Python for Power System Analysis (PyPSA): Tool for Energy System Modelling

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Why Energy System Modelling?

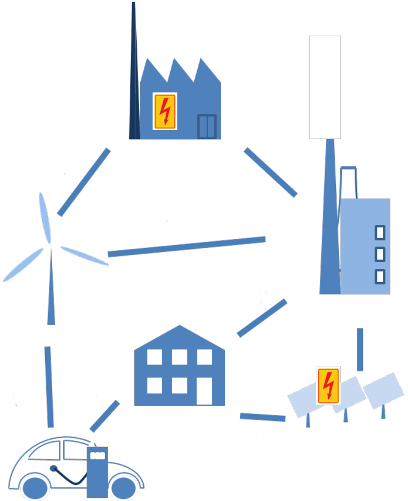
What is Energy System Modelling?

Energy System Modelling is about the overall **design** and **operation** of the energy system.

- What are our **energy needs**?
- What **infrastructure** do they require?
- **Where** should it go?
- How much will it **cost**?

The answers to these questions affect **hundreds of billions** of euros of spending per year in Europe.

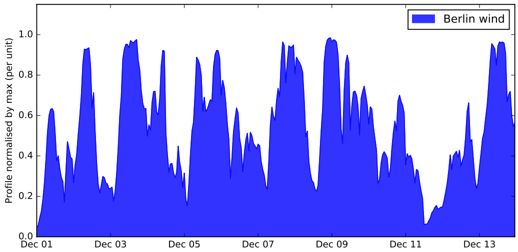
Researchers deal with these questions by **building computer models** of the energy system and then, for example, **optimizing** its design and operation.

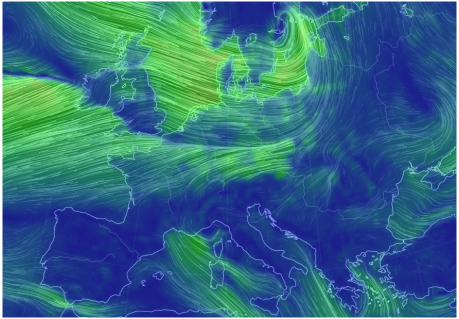


Must take account of variability

Need **high resolution** to see variability of wind and solar both in **time** and **space**.

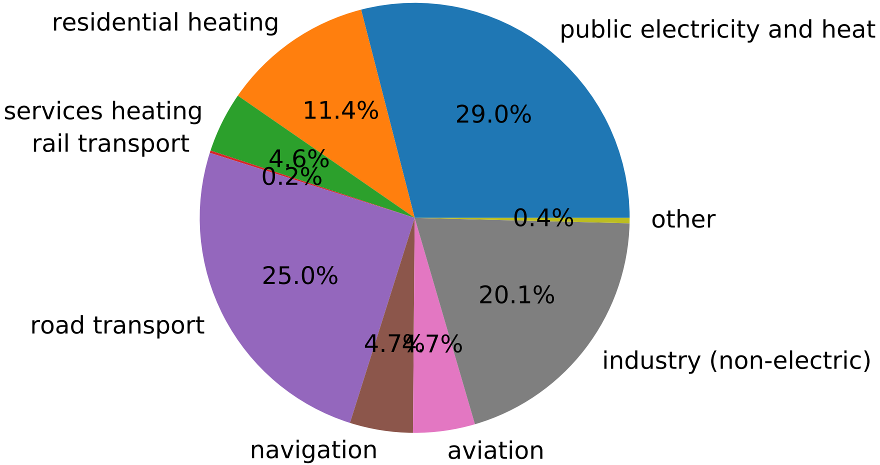
This is necessary to **dimension flexibility** (from storage and demand) correctly.





It's not just about electricity demand...

EU28 CO_2 emissions in 2016 (total 3.5 Gt CO_2, 9.7% of global):



Source: Brown, data from **EEA**

...but electrification of other sectors is critical for decarbonisation

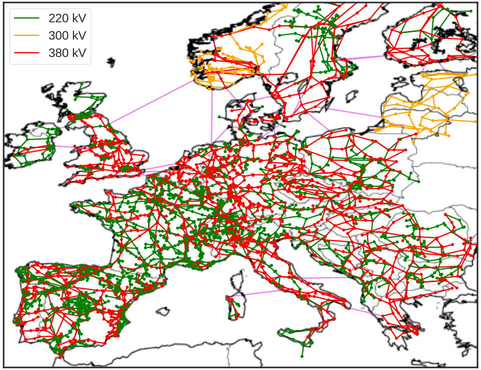
Electrification is essential to decarbonise sectors such as transport, heating and industry, since we can use low-emission electricity for electric vehicles and heat pumps.

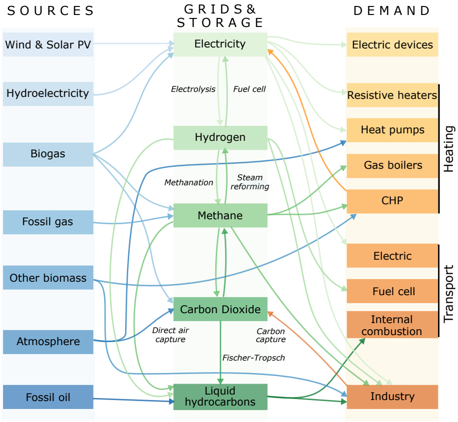
Some scenarios show a **doubling or more of electricity demand**.

Source: Tesla; heat pump: Kristoferb at English Wikipedia

Why it's hard: many components and interactions

Need to model: (at least) all of Europe for market integration; enough spatial and temporal detail to capture all important effects; all interactions between energy sectors; correct physics.





Why Energy Modelling in Particular Need to be Open

What makes energy modelling special?

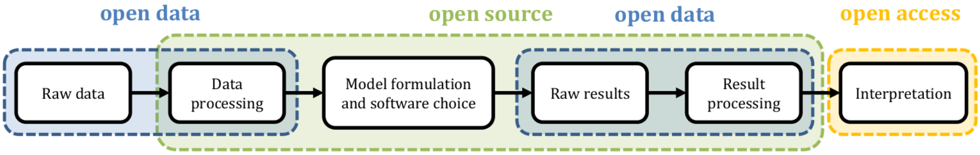
- Energy has **high social, political and economic relevance** (large positive role in economy, but also negative role in climate change, air pollution, resource conflicts)
- Large role of **business interests** in energy (hundreds of billions of euros spent each year in Europe on energy, much of it imported)
- Large **uncertainties about future** (renewables v nuclear v fossil carbon sequestration, public acceptance (nuclear, power lines, wind), fast-moving costs (a 2005 report projected cost of solar panels in 2050 at € 5500/kWp, today it's € 500/kWp))
- Need for **computer modelling** to avoid bad investment decisions (and save the planet)

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:



Why open modelling?

openness . . .

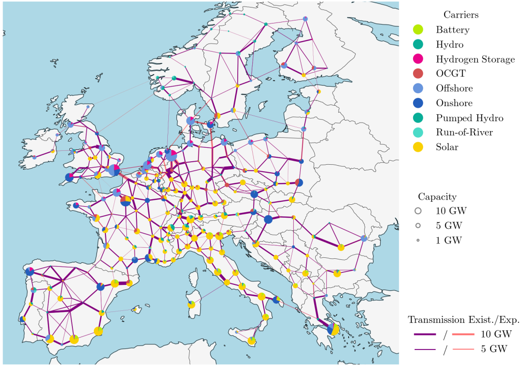
- increases **transparency**, **reproducibility** and **credibility**, which lead to better research and policy advice (no more 'black boxes' determining hundreds of billions of energy spending)
- reduces **duplication of effort** and frees time/money to develop **new ideas**
- *can* improve research **quality** through feedback and correction
- allows easier **collaboration** (no need for contracts, NDAs, etc.)
- is a **moral imperative** given that much of the work is publicly funded
- puts pressure on **official data holders** to open up
- is essential given the increasing **complexity** of the energy system - we all need data from different domains (grids, buildings, transport, industry) and cannot collect it alone
- can increase **public acceptance** of difficult infrastructure trade-offs

See also S. Pfenninger et al, 'The importance of open data and software: Is energy research lagging behind?,' Energy Policy, V101, p211, 2017 and S. Pfenninger, 'Energy scientists

Python for Power System Analysis (PyPSA)

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)

Capabilities

- **capacity expansion planning** (linear)
- **market modelling** (linear)
- **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** 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** but Jupyter notebooks

Comparison to Other Software Tools

				Grid Analysis			Economic Analysis							
	Software	Version	Free Software	Power Flow	Continuation Power Flow	Dynamic Analysis	Transport Model	Linear OPF	SCLOPF	Nonlinear OPF	Multi-Period Optimisation	Unit Commitment	Investment Optimisation	Other Energy Sectors
Power system tools	MATPOWER	6.0	✓	✓	✓		✓	✓		✓				
	NEPLAN	5.5.8		✓		✓	✓	✓	✓	✓				✓
	pandapower	1.4.0	✓	✓			✓	✓		✓				
	PowerFactory	2017		✓		✓		✓	✓	✓				
	PowerWorld	19		✓		✓	✓	✓	✓	✓				
	PSAT	2.1.10	✓	✓	✓	✓		✓		✓	✓	✓		
	PSS/E	33.10		✓		✓		✓	✓	✓				
	PSS/SINCAL	13.5		✓		✓				✓				✓
	PYPOWER	5.1.2	✓	✓			✓	✓		✓				
	PyPSA	0.9.0	✓	✓			✓	✓	✓		✓	✓	✓	✓
Energy system tools	calliope	0.5.2	✓				✓				✓		✓	✓
	minpower	4.3.10	✓				✓	✓			✓	✓		
	MOST	6.0	✓	✓	✓		✓	✓	✓	✓	✓	✓		
	oemof	0.1.4	✓				✓				✓	✓	✓	✓
	OSeMOSYS	2017	✓				✓				✓		✓	✓
	PLEXOS	7.400					✓	✓	✓		✓	✓	✓	✓
	PowerGAMA	1.1	✓				✓	✓			✓			
	PRIMES	2017					✓	✓			✓	✓	✓	✓
	TIMES	2017					✓	✓			✓	✓	✓	✓
	urbs	0.7	✓				✓				✓	✓	✓	✓

