RESILIENT – Resilient Energy System Infrastructure Layouts for Industry, E-Fuels and Network Transitions

https://resilient-project.github.io/

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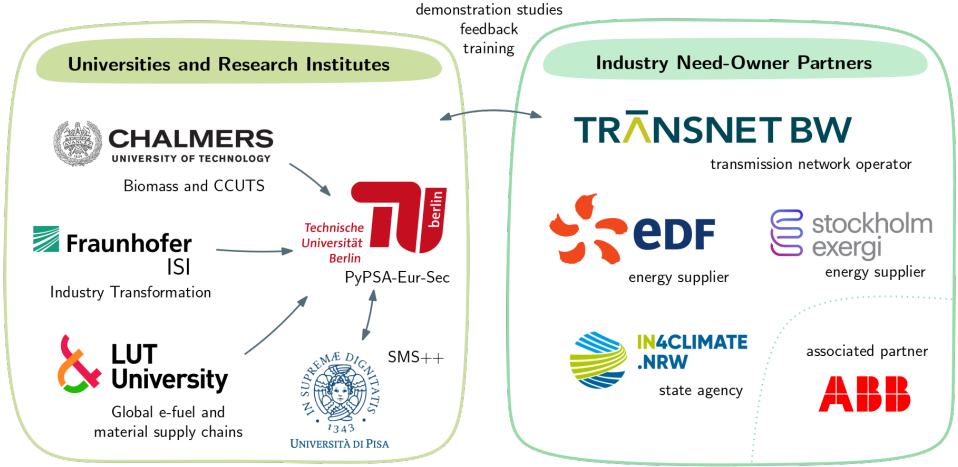
Collegial exchange with Man0EvRE team — 08 April 2025

Supported by:

Federal Ministry
for Economic Affairs
and Climate Action

on the basis of a decision
by the German Bundestag

RESILIENT Partners



Funded via **CETPartnership 2022** Call – **BMWK** for all German partners.

Source: https://resilient-project.github.io/

What is PyPSA?

Our research focus:

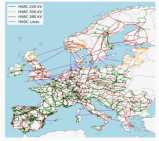
- Cost-effective pathways to reduce greenhouse gas emissions
- Evaluation of grid expansion, hydrogen strategies, carbon management strategies
- Co-optimisation of generation, storage, conversion and transmission infrastructure
- Algorithms to improve the tractability of models
- All open source and open data

PyPSA

A python software toolbox for simulating and optimising modern power systems.

Documentation »

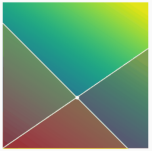
PyPSA-Eur



A Sector-Coupled Open Optimisation Model of the European Energy System

Documentation »

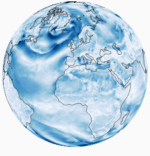
Linopy



Linear optimization interface for N-D labeled variables.

Documentation »

Atlite



A Lightweight Python Package for Calculating Renewable Power Potentials and Time Series

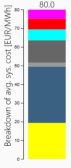
Documentation »

Powerplantmatching

A toolset for cleaning, standardizing and combining multiple power plant databases.

Documentation »

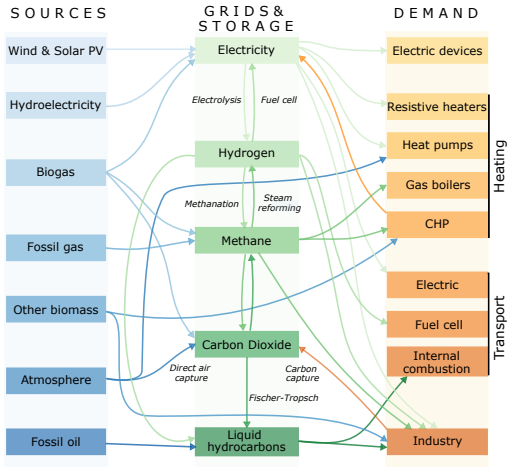
Model Energy



An online toolkit for calculating renewable electricity supplies.

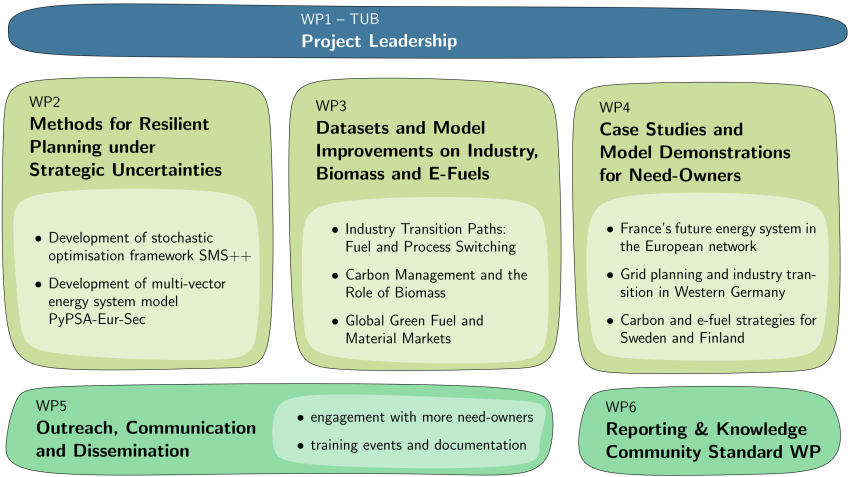
A typical setup for open-source modelling with PyPSA-Eur

- Couple **all energy sectors** (power, heat, industry, feedstocks, transport)
- **Co-optimise** generation, transmission, storage, and power-to-X conversion with future **cost projections**
- Resolve **100-200 regions** in Europe
- **2-3 hourly** segmented time series
- Reduce net CO_2 emissions **to zero**
- Minimise system cost in **LP** on **HPC**
- Run a large number of **scenarios**



Source: https://pypsa-eur.readthedocs.io/

Work Plan


WP1 – TUB
Project Leadership
WP2
Methods for Resilient Planning under Strategic Uncertainties
• Development of stochastic optimisation framework SMS++
• Development of multi-vector energy system model PyPSA-Eur-Sec
WP3
Datasets and Model Improvements on Industry, Biomass and E-Fuels
• Industry Transition Paths: Fuel and Process Switching
• Carbon Management and the Role of Biomass
• Global Green Fuel and Material Markets
WP4
Case Studies and Model Demonstrations for Need-Owners
• France's future energy system in the European network
• Grid planning and industry transition in Western Germany
• Carbon and e-fuel strategies for Sweden and Finland
WP5
Outreach, Communication and Dissemination
• engagement with more need-owners
• training events and documentation
WP6
Reporting & Knowledge Community Standard WP

Selection of Ongoing Model Developments

Computational methods for uncertainties

- decomposition techniques
- using SMS++ framework
- large-scale stochastic optimisