PyPSA: Modelling Energy System Infrastructure for Climate-Neutral Scenarios

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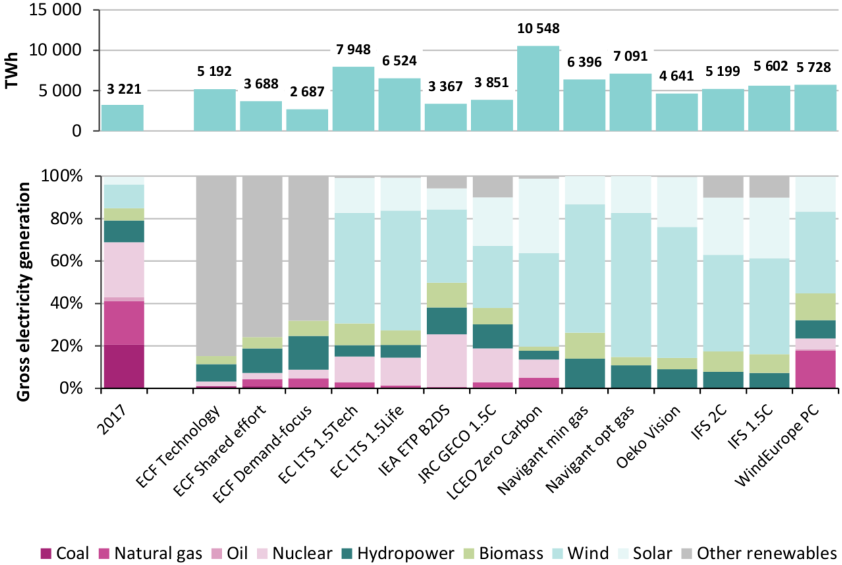
2050 scenarios for EU: power demand doubles, mostly met by VRE



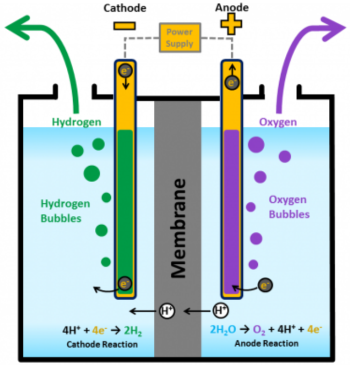
Source: JRC, 2020

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

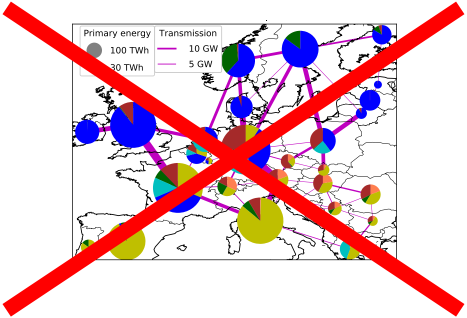
...and low acceptance for onshore wind

Can electrolytic hydrogen and a hydrogen network help?

Can we substitute for power grid by producing **electrolytic hydrogen** and transporting it through a new and/or re-purposed **hydrogen pipeline network**? Or with **imported green fuels** from outside EU?

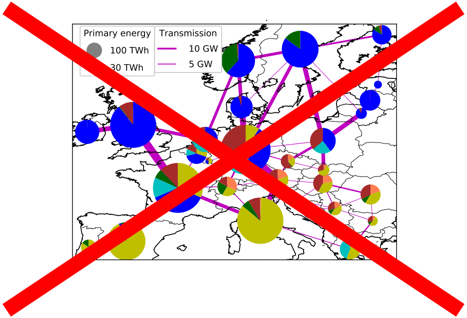


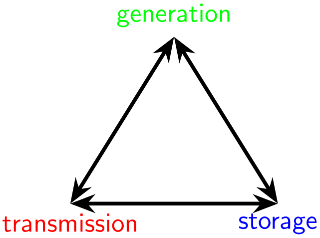
Challenge 1: Need spatial resolution to see grid bottlenecks & infrastructure trade-offs. One node per country or continent won't work.



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.

