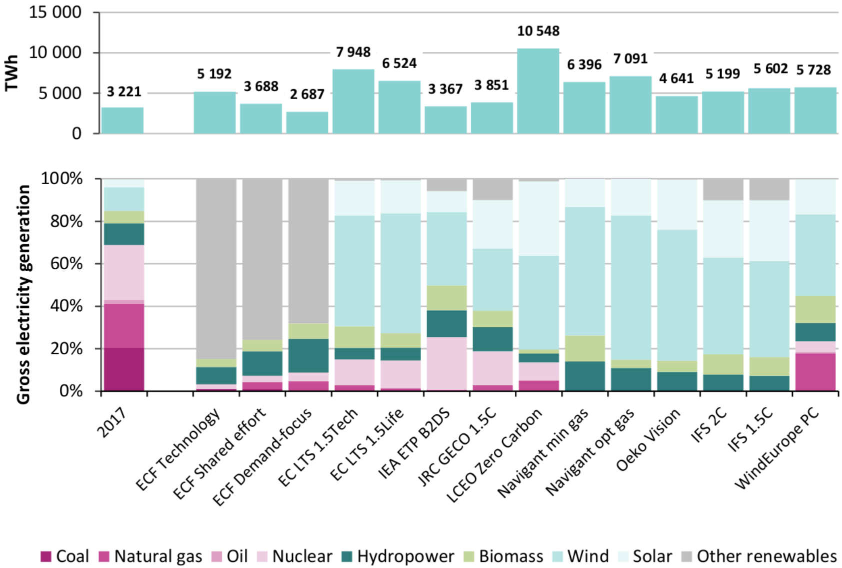
Can a Hydrogen Network Replace Electricity Transmission Network Expansion in a Climate-Neutral Scenario for Europe?

Tom Brown, Marta Victoria (Aarhus), Fabian Neumann, Lisa Zeyen (TUB), Martha Frysztacki (KIT)
t.brown@tu-berlin.de, Department of Digital Transformation in Energy Systems TU Berlin

EMP-E, 27th October 2021

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

Technische Universität Berlin



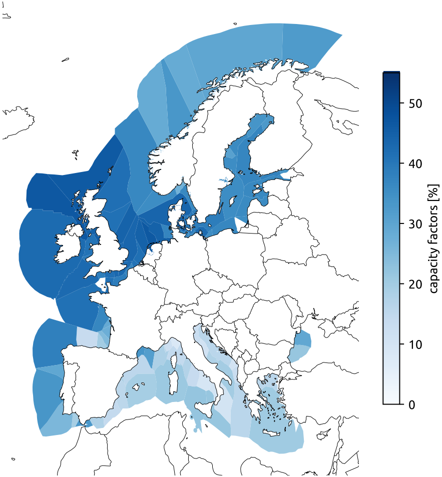
Source: JRC, 2020

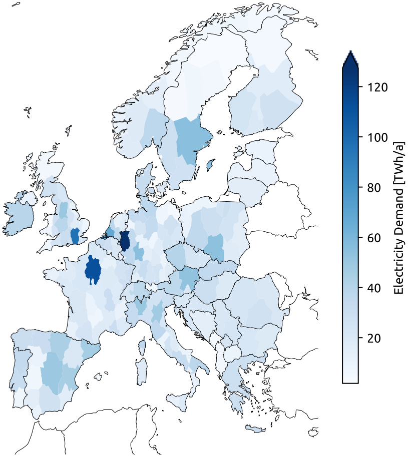
Problem: collides with low acceptance for power grid expansion...

...and low acceptance for onshore wind

Is offshore wind the answer?

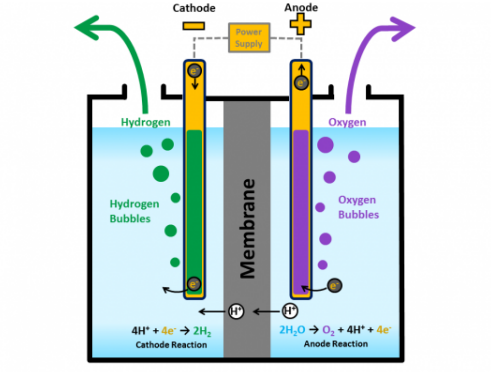
Offshore wind can certainly help, but you still need to get the electricity to loads inland.



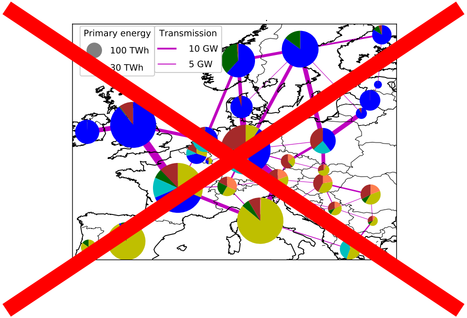


Can electrolytic hydrogen and a hydrogen network help?

Can we substitute for the electricity grid by producing **electrolytic hydrogen** and transporting it through a new and/or re-purposed **hydrogen pipeline network**?

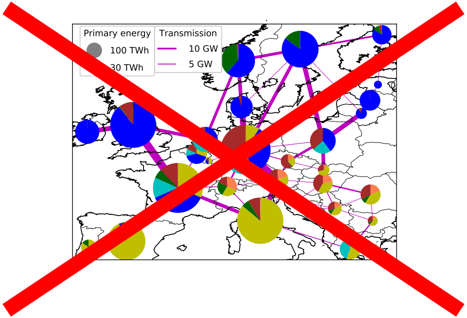


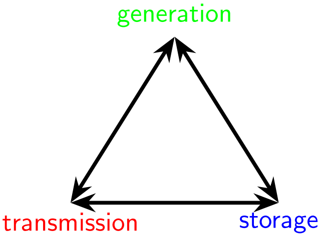
Challenge 1: Need spatial resolution to see grid bottlenecks & infrastructure trade-offs.
One node per country or continent won't work.



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

Challenge 2: Need to co-optimise balancing solutions with generation. Optimising separately won't work.



