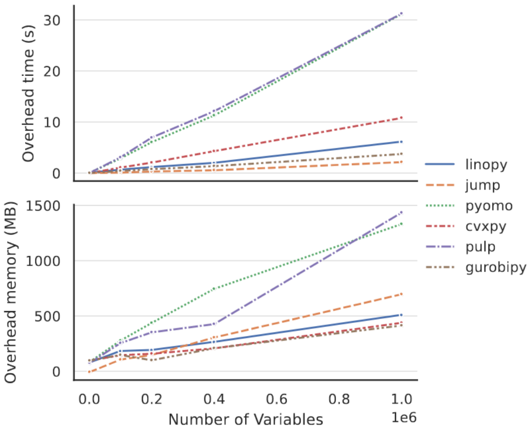
subject to

- 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: investment optimisation, multi-period with linear power flow.

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

Customizability with linopy



- PyPSA uses open-source **linopy** optimisation framework
- linopy is flexible and performant for **large optimisation models**
- supports linear, mixed-integer and quadratic programming
- based around **xarray** for flexible data-handling features
- supports **major solvers** (Gurobi, Cplex, Xpress, HiGHS, Cbc, GLPK)

Source: **Hofmann, linopy, 2023**

Example customization of linopy model in PyPSA

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```
network.optimize.create_model()

#grab generator capacities
p_nom = network.model["Generator-p_nom"]

#make the sum bigger than 10 GW
network.model.add_constraints(p_nom.sum() >= 1e4, name="cap_constraint")

network.optimize.solve_model(solver_name="gurobi")
```

Recent developments for PyPSA

Recently we have implemented:

- **Elastic demand** via quadratic programming (to complement standard VOLL and battery-like DSR)
- **Improvements to unit commitment approximations**
- **Modelling-to-generate-alternatives (MGA)**
- **New network clustering algorithms**
- **Stochastic and robust optimisation** (e.g. over gas prices and other inputs)
- **Learning curves** for multiple investment horizons

Links to further resources

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Python for Power System Analysis (PyPSA):

a free software toolbox for simulating and optimising modern power systems

- **GitHub**: https://github.com/PyPSA/PyPSA
- **Documentation**: https://pypsa.readthedocs.io/
- **Examples** showcasing open data: https://pypsa.readthedocs.io/
- **Training course**: https://fneum.github.io/data-science-for-esm/intro.html
- **Mailing list**: https://groups.google.com/forum/#!forum/pypsa
- **Research paper description**: https://arxiv.org/abs/1707.09913

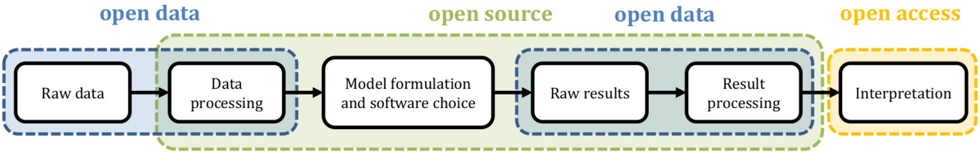
What is open modelling?

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

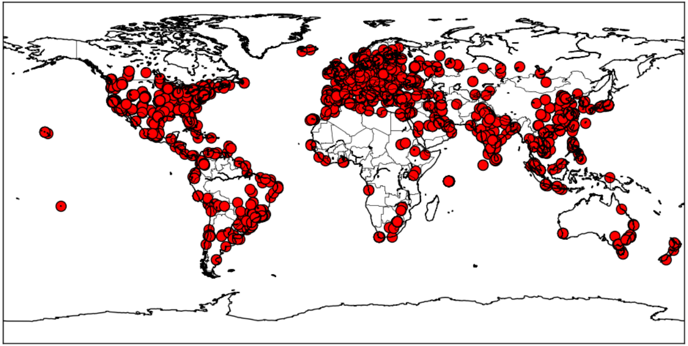
Open means that anybody is free to download the software/data/publications, inspect it, machine process it, share it with others, modify it, and redistribute the changes.

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:

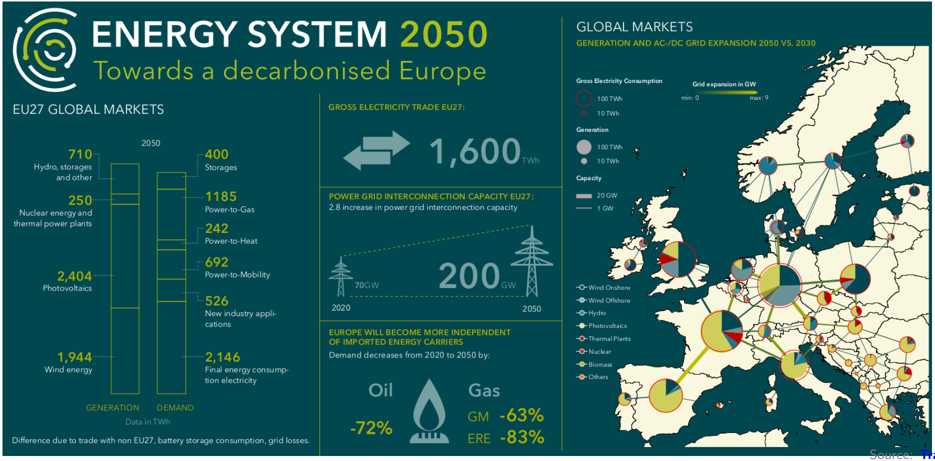


PyPSA is used worldwide by **dozens of research institutes and companies** (IEA, TU Delft, KIT, Octopus Centre for Net Zero, CLIMACT, Fraunhofer ISI/IEG/ISE, Shell, TSOs TransnetBW and APG, TERI, Agora Energiewende, RMI, Ember, Instrat, Climate Analytics, DLR, FZJ, RLI, Saudi Aramco, Edison Energy, spire and many others). Used for studies for government ministries in EU Commission, Netherlands, Flanders, Canada and elsewhere. Open models available for almost all countries.



PyPSA example: TransnetBW used PyPSA-Eur

German **Transmission System Operator (TSO) TransnetBW** used an open model (PyPSA-Eur) 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: International Energy Agency (IEA)

For the World Energy Outlook (WEO) 2023 the IEA used PyPSA coupled to their Global Energy and Climate (GEC) model to investigate seasonal variability and long-term storage.