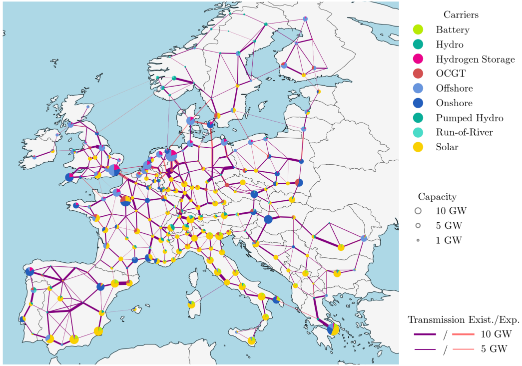




⇒ Need **very large** models, big data and methods for complexity management

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:

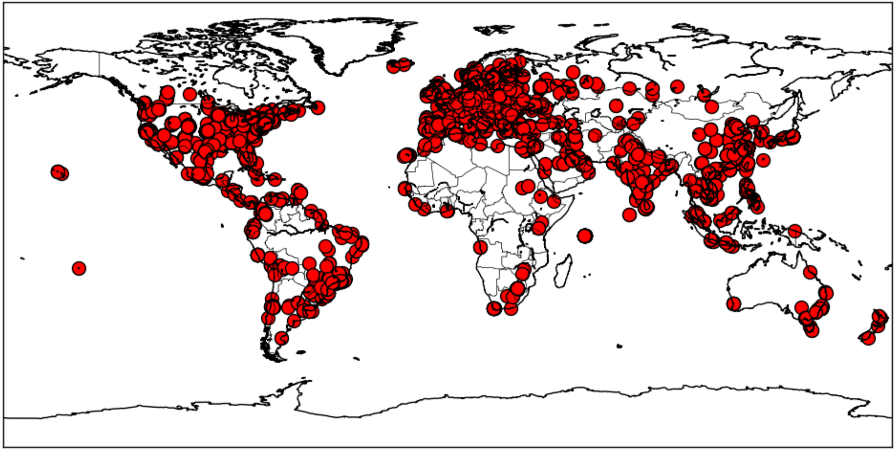
- AC and DC **power networks**
- generators with **unit commitment**
- **variable generation** with time series
- **storage** and **conversion**
- **power-to-mobility/heat/gas**

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**

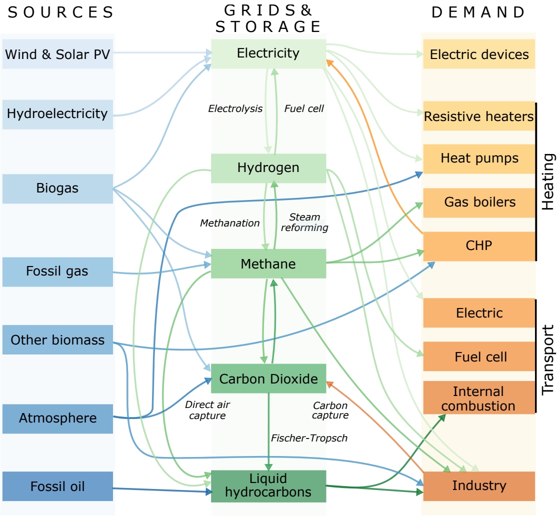
Python for Power System Analysis: Worldwide Usage

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

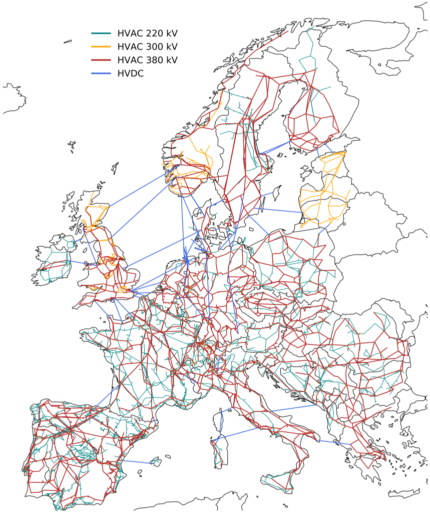


What is PyPSA-Eur-Sec?