Optimisation of annual system costs

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

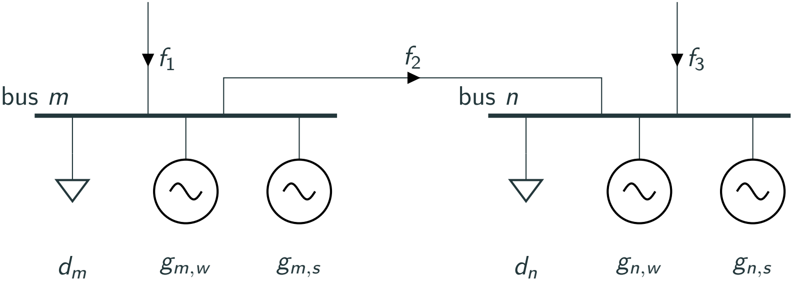
- meeting **energy demand** at each node n (e.g. region) and time t (e.g. hour of year)
- wind, solar, hydro (variable renewables) **availability time series** $\forall\, n, t$
- **transmission constraints** between nodes, **linearised power flow**
- (installed capacity) $\leq$ (**geographical potentials**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

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

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

Model structure

The model is built up out of **components**. A **network** object contains all other components. Fundamental **buses** represent individual locations and energy carriers. To these buses you can connect either **loads**, **generators** or **storage**. You can connect two buses with a power **line** or an energy conversion **link**.



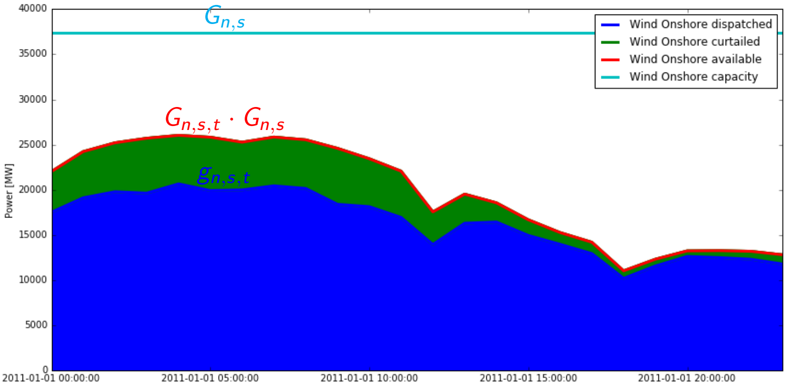
$d_m = g_{m,w} + g_{m,s} + f_1 - f_2$

$d_n = g_{n,w} + g_{n,s} + f_2 + f_3$

Generation availability time series

Generator/storage dispatch $g_{n,s,t}$ cannot exceed availability $G_{n,s,t} \cdot G_{n,s}$, made up of per unit availability $0 \leq G_{n,s,t} \leq 1$ multiplied by the capacity $G_{n,s}$. The capacity is bounded by the installable potential $\hat{G}_{n,s}$.

$$0 \leq g_{n,s,t} \leq G_{n,s,t} \cdot G_{n,s} \leq G_{n,s} \leq \hat{G}_{n,s}$$



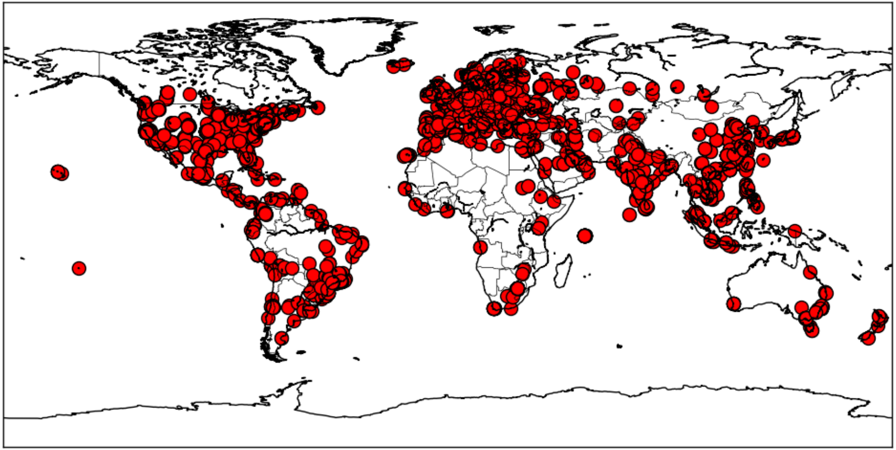
Links to further resources

Python for Power System Analysis (PyPSA):

a free software toolbox for simulating and optimising modern power systems

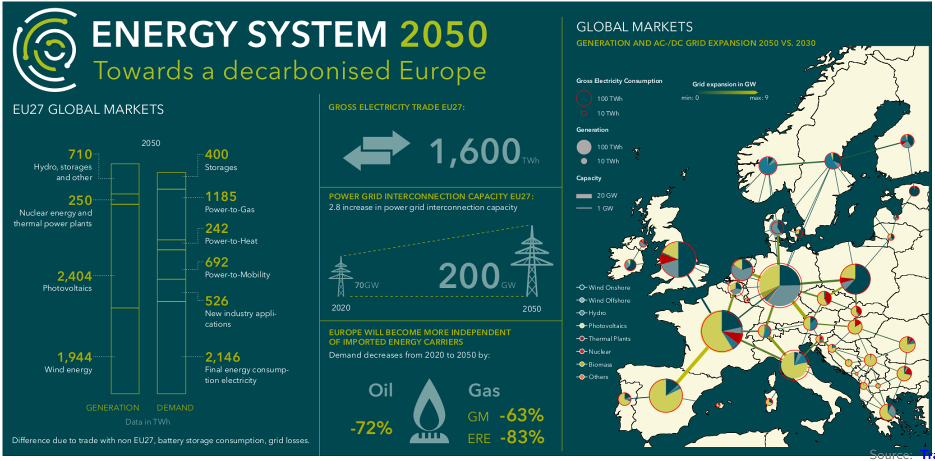
- **GitHub**: https://github.com/PyPSA/PyPSA
- **Documentation**: https://pypsa.readthedocs.io/
- **Examples** showcasing open data: https://pypsa.readthedocs.io/
- **Training course**: https://fneum.github.io/data-science-for-esm/intro.html
- **Mailing list**: https://groups.google.com/forum/#!forum/pypsa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

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



PyPSA example: TransnetBW used PyPSA-Eur

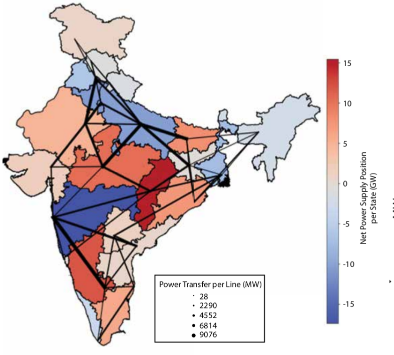
German **Transmission System Operator (TSO) TransnetBW** used an open model (PyPSA-Eur) to model the European energy system in 2050. Why? Easier to build on an existing model than reinvent the wheel.

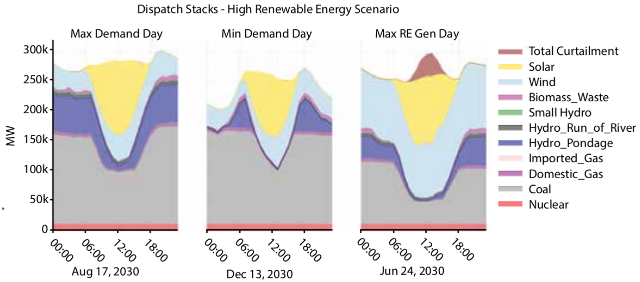


Source: TransnetBW, 2022

PyPSA example: 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.

