Open Energy Modelling:
Discussion & Examples from PyPSA Modelling for Europe

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Table of Contents

Motivation: Openness and Transparency

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** (technology cost & availability, acceptance, politics, geopolitics)
- Many **trade-offs beyond cost** (environmental impact, acceptance, political/social support, land use, industry relocation versus security, e-fuel imports)
- Need for **computer modelling** to avoid bad investment decisions (and save the planet)
- But results are **strongly driven by inputs and assumptions** (cost, demand, constraints)

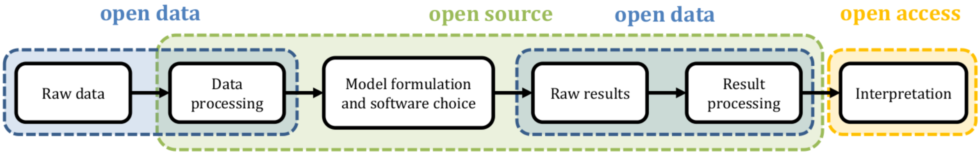
What is open modelling?

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:



How does openness and transparency help?

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**
- allows a **high level of customisability** given code is open
- enables **new actors to participate in debate** (e.g. NGOs, researchers, public)
- *can* improve research **quality** through feedback and correction
- allows easier **collaboration** (no need for contracts, NDAs, etc.)
- 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

Common objections from modellers

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- **It's too much work to prepare/support**: You don't have to do either of these things. Publishing undocumented data may also help somebody.
- **There's no benefit to me**: Your work describing the dataset will be highly cited. The two `https://renewables.ninja` papers have 1879 citations since 2016, PyPSA paper has 353 citations since 2018.
- **But we've put in 10,000 person-hours!**: Let's avoid more duplicated effort in future by pooling our efforts.
- **There are mistakes in open datasets**: Thank you for your feedback, please tell us where, and we'll fix it. Mistakes in closed models never come to light.

See also the **openmod FAQ** for a complete list.

What open models are out there?

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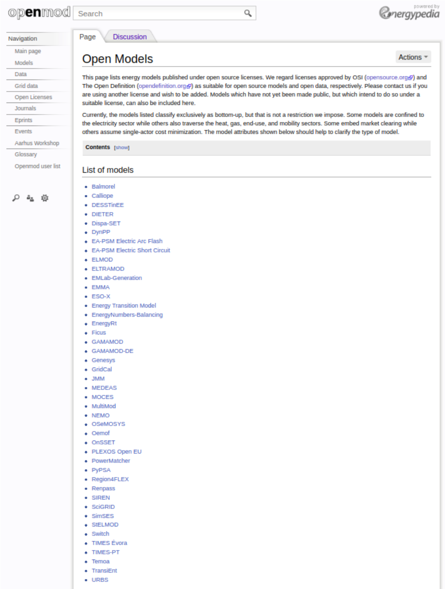


- The first three appeared before 2010
- Since then there has been a flood, with **over 80 models** listed on the openmod wiki pages: `https://wiki.openmod-initiative.org/wiki/Open_Models`
- Why the boom? Interest in GHG reduction, renewables integration, new generation of modellers raised on free software, funding bodies demanding openness
- They are used in academia, research institutes, government bodies and private companies

The killer app: open data

Personal opinion: anybody can build a modelling framework. The real killer app of openness is **high quality, validated datasets**.

It's very important to open the framework for transparency and reproduceability, but there are hundreds out there already and they all "cook with water".

Collecting data on the other hand is **hard work**, and validating it is **even harder**.

Examples of datasets we need:

- Spatially and temporally resolved demand for electricity, transport, heating and industry
- Spatially and temporally resolved renewable availability
- Biomass by type and usage pathway
- Detailed knowledge of industrial processes
- Detailed knowledge of existing network infrastructure

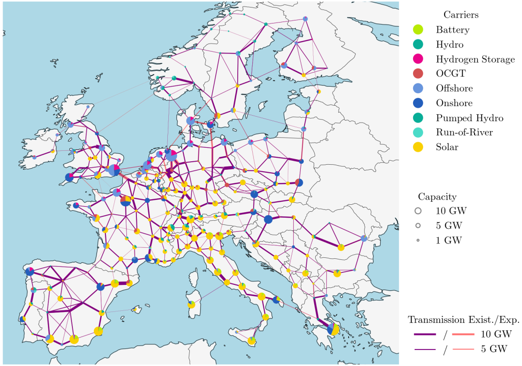
openmod **open energy modelling initiative**

- **grass roots community** of open energy modellers from universities, research institutions and the interested public
- 950+ participants from all continents except Antarctica
- first meeting Berlin 18–19 September 2014
- promoting **open code**, **open data** and **open science** in energy modelling
- check out the **mailinglist**, **forum** and **wiki**

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)

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Capabilities

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

with components for:

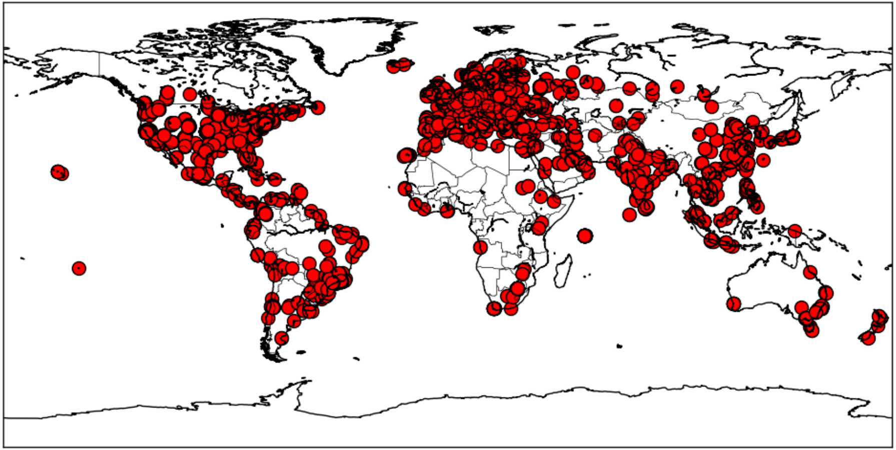
- AC and DC **power networks**
- generators with **unit commitment**
- **variable generation** with time series
- **storage** and **conversion**
- **power-to-mobility/heat/gas**

Backend

- 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
- highly **customisable**