Model for Europe with all energy flows...

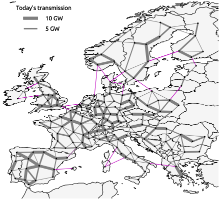


and bottlenecks in energy networks.

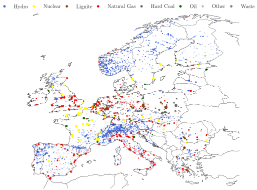


Lots of different types of data and process knowledge come together for the modelling.

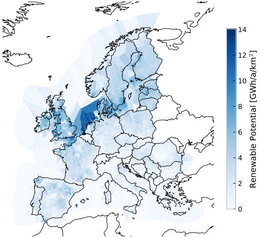
clustered network model



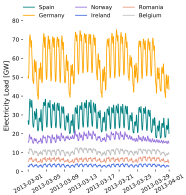
power plants and technology assumptions



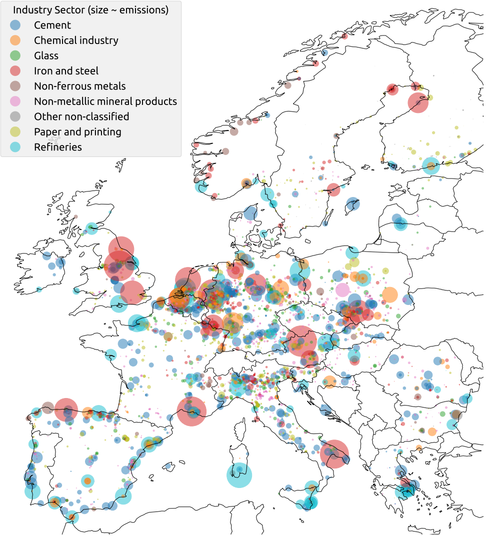
renewable potentials and hourly time series for each region



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

Preliminary results: 181-node model of European energy system

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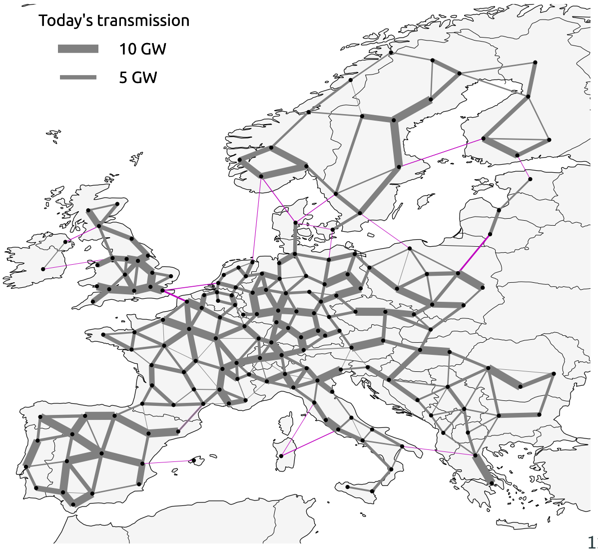
Model set-up:

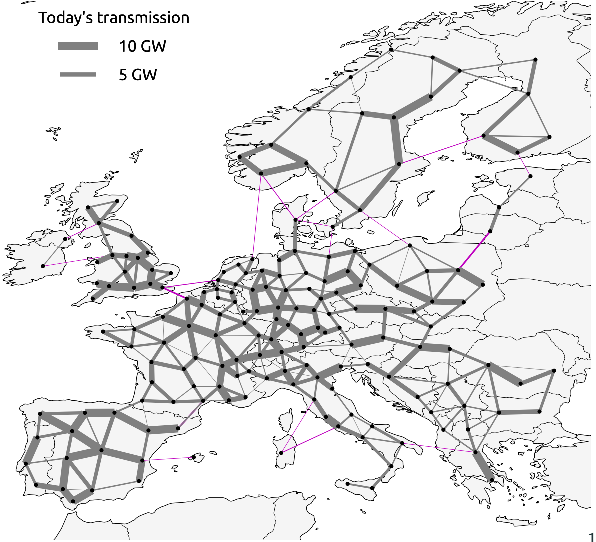
- Couple **all energy sectors** (power, heat, transport, industry)
- Reduce net CO_2 emissions **to zero**
- Assume 181 **smaller bidding zones** and **widespread dynamic pricing**
- **Conservative** technology assumptions (for 2030 from Danish Energy Agency)