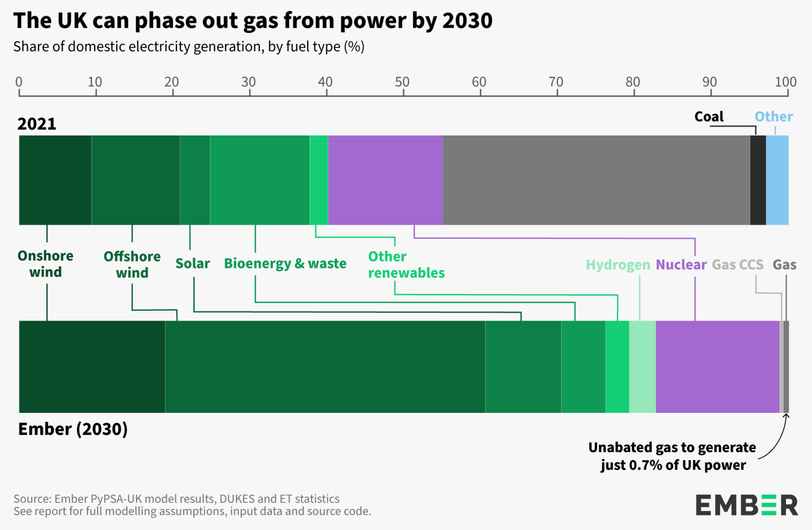




Source: TERI

PyPSA example: NGO Ember in United Kingdom

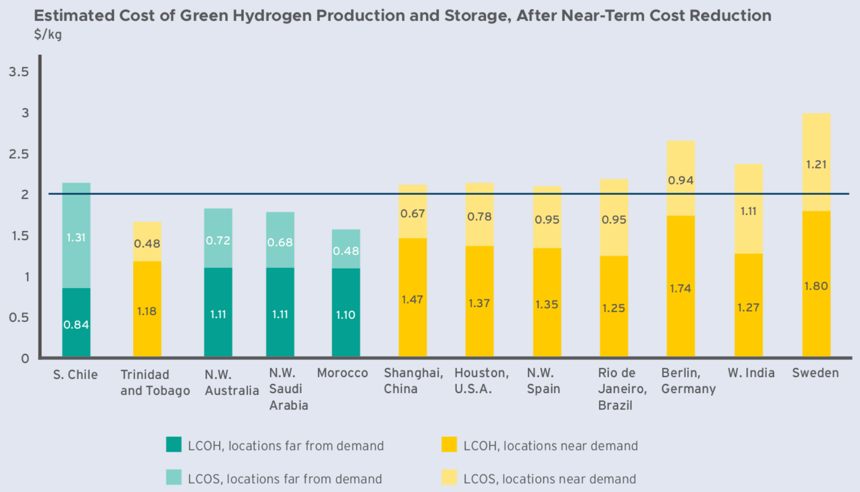
NGO Ember used PyPSA to model a gas phase out in the UK by 2030, releasing all code on **github**.



Source: Ember, 2022

Example User of PyPSA: RMI in United States

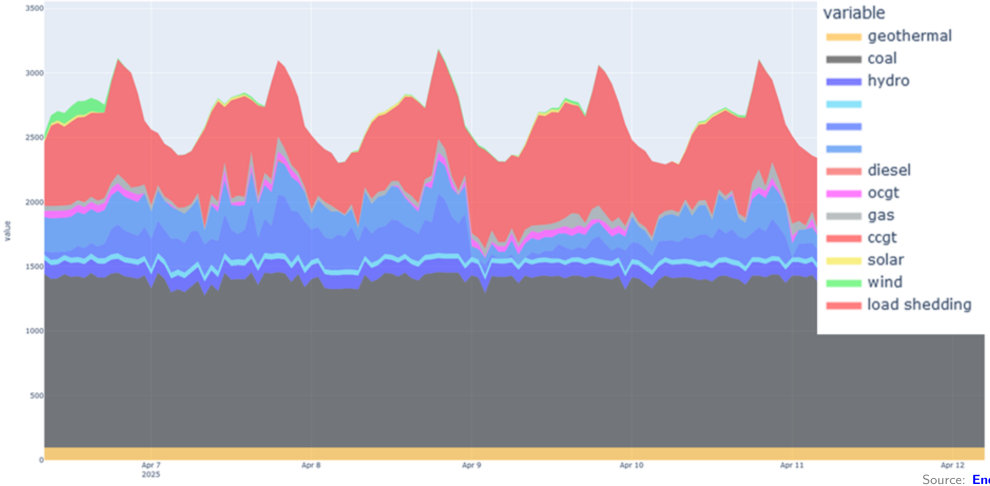
The Rocky Mountain Institute (RMI) in Boulder, Colorado used PyPSA to model hydrogen production costs around the world, since PyPSA had a track record for such calculations.



Source: RMI, 2021

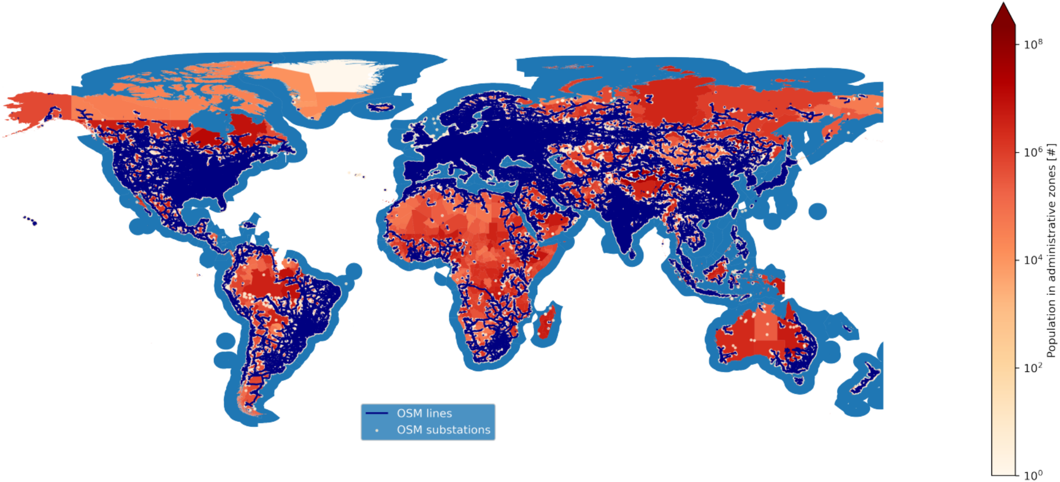
‘1,000 Islands – Renewable Energy for Electrification Programme’

A GIZ-funded project by **Energynautics** looked at renewables in the islands of **Indonesia**. A mixed-integer operational planning study was done for the power systems of Sulawesi.



Source: [Energynautics, 2023]

The **PyPSA meets Earth** initiative is extending PyPSA-Eur to the planet.



Source: **PyPSA meets Earth, 2022**

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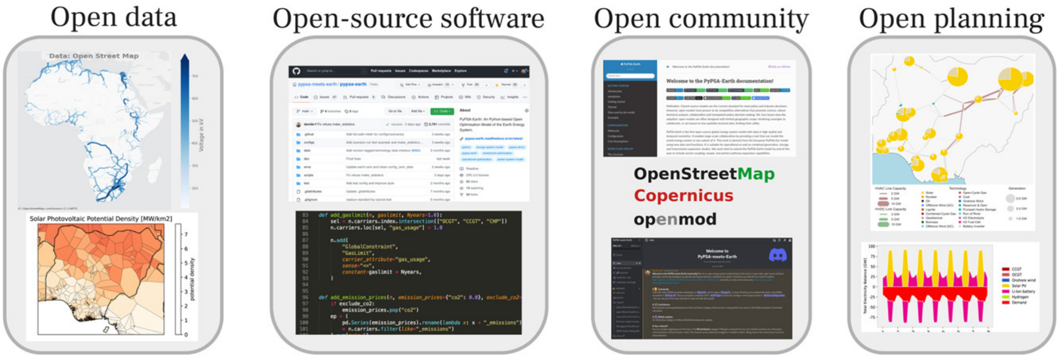
PyPSA-Earth is an open energy system model with **global coverage** and high-resolution data. Includes **model-ready data** for any set of countries. Validation done for Africa and in detail for Nigeria. Uses OpenStreetMap network and generation data.



Source: Parzen et al, 2023

European Sector-Coupled Model PyPSA-Eur

What is PyPSA-Eur?

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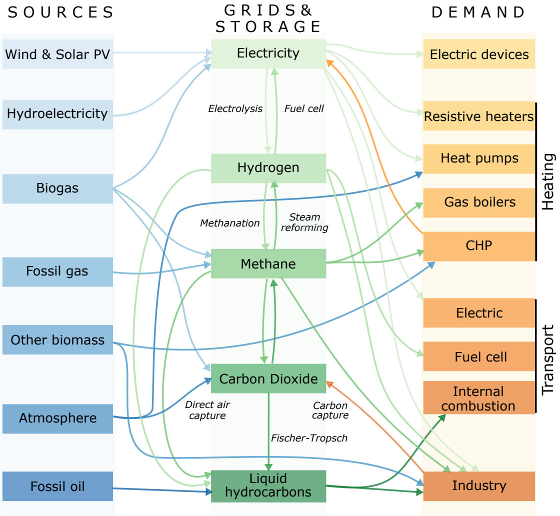
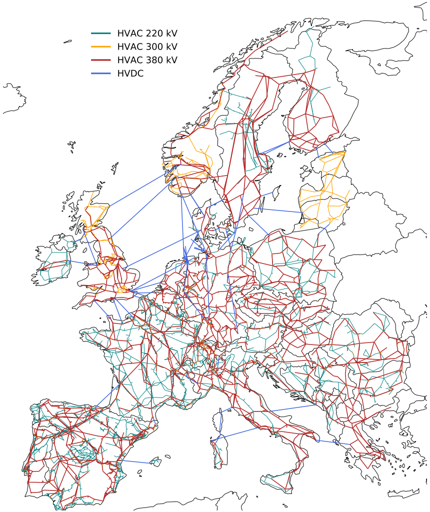
Model for Europe with all energy flows... and bottlenecks in energy networks.





