PyPSA-DE: Open German energy model reveals savings from integrated planning

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Ariadne Scenario Report (2025)

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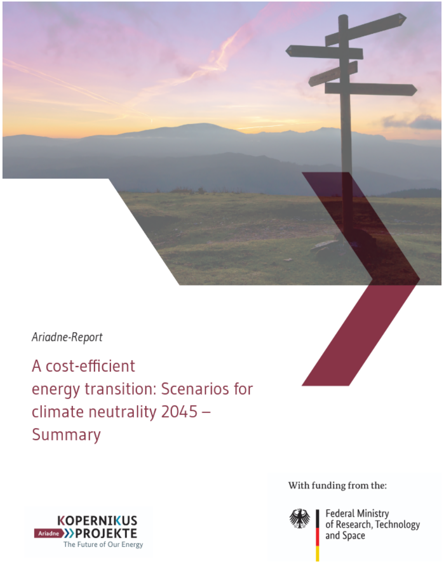
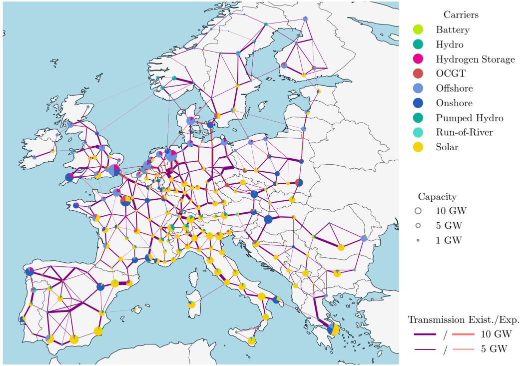
- The **Ariadne scenarios** are published by the Ariadne project, funded by the German government (BMFTR)
- One of the **‘Big 5’ modelling exercises** for Germany (next to BMWE/K Longterm Scenarios, Agora, BDI, dena)
- **Whole system models:** REMIND, PyPSA, REMod
- **Sector-specific models:** FORECAST for industry, ALADIN for transport, REMod for buildings
- **Scenarios:** Electricity, H2, Mixed, Low/High-Demand, Current Policies



Source: Ariadne, 2025

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**.

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Capabilities

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

with components for:

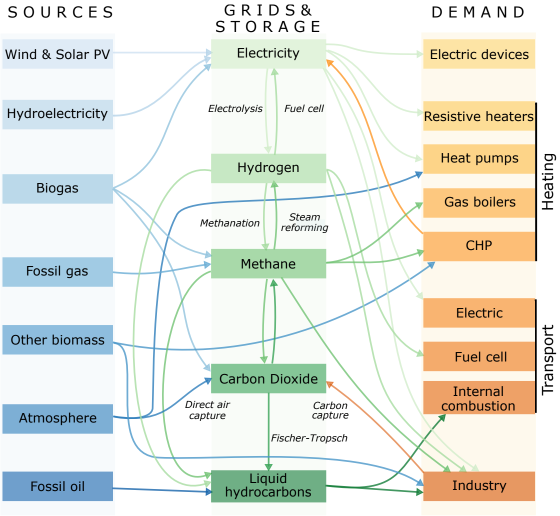
- AC and DC **power networks**
- **unit commitment** as MILP
- **variable generation** with time series
- **storage** and **conversion**
- **power-to-mobility/heat/gas**

Backend

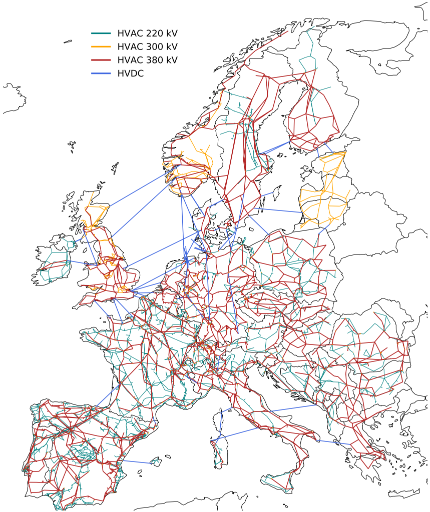
- PyPSA integrates with **widely-used Python** programming language ecosystem
- all data for components stored in **pandas** DataFrames for easy manipulation
- **optimisation framework linopy** built for large networks and long time series
- interfaces to **major solvers** (Gurobi, CPLEX, Express, cbc,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

What is PyPSA-Eur?