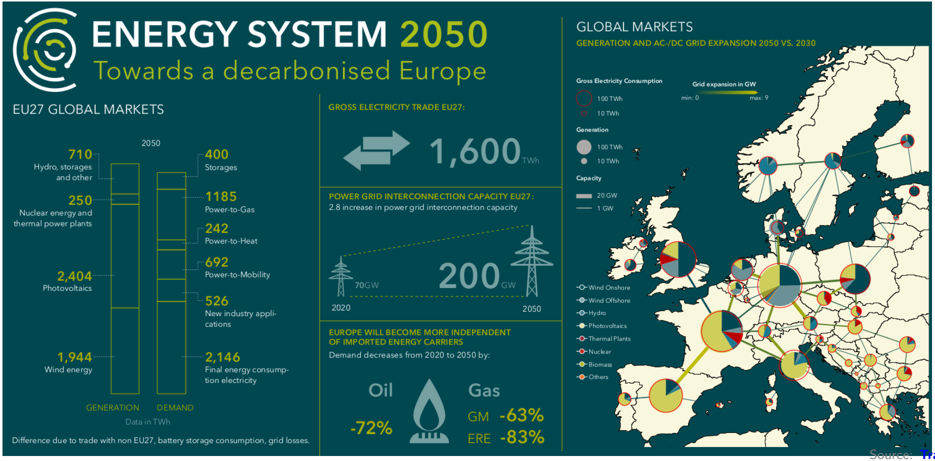
Python for Power System Analysis: Worldwide Usage

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-Sec

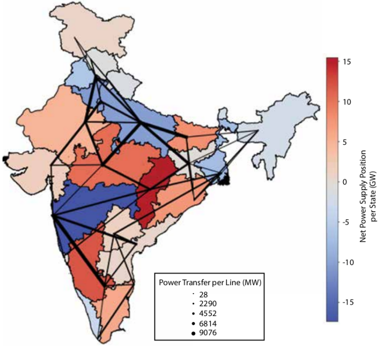
German **Transmission System Operator (TSO) TransnetBW** used an open model (PyPSA-Eur-Sec) to model the European energy system in 2050. Why? Easier to build on an existing model than reinvent the wheel.

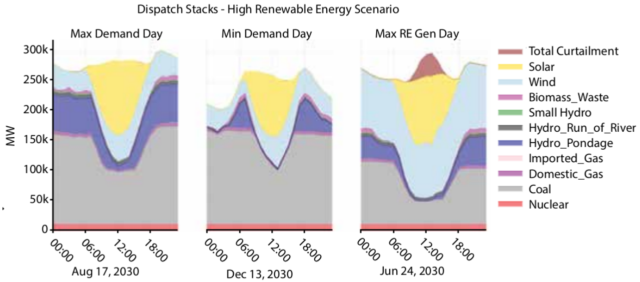


Source: TransnetBW, 2022

PyPSA example: TERI in India

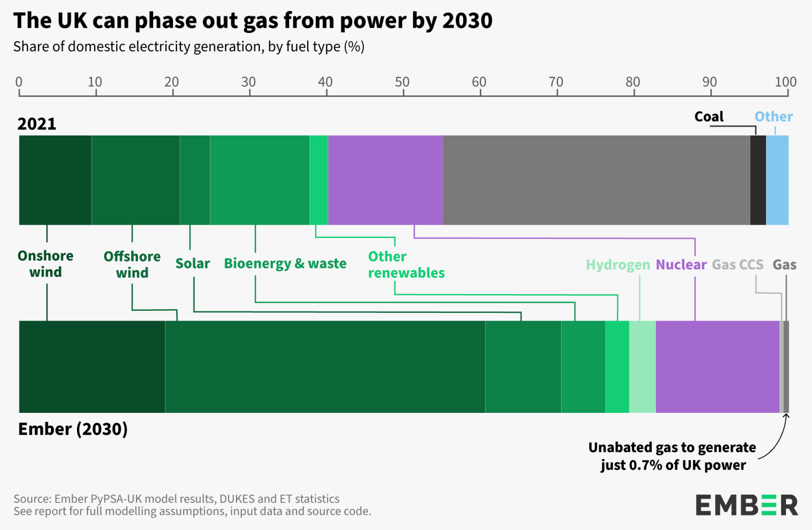
For a government-backed study of India's power system in 2030, The Energy and Resources Institute (TERI) in New Delhi used open framework PyPSA. Why? **Easy to customize**, lower cost than commercial alternatives like PLEXOS, good for building up skills and reproducible by other stakeholders.





Source: TERI

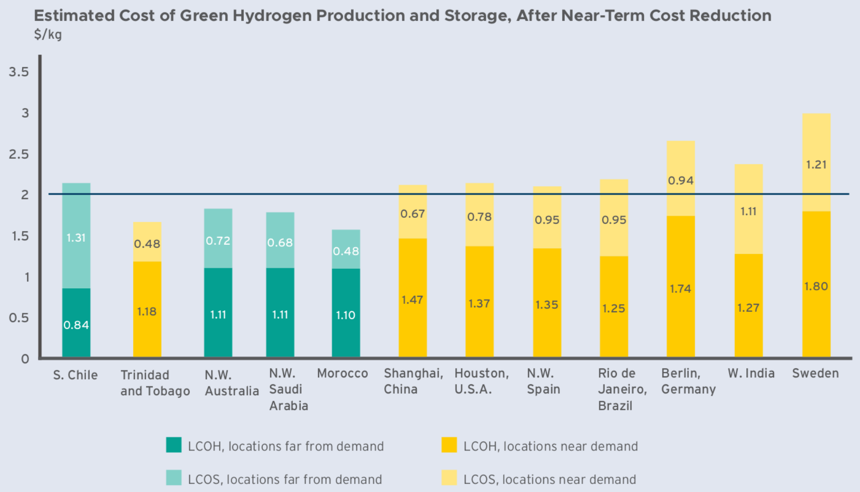
NGO Ember used PyPSA to model a gas phase out in the UK by 2030, releasing all code on github.