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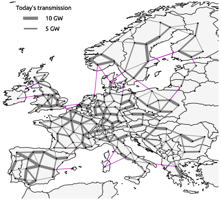
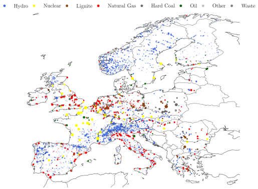
Lots of different types of data and process knowledge come together for the modelling.

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

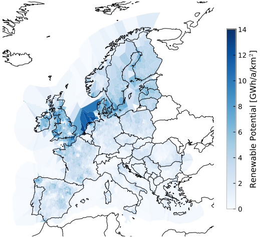
clustered network model



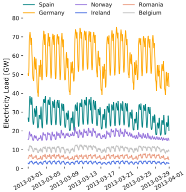
power plants and technology assumptions



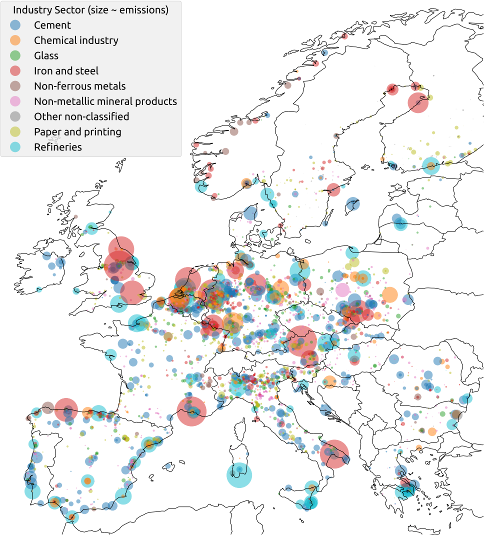
renewable potentials and hourly time series for each region



demand projections time series



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 and solid biomass; 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	Liquid hydrogen, ammonia & methanol
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

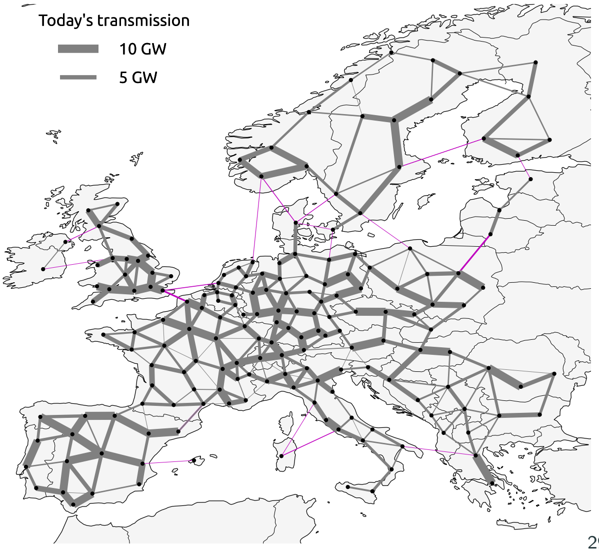
Results for 181-node model of European energy system

Model set-up:

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

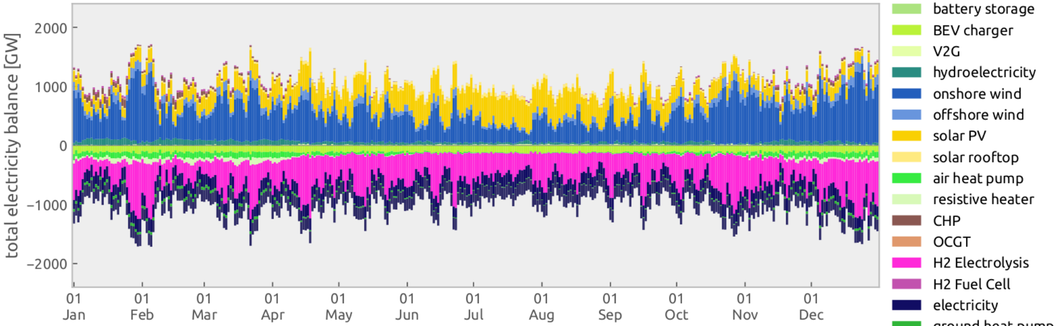
Examine effects of:

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



Daily average of hourly electricity balance

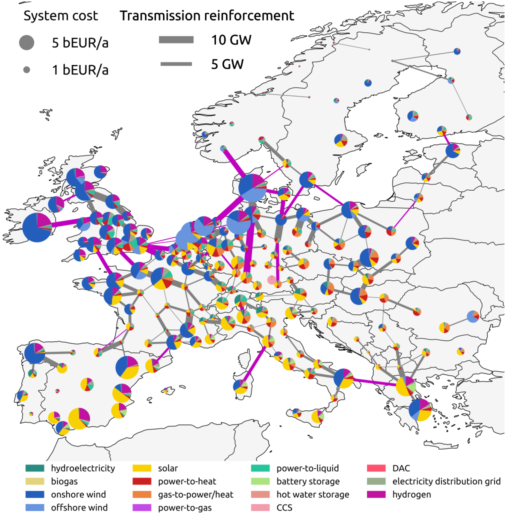
Demand (negative values) is higher in winter thanks to power-to-space-heat; complemented by winter wind; electrolysers have capacity factors in 40-60% range.



Source: Neumann et al, 2022

Distribution of technologies: 50% more power grid volume

Electricity grid expansion of 162 TWkm...



Distribution of technologies: 50% more power grid volume

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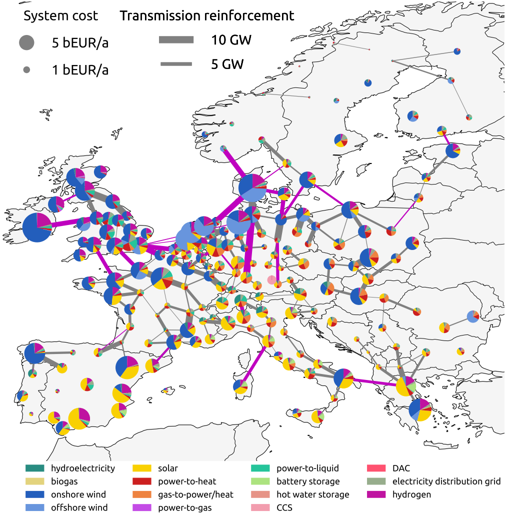
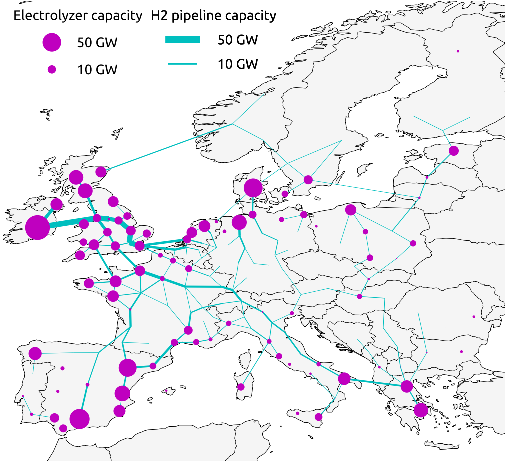
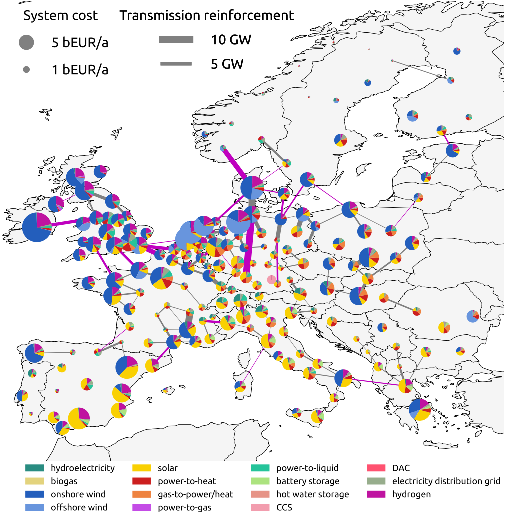


...and new hydrogen grid of 260 TWkm.

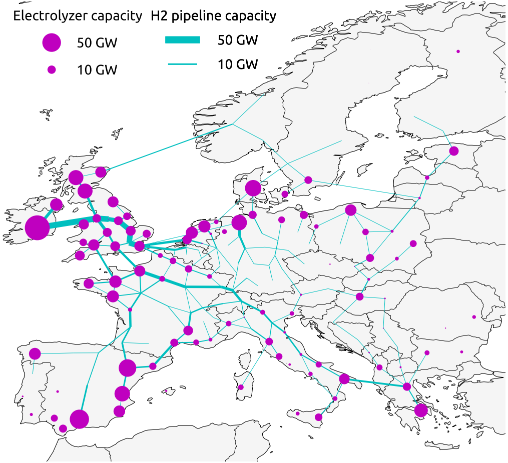


Distribution of technologies: 25% more power grid volume

Electricity grid expansion of 81 TWkm...

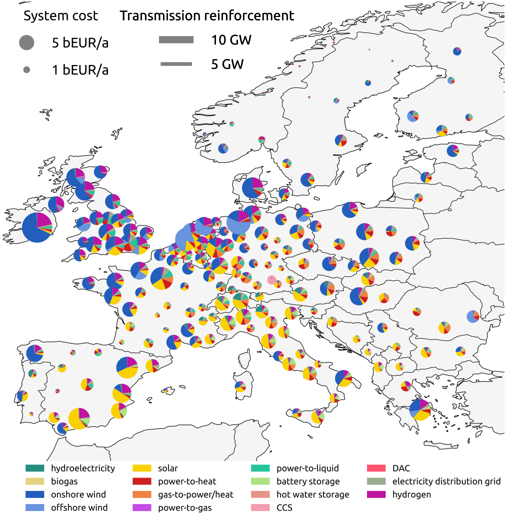


...and new hydrogen grid of 282 TWkm.

