What are open energy models and what can they contribute?

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Motivation: Why openness?

Energy modelling is special

Energy modelling simulates changes to our energy system in computers. Why is it so special?

- Energy has **high economic, social and political relevance** (large positive role in economy, but also negative role in climate change, air pollution, resource conflicts)
- Big role of **commercial interests** in energy (trillions of euros per year spent worldwide on energy, much of it going directly to fossil rents)
- **Large uncertainties** (technology cost & availability, acceptance, 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)
- Modelling results are **strongly driven by assumptions** (cost, demand, constraints)
- Many models are **closed black boxes** (preventing scrutiny, hiding potential manipulation)

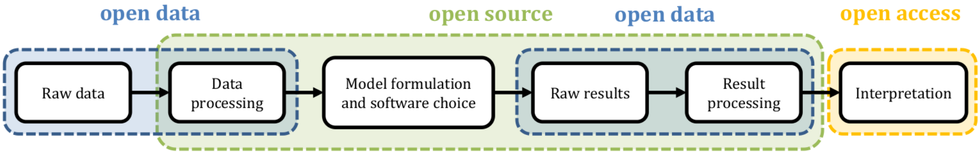
What is open modelling?

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:



Source: Open Energy Modelling Initiative, 2014

There are now many, many mature open energy models

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Open electricity sector models

Project	Host	License	Access	Coding	Documentation	Scope/type
AMIRIS	German Aerospace Center	Apache 2.0	GitLab	Java	wiki	agent-based electricity market modeling
Breakthrough Energy Model	Breakthrough Energy Foundation	MIT	GitHub	Python, Julia	website, GitHub	power sector modeling
DIETER	DIW Berlin	MIT	download	GAMS	publication	dispatch and investment
Dispa-SET	EC Joint Research Centre	EUPL 1.1	GitHub	GAMS, Python	website	European transmission and dispatch
E4ST	Resources for the Future	GPLv3	GitHub	Julia	website	US and Canada detailed dispatch and investment, regional gas markets, coupling with other sectors
EMLab-Generation	Delft University of Technology	Apache 2.0	GitHub	Java	manual, website	agent-based
EMMA	Neon Neue Energieökonomik	CC BY-SA 3.0	download	GAMS	website	electricity market
GENESYS	RWTH Aachen University	LGPLv2.1	on application	C++	website	European electricity system
NEMO	University of New South Wales	GPLv3	git repository	Python	website, list	Australian NEM market
OnSSET	KTH Royal Institute of Technology	MIT	GitHub	Python	website, GitHub	cost-effective electrification
pandapower	University of Kassel Fraunhofer Institute IEE	BSD-new	GitHub	Python	website	automated power system analysis
PowerMatcher	Flexiblepower Alliance Network	Apache 2.0	GitHub	Java	website	smart grid
Power TAC	Erasmus Centre for Future Energy Business Rotterdam School of Management Erasmus University	Apache 2.0	GitHub	Java	website, forum	automated retail electricity trading simulation
renpass	University of Flensburg	GPLv3	by invitation	R, MySQL	manual	renewables pathways
SciGRID	DLR Institute of Networked Energy Systems	Apache 2.0	git repository	Python	website, newsletter	European transmission grid
SIREN	Sustainable Energy Now	AGPLv3	GitHub	Python	website	renewable generation
SWITCH	University of Hawaiʻi	Apache 2.0	GitHub	Python	website	optimal planning
URBS	Technical University of Munich	GPLv3	GitHub	Python	website	distributed energy systems

Access refers to the methods offered for accessing the codebase.