Source: Ember, 2022

Example User of PyPSA: RMI in United States

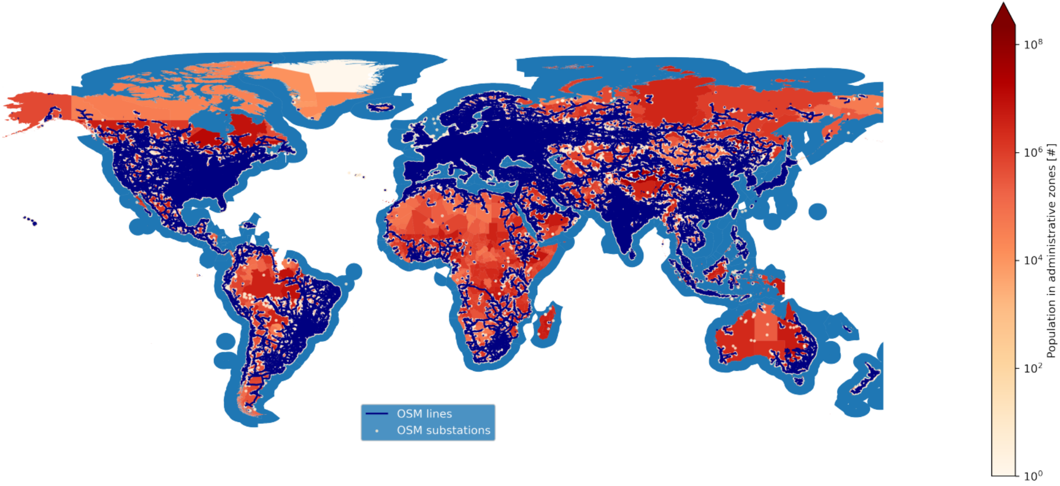
The Rocky Mountain Institute (RMI) in Boulder, Colorado used PyPSA to model hydrogen production costs around the world, since PyPSA had a track record for such calculations.



Source: RMI, 2021

PyPSA meets Earth Initiative

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



Source: **PyPSA meets Earth, 2022**

European Sector-Coupled Model PyPSA-Eur-Sec

What is PyPSA-Eur-Sec?

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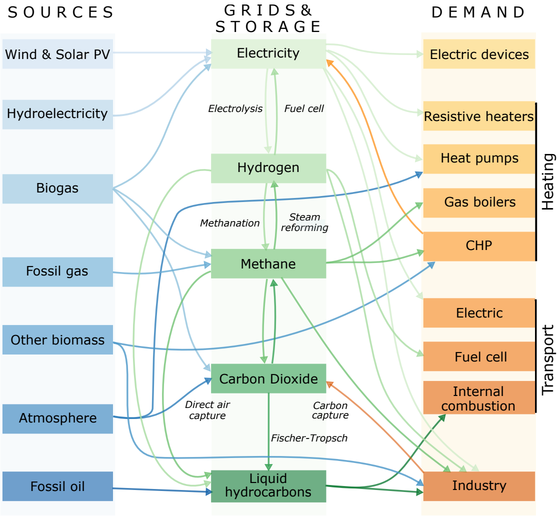
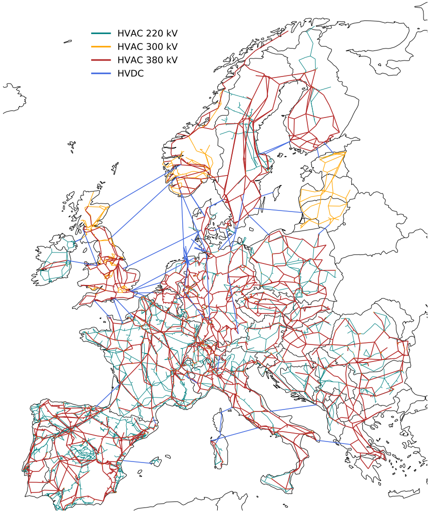
Model for Europe with all energy flows... and bottlenecks in energy networks.



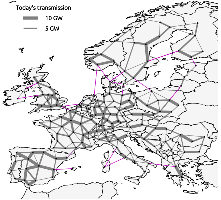


Data-driven energy modelling

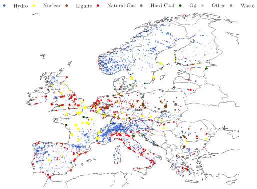
Lots of different types of data and process knowledge come together for the modelling.

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

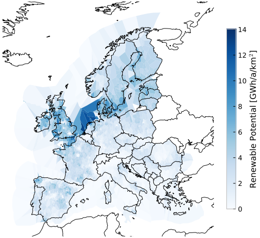
clustered network model



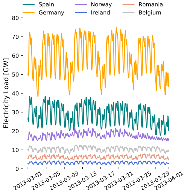
power plants and technology assumptions



renewable potentials and hourly time series for each region



demand projections time series



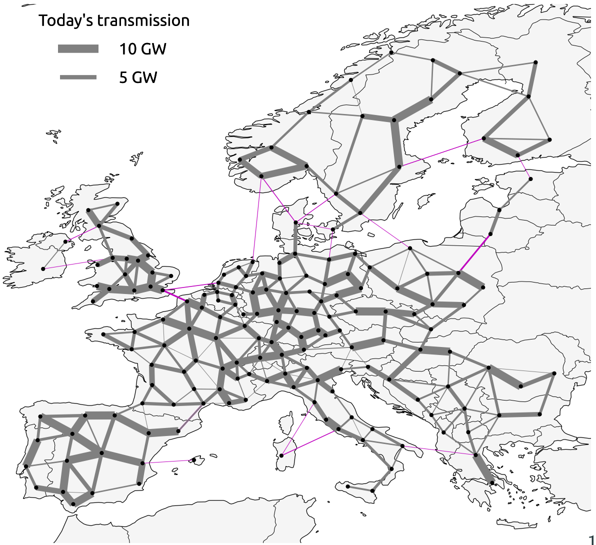
Results for 181-node model of European energy system

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)

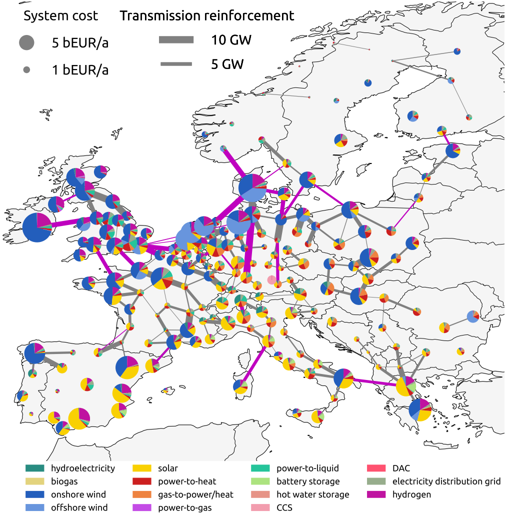
Examine effects of:

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



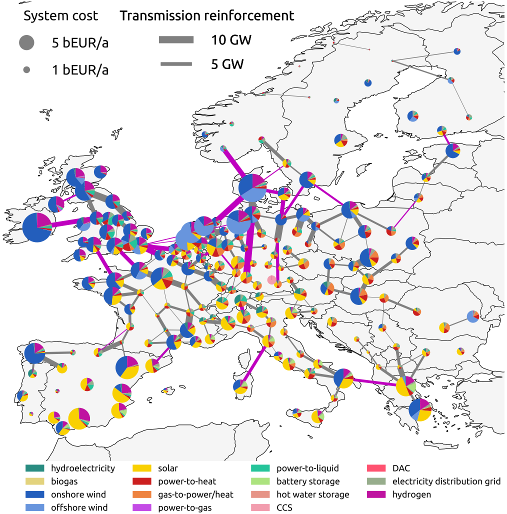
Distribution of technologies: 50% more power grid volume

Electricity grid expansion of 162 TWkm...