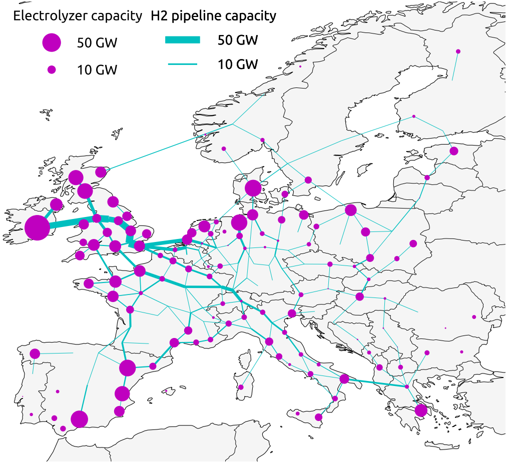


Distribution of technologies: no power grid expansion

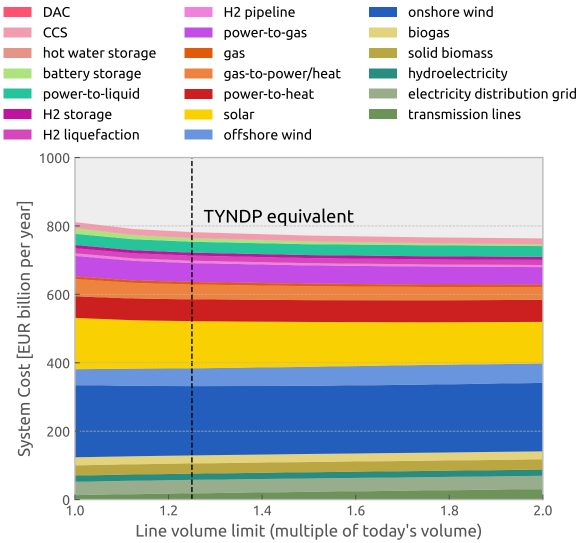
No electricity grid expansion...



...and new hydrogen grid of 308 TWkm.

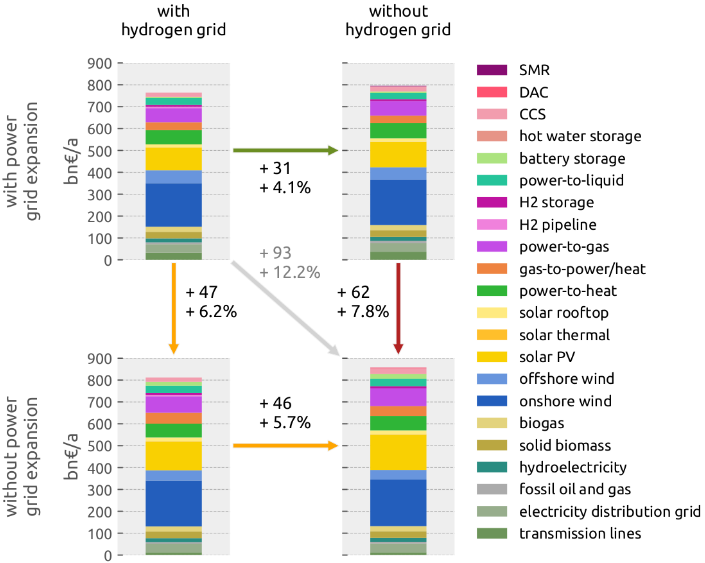


Benefit of power grid expansion for sector-coupled system



- 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: $\sim$ € 47 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 much higher: € 31-46 billion per year (4-5% of total)
- Hydrogen network brings **robust benefit**
- Benefit is strongest without power grid expansion
- Power grid expansion is better if you have to choose; having both saves 11%

Source: Neumann et al, 2022

Open source, open data, online customisable model

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All the code and data behind PyPSA-Eur is **open source**. You can run your own scenarios 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

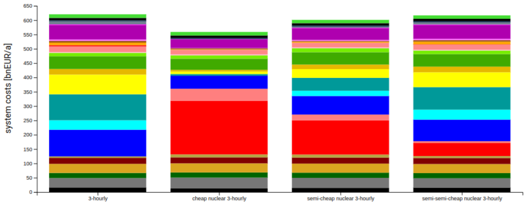
Demand for electricity in residential and services sector compared to today	0.9	per unit
Demand for space heating in buildings compared to today	0.71	per unit
Demand for hot water in buildings demand compared to today	1	per unit
Demand for land transport (road and rail) compared to today	1	per unit
Demand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

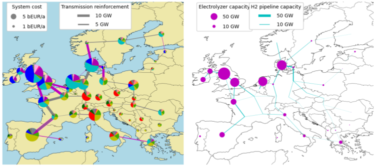
Sector coupling options

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

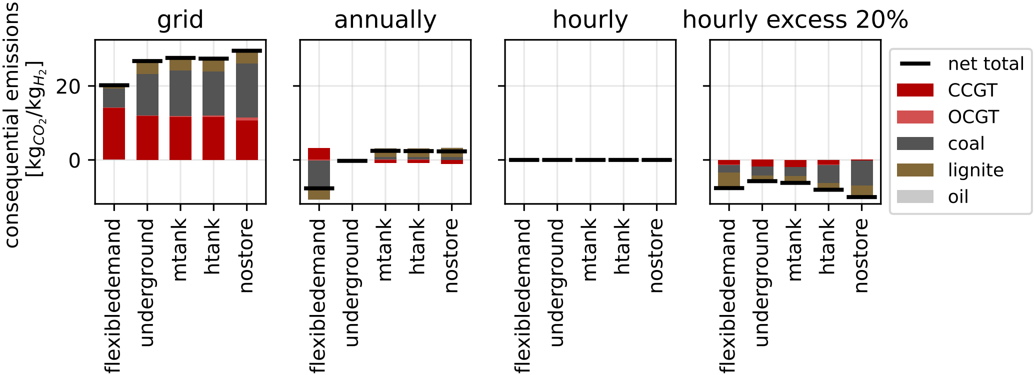
Breakdown of yearly system costs

All costs are in 2015 euros, EUR-2015.





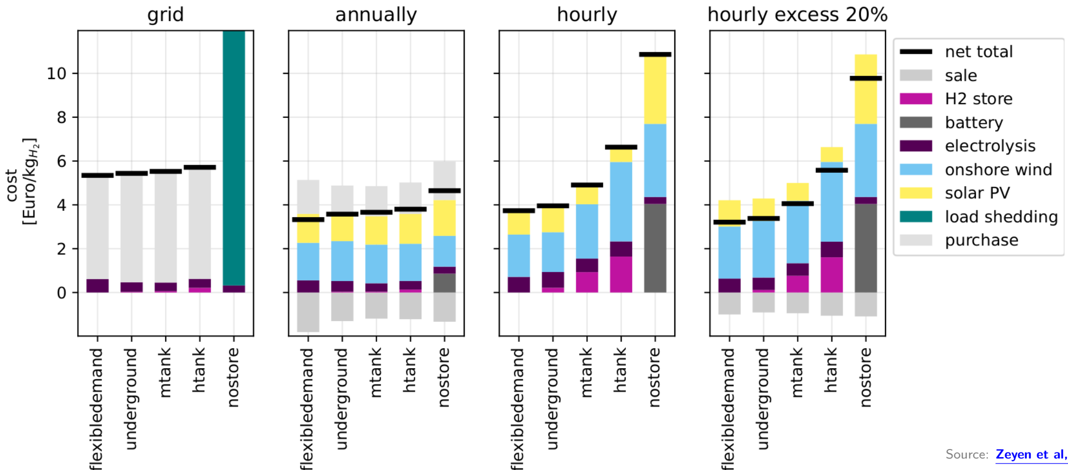
Without additionality, emissions from **hydrogen production** are high (grid). Hourly matching guarantees **low emissions impact**; annual has low emissions only if demand is flexible.



Source: Zeyen et al, 2022

Hydrogen production in Germany in 2025: impact on costs

However, the costs of hydrogen production with hourly matching can be **high unless flexible operation is possible**, e.g. enabled by low-cost hydrogen storage or flexible demand.



Source: Zeyen et al, 2022

Conclusions

Conclusions

- **Detailed modelling** is necessary for the integration of variable renewables and electrification of buildings, transport and industry
- **Openness and transparency** and critical to ensure **re-usability**, **customisability** and **swift policy response** by diverse actors
- Openness is guaranteed by **open licences** for data and code
- PyPSA is an **open modelling framework** for modern energy system analysis that includes variable renewable generation and sector-coupling
- PyPSA is now **widely used** across academia, government, NGOs and industry

More information

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

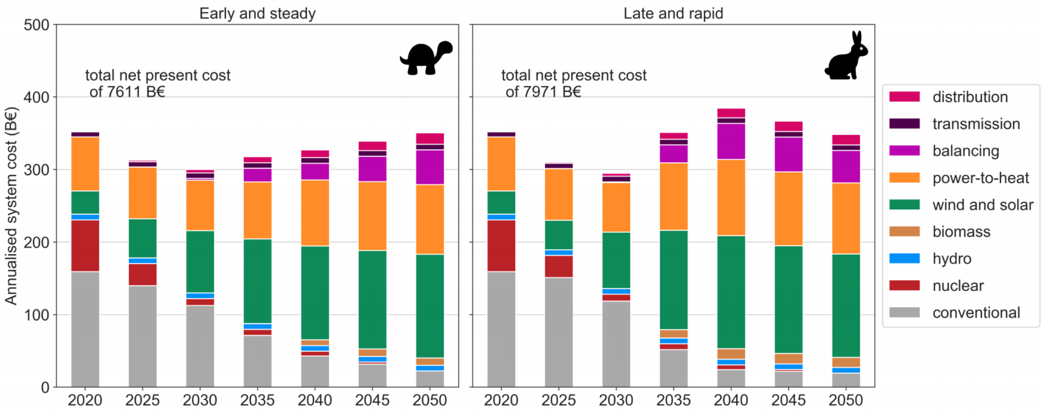
1. `https://github.com/pypsa/pypsa`: The modelling framework
2. `https://github.com/pypsa/pypsa-eur`: The energy system model for Europe

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**.