Open energy-system models (bottom-up, with support for heat, gas, and such, in addition to electricity)

Project	Host	License	Access	Coding	Documentation	Scope/type
AnyMOD.jl	Technische Universität Berlin	MIT	GitHub	Julia	website	system planning framework
Backbone	VTT	LGPLv3	GitLab	GAMS	website	dispatch, investment, all sectors, LP/MILP
Balmorel	Denmark	ISC	registration	GAMS	manual	energy markets
Calliope	ETH Zurich	Apache 2.0	download	Python	manual, website, list	dispatch and investment
DESSTinEE	Imperial College London	CC BY-SA 3.0	download	Excel/VBA	website	simulation
Energy Transition Model	Quintel Intelligence	MIT	GitHub	Ruby (on Rails)	website	web-based
EnergyPATHWAYS	Evolved Energy Research	MIT	GitHub	Python	website	mostly simulation
ETEM	ORDECSYS, Switzerland	Eclipse 1.0	registration	MathProg	manual	municipal
ficus	Technical University of Munich	GPLv3	GitHub	Python	manual	local electricity and heat
GENeSYS-MOD	Technische Universität Berlin	Apache-2.0	GitHub	GAMS Julia	GitHub	multi-commodity optimization
GenX	MIT and Princeton University	GPLv2	GitHub	Julia	website	multi-commodity sector investment planning
oemof	oemof community supported by Reiner Lemoine Institute University of Flensburg Flensburg University of Applied Sciences	MIT	GitHub	Python	website	dispatch, investment, all sectors, LP/MILP
OSeMOSYS	KTH Royal Institute of Technology	Apache 2.0	GitHub	GAMS MathProg Python	website, forum	planning at all scales
PyPSA	Goethe University Frankfurt	MIT	GitHub	Python	website	electric power systems with sector coupling
REMix	Deutsches Zentrum für Luft- und Raumfahrt e.V.	BSD 3-Clause	GitLab	Python/ GAMS	website	dispatch, investment, all sectors, LP/MILP
TEMOA	North Carolina State University	GPLv2+	GitHub	Python	website, forum	system planning

Source: Wikipedia, 2025

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 trillions of euros 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)
- allows **reuseability** and avoids **lock-in** with software or consultants
- allows easier **collaboration** (no need for contracts, NDAs, etc.)
- 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 must show their workings,' Nature, V542, p393, 2017.

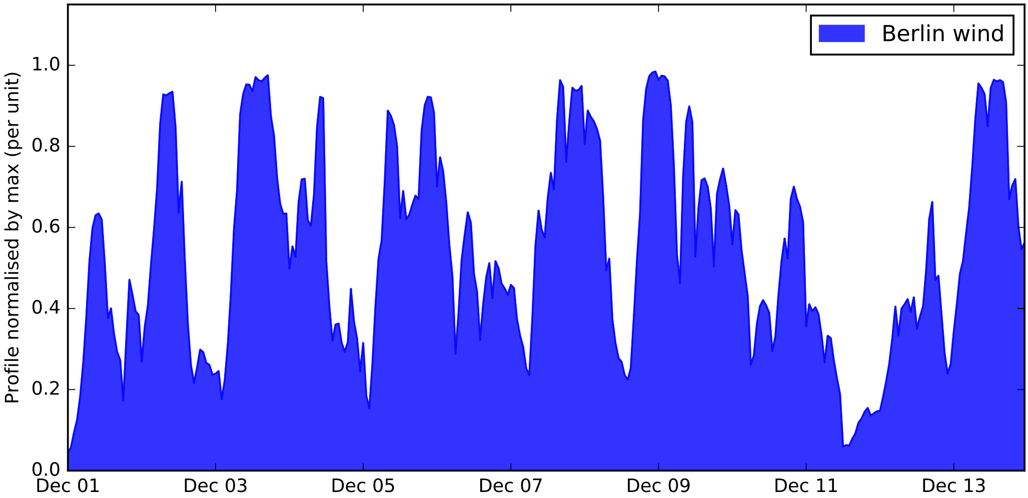
Long-term utopic vision

A **set of open models** recognised by industry, academia, government and NGOs.