Preliminary results: 181-node model of European energy system

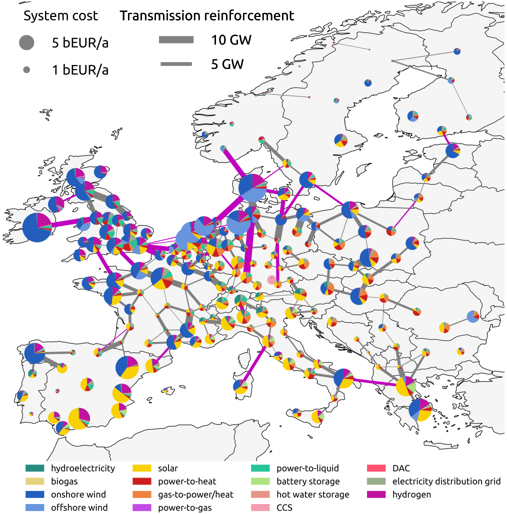
Examine effect of:

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



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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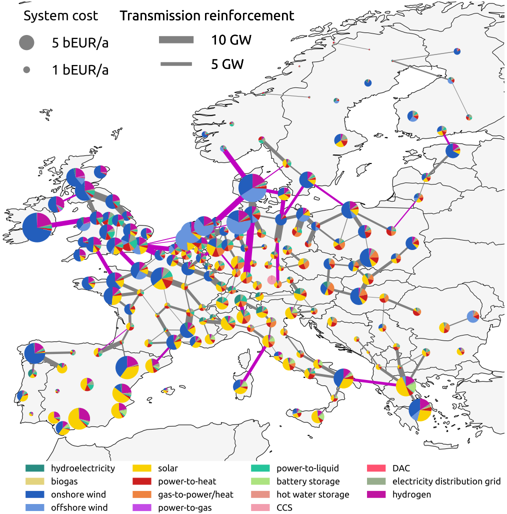
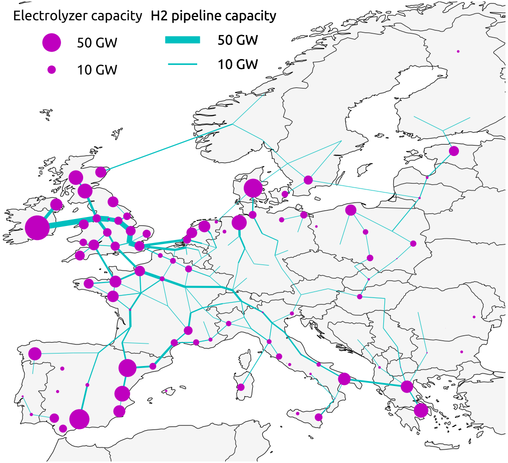
Electricity grid expansion of 162 TWkm...

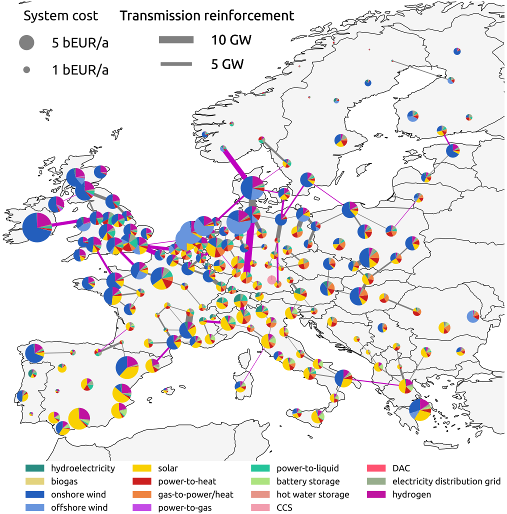


...and new hydrogen grid of 260 TWkm.