Model for Europe with all energy flows...



and bottlenecks in energy networks.

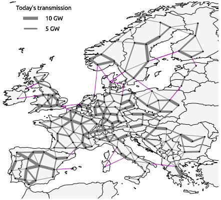


PyPSA-Eur: Data-driven energy modelling

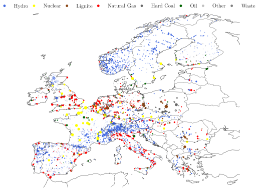
Lots of different types of data and process knowledge come together for the modelling.

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

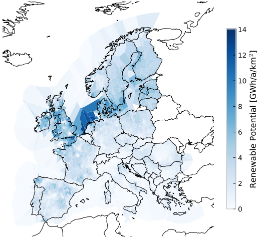
clustered network model



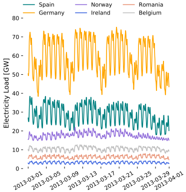
power plants and technology assumptions



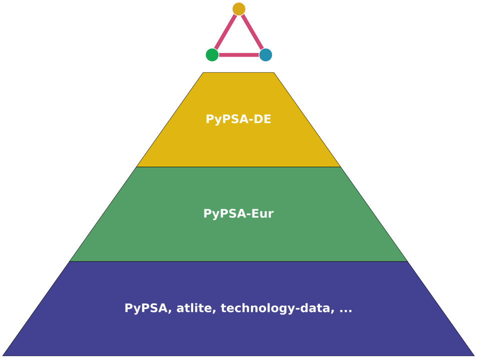
renewable potentials and hourly time series for each region



demand projections time series



PyPSA-DE: Focus on Germany embedded in Europe



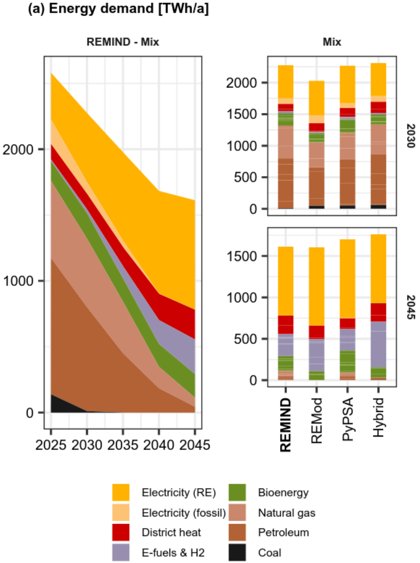
PyPSA-DE adjusts PyPSA-Eur as following:

- **Focus on Germany**: 30 regions for Germany, one node per country for rest
- **National infrastructure plans**: Network Development Plan 2023 for power transmission (forced until 2030) and Core Network for hydrogen
- **Custom policy constraints**: 2030 RES targets, climate neutrality by 2045
- **Custom demand**: for transport and industry from Fraunhofer ISI models
- **Custom cost data**

Source: Ariadne, 2025

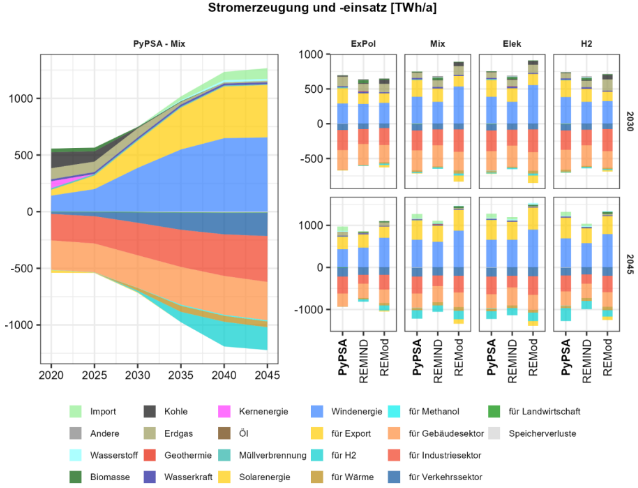
Final energy: electrification rises

- **Clean electricity:** CO_2 intensity drops in 2030 to below 90 g/kWh
- **Electrification:** Share of electricity in final energy rises by 2045 to 47-59 % (53-80 % excluding aviation/shipping and feedstocks)
- Non-electric demand must increasingly be met by biomass, hydrogen and hydrogen-derivatives
- **Fossil phase-out:** Use of fossil energy drops below 5% of current use