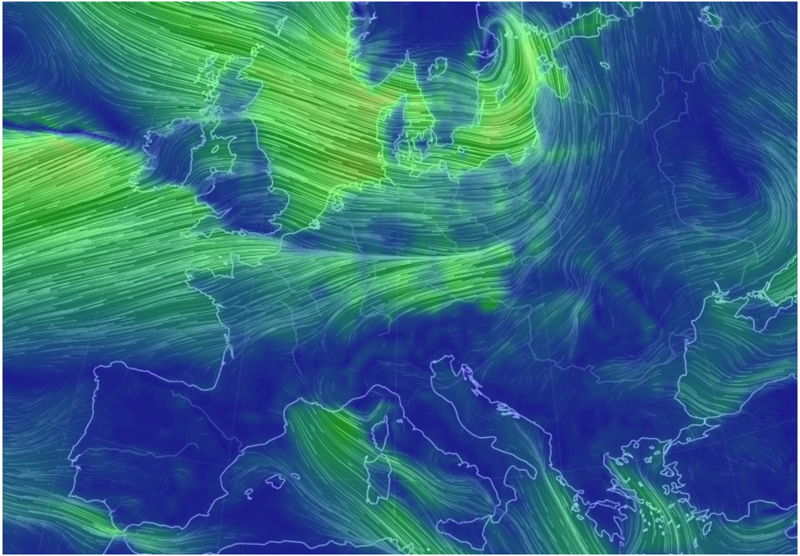
- Grid operator X uses model to show network expansion is required under assumptions Y
- Academic Z shows changing regulation A would require less grid expansion
- Regulator C adapts regulation correspondingly
- NGO D shows in the model that stronger efficiency measures at reasonable cost could reduce build-out of onshore wind in an area of high bird and bat biodiversity
- Government F takes note, increases incentives for efficiency measures
- Public confidence in the Energy Transition rises

This is **difficult** in the current fragmented model landscape, since many models are **closed black boxes** and there is neither **comparability** nor **common sets of assumptions**.

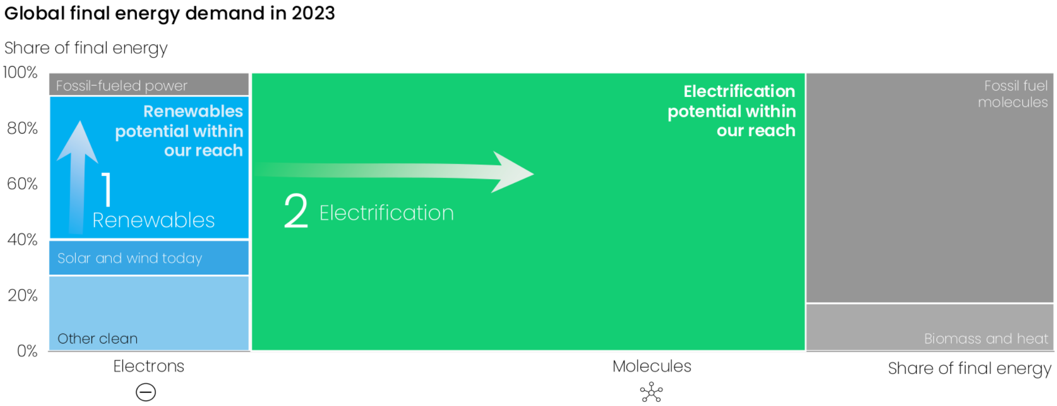
Modelling challenge 1: variability of wind & solar in time...



… and space



Challenge 2: electrification of other sectors (molecules for rest)

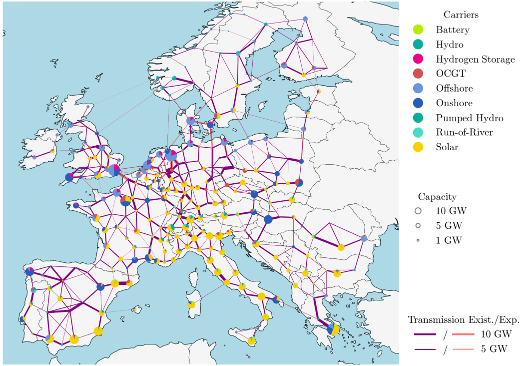


Source: Ember Electrotech Revolution, 2025

Example: PyPSA ecosystem

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, quadratic)
- **power flow** (non-linear)

with components for:

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

Backend

- PyPSA integrates with **widely-used Python** programming language ecosystem
- all data for components stored in **pandas** DataFrames for easy manipulation
- **optimisation framework linopy** built for large networks and long time series
- interfaces to **major solvers** (Gurobi, CPLEX, Express, HiGHS, cbc, etc.)
- suitable for **greenfield**, **brownfield** and **pathway** planning
- **GUI**: visualisation in Jupyter notebooks