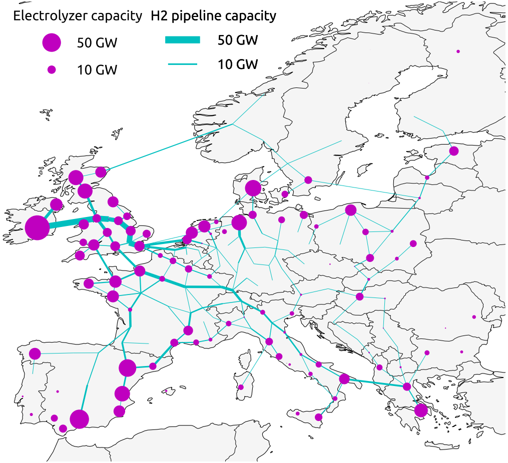


Distribution of technologies: 25% more power grid volume

Electricity grid expansion of 81 TWkm...

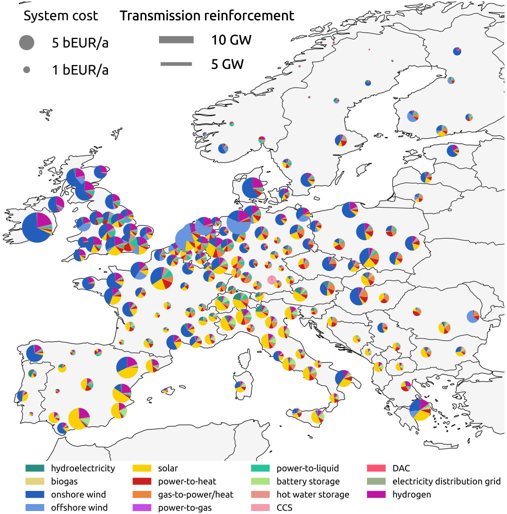


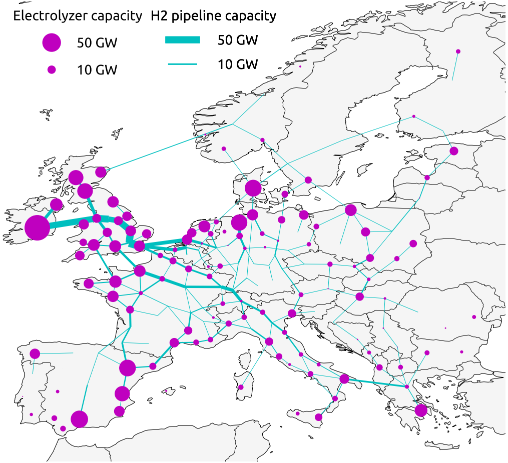
...and new hydrogen grid of 282 TWkm.



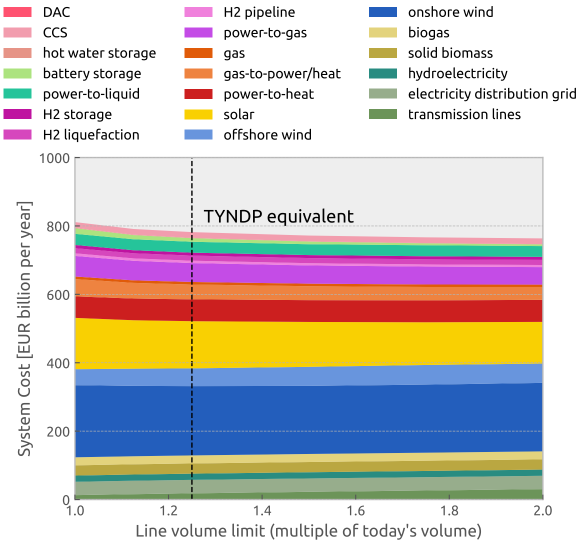
Distribution of technologies: no power grid expansion