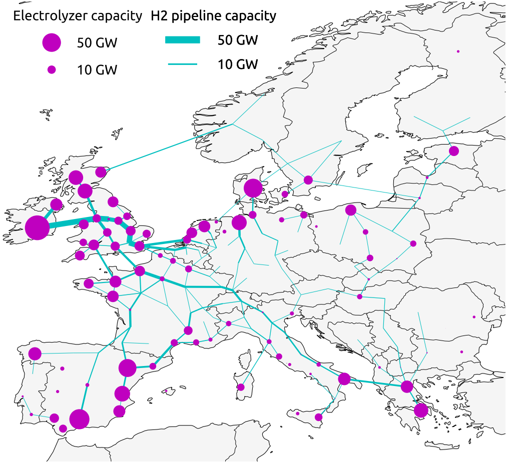


Distribution of technologies: 50% more power grid volume

Electricity grid expansion of 162 TWkm...



...and new hydrogen grid of 260 TWkm.



Distribution of technologies: 25% more power grid volume

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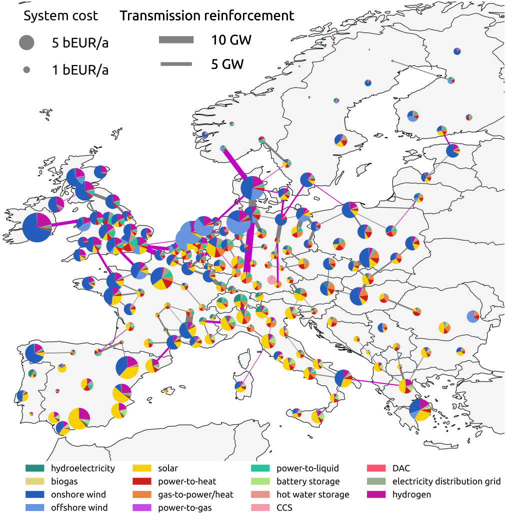
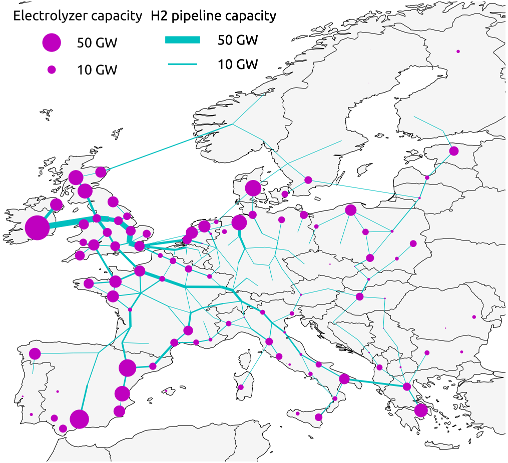
Electricity grid expansion of 81 TWkm...

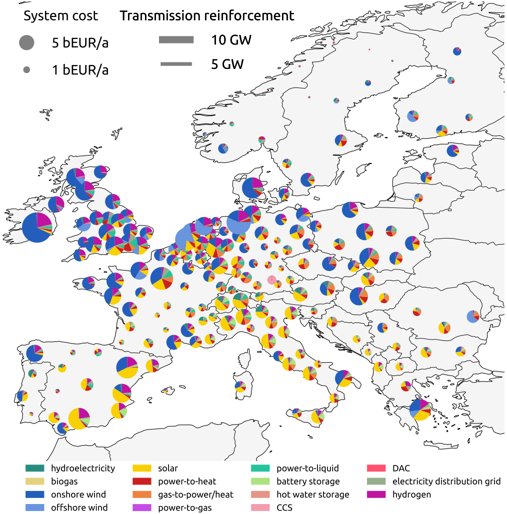


...and new hydrogen grid of 282 TWkm.

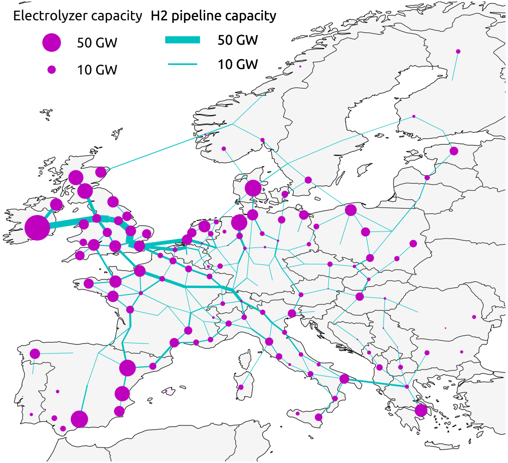


Distribution of technologies: no power grid expansion

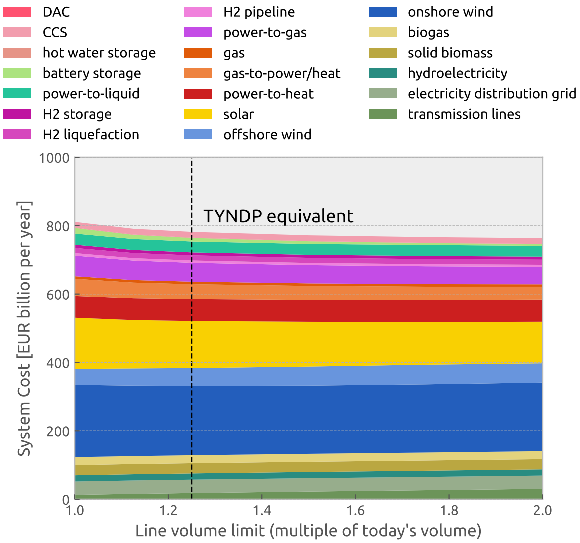
No electricity grid expansion...



...and new hydrogen grid of 308 TWkm.