Links to further resources

Python for Power System Analysis (PyPSA):

a free software toolbox for simulating and optimising modern power systems

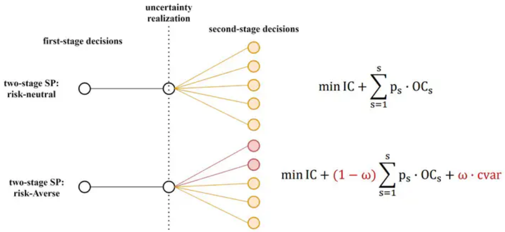
- **GitHub**: `https://github.com/PyPSA/PyPSA`
- **Documentation**: `https://pypsa.readthedocs.io/`
- **Examples** showcasing open data: `https://pypsa.readthedocs.io/`
- **Training course**: `https://fneum.github.io/data-science-for-esm/intro.html`
- **Mailing list**: `https://groups.google.com/forum/#!forum/pypsa`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

October 2025: PyPSA version 1.0 released

To celebrate PyPSA's 10th birthday in October 2025, v1.0 was released with many new features:

- **Two-stage stochastic optimisation** (e.g. over uncertain gas prices or other inputs)
- **CVar-based risk-averse optimisation**
- **Interactive map plotting**
- **Modelling-to-generate-alternatives (MGA)** baked in
- **Revamped documentation**
- **Reworked backend**

PyPSA



Others find the best use case

Rufus Pollock, founder of the Open Knowledge Foundation:

> *The best thing to do with your data [or software] will be thought of by someone else*

Source: **Rufus Pollock, 2006**

Python for Power System Analysis: Worldwide Usage

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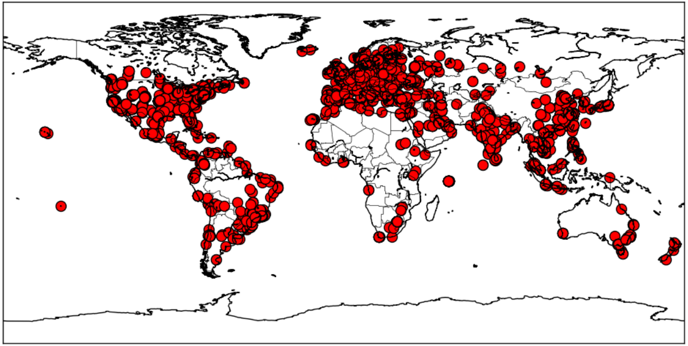
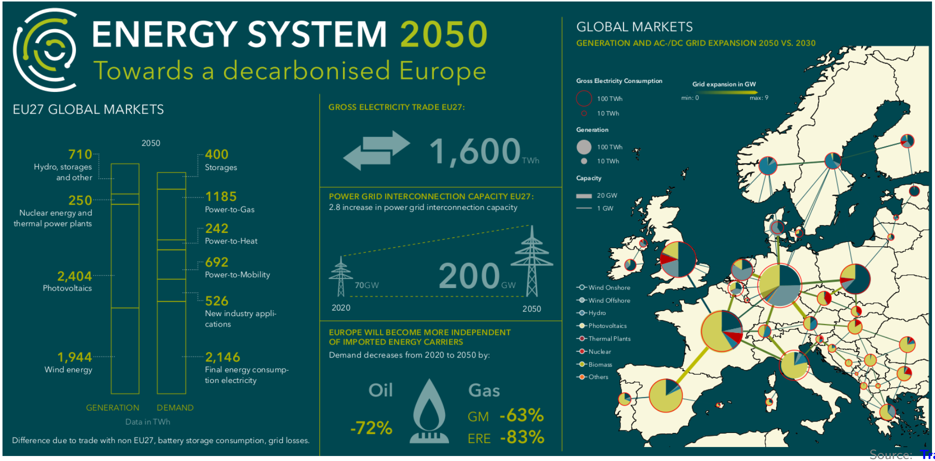
PyPSA is **used worldwide** by **dozens of research institutes and companies** (IEA, TU Delft, KIT, Octopus Centre for Net Zero, CLIMACT, Fraunhofer ISI/IEG/ISE, Shell, TSOs TransnetBW and APG, TERI, Agora, RMI, Ember, Instrat, Climate Analytics, Open Energy Transition, TransitionZero, DLR, FZJ, RLI and many others). Used for studies for government ministries in EU Commission, Netherlands, Flanders, Canada and elsewhere. Open models available for almost all countries.