Source: Ariadne, 2025

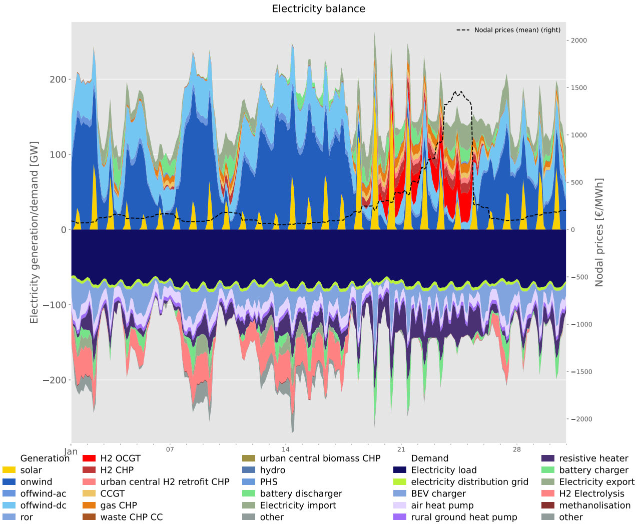
Electricity: doubling, met by wind and solar



- Electricity demand **more than doubles** to 1100-1300 TWh/a in 2045 in the target scenarios, due to **electrification** (2030 demand: 670-800 TWh/a)
- 80% RES goal for 2030 is met
- VRE share rises in 2035 to 84–91%
- Remainder: hydrogen, fossil gas, hydro, biomass and imports
- PyPSA Mix in 2045: 64 GW Offshore, 160 GW Onshore, 468 GW PV, 68 GW H_2 plants, 19 GW gas plants, 436 GWh batteries

Source: Ariadne, 2025

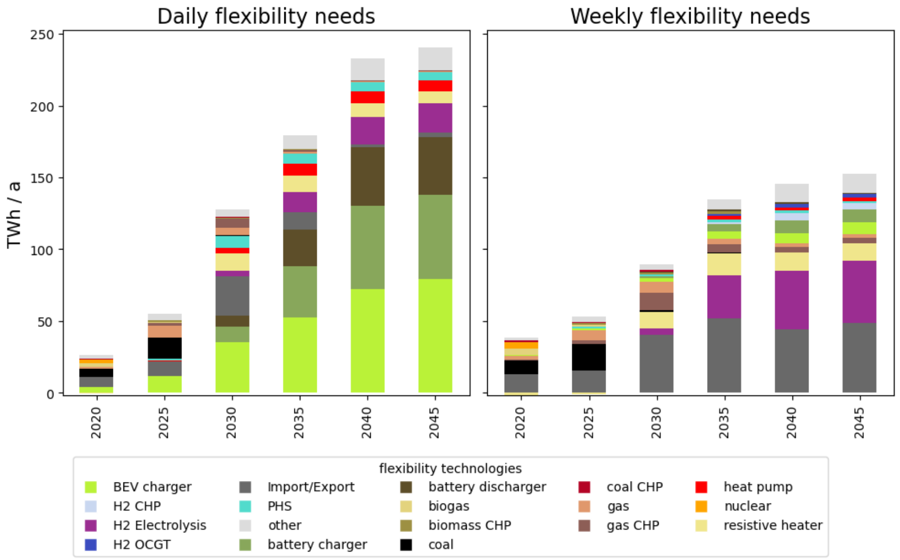
2045 electricity supply/demand in January



- **Hourly flexibility** is met by demand side management of electric vehicles (blue) and batteries (green)
- **Multi-day flexibility** is met by imports, hydrogen plants and electrolysis
- Backup in the **dark wind lull**: H_2 plants (68 GW), gas plants (19 GW), imports (up to 30 GW)