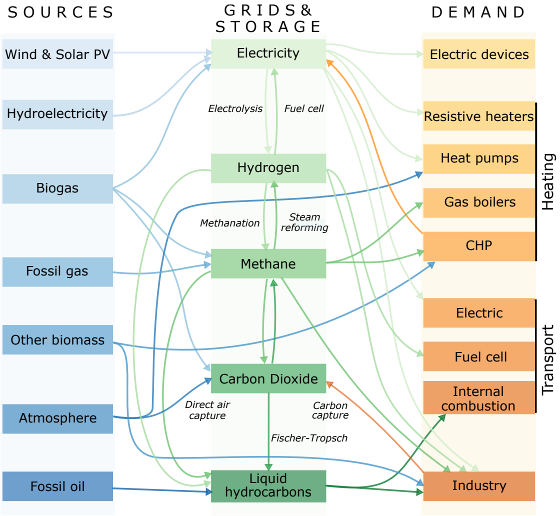


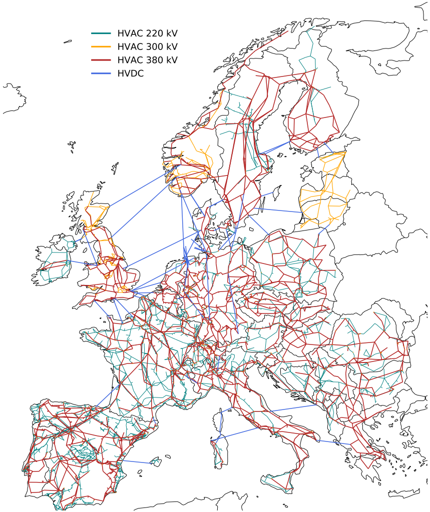
⇒ Need **very large** models, big data and methods for complexity management

What is PyPSA-Eur-Sec?

Technische Universität Berlin

Represents all energy flows... and bottlenecks in energy networks.

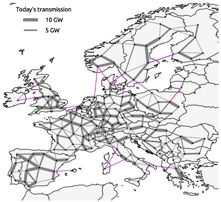




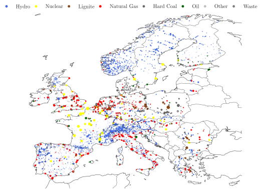
Data-driven energy modelling

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

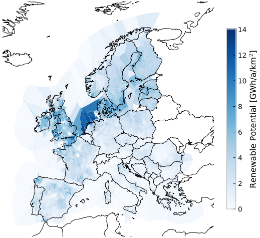
clustered network model



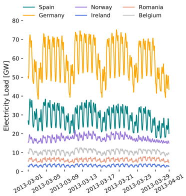
power plants and technology assumptions



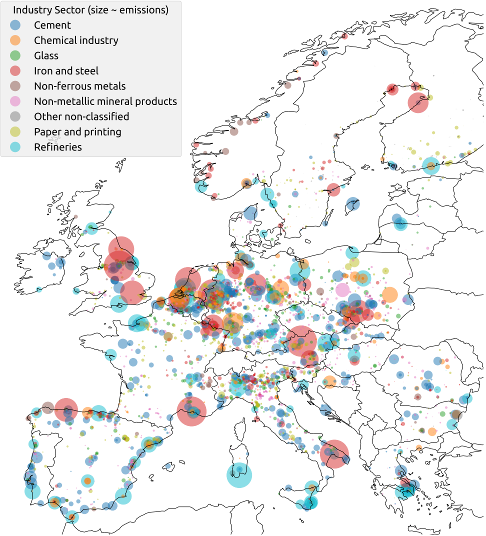
renewable potentials and hourly time series for each region



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

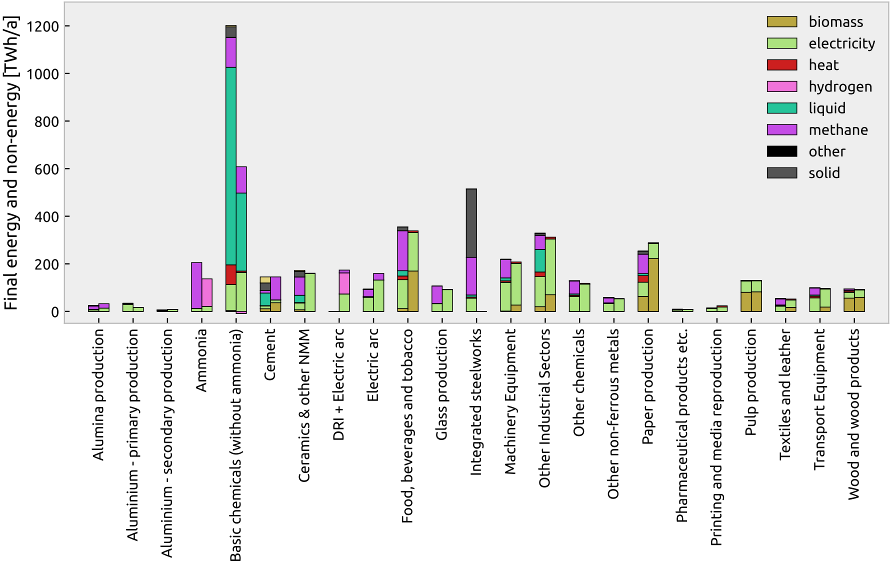
Process- and fuel-switching in industry, aviation, shipping