PyPSA example: TransnetBW used PyPSA-Eur

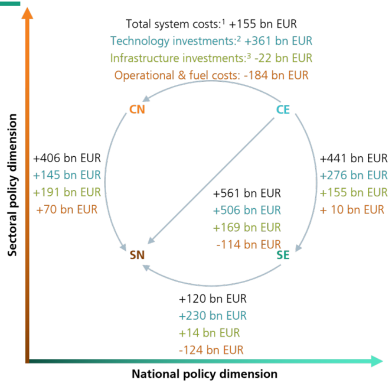
German **Transmission System Operator (TSO) TransnetBW** used an open model (PyPSA-Eur) to model the European energy system in 2050. Why? Easier to build on an existing model than reinvent the wheel.



Source: [TransnetBW, 2022]

Agora study on cross-sectoral, cross-border EU infrastructure

Benefits of Integration
Cumulative System Costs



[1]Capital, operational and fuel costs
[2]Power generation, heat generation, storage and transformation technologies (e.g. H_2 electrolysis)
[3]Electricity, hydrogen, methane and CO_2 network

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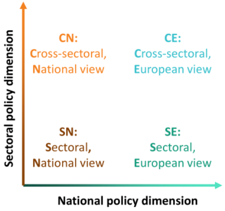


Total system costs of about 560 bn € can be saved until 2050 due to European and sectoral integration.

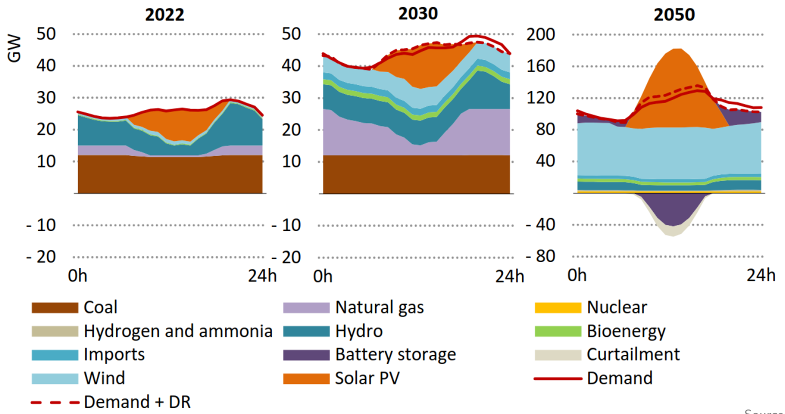
Avoided **investments in generation assets** followed by **avoided infrastructure investments** and **avoided operational and fuel costs** drive these **cost savings**.

Source: d-fine, Fraunhofer IEG/ISI, 2025

PyPSA example: International Energy Agency (IEA)

The IEA has used PyPSA for long-term flexibility needs in its World Energy Outlook (WEO) and for country studies (here for a net-zero electricity system in Viet Nam).

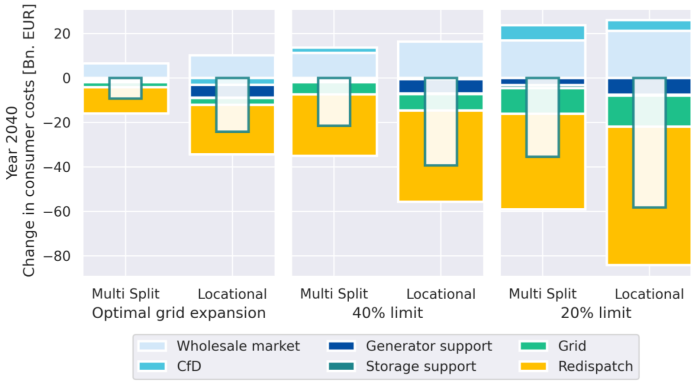
Figure 8.1 ▷ Hourly electricity supply for a sample day in Viet Nam in the NZE Scenario, 2022, 2030 and 2050