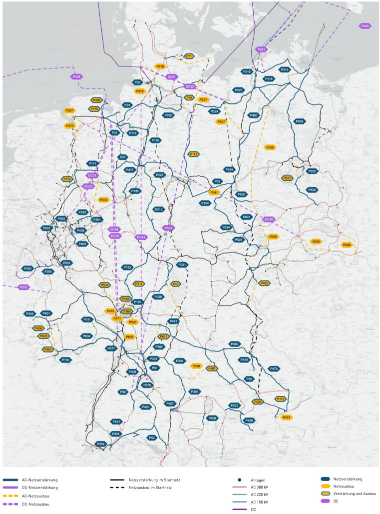
Source: Ariadne, 2025

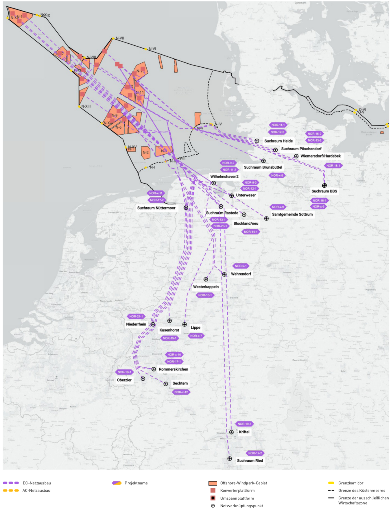
Flexibility needs quadruple by 2045



Source: Ariadne, 2025

German Network Development Plan 2023: High Transmission Costs



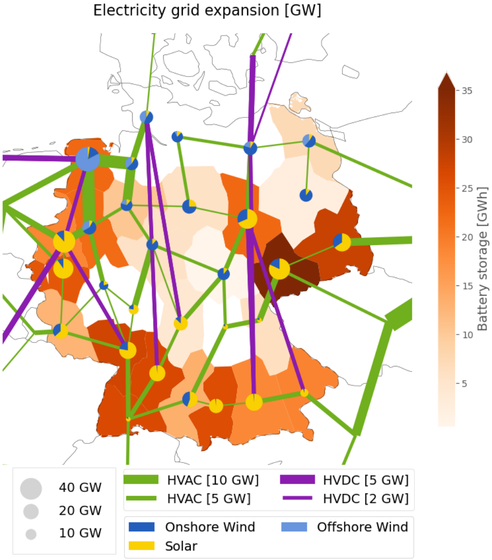


High costs of $\sim$ 300 bn€ due to

- long offshore connections to avoid overloading north-east grid
- underground cables for HVDC
- single bidding zone, attempt to eliminate redispatch
- inflation in component costs

Source: German TSOs, NEP 2023

Transmission needs reduced by integrated planning

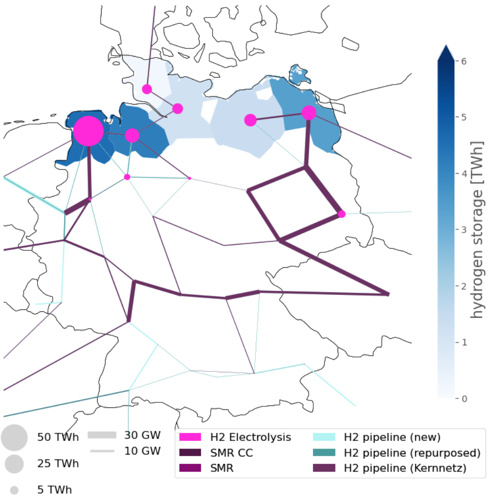


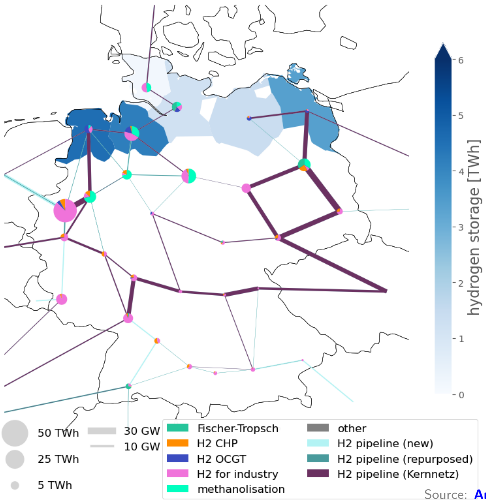
- Ariadne Scenario Report for Germany pursued an **integrated planning approach** for power and hydrogen, reduced transmission costs by 92 bn€ from 283 bn€ to 191 bn€ (all €2020)
- Savings from: absorbing offshore with electrolysis at coast, reducing offshore capacity, overhead lines instead of underground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