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

Decarbonisation of industry: process and fuel switching

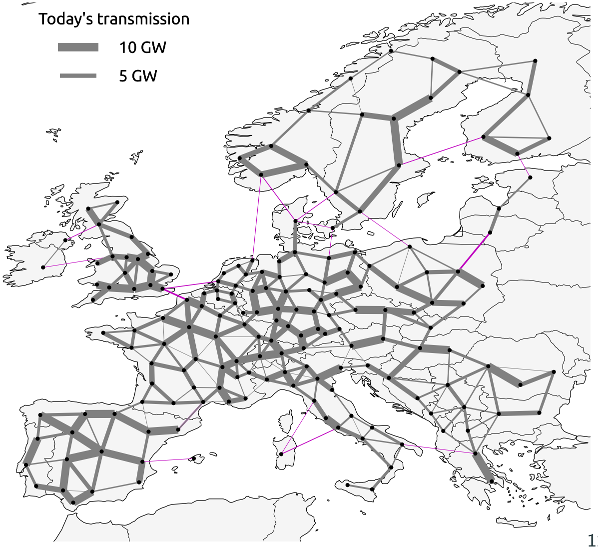
Technische Universität Berlin



Technische Universität Berlin

Model set-up:

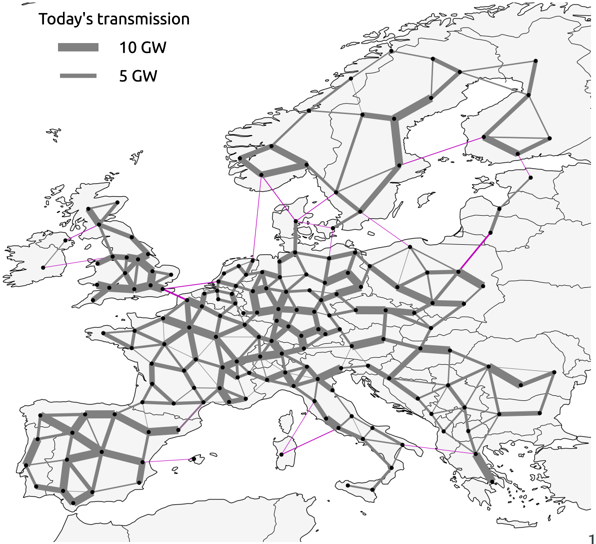
- Couple **all energy sectors** (power, heat, transport, industry)
- Reduce net CO_2 emissions **to zero**
- Assume 181 **smaller bidding zones** and **widespread dynamic pricing**
- **Conservative** technology assumptions (for 2030 from Danish Energy Agency)



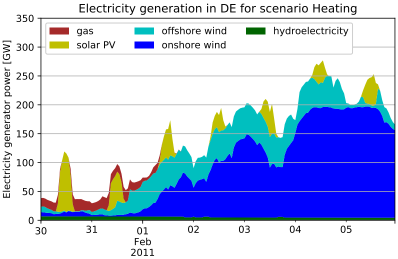
Technische Universität Berlin

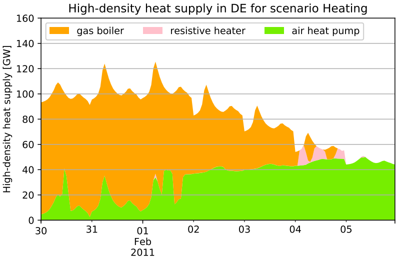
Examine effect of:

- Limiting **power grid expansion**
- Limiting **onshore wind potentials**
- Removing **hydrogen grid**



Example problem with balancing: Cold week in winter





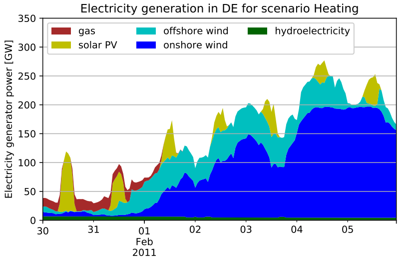
There are difficult periods in winter with:

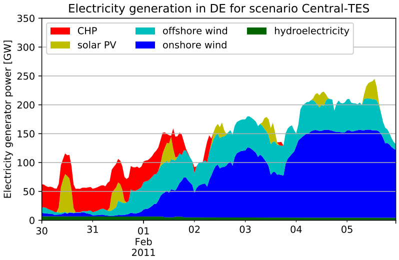
- **Low** wind and solar ($\Rightarrow$ high prices)
- **High** space heating demand
- **Low** air temperatures, which are bad for air-sourced heat pump performance

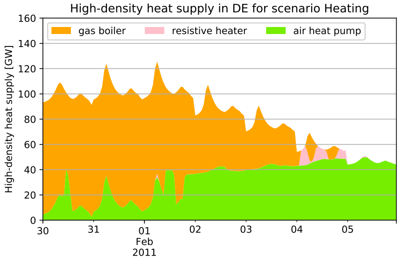
Less-smart solution: **backup gas boilers** burning either natural gas, or synthetic methane.

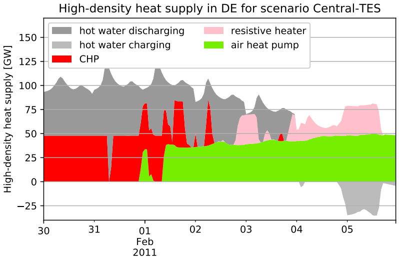
Smart solution: **building retrofitting**, **long-term thermal energy storage** in **district heating networks** and efficient **combined-heat-and-power plants**.

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





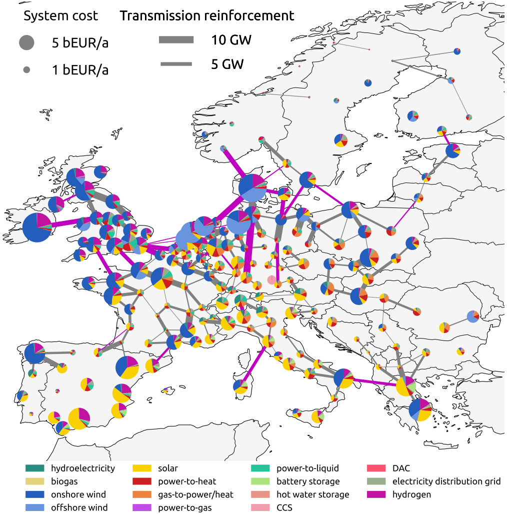




Source: Brown et al, "Synergies of sector coupling," 2018

Distribution of technologies: 50% more power grid volume

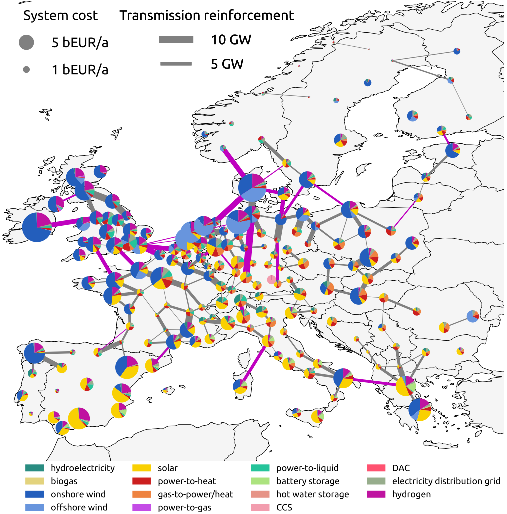
Electricity grid expansion of 162 TWkm...