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



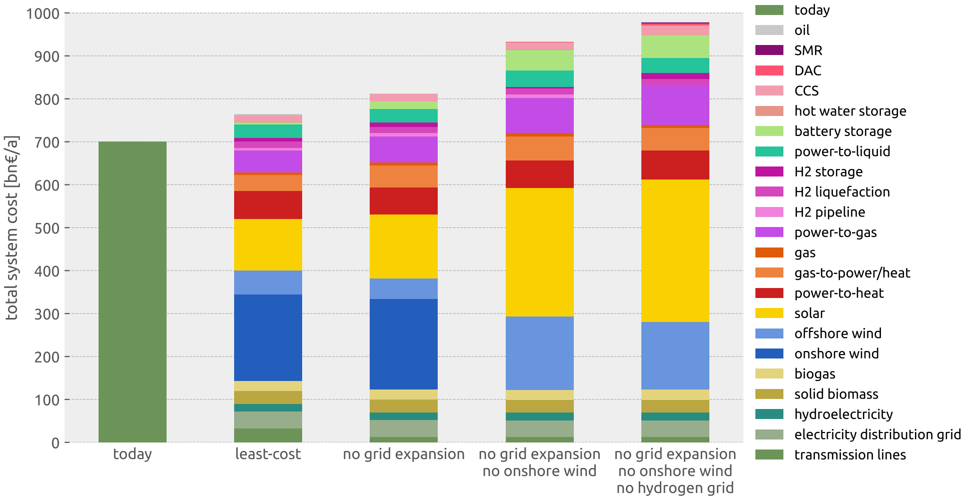


Benefit of power grid expansion for sector-coupled system



- 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)

Summary of effect of increasing restrictions

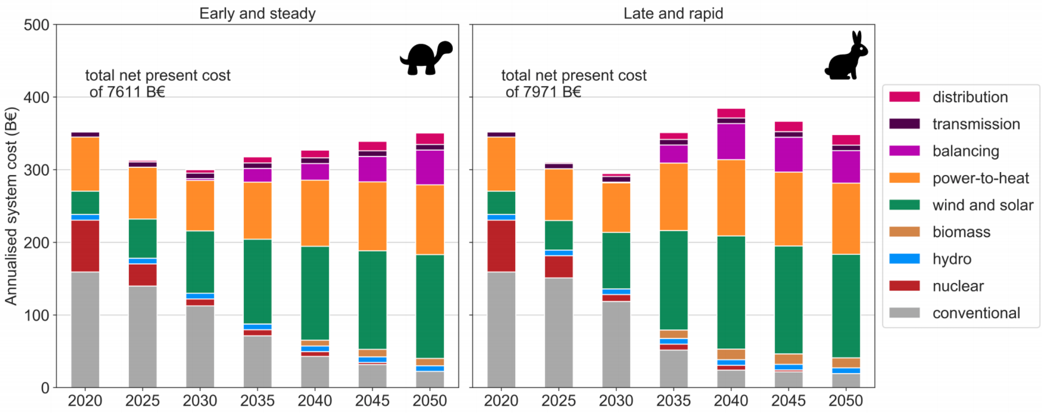


Electrolyser capacity rises 1100 GW, 1300 GW, 1700 GW, 1800 GW.