Modelling seasonal variability and long-term storage

To assess the impact of weather-induced variability on power system operations and long-term flexibility needs in systems characterised by rising shares of variable renewables and temperature-sensitive end-uses such as electric heating and cooling, a new hourly dispatch model was developed for the *WEO-2023*. Building on the annual projections of the GEC Model, it is applied to quantify power system flexibility needs on timescales ranging from hours over days and weeks to seasons and identify how these needs can be met in a cost-optimal manner. It represents all hours in a year, setting the objective of meeting electricity demand in each hour of the year at the lowest possible cost, while respecting operational constraints. The model was built in Python using the *PyPSA* open-source python environment for energy system modelling[3] and is solved using linear optimisation. The optimisation ensures that power plants, energy storage technologies, demand response and electrolysers are operated in a way that minimises the total system cost (thus maximising their utility to the system).

Source: GEC Model Documentation, 2023

JRC used PyPSA for Redispatch Study in 2024

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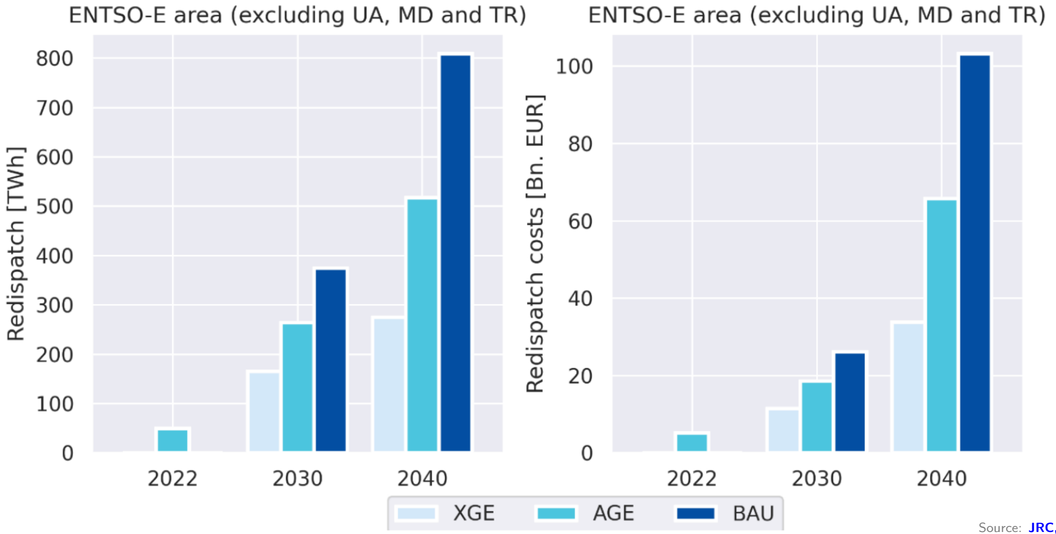
JRC used PyPSA-Eur for their study of redispatch and congestion management in Europe.



Source: JRC, 2024

PyPSA for flexibility needs by ACER

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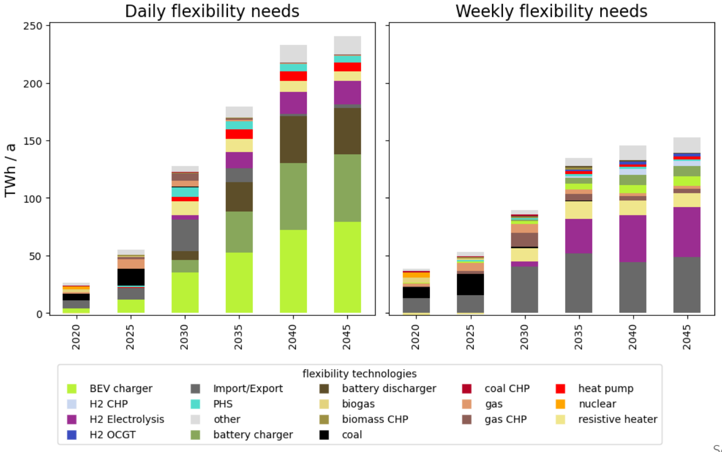
ACER has chosen PyPSA for its **EU-wide flexibility needs assessment** for use in its EU-Flex Platform. They are supported here by Open Energy Transition GmbH. Example decomposition of **flexibility needs** in Germany from **Ariadne Scenario Report**:



Source: ACER, 2025,Ariadne, 2025

ENTSO-E collaborating on project with PyPSA for TYNDP

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🔧 ENTSO-E collaborates on open-source tools for energy planning 🔍

ENTSO-E's TYNDP and adequacy studies rely on a comprehensive suite of modelling tools used by TSO experts. To enhance transparency, reproducibility, and accessibility, we are working on fit-for-purpose open-source tools that complement our existing planning data and methodologies.

🚀 In collaboration with Open Energy Transition , we have launched a research and innovation project to develop a complementary open-source tool in PyPSA for Scenario Building and Cost-Benefit Analysis within the TYNDP process. A first workshop on 16 January brought together TSO and OET experts to explore how PyPSA can be integrated into the modelling suite.

#EnergyTransition #OpenSource #Innovation #TYNDP

Source: ENTSO-E, 2025

Study for Google on 24/7 Carbon-Free Energy (CFE)

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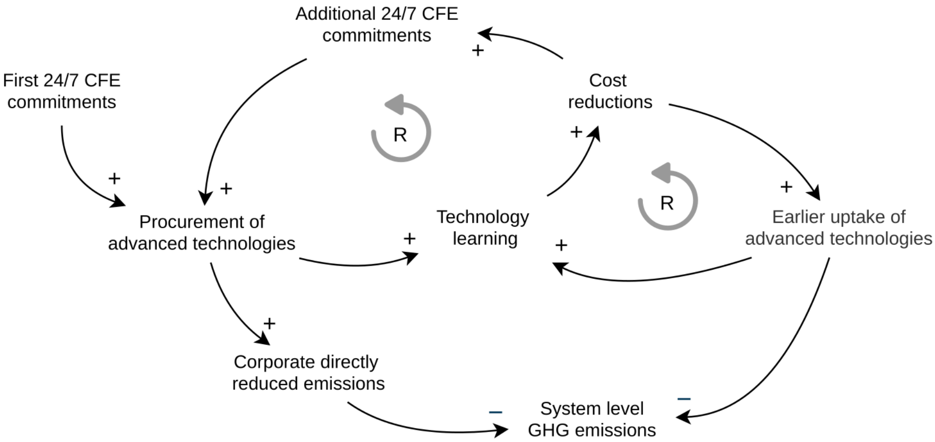
In a study for Google we showed how **hourly-matched** power purchase agreements, known as **24/7 CFE**, not only reduce emissions directly, but also **stimulate innovation** in new technologies like long-duration storage or advanced dispatchable generation (e.g. geothermal).