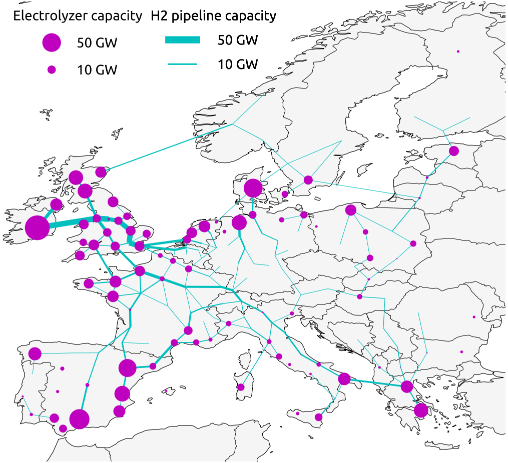


Distribution of technologies: 50% more power grid volume

Technische Universität Berlin

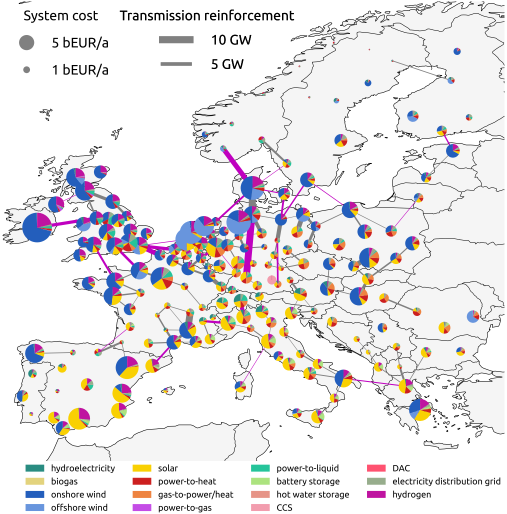
Electricity grid expansion of 162 TWkm... ...and new hydrogen grid of 260 TWkm.



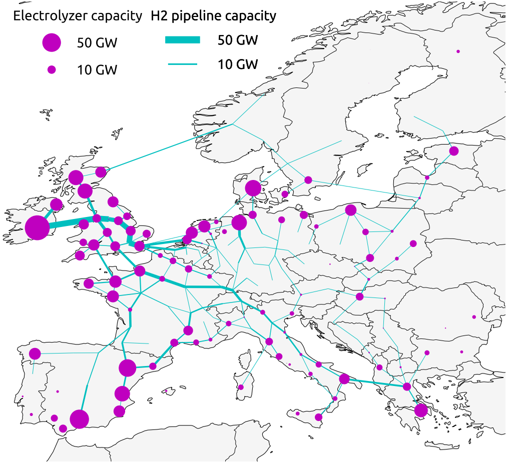


Distribution of technologies: 25% more power grid volume

Electricity grid expansion of 81 TWkm...

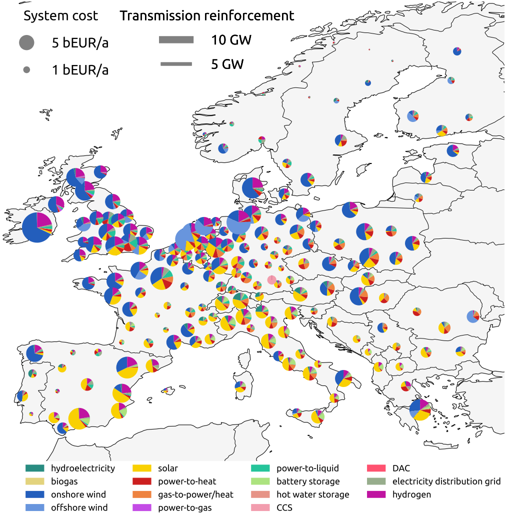


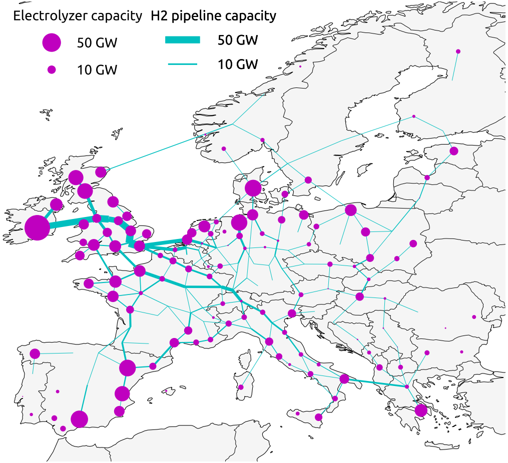
...and new hydrogen grid of 282 TWkm.