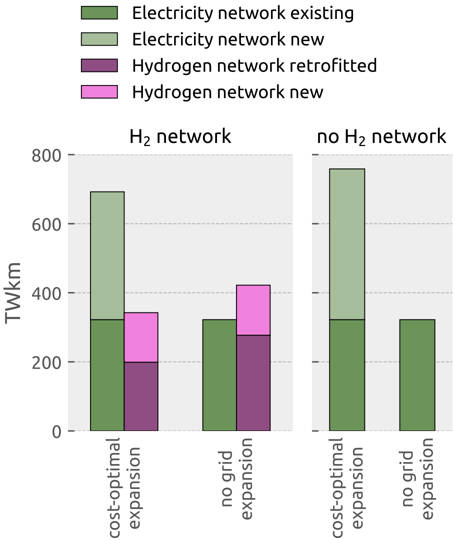
For a fixed CO_2 budget, it's more cost-effective to **cut emissions early** than wait.

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



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

Energy grid in different cases

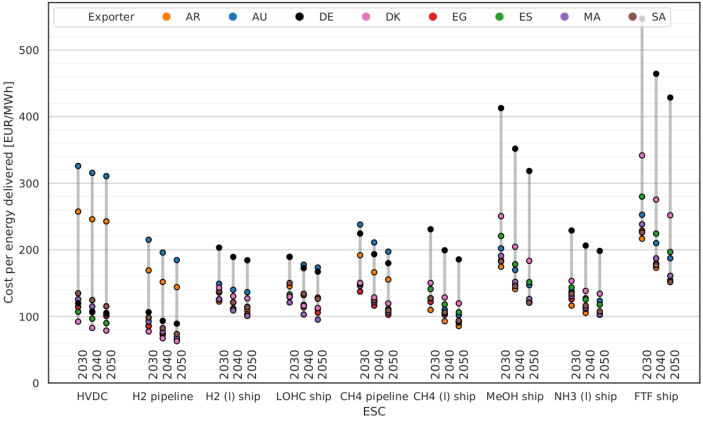


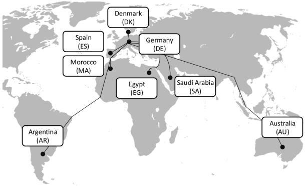
- Optimal hydrogen grid capacity rises as grid expansion is restricted
- Hydrogen grid is not a perfect substitute
- Around two-thirds of hydrogen grid can re-purpose existing methane network
- NB: These results come from an updated model which allows pipeline re-purposing

Source: Neumann et al, 2022

Synthetic fuels from outside Europe?

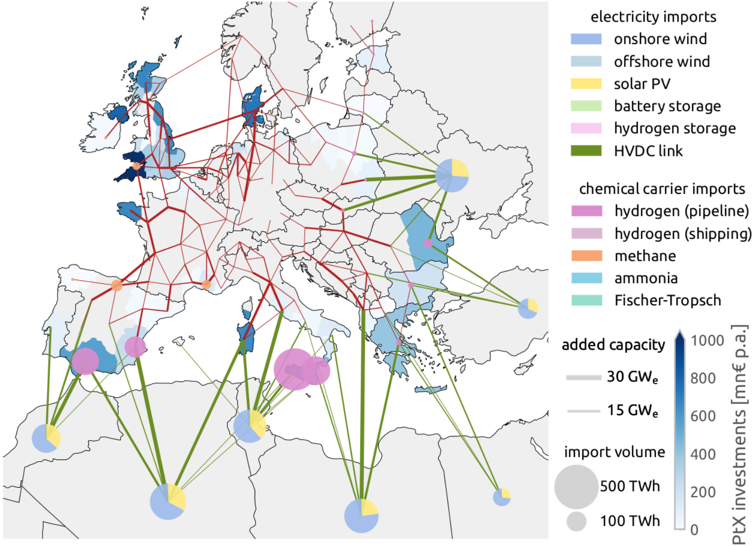
Green hydrogen with pipeline transport costs around ∼ 80 €/MWh in model. Shipping green hydrogen from **outside Europe** in liquid, LOHC or NH_3 form may not compete on cost (depends e.g. on WACC), but scarce land in Europe may still drive adoption.





Source: Hampp et al, 2021

With e-fuel imports instead of autarky

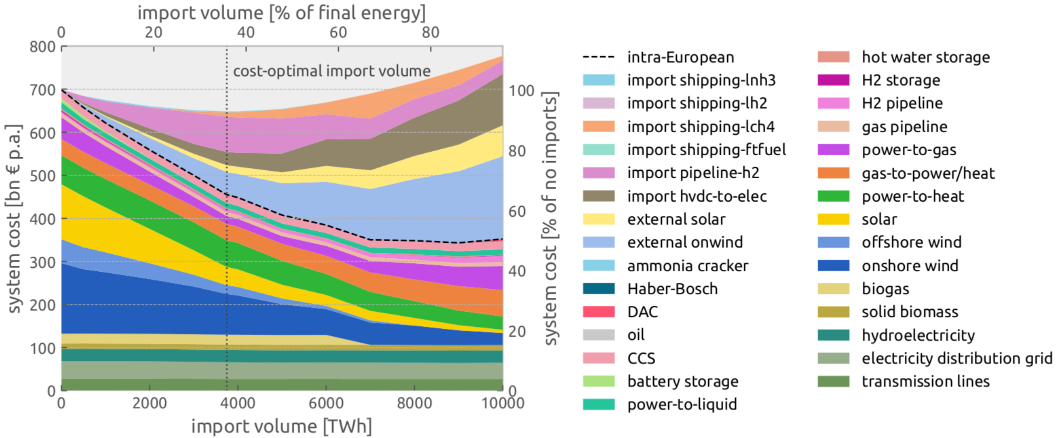


- Allowing imports of electricity, green hydrogen, e-fuels, **changes infrastructure needs completely**
- PtX out-sourced from Europe
- Electricity imported too, providing seasonal balancing

Source: Hampp, Brown, Neumann; 2022/3

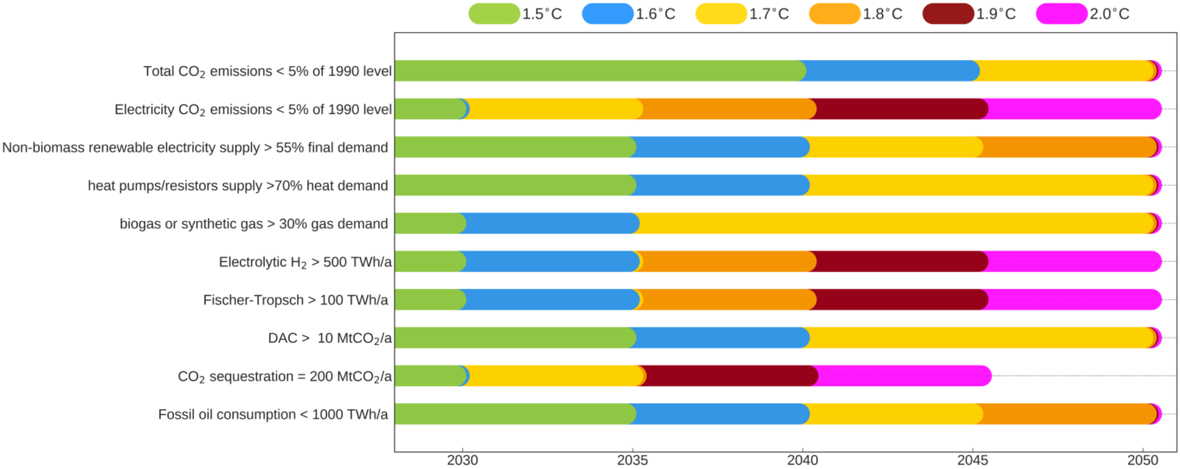
E-fuel imports reduce costs, but not completely

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



Source: Hampp, Brown, Neumann; 2022/3

Appearance of technologies until 2050 depends on temperature target



Source: M. Victoria et al, 2021

Future work

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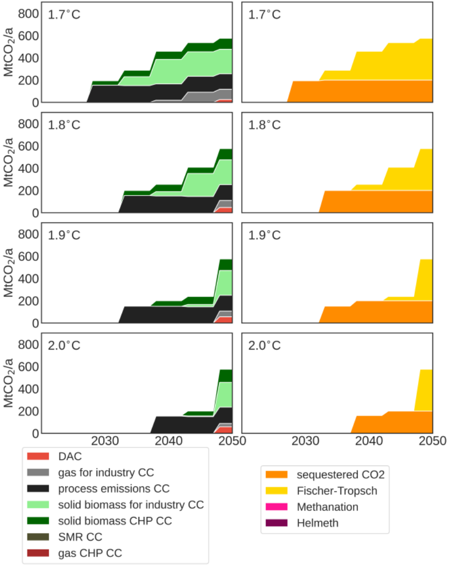
- Consider **pathway** of investments 2020-2050 at high resolution
- Compare local production with import of **synfuels from outside Europe**
- Extend offshore wind potentials by including **floating wind** for depths > 50 m
- Examine benefits of offshore **hub-and-spoke grid topology**
- Proper consideration of **wake effects** (currently 11% linear reduction of CF)
- Cost-benefit of **sufficiency**
- Improving **open access** to models