Source: Ariadne, 2025

Hydrogen pipeline infrastructure

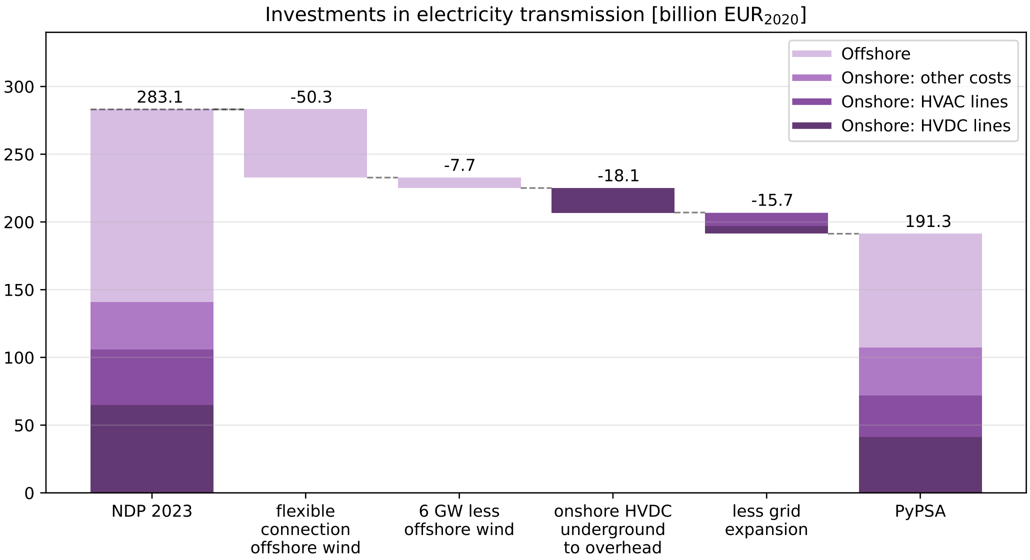
Electrolysis **positioned at coast** to absorb wind, planned Core Network appropriate for 2045.





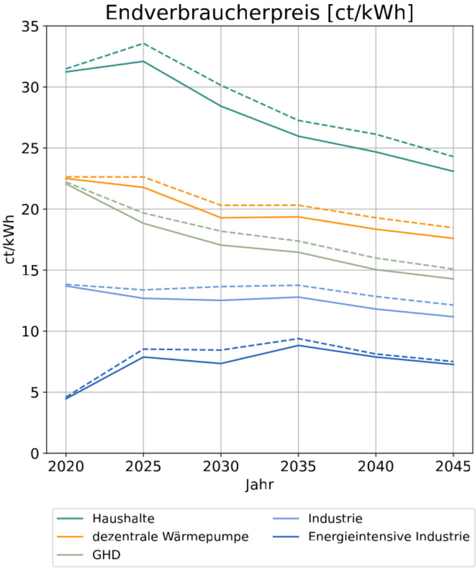
Source: [Ariadne, 2025](#)

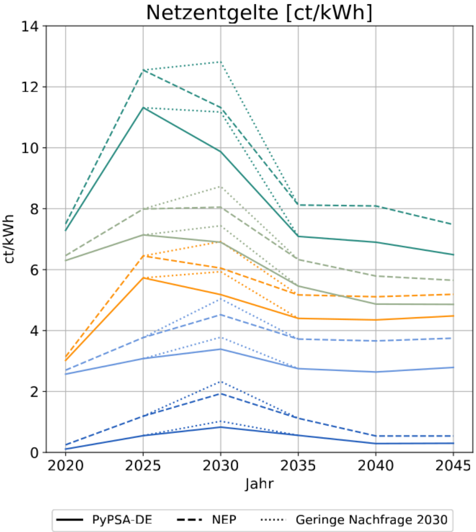
Waterfall of electricity transmission savings