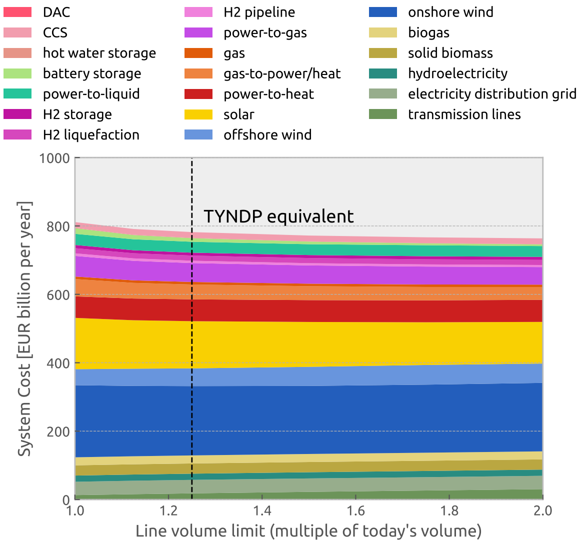
Distribution of technologies: no power grid expansion

No electricity grid expansion... ...and new hydrogen grid of 308 TWkm.





Benefit of power grid expansion for sector-coupled system

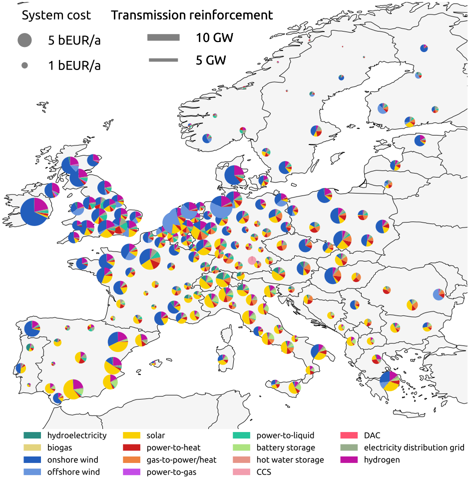


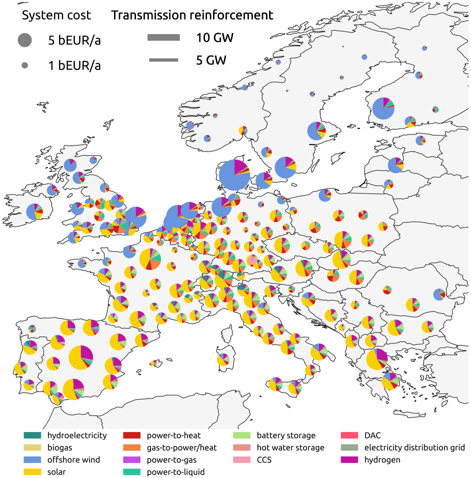
- Direct system costs **bit higher than today's system** (€ 700 billion per year with same assumptions)
- Systems **without grid expansion** are feasible, but more costly
- As grid is expanded, **costs reduce** from solar, power-to-gas and H_2 network; more offshore wind
- Total cost benefit of extra grid: $\sim$ € 47 billion per year
- **Over half of benefit available at 25% expansion** (like TYNDP)

What about restricting onshore wind potentials?

With onshore: 1900 GW onshore, 220 GW offshore, 2700 GW utility PV, 320 GW rooftop.

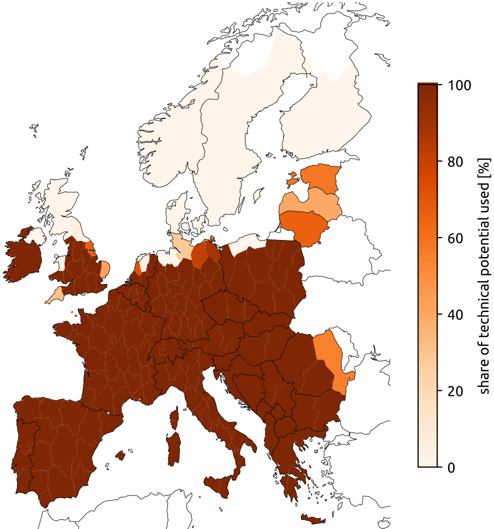
Without onshore: 820 GW offshore, 5600 GW utility PV, 450 GW rooftop.