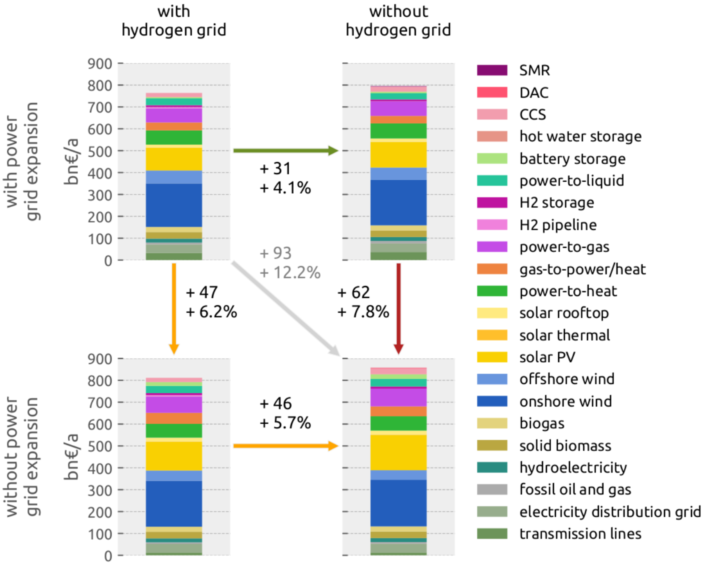


Benefit of power grid expansion for sector-coupled system



- 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)

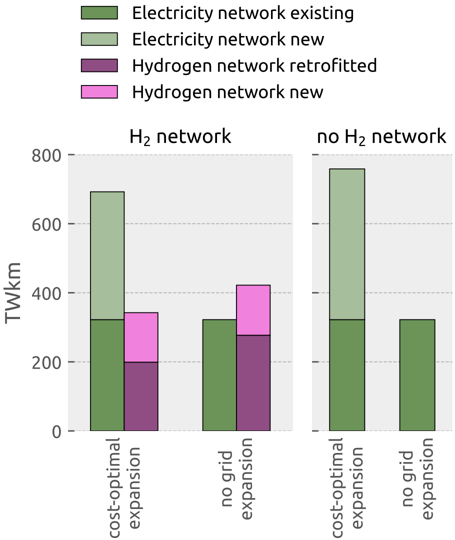
With and without hydrogen network



- **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

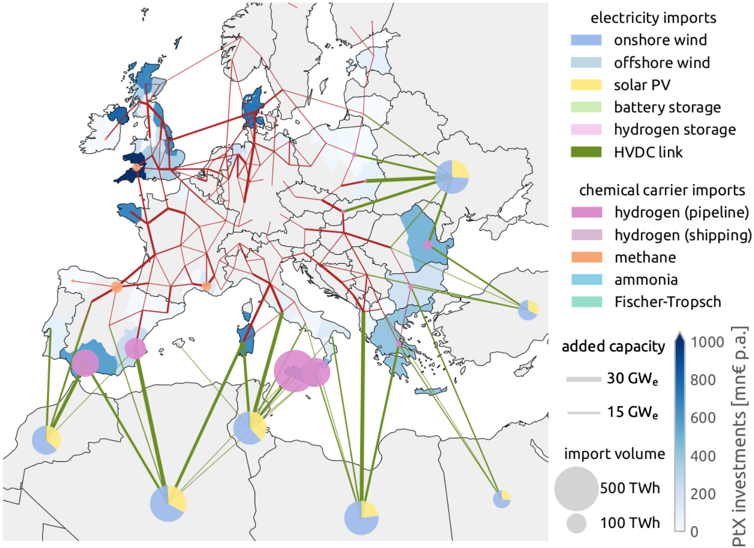
Energy grid in different cases



- 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

With e-fuel imports instead of autarky

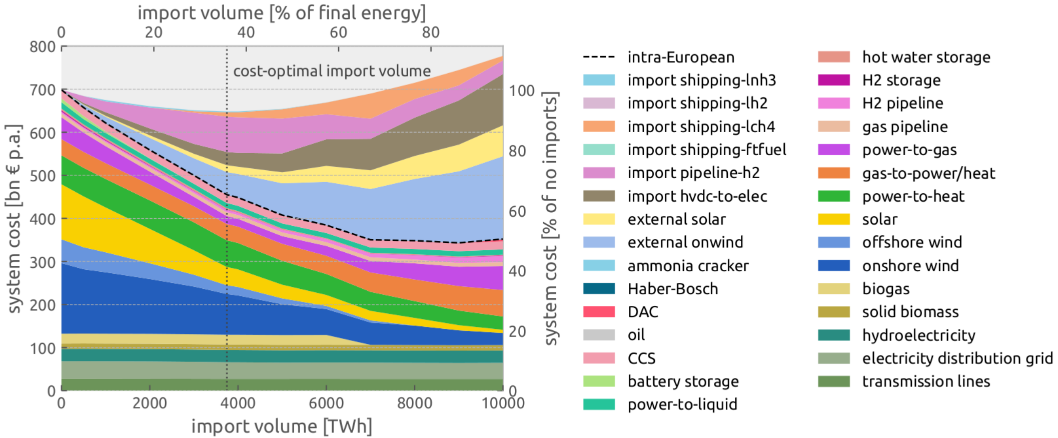


- Allowing imports of electricity, green hydrogen, e-fuels, **changes infrastructure needs completely**
- PtX out-sourced from Europe
- Electricity imported too, providing seasonal balancing

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

Open source, open data, online customisable model

All the code and data behind PyPSA-Eur-Sec 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

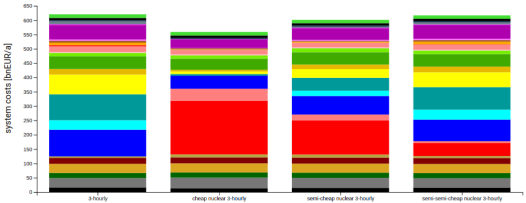
Demand for electricity in residential and services sector compared to today	0.9	per unit
Demand for space heating in buildings compared to today	0.71	per unit
Demand for hot water in buildings demand compared to today	1	per unit
Demand for land transport (road and rail) compared to today	1	per unit
Demand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

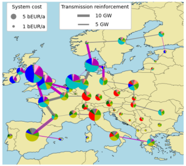
Sector coupling options

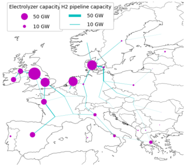
Yearly sequestration potential for carbon dioxide	200	MtCO2/a
Share of battery electric vehicles in land transport	0.85	per unit
Share of fuel cell electric vehicles in land transport	0.15	per unit

Breakdown of yearly system costs

All costs are in 2015 euros, EUR-2015.