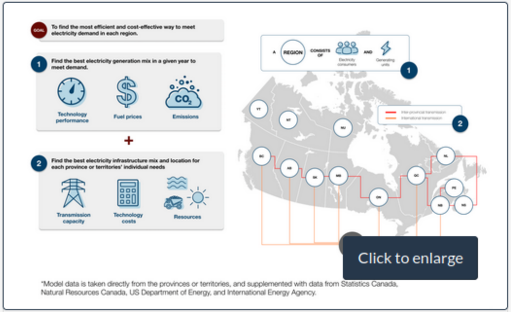


Source: Riepin et al, 2025

Canadian Energy Regulator (CER): Energy Future (EF) reports

The CER has used PyPSA since 2023 for its Energy Future reports.

Figure A3.3: Electricity Supply Model (ESM) overview



▸ Source and Description

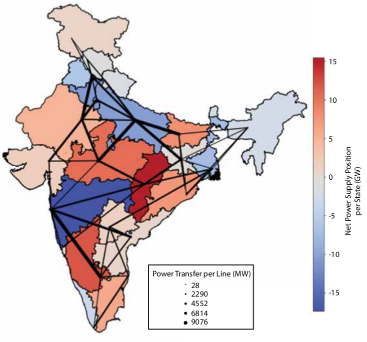
Electricity

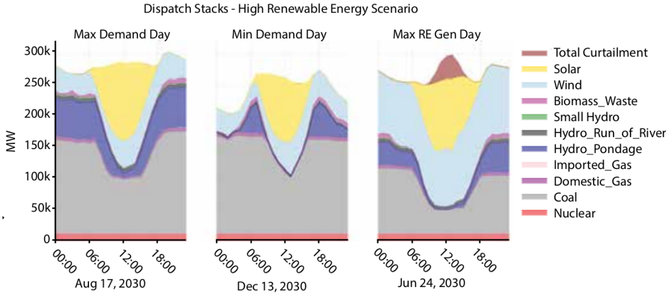
The electricity projections are created using a CER-developed model. The core model is developed based on Python for Power System Analysis (PyPSA), an open-source, electric power system planning and simulation model. The CER model simulates how the future electricity demand of the different Canadian economic sectors is satisfied by a combination of electricity-generating units and delivery systems. It models electricity-generating and storage units (including their technical and economic attributes), electricity transmission infrastructure, energy resource availability, electricity demand, and applicable regulations. The model simulates the operation of electric power systems at hourly intervals.

Source: CER EF 2023

PyPSA example: TERI in India: 2030 study

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





Source: TERI 2020

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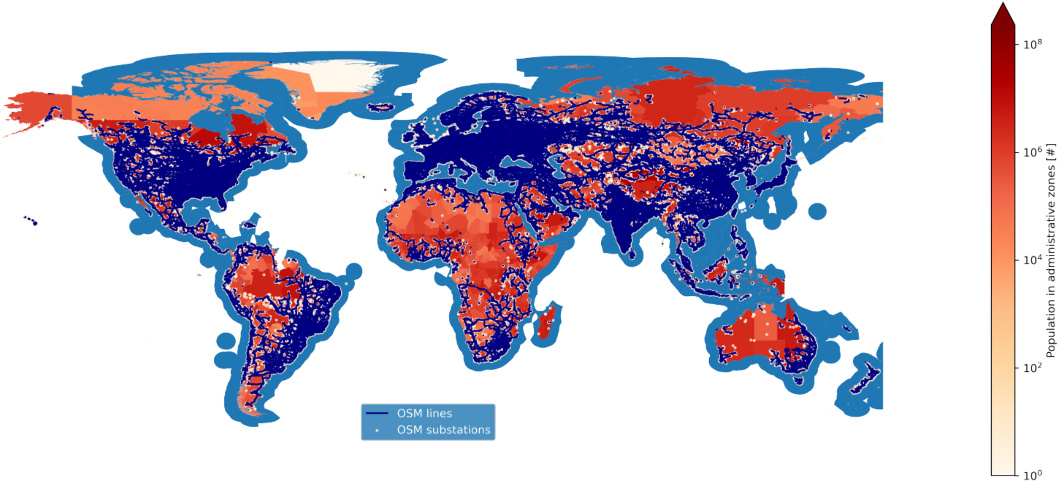
The **PyPSA meets Earth** initiative is enabling datasets in PyPSA for the planet.



Source: PyPSA meets Earth, 2022

What is PyPSA-Eur?

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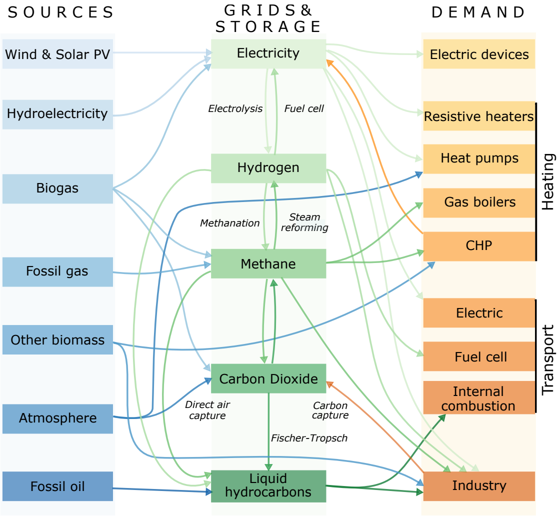
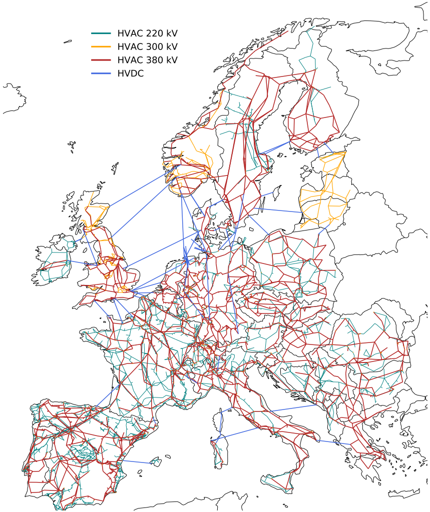
Model for Europe with all energy flows...



and bottlenecks in energy networks.

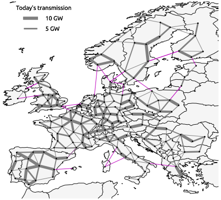


Data-driven energy modelling

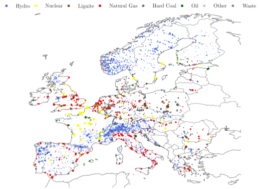
Lots of different types of data and process knowledge come together for the modelling.