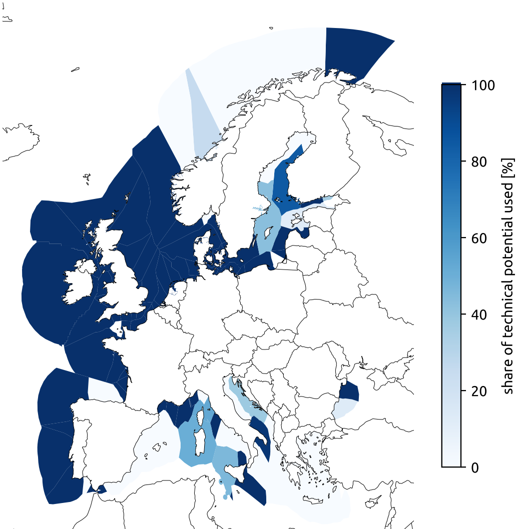




Without onshore: solar rooftop and offshore potentials maxxed out

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

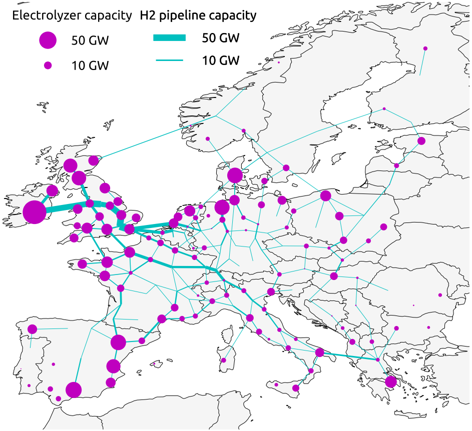


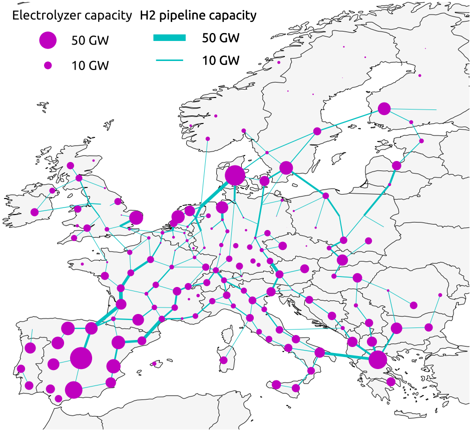


Effect of onshore wind potentials on hydrogen network

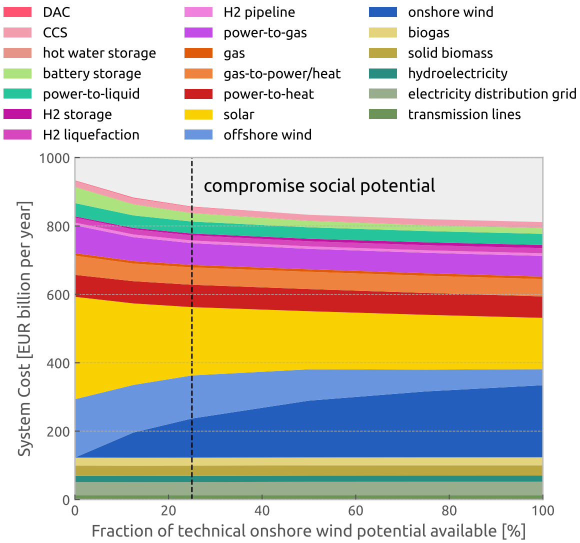
With onshore: British Isles and North Sea dominate hydrogen production.

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



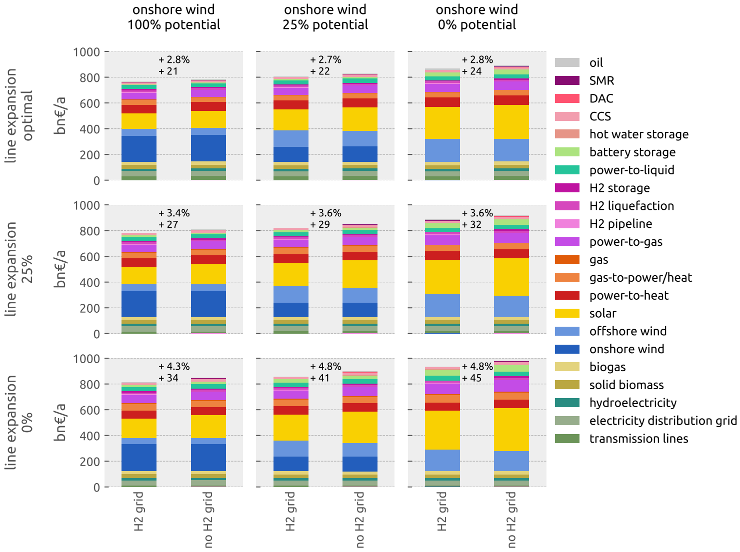


Benefit of full onshore wind potentials



- **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)

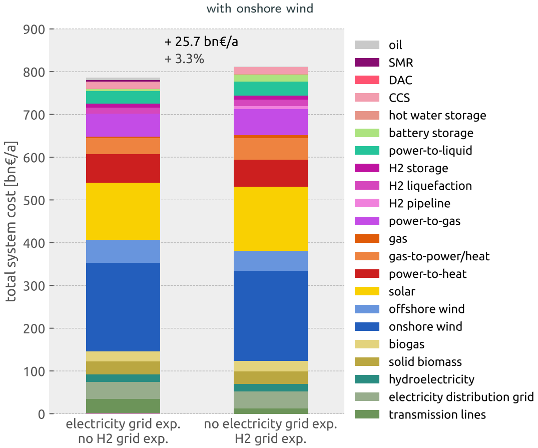
Finally: with and without hydrogen network



- **Cost** of hydrogen network: € 6-8 billion per year (depending on scenario)
- **Net benefit** is much higher: € 21-48 billion per year (2.7-4.8% of total)
- Hydrogen network is **robustly beneficial infrastructure**
- Benefit is strongest when there is no power grid expansion

Transmission grid expansion versus hydrogen network

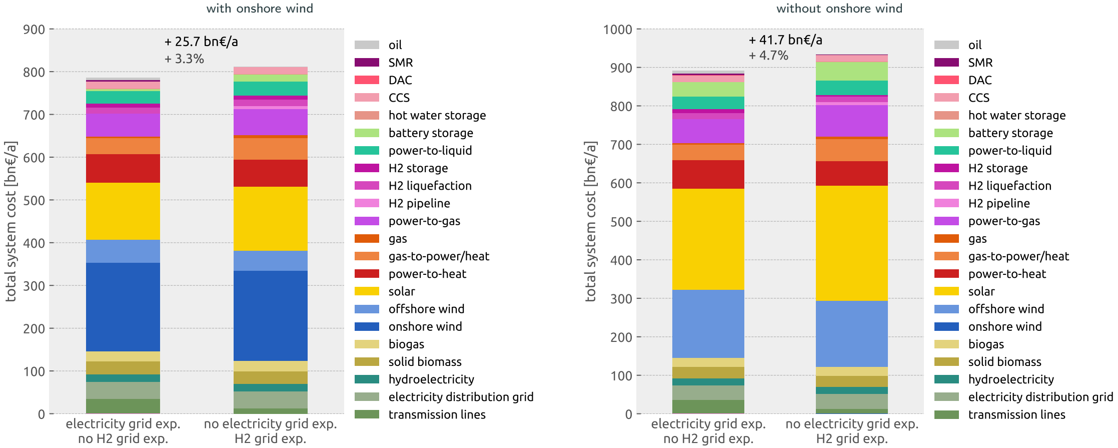
Compare power grid expansion and no H_2 grid (left) versus no power grid expansion and H_2 grid (right). Conclusion: both are important for costs; **grid expansion brings more cost benefit**; hydrogen network can partially substitute transmission expansion, but at higher system cost.