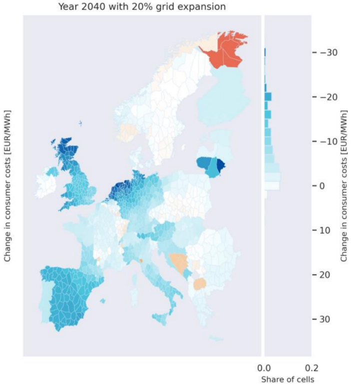


Source: IEA Viet Nam Study, 2024

JRC used PyPSA for Locational Pricing Study in 2025

The Joint Research Centre (JRC) of the European Commission used PyPSA-Eur for their study of **locational price signals** in Europe, as well as a 2024 study on **redispatch**.





Source: **JRC, 2025**

PyPSA for flexibility needs by ACER

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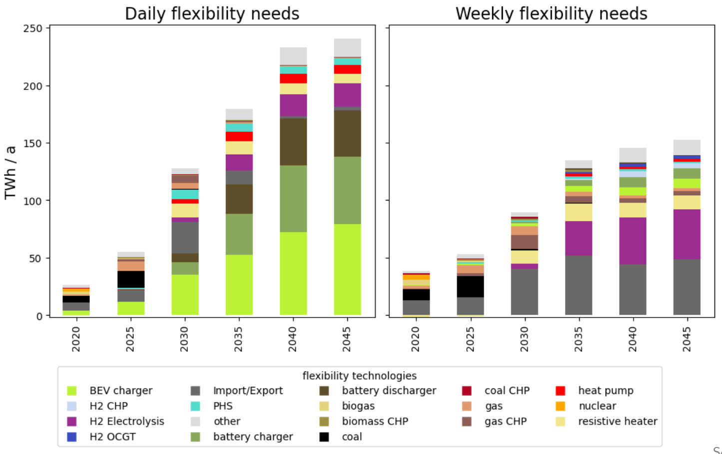
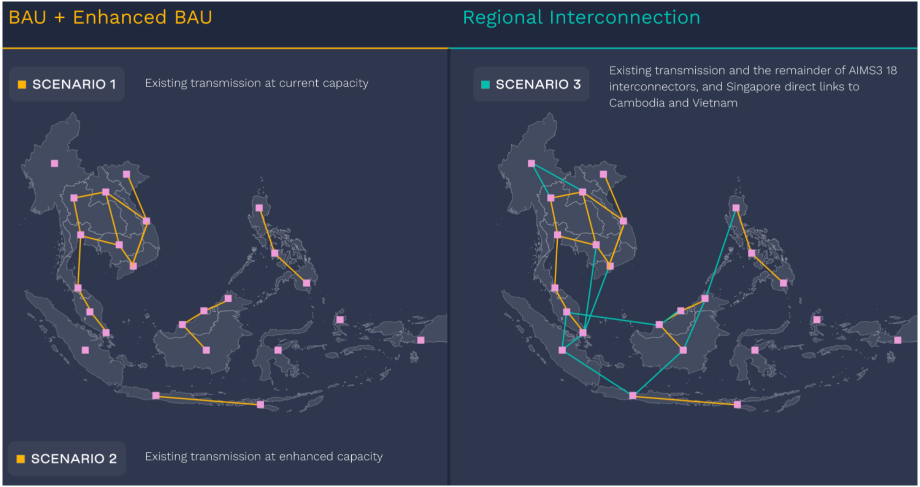
ACER has chosen PyPSA for its **EU-wide flexibility needs assessment** for use in its EU-Flex Platform. They are supported here by Open Energy Transition GmbH. Example decomposition of **flexibility needs** in Germany from **Ariadne Scenario Report**:



Source: [ACER, 2025](), [Ariadne, 2025]()

TransitionZero using PyPSA for Southeast-Asia

TransitionZero modelling grid integration in Southeast-Asia with TZ-APG model.