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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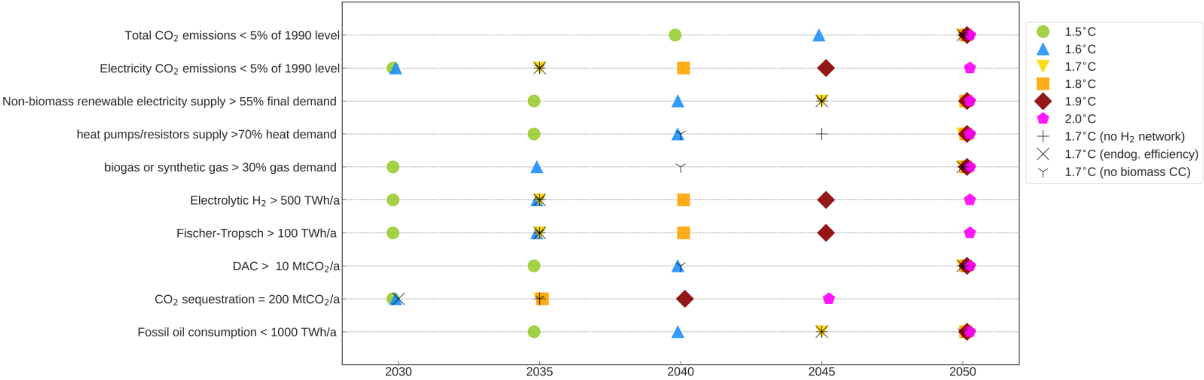
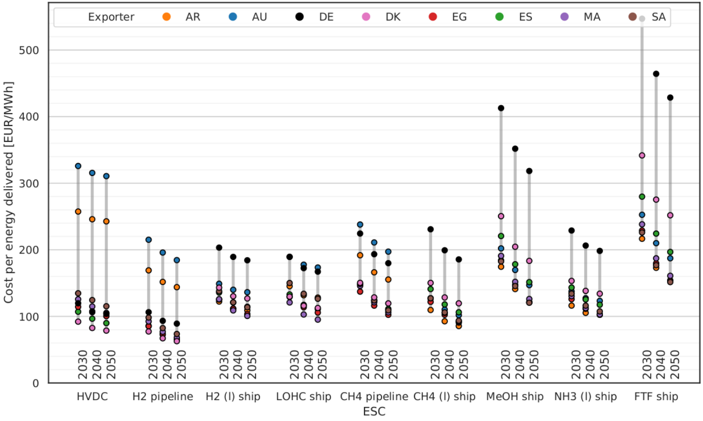
When key transformations occur depends on the carbon budget.

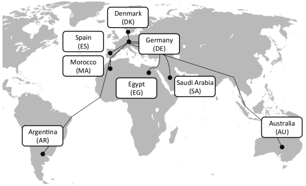


Source: M. Victoria et al, 2021

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

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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]

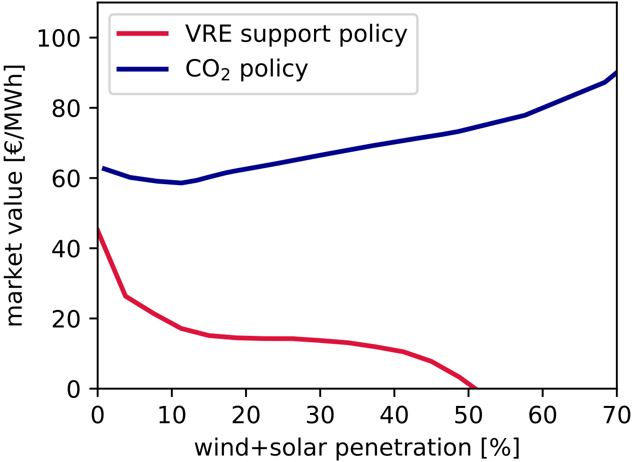
[0.15] Share of fuel cell electric vehicles in land transport [per unit]

☑ Allow battery electric vehicles to perform demand response

Market value decline depends on market structure

Implicit assumption in literature: VRE are forced in with subsidies or quotas, pushing MV down.

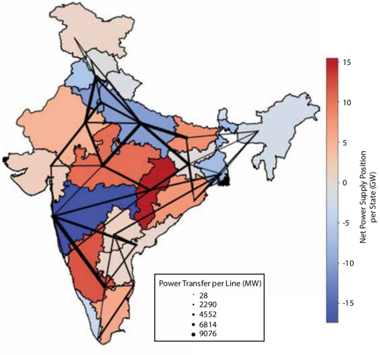
However, if VRE are drawn in with CO_2 pricing, MV does not decline.

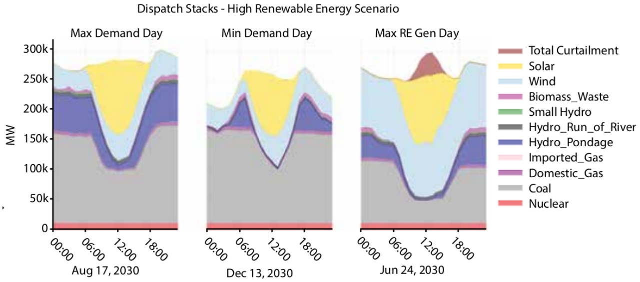


Source: Brown & Reichenberg (2021)

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.