Source: **Ariadne, 2025**

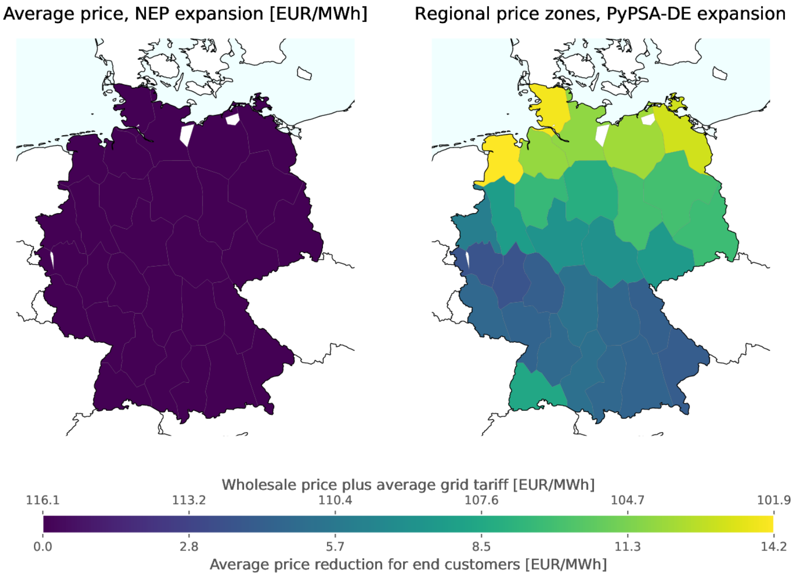
From 2025 consumer prices sink in almost all categories





Source: Ariadne, 2025

Nodal pricing reduces consumer prices in all regions



Source: [Ariadne, 2025]

Conclusions

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- **New open-source German energy system**, PyPSA-DE, used for Ariadne scenario report
- Electricity demand **doubles by 2045** due to **electrification** of other sectors
- Electricity supply is almost **completely renewable** by 2035
- Flexibility requirements **quadruple**, needs incentives for **time-varying consumer prices**
- **Integrated planning** of power and flexibility, enabled through **regional pricing** can **save a third of transmission expansion costs** (saving 92 bn€ from 283 bn€ to 191 bn€, savings come from flexible connection of offshore, overhead lines and regional price signals)
- Electricity market prices stabilise around 70-80 €/MWh, **consumer prices sink** thanks to sinking network charges
- Results in **lower prices in all regions of Germany**, saving 7.5 €/MWh on average

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 European model

Publications (selection):

1. F. Neumann, E. Zeyen, M. Victoria, T. Brown, *"The Potential Role of a Hydrogen Network in Europe,"* Joule (2023), **DOI**, **arXiv**.
2. M. Victoria, E. Zeyen, T. Brown, *"Speed of technological transformations required in Europe to achieve different climate,"* Joule (2022), **DOI**, **arXiv**.
3. 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**.
4. 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**.
5. 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**
6. T. Brown, J. Hörsch, D. Schlachtberger, *"PyPSA: Python for Power System Analysis,"* Journal of Open Research Software, 6(1), 2018, **DOI**, **arXiv**.
7. 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**.

Recent and future developments for PyPSA

Recently we have implemented:

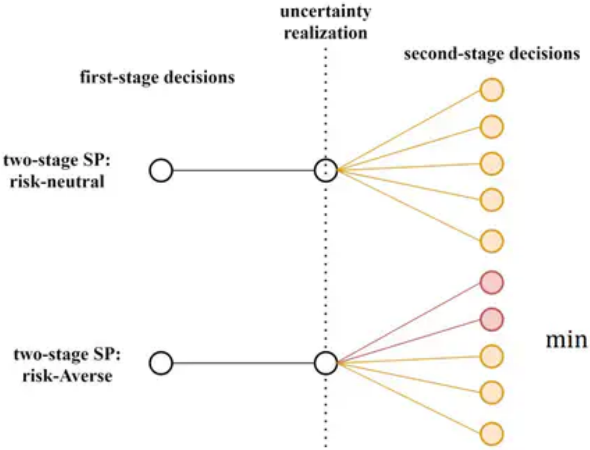
- **Elastic demand** via quadratic programming (to complement standard VOLL and battery-like DSR)
- **Improvements to unit commitment approximations**
- **Modelling-to-generate-alternatives (MGA)**
- **New network clustering algorithms**

Coming soon in version 1.0:

- **Stochastic and risk-averse optimisation** (e.g. over gas prices and other inputs)
- **Interactive visualisation** via HTML interfaces
- **Learning curves** for multiple investment horizons

Stochastic and risk-averse optimisation

Two-stage stochastic optimisation (first investments, then uncertainty on e.g. gas price or hydrogen volume) allows for Conditional Value-at-Risk (CVaR) formulation of risk-aversion.



$$\min \mathrm{IC} + \sum_{s=1}^{S} p_s \cdot \mathrm{OC}_s$$

$$\min \mathrm{IC} + (1-\omega) \sum_{s=1}^{S} p_s \cdot \mathrm{OC}_s + \omega \cdot \mathrm{cvar}$$

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`