Source: [TransitionZero, 2024]

PyPSA-DE: German transmission reduced by integrated planning

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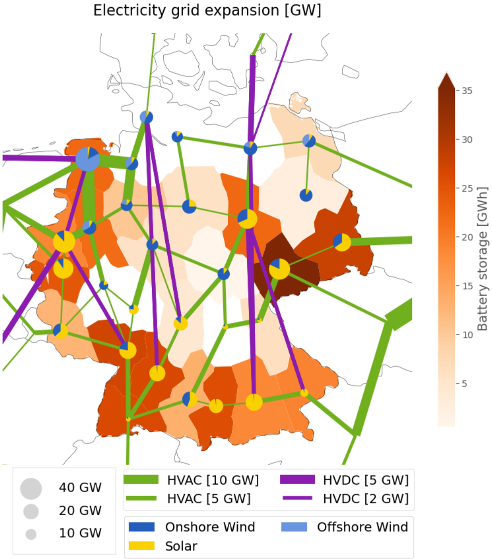
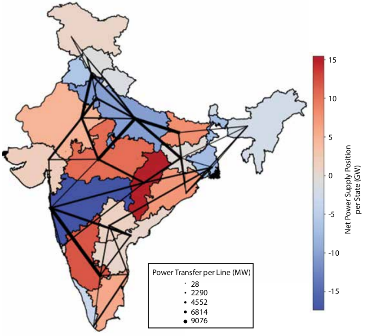


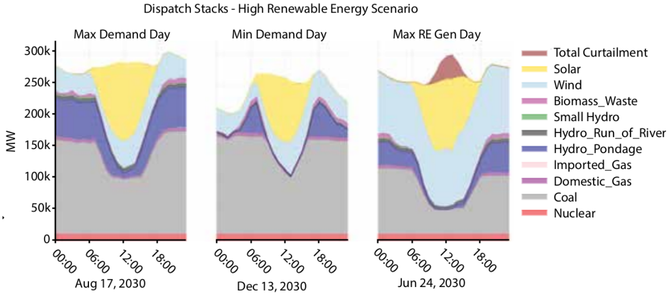
- Ariadne Scenario Report for Germany pursued an **integrated planning approach** for power and hydrogen, reduced transmission costs by 92 bn€ from 283 bn€ to 191 bn€ (all €2020)
- Savings from: absorbing offshore with electrolysis at coast, reducing offshore capacity, overhead lines instead of underground 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

PyPSA example: TERI in India: 2030 study

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 like PLEXOS, good for building up skills and sharing with stakeholders.

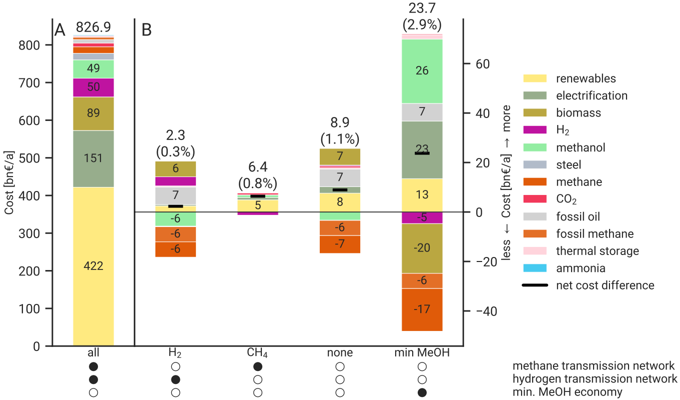




Source: TERI 2020

Minimal methanol backstop avoids large gas infrastructure

Using **green methanol** for backup power avoids large gas infrastructure; as a **liquid**, it's easy to transport and store; it's **needed anyway** for chemicals, shipping and kerosene for aviation.



Source: Yves Meur, **Glaum et al, 2025**

Conclusions

Conclusions

- Energy modelling is critical for understanding the future energy system, but **most energy models are closed and intransparent**
- Energy modelling results depend strongly on assumptions and approach - therefore **openness and transparency are critical**, guaranteed by **open licences** for data and code
- Openness offers **multiple benefits** to academics, private actors, governments, NGOs and the public: easy customisation, avoided software/vendor lock-in, shared innovation
- Established models like **PyPSA** offer many features for high-resolution modelling of **renewables**, **grids**, **electrification** and **molecule synthesis**

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**.