Carbon Management

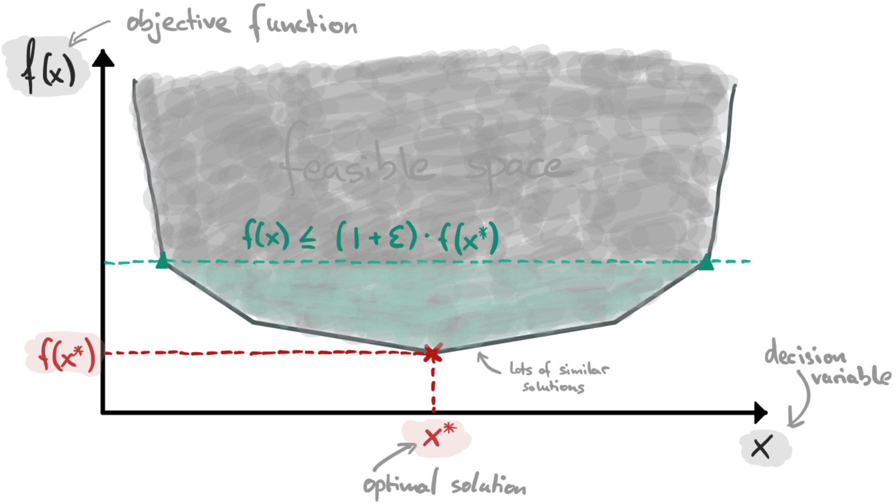


- Carbon capture (left): from process emissions, but also from heat production in industry and for combined-heat-and-power (CHP) plants
- Sequestration limited to 200 $MtCO_2/a$ (enough to cover today's process emissions)
- Further carbon capture is used for Fischer-Tropsch fuels (kerosene and naphtha)
- 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

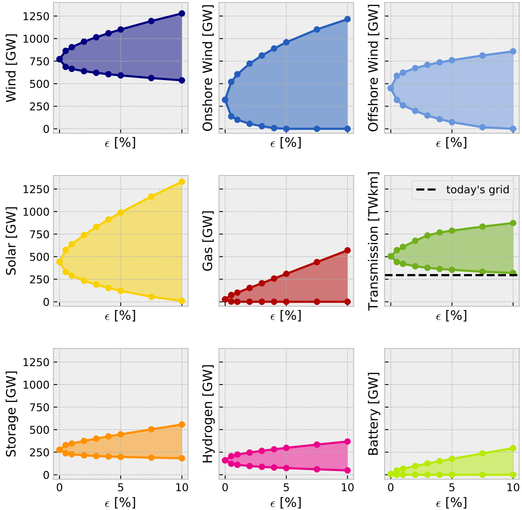
Large Space of Near-Optimal Energy Systems

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



Source: Neumann & Brown, 2020

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

Synthetic fuels from outside Europe?

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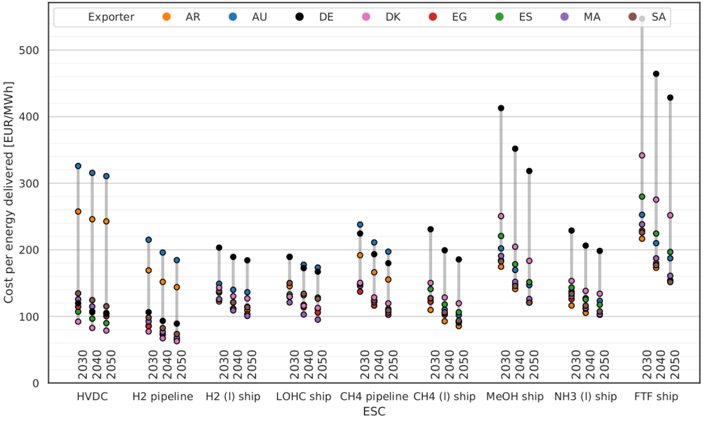
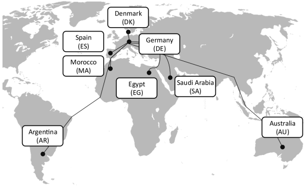
Green hydrogen with pipeline transport costs around ∼ 80 €/MWh in model. Shipping green hydrogen from **outside Europe** in liquid, LOHC or NH_3 form may not compete on cost (depends e.g. on WACC), but scarce land in Europe may still drive adoption.





Source: **Hampp et al, 2021**

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Submit a new scenario

Here you can customise settings for the model PyPSA-Eur-Sec, a sector-coupled model of the European energy system. The model minimises the costs of the energy system assuming all capacity investments in generation, storage, energy conversion and energy transport can be re-optimised. Energy services (electricity, heating, transport, industrial demand) are provided at today's levels by default, but they can also be altered. Default cost assumptions are taken from forecasts for 2050, mainly from the Danish Energy Agency Technology Data. A weighted average cost of capital of 7% is applied. 45 regions are assumed. A full year of representative weather and load data is used, but sampled n-hourly.

193-hourly temporal resolution takes only around 1 minute to solve, but gives reasonable results. This model can only be run at up to 25-hourly resolution (25-hourly takes around 10 minutes to run). Higher resolutions are not offered here because of the computational burden. If you want to run at up to hourly resolution, download the full model and run it yourself, or contact us to discuss terms.

Basic scenario settings

[no name] Scenario name so you can identify the scenario later

[0] Fraction of 1990 CO2 emissions allowed [per unit]

[193] Sampling frequency n-hourly for representative year, for computational reasons n>=25 [integer]

Demand

[0.9] Demand for electrical devices in residential and services sector compared to today [per unit]

[0.71] Demand for space heating in buildings compared to today [per unit]

[1] Demand for hot water in buildings demand compared to today [per unit]

[1] Demand for land transport (road and rail) compared to today [per unit]

[1] Demand for shipping compared to today [per unit]

[1.2] Demand for aviation compared to today [per unit]

[0.9] Demand in industry compared to today [per unit]

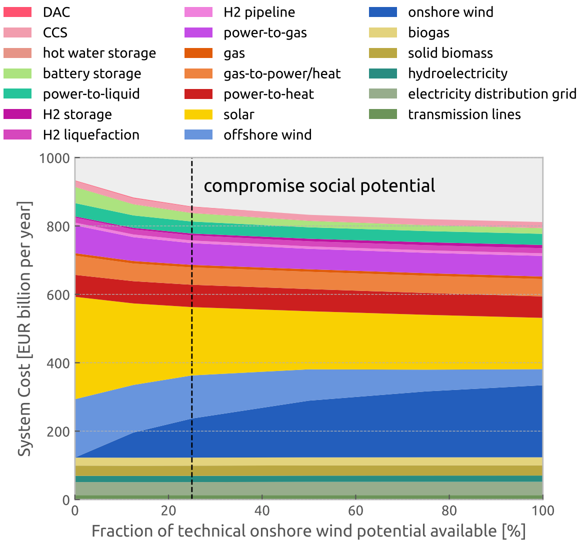
Sector coupling options

[0.85] Share of battery electric vehicles in land transport [per unit]

[0.15] Share of fuel cell electric vehicles in land transport [per unit]

☑ Allow battery electric vehicles to perform demand response

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 ∼ € 122 billion per year as we **eliminate onshore wind** (with no grid expansion)
- Rise is only ∼ € 45 billion per year if we **allow a quarter of technical potential** (∼ 120 GW for Germany)

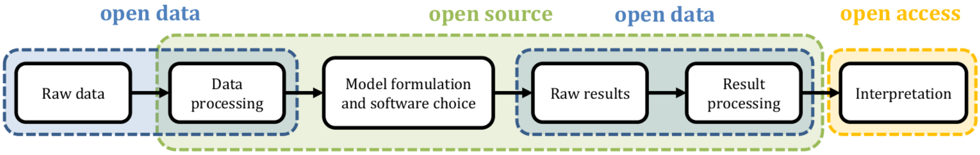
What is open modelling?

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:



Optimisation of annual system costs

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. 95% 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.