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

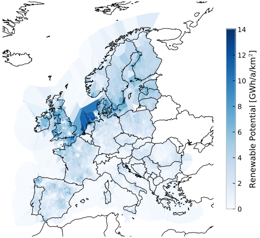
clustered network model



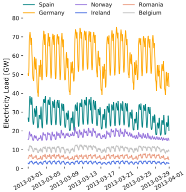
power plants and technology assumptions



renewable potentials and hourly time series for each region



demand projections time series



Only openly-available data

Files	BY	NC	SA	Mark Changes	Detail
corine/*	x			x	https://land.copernicus.eu/pan-european/corine-land-cover/clc-2012?tab=metadata
eez/*	x	x	x		http://www.marineregions.org/disclaimer.php
natura/*	x				https://www.eea.europa.eu/data-and-maps/data/natura-10#tab-metadata
naturalearth/*					http://www.naturalearthdata.com/about/terms-of-use/
NUTS_2013 _60M_SH/*	x	x		x	https://ec.europa.eu/eurostat/web/gisco/geodata/reference-data/administrative-units-statistical-units
cantons.csv	x		x		https://en.wikipedia.org/wiki/Data_codes_for_Switzerland
EIA_hydro_generation _2000_2014.csv	x				https://www.eia.gov/about/copyrights_reuse.php
GEBCO_2014_2D.nc	x				https://www.gebco.net/data_and_products/gridded_bathymetry_data/documents/gebco_2014_historic.pdf
hydro_capacities.csv	x				
je-e-21.03.02.xls	x	x			https://www.bfs.admin.ch/bfs/en/home/fso/swiss-federal-statistical-office/terms-of-use.html
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description	file/folder	licence	source
JRC IDEES database	jrc-idees-2015/	CC BY 4.0	https://ec.europa.eu/jrc/en/potencia/jrc-idees
urban/rural fraction	urban_percent.csv	unknown	unknown
JRC biomass potentials	biomass/	unknown	https://doi.org/10.2790/39014
JRC ENSPRESO biomass potentials	remote	CC BY 4.0	https://data.jrc.ec.europa.eu/dataset/74ed5a04-7d74-4807-9eab-b94774309d9f
EEA emission statistics	eea/UNFCCC_v23.csv	EEA standard re-use policy	https://www.eea.europa.eu/data-and-maps/data/national-emissions-reported-to-the-unfccc-and-to-the-eu-greenhouse-gas-monitoring-mechanism-16
Eurostat Energy Balances	eurostat-energy_balances-*/	Eurostat	https://ec.europa.eu/eurostat/web/energy/data/energy-balances
Swiss energy statistics from Swiss Federal Office of Energy	switzerland-sfoe/	unknown	http://www.bfe.admin.ch/themen/00526/00541/00542/02167/index.html?dossier_id=02169
BASt emobility statistics	emobility/	unknown	http://www.bast.de/DE/Verkehrstechnik/Fachthemen/v2-verkehrszaehlung/Stundenwerte.html?nn=626916

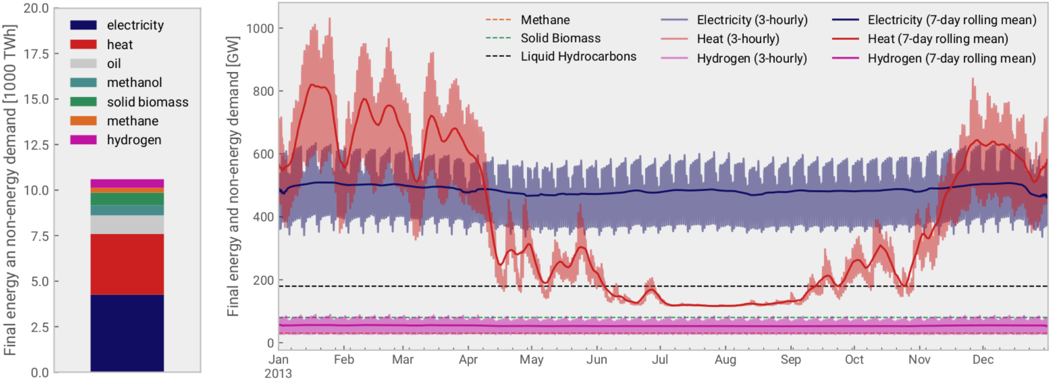
Source: PyPSA-Eur documentation

Workflow tool snakemake manages processing of data

- Workflow tool **snakemake** manages many scripts to process data
- Raw input data is processed (e.g. wind speeds into wind power plant hourly capacity factors; geospatial data into installable potentials)
- PyPSA model is built
- Then the model is solved for several parameters (e.g. sensitivity sweep)
- Then the results are processed and graphed

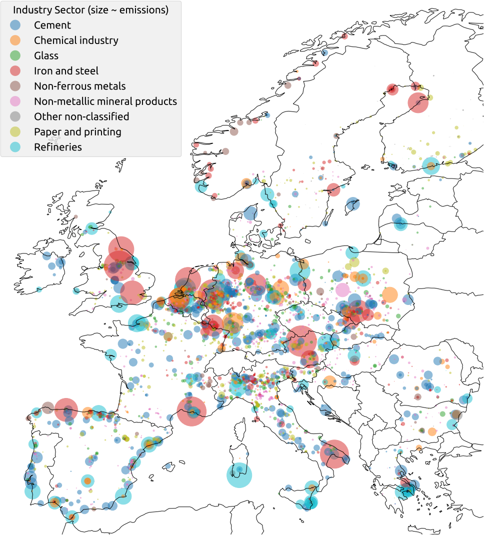
Source: **PyPSA-Eur documentation**

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



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

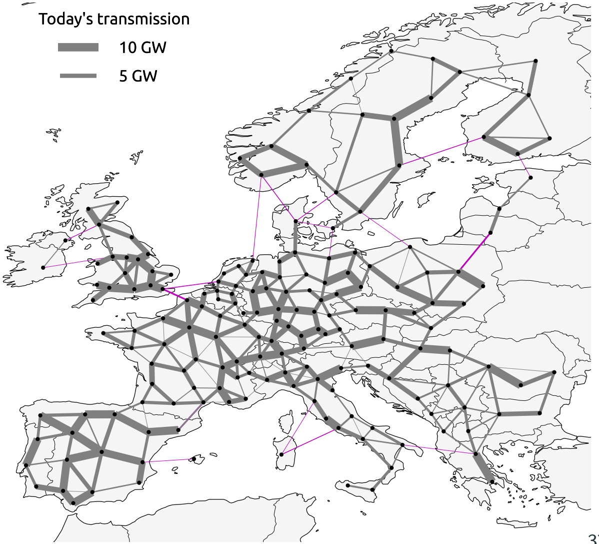
Source: Fraunhofer ISI

Potential Roles for Hydrogen and Carbon Dioxide Networks

- Couple **all energy sectors** (power, heat, transport, industry)
- Reduce net CO_2 emissions **to zero**
- Base case of **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**



Distribution of technologies: double today's power grid volume

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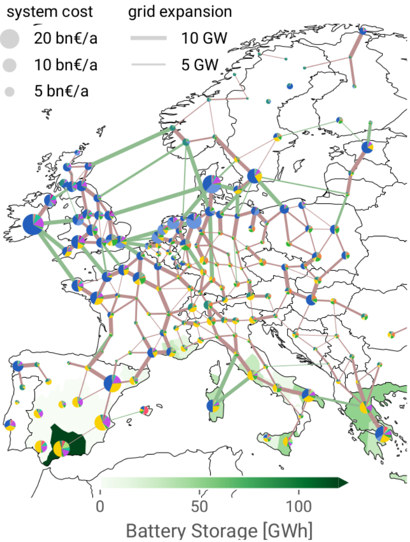
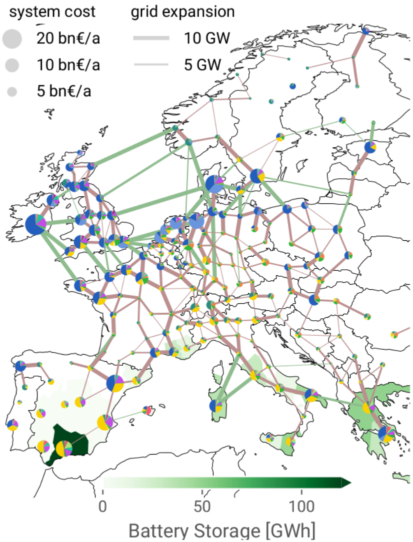
Electricity grid expansion of 413 TWkm...