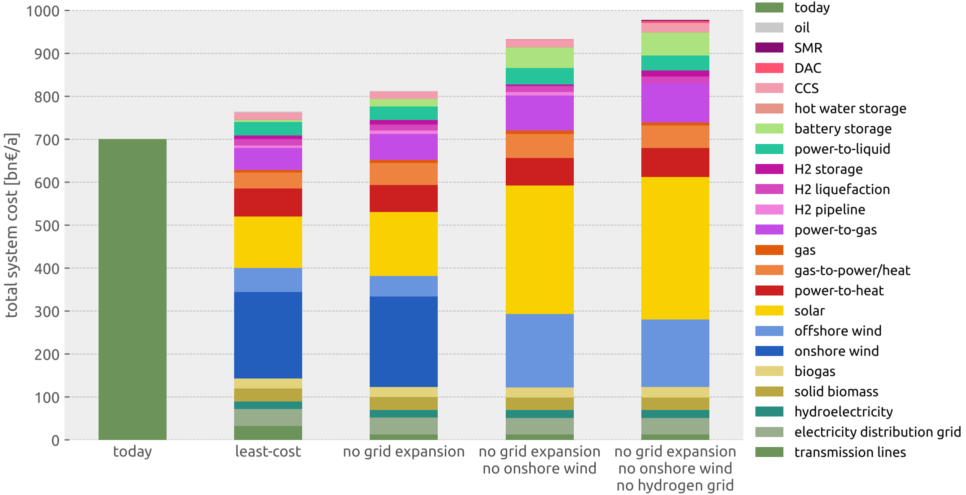
Transmission grid expansion versus hydrogen network

Technische Universität Berlin

Compare power grid expansion and no H_2 grid (left) versus no power grid expansion and H_2 grid (right). Conclusion: both are important for costs; **grid expansion brings more cost benefit**; hydrogen network can partially substitute transmission expansion, but at higher system cost.



Summary of effect of increasing restrictions



Electrolyser capacity rises 1100 GW, 1300 GW, 1700 GW, 1800 GW.

Future work

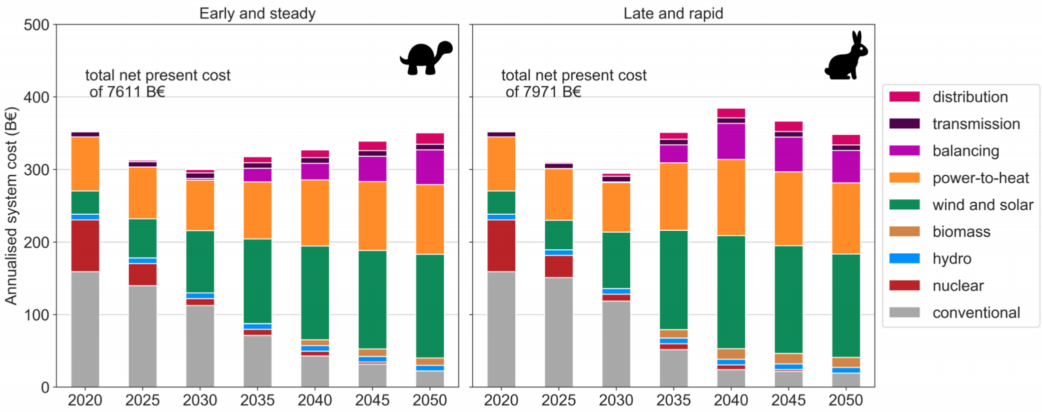
Technische Universität Berlin

- Consider **pathway** of investments 2020-2050
- 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)
- Benefits of **repurposing fossil gas grid** versus greenfield H_2 pipelines
- Cost-benefit of **sufficiency**

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.

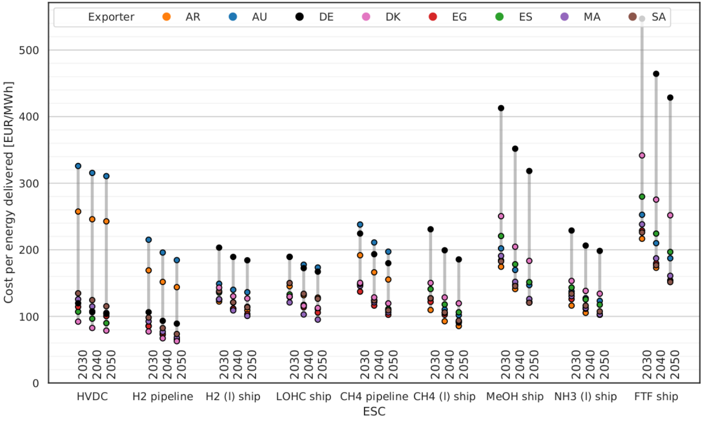
NB: These results only include electricity, heating in buildings and land-based transport.

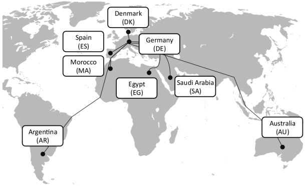


Source: M. Victoria et al, Nature Communications (2020)

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

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

Conclusions

- **Cross-sectoral** approaches are important to reduce CO2 emissions **and** for flexibility
- There are many **trade-offs** between unpopular infrastructure and system cost
- In our model, limiting power grid expansion **costs** $\sim$ **€40-50 billion per year more**
- If onshore wind expansion is restricted too, costs **rise by futher** $\sim$ **€120 billion per year**
- If all sectors included and Europe self-sufficient, effect of **installable potentials** is critical
- BUT: many **near-optimal compromise** energy systems with lower costs and **higher public acceptance** (see talk later by Dr. Fabian Neumann)
- **Hydrogen networks** can partially substitute for power grid expansion, but system costs are 3-5% higher; can also get away with neither power grid expansion nor H_2 network
- All results depend strongly on assumptions and modelling approach - therefore **openness and transparency are critical**, guaranteed by open licences for data and code

More information

Technische Universität Berlin

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. 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.
2. 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.
3. 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
4. D. Schlachtberger, T. Brown, M. Schäfer, S. Schramm, M. Greiner, *"Cost optimal scenarios of a future highly renewable European electricity system: Exploring the influence of weather data, cost parameters and policy constraints,"* Energy (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.