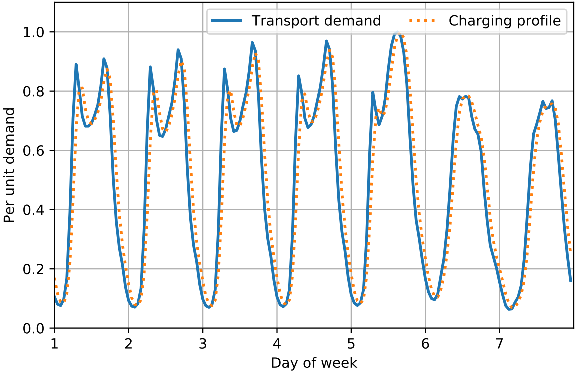
Technology Choices: Exogenous Versus Endogenous

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: LH_2, NH_3, MeOH)
- steel production 2050: DRI with hydrogen, then electric arc (could compete with BF+CCS)
- electrification & recycling in industry

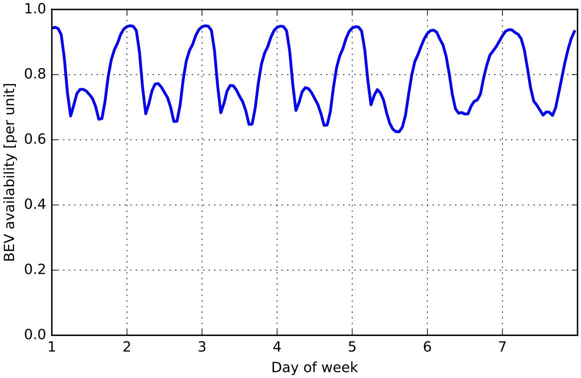
Endogenous (model optimizes):

- electricity generation fleet
- transmission reinforcement
- space and water heating technologies (including building renovations)
- all P2G/L/H/C
- supply of process heat for industry
- carbon capture



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

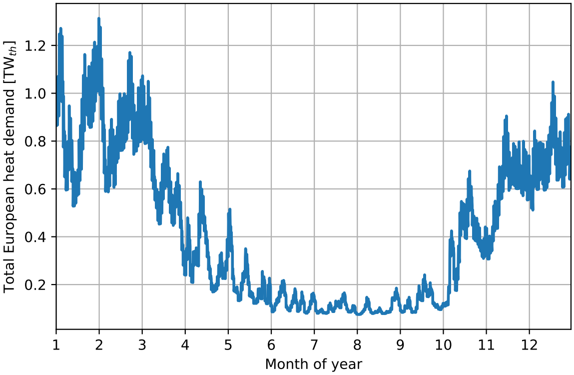
- Road and rail transport is fully electrified (vehicle costs are not considered)
- Because of higher efficiency of electric motors, final energy consumption 3.5 times lower than today at 1100 TWh_{el}/a for Europe
- In model can replace Battery Electric Vehicles (BEVs) with Fuel Cell Electric Vehicles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



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.

Centralised District Heating versus Decentralised Heating for Buildings

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:

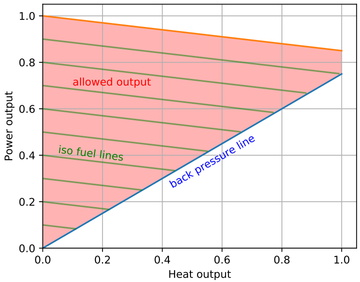
Decentral individual heating can be supplied by:

- 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:

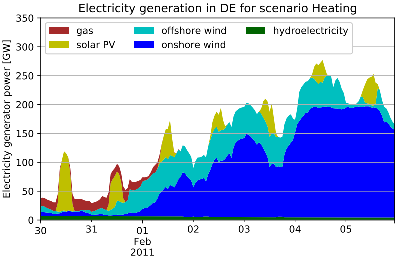
- Air-sourced heat pumps
- Resistive heaters
- Gas boilers
- Large solar thermal
- Water tanks with long time constant $\tau = 180$ days
- CHPs

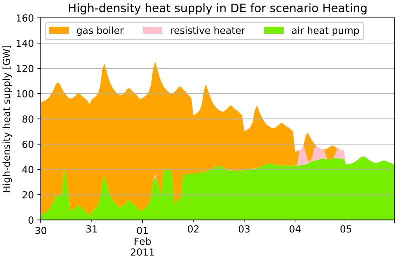
CHP feasible dispatch:



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

Example problem with balancing: Cold week in winter





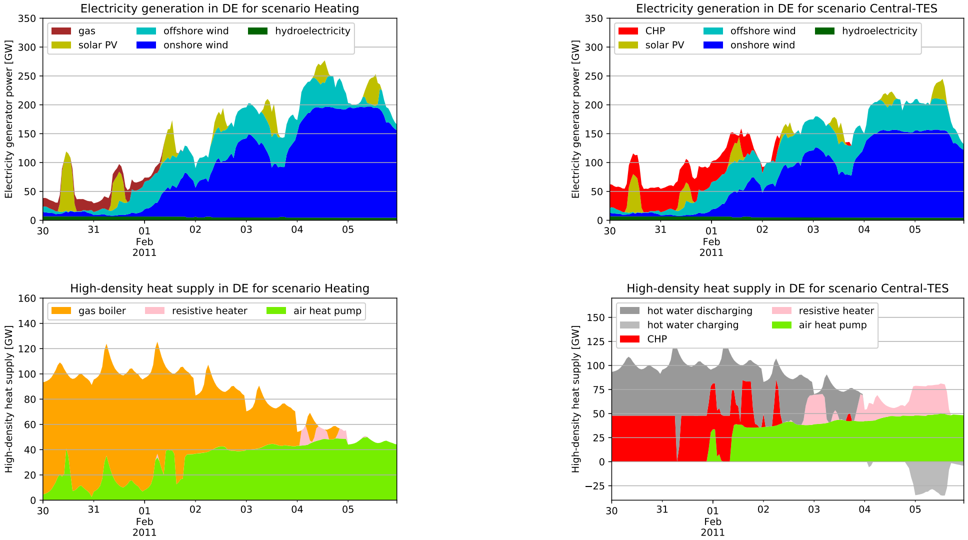
There are difficult periods in winter with:

- **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**

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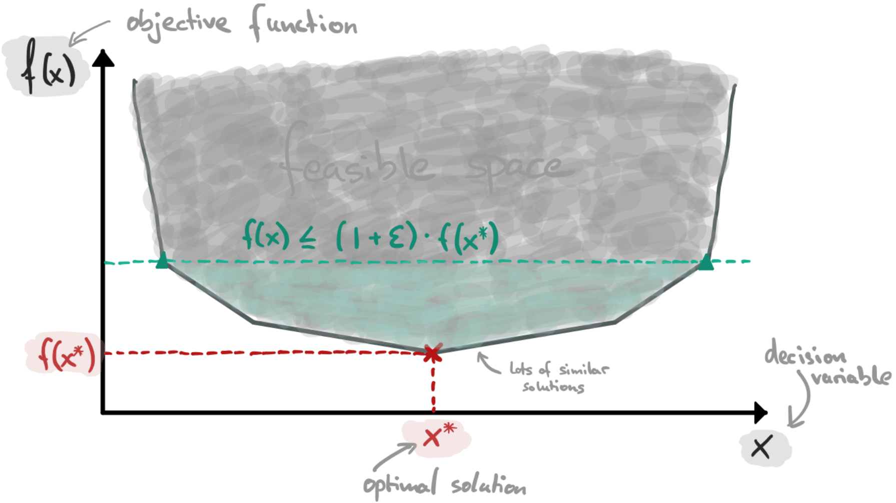
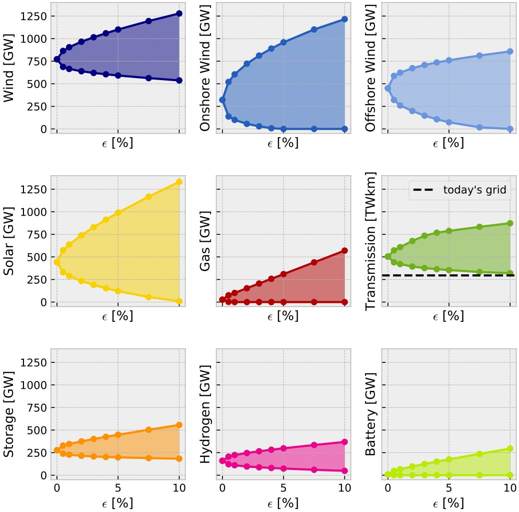


Source: Neumann & Brown, 2020

Example: 100% renewable electricity system for Europe



Within 10% of the optimum we can:

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- Exclude battery or most hydrogen storage

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

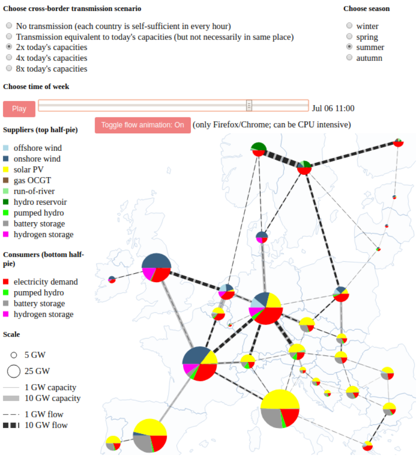
This gives space to choose solutions with **higher public acceptance**.

Source: Neumann & Brown, 2020

Online Visualisations and Interactive 'Live' Models

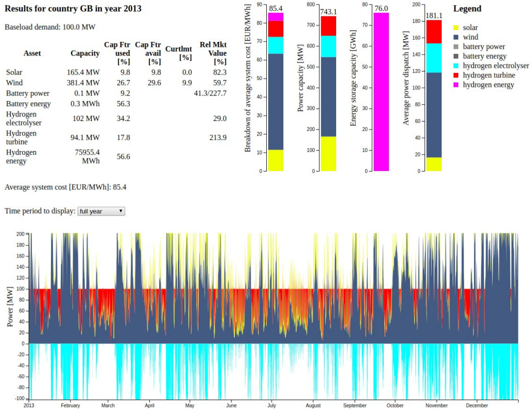
Online animated simulation results:

pypsa.org/animations/



Live user-driven energy optimisation:

model.energy



Without onshore: solar rooftop and offshore potentials maxxed out

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