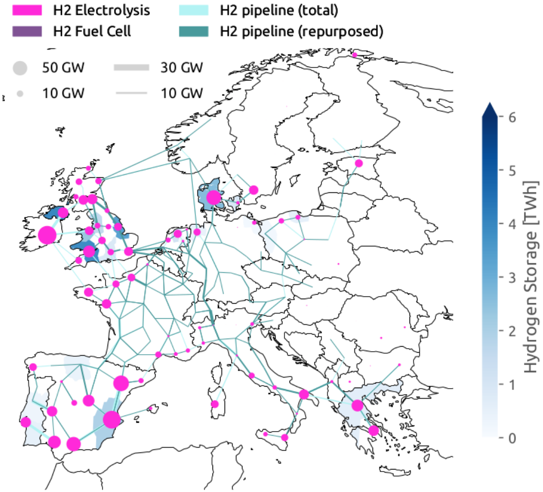
Source: Neumann et al, 2023

Distribution of technologies: double today's power grid volume

Electricity grid expansion of 413 TWkm...

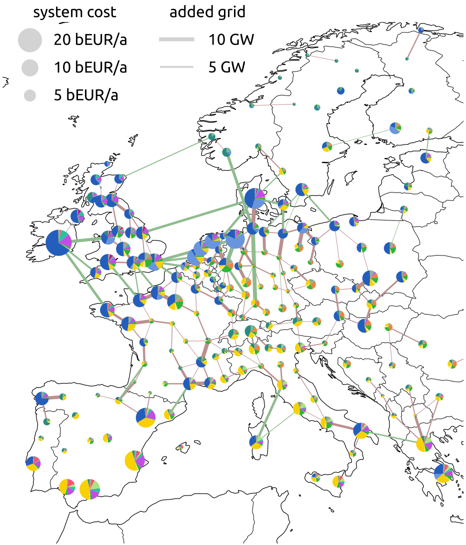


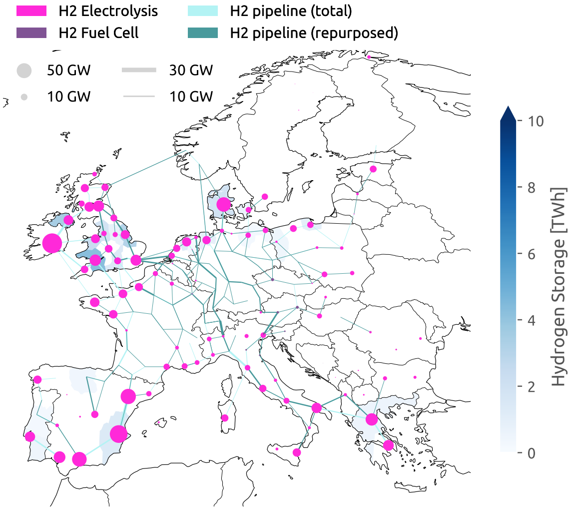
...and new hydrogen grid of 204 TWkm.



Source: Neumann et al, 2023

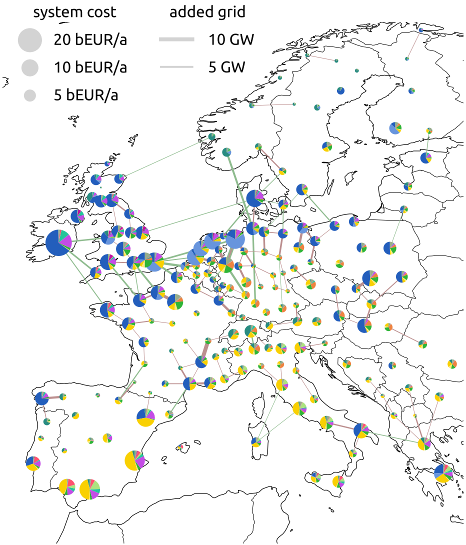
Distribution of technologies: 50% more power grid volume

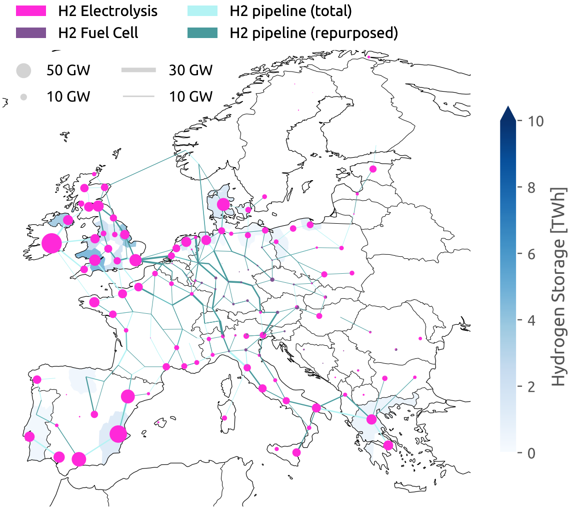




Source: Neumann et al, 2023

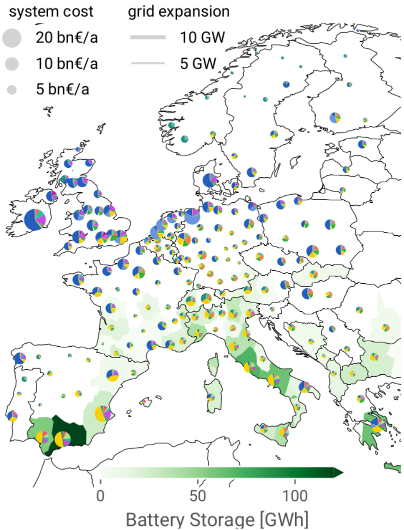
Distribution of technologies: 25% more power grid volume



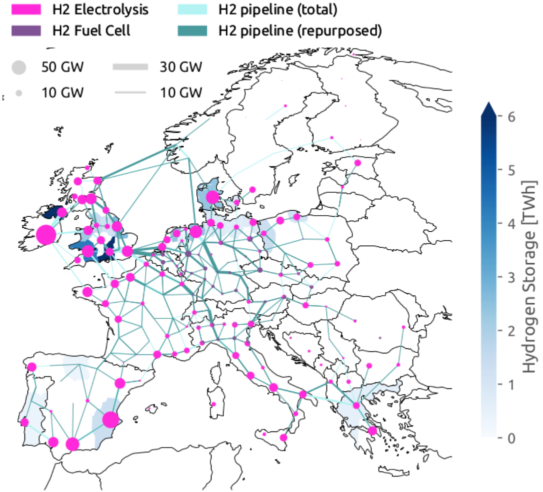


Source: Neumann et al, 2023

No electricity grid expansion...