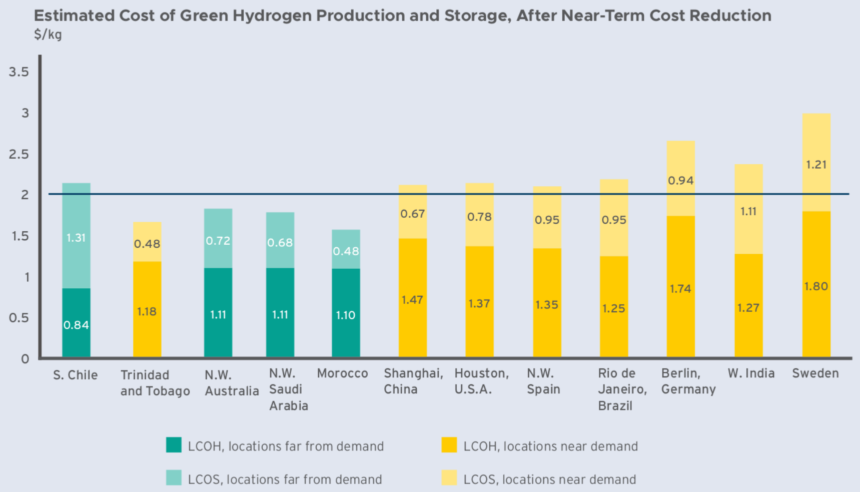




Source: TERI

Example User of PyPSA: RMI in United States

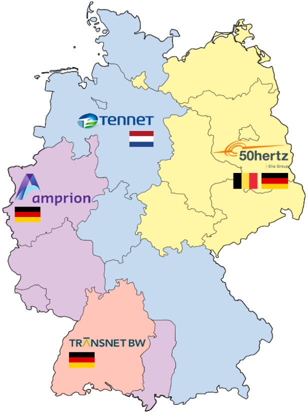
The Rocky Mountain Institute (RMI) in Boulder, Colorado used PyPSA to model hydrogen production costs around the world, since PyPSA had a track record for such calculations.



Source: RMI, 2021

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: TransnetBW, 2020

Conclusions

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- **Cross-sectoral** approaches are important to reduce CO2 emissions **and** for flexibility
- There are many **trade-offs** between unpopular infrastructure and system cost
- Need to combine the best of **grid modelling** and **capacity expansion**
- To examine these trade-offs, **new generation of tools** with high resolution needed
- **PyPSA** and **calliope** are two leading frameworks for modelling energy systems, battle-tested worldwide both in research and in commercial projects
- 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

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**.

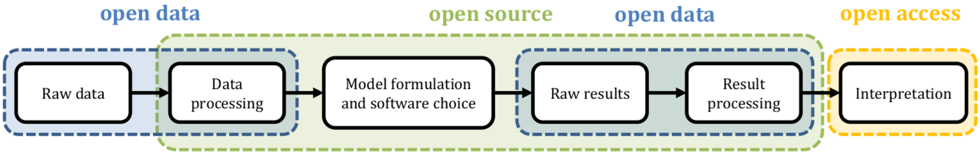
What is open modelling?

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:



Online Visualisations and Interactive ‘Live’ Models

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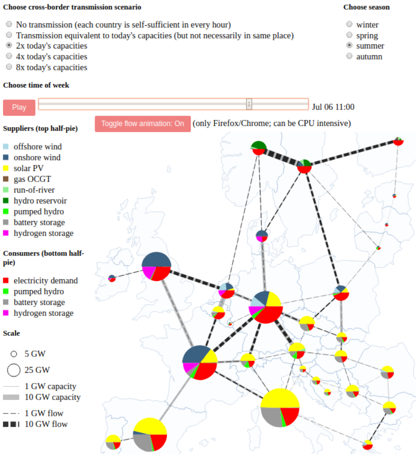
Online animated simulation results:

pypsa.org/animations/



Live user-driven energy optimisation:

model.energy