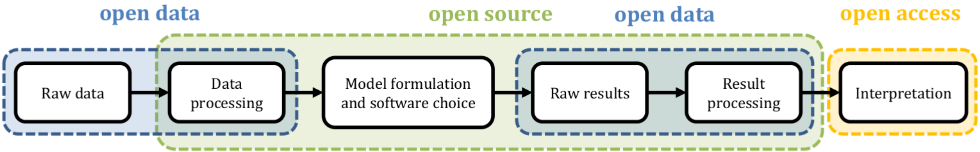
What is open modelling?

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.

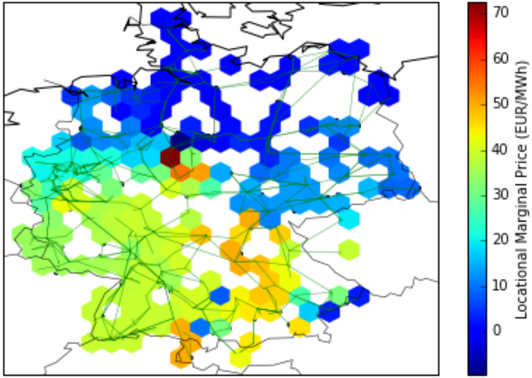
This is typically done by uploading the model to an online platform with an **open licence** telling users what their reuse rights are.

The **whole pipeline** should be open:



Python for Power System Analysis (PyPSA)

- **Open source** tool for modelling energy systems at **high resolution**.
- Fills missing gap between **load 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.

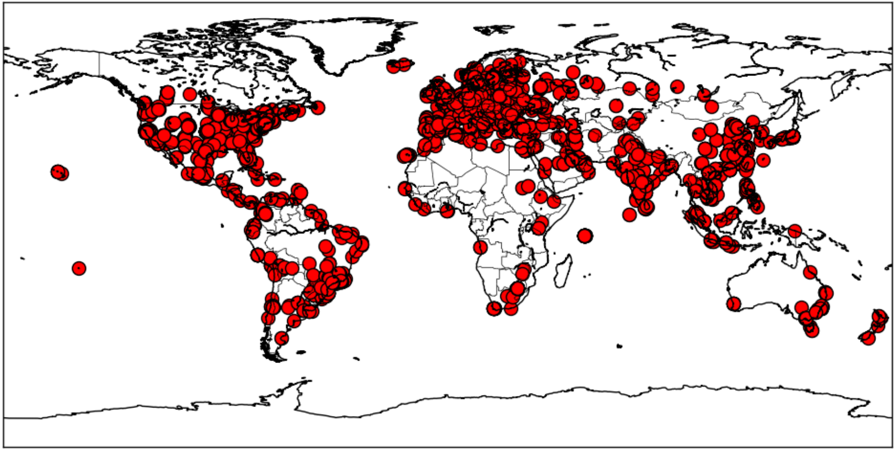


PyPSA is available on GitHub.

Python for Power System Analysis: Worldwide Usage

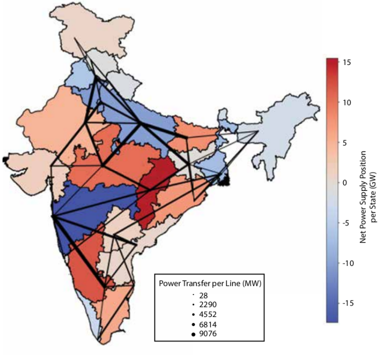
Technische Universität Berlin

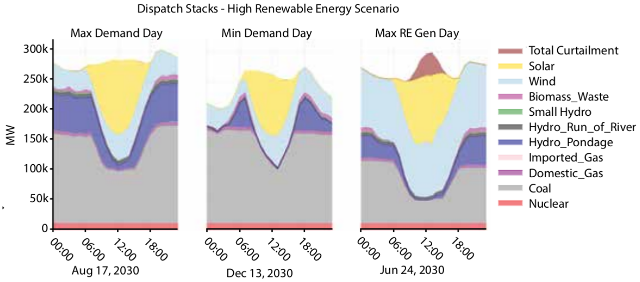
PyPSA is used worldwide by **dozens of research institutes and companies** (TU Delft, Shell, TransnetBW, Fraunhofer ISE, DLR Oldenburg, FZJ, TU Berlin, RLI, TERI, Saudi Aramco, Edison Energy, spire and many others). Visitors to the website:



Example User of PyPSA: 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 PyPSA. Why? Easy to customize, lower cost than commercial alternatives, good for building up skills and reproducible by other stakeholders.

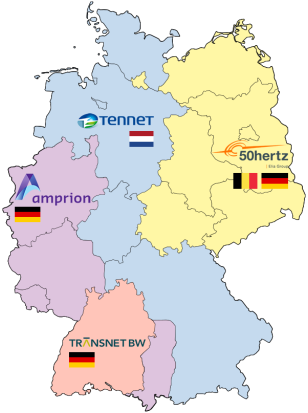




Source: TERI

Example User of PyPSA-Eur-Sec: TransnetBW in Germany

German Transmission System Operator (TSO) TransnetBW for South-West Germany used an open model (PyPSA-Eur-Sec) to model the energy system in 2050, because it was better and easier than building their own model from scratch.



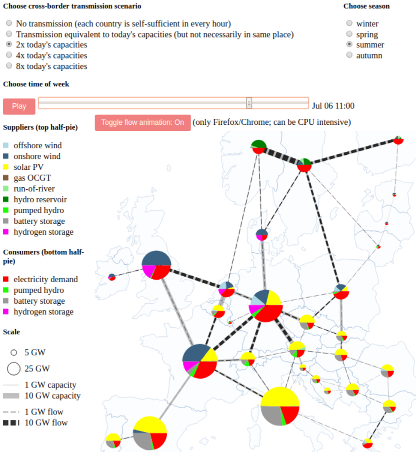
Source: https://www.transnetbw.de/de/stromnetz2050/

Online Visualisations and Interactive 'Live' Models

Technische Universität Berlin

Online animated simulation results:

pypsa.org/animations/



Live user-driven energy optimisation:

model.energy