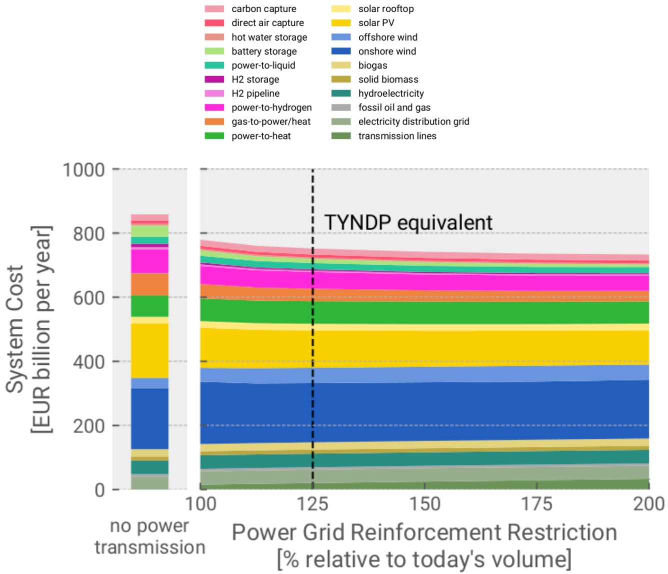


...and new hydrogen grid of 307 TWkm.



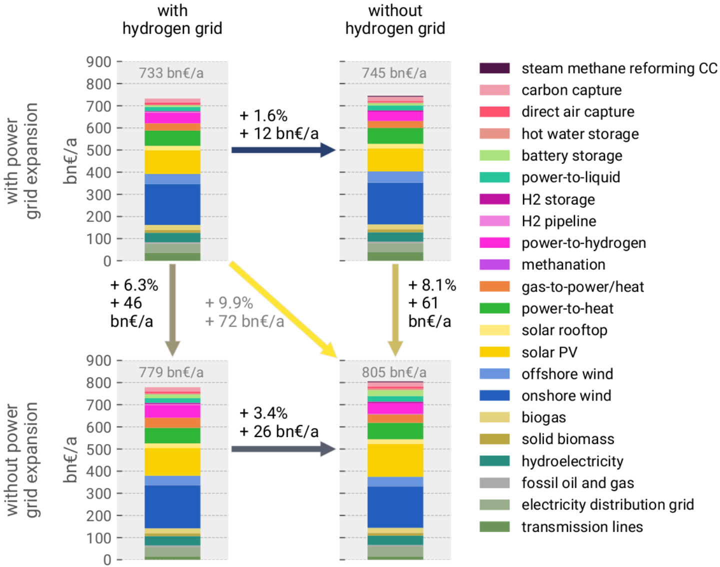
Source: Neumann et al, 2023

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)

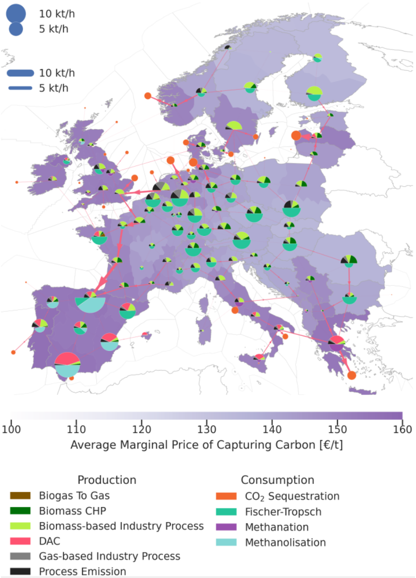
With and without hydrogen network



- **Net benefit** of hydrogen network: € 12-26 billion per year (1.6-3.4% of total)
- Hydrogen network brings **robust benefit** if you assume energy autarky and no industry relocation
- Benefit is strongest without power grid expansion
- Power grid expansion is better if you have to choose

Source: Neumann et al, 2023

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

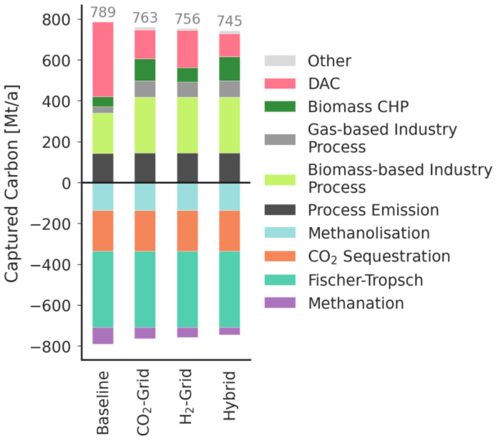


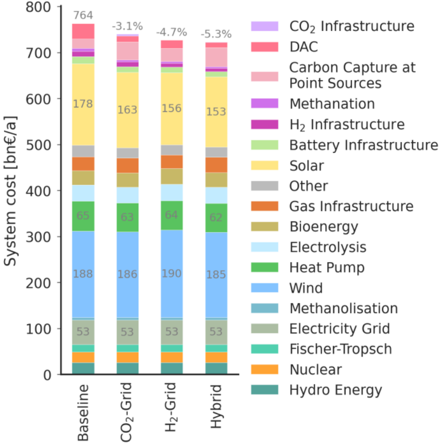
- Need **carbon capture** with **sequestration** (CCS) for industrial process emissions (e.g. from cement), with **usage** (CCU) for synfuels and basic chemicals, net **carbon dioxide removal** (CDR) for unabatable and negative emissions
- These are grouped under **carbon dioxide management**
- For synthetic 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: Hofmann et al, 2024

Use networks to align sinks and sources spatially, avoid DAC

Scenarios: 'Baseline' without H_2 or CO_2 networks, only one, or a 'Hybrid' with both.