Conclusions

Conclusions

- **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
- Open energy modelling is now **widely accepted** and used across academia, government, NGOs and industry
- There are many **trade-offs** between unpopular infrastructure, cost and security
- BUT: many **near-optimal** compromise solutions with **favourable properties**
- Many more **tricky topics to come**: e-fuel imports, industry relocation, carbon management infrastructure

More information

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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

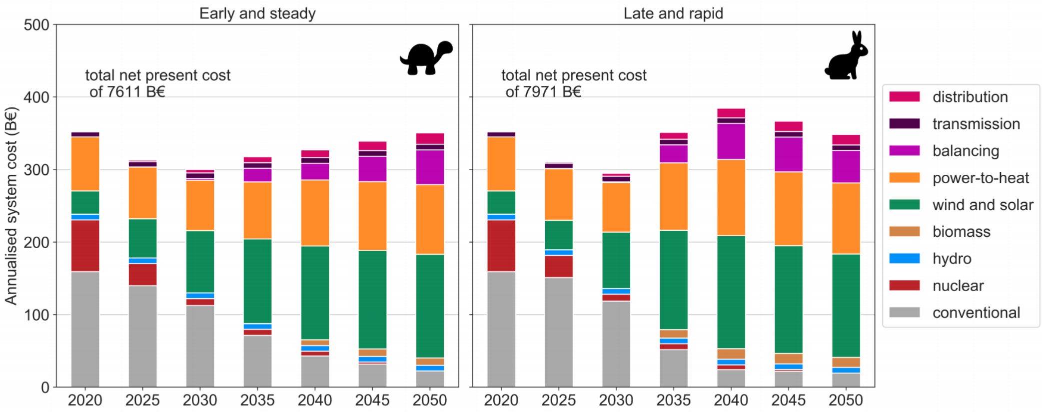
Publications (selection):

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**.

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

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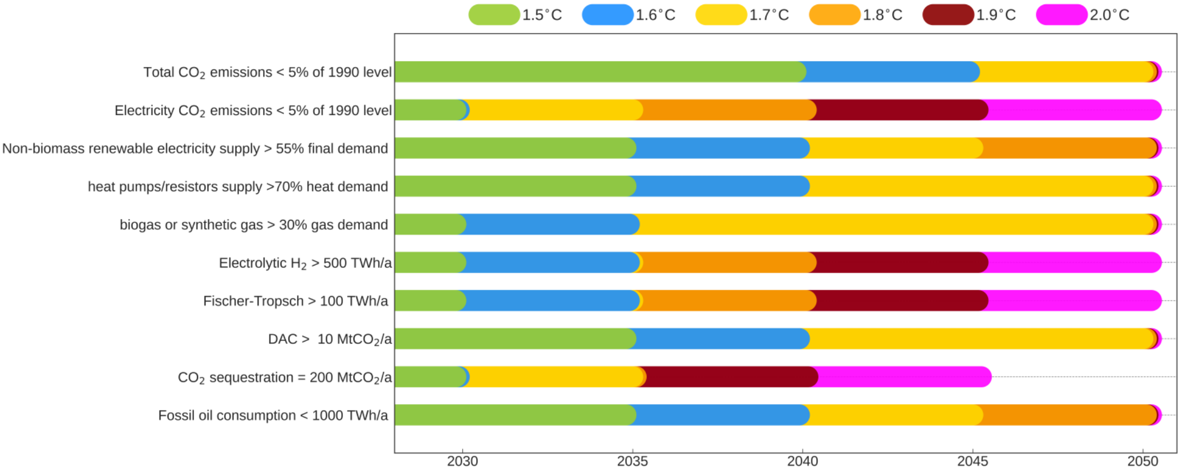

Source: M. Victoria et al, 2021

Future work

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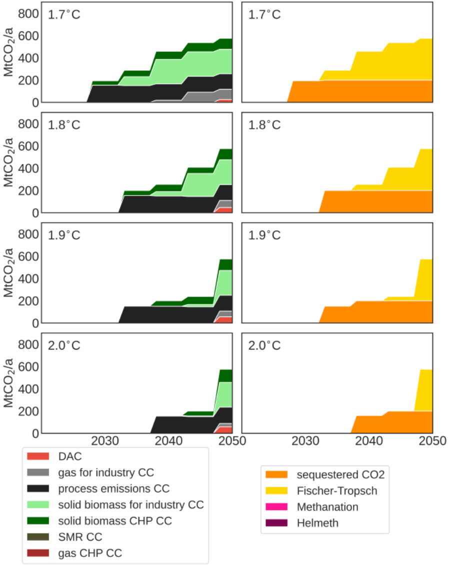
- Consider **pathway** of investments 2020-2050 at high resolution
- Compare local production with import of **synfuels from outside Europe**
- Extend offshore wind potentials by including **floating wind** for depths > 50 m
- Examine benefits of offshore **hub-and-spoke grid topology**
- Proper consideration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

Carbon Management

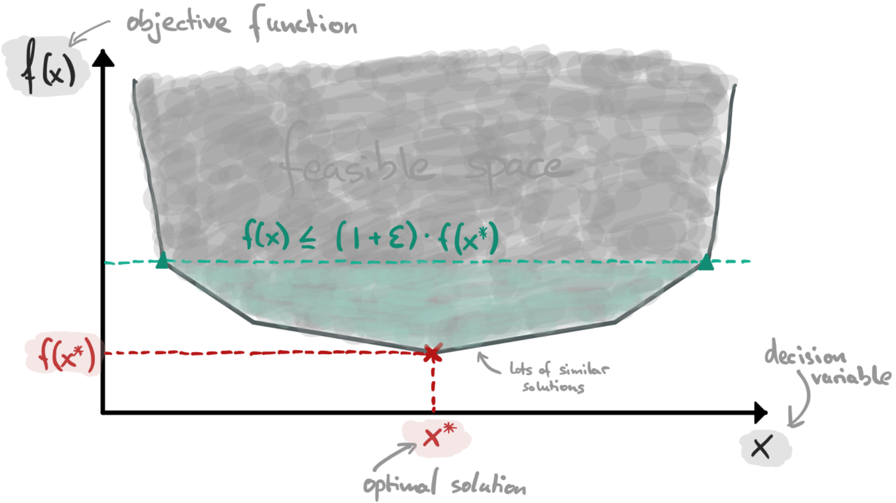


- Carbon capture (left): from process emissions, but also from heat production in industry and for combined-heat-and-power (CHP) plants
- Sequestration limited to 200 $MtCO_2/a$ (enough to cover today's process emissions)
- Further carbon capture is used for Fischer-Tropsch fuels (kerosene and naphtha)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

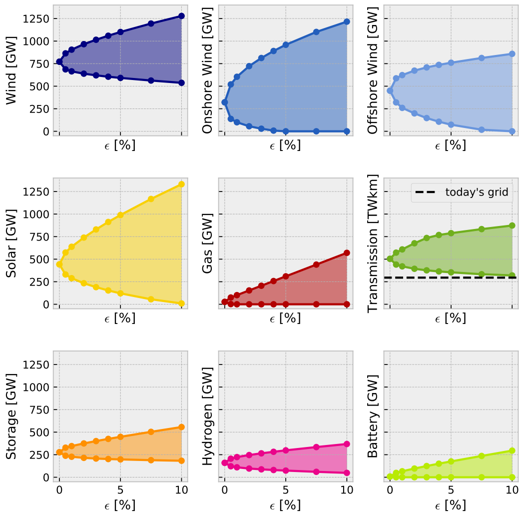
Large Space of Near-Optimal Energy Systems