Benefit of both: maximise use of sustainable biomass, **minimise direct air capture** (DAC).

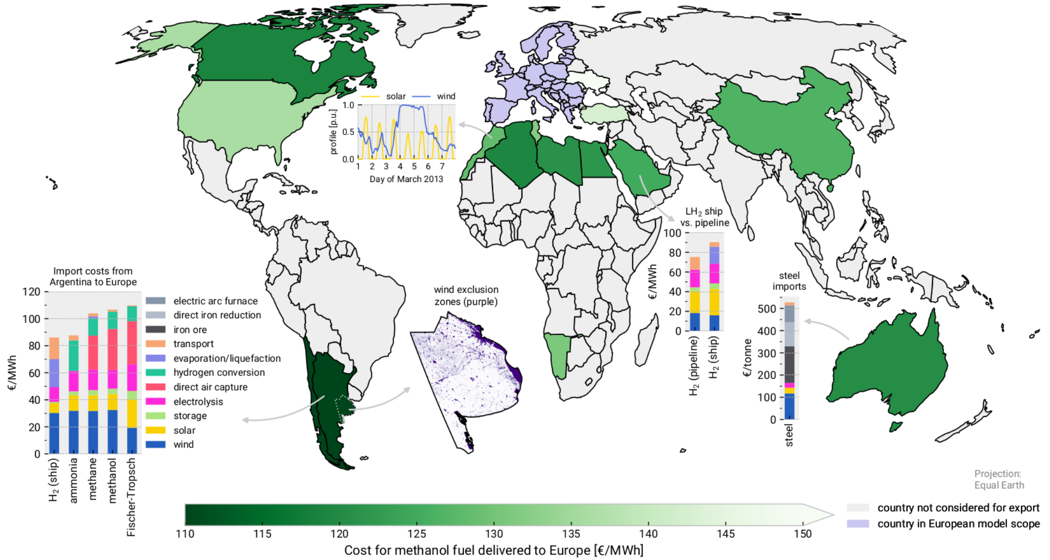




Source: Hofmann et al, 2024

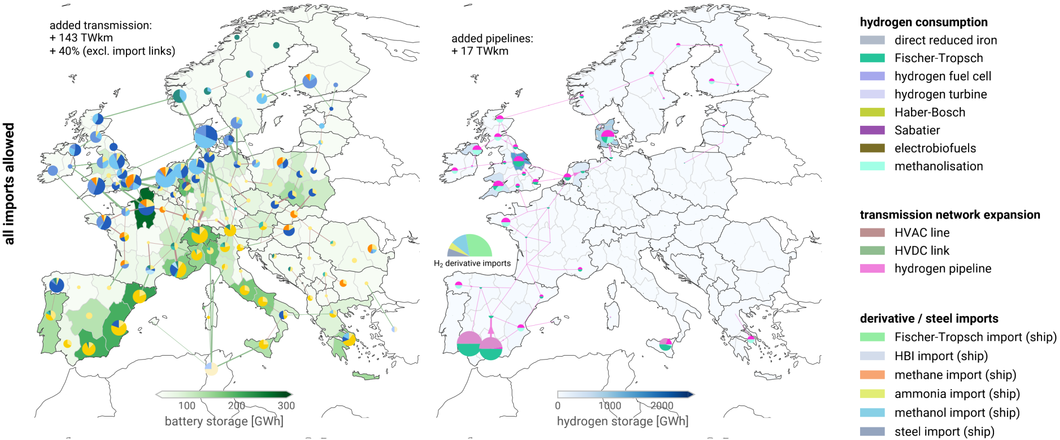
Highlights from Other Projects

Allowing global green energy imports to Europe



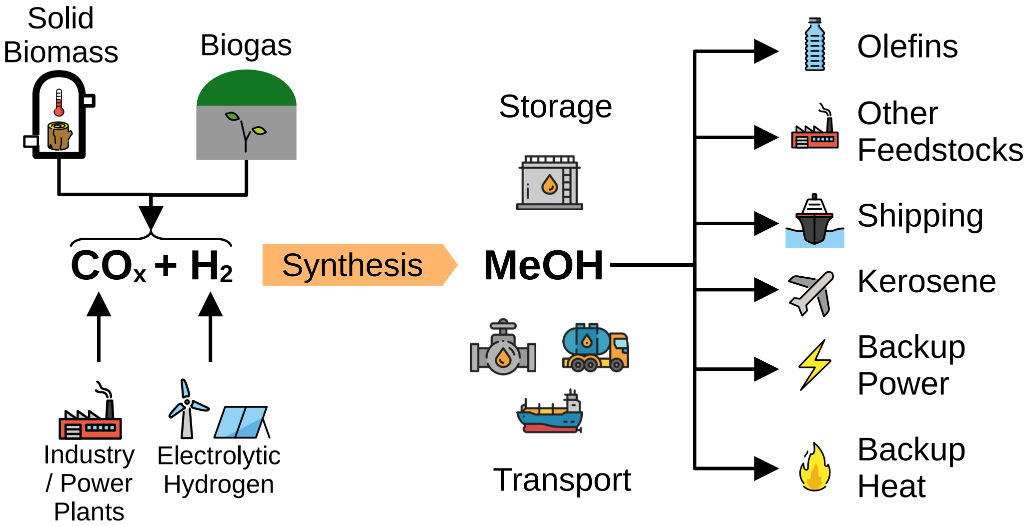
Source: Neumann et al, 2024

Allowing ~2000 TWh/a of green imports reduces H_2 network



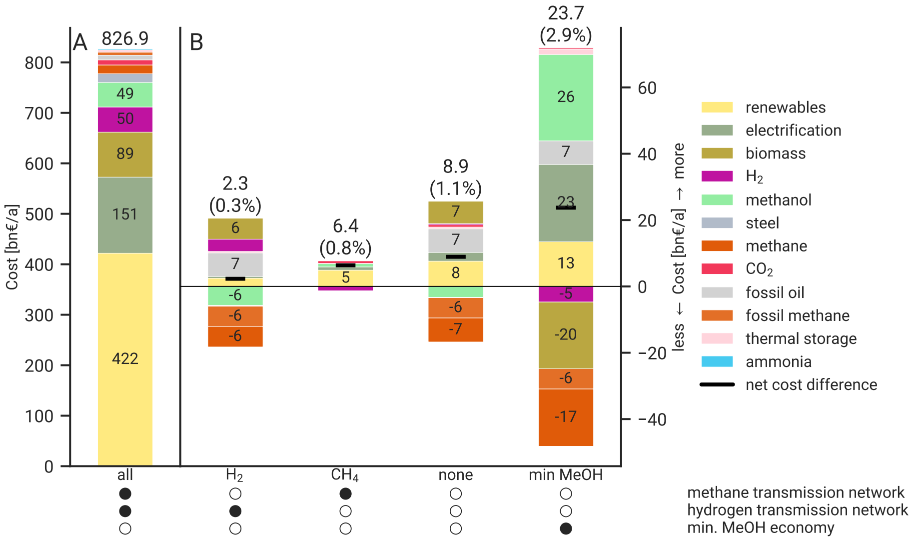
Source: Neumann et al, 2024

Methanol as a platform for hard-to-electrify sectors



Source: Glaum et al, 2025

Remove CH_4 and H_2 networks, use methanol: costs only 3% more



Source: Glaum et al, 2025

Ariadne: German transmission needs reduced by integrated planning

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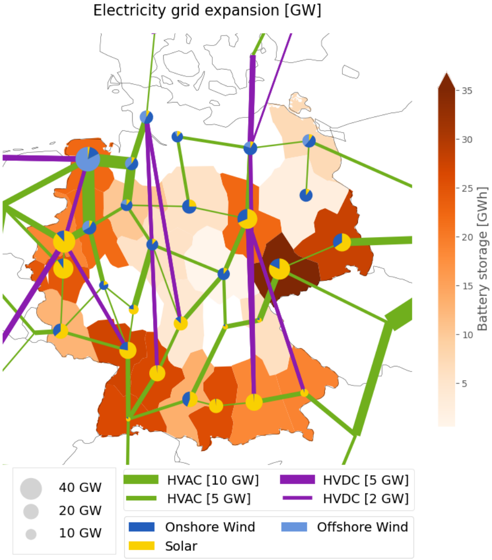
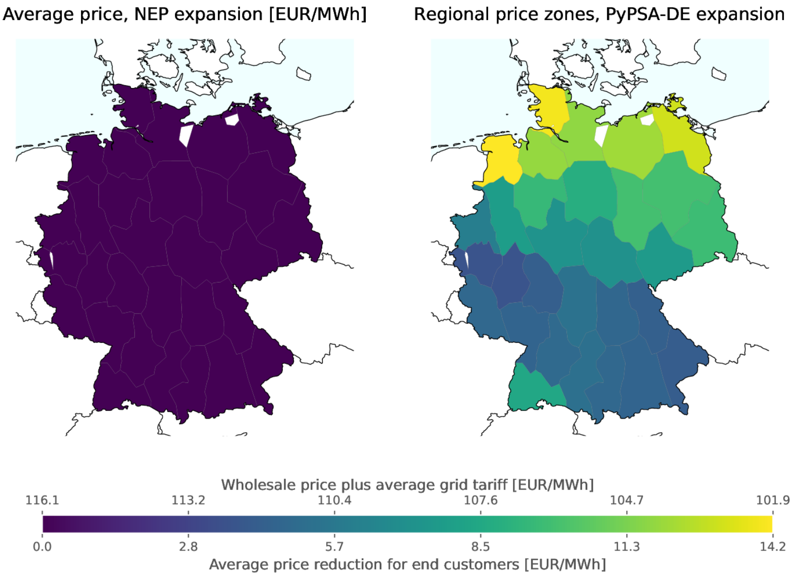


- Ariadne Scenario Report for Germany pursued an **integrated planning approach** for power and hydrogen, reduced transmission costs by 92 bn€ from 283 bn€ to 191 bn€ (all €2020)
- Savings from: absorbing offshore with electrolysis, reducing offshore capacity, overhead lines instead of underground cables, **nodal pricing** to manage grid congestion
- saves 7.5 €/MWh on average from network charges (internal congestion rent contributes 7 bn€ per year)

Source: Ariadne, 2025

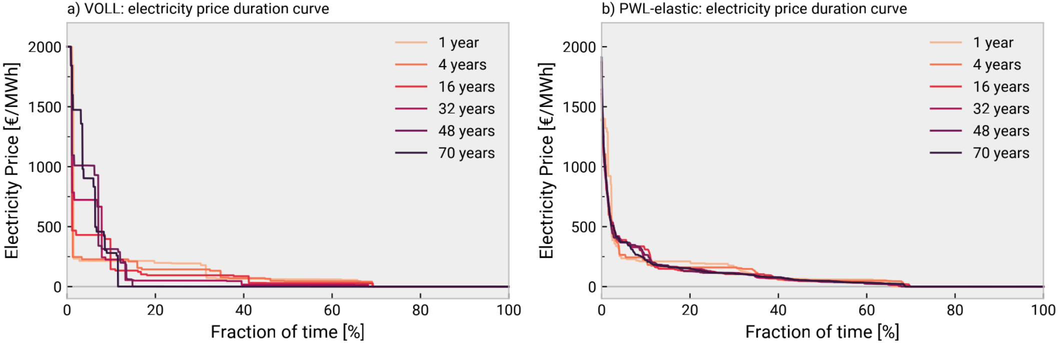
Nodal pricing reduces consumer prices in all regions



Source: [Ariadne, 2025]