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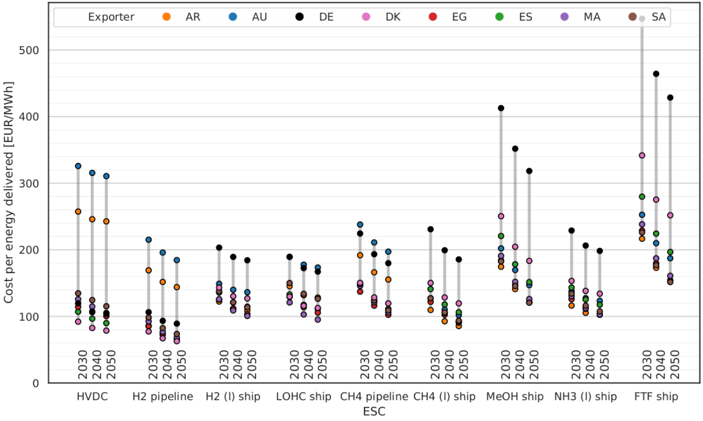
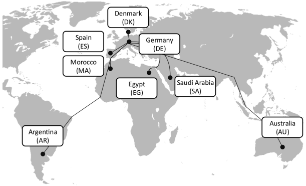
Green hydrogen with pipeline transport costs around ~ 80 €/MWh in model. Shipping green hydrogen from **outside Europe** in liquid, LOHC or NH_3 form may not compete on cost (depends e.g. on WACC), but scarce land in Europe may still drive adoption.





Source: **Hampp et al, 2021**

Open source, open data, online customisable model

All the code and data behind PyPSA-Eur-Sec 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/`

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]

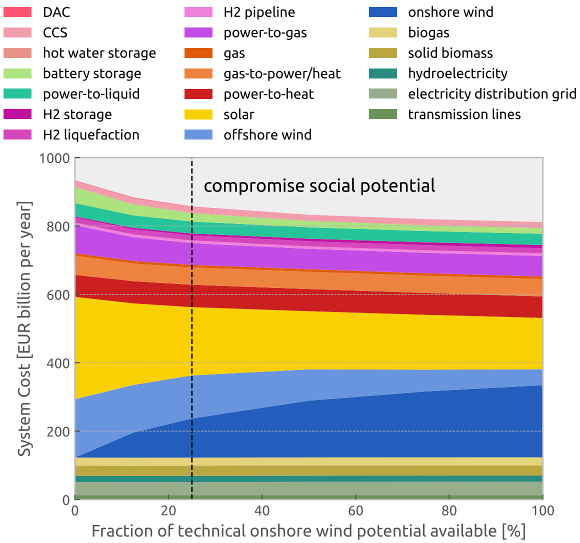
Sector coupling options

[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)

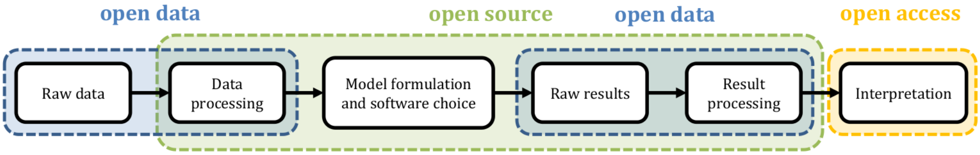
What is open modelling?

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

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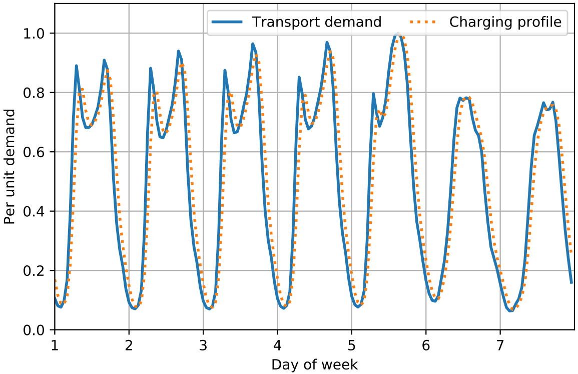
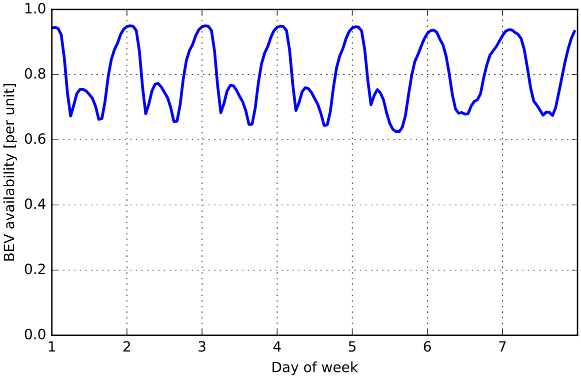


Weekly profile for the transport demand based on statistics gathered by the German Federal Highway Research Institute (BASt).

- 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.

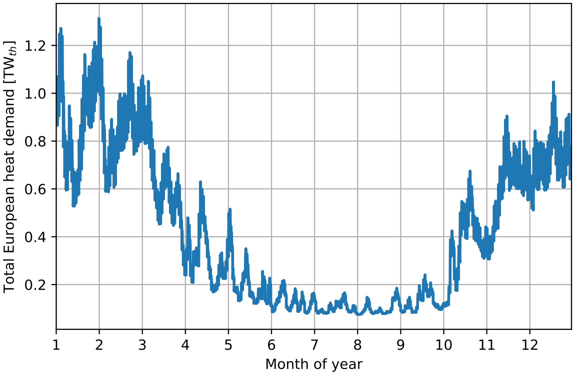
Transport sector: Battery Electric Vehicles



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:

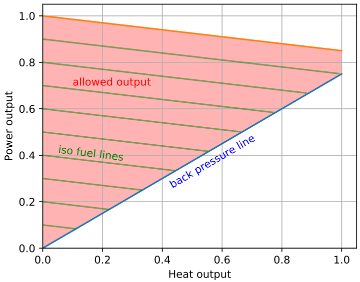
Decentral individual heating can be supplied by:

- 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:

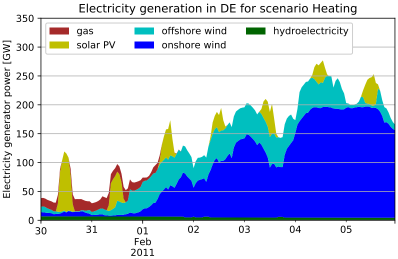
- Air-sourced heat pumps
- Resistive heaters
- Gas boilers
- Large solar thermal
- Water tanks with long time constant $\tau = 180$ days
- CHPs

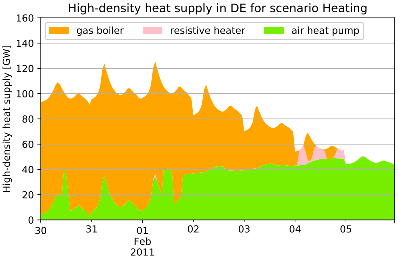
CHP feasible dispatch:



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

Example problem with balancing: Cold week in winter





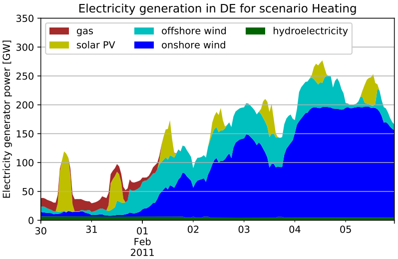
There are difficult periods in winter with:

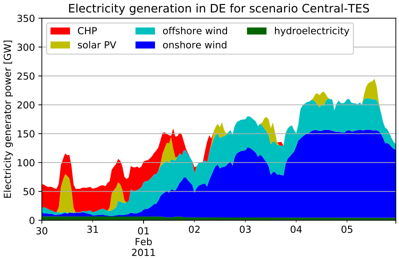
- **Low** wind and solar ($\Rightarrow$ high prices)
- **High** space heating demand
- **Low** air temperatures, which are bad for air-sourced heat pump performance

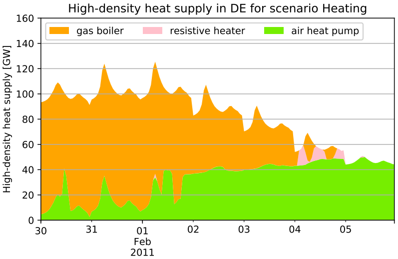
Less-smart solution: **backup gas boilers** burning either natural gas, or synthetic methane.

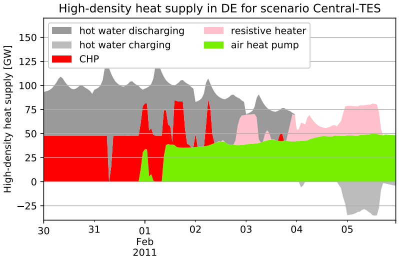
Smart solution: **building retrofitting**, **long-term thermal energy storage** in **district heating networks** and efficient **combined-heat-and-power plants**.

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





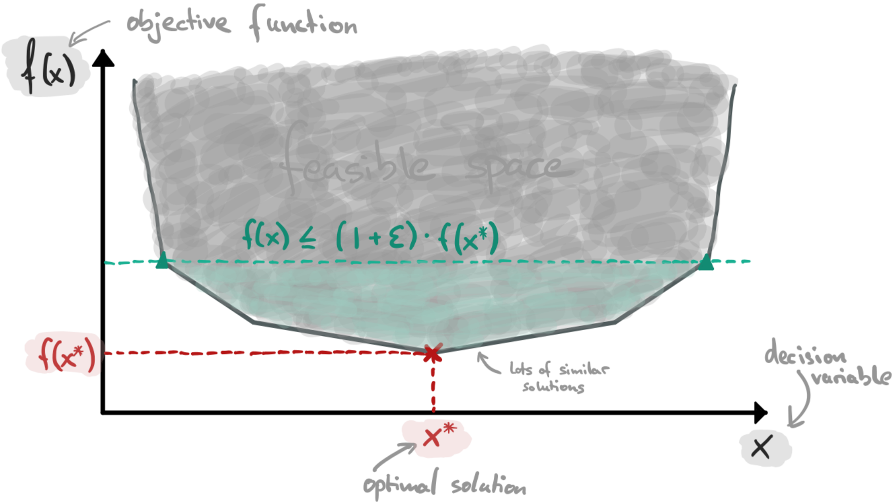




Source: **Brown et al, "Synergies of sector coupling," 2018**

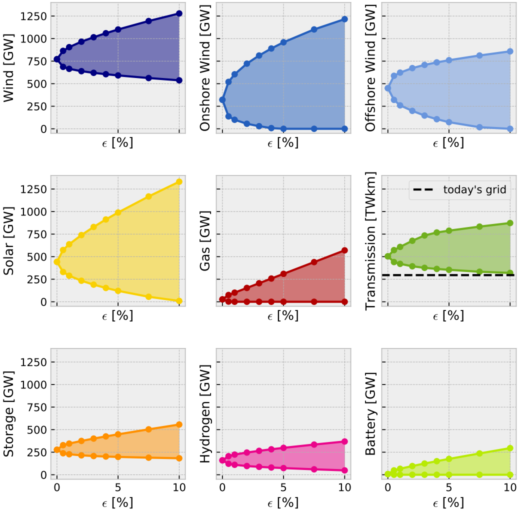
Large Space of Near-Optimal Energy Systems

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

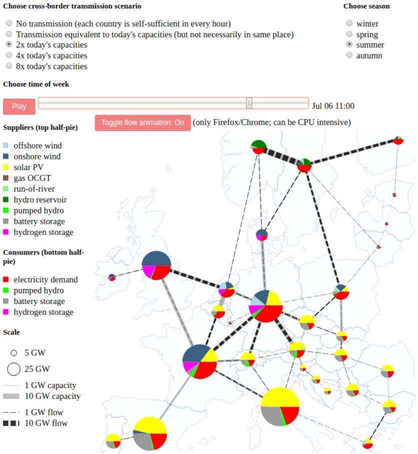
Online Visualisations and Interactive 'Live' Models

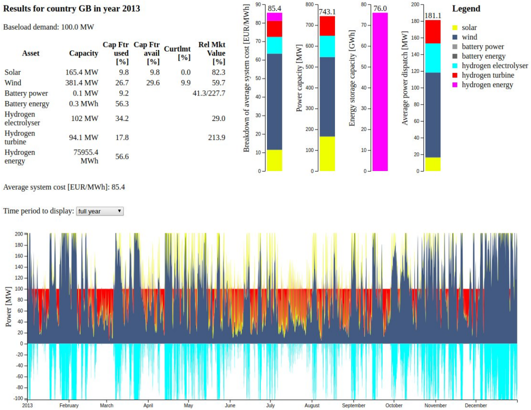
Online animated simulation results:

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.