Demand elasticity stabilises price duration curves

With completely inelastic demand (VOLL, left) the prices become binary (either high or zero) for long simulations. With **demand elasticity** of -5% (right) the curves are **stable**.



Source: Brown, Neumann, Riepin, 2024

Conclusions

Conclusions

- High **electrification** is robust; last ∼20% of final energy: mix of H_2, bioenergy, CCS
- Modelling infrastructure pushes complexity to limit, requires **performant optimisation**
- A European **hydrogen network** can reduce system costs by € 12-26 billion per year (1.6-3.4% of total), but **power grid expansion** brings even higher benefit (6.3-8.1%)
- A **CO_2 network** connects sustainable biomass sources to demand, avoiding expensive DAC
- **E-fuel imports** reduce costs and infrastructure needs; **methanol** can step in as **gap-filler**
- Policy conclusions: need **fully sector-integrated planning**; **local & dynamic prices**
- Need to find solutions which are **robust to uncertainty** ⇒ calculate many scenarios
- **Openness and transparency** are critical to ensure **re-usability**, **customisability** and **swift policy response** by diverse actors

More information

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

1. `https://github.com/pypsa/pypsa`: The modelling framework
2. `https://github.com/pypsa/pypsa-eur`: The European model

Publications (selection):

1. F. Neumann, E. Zeyen, M. Victoria, T. Brown, *"The Potential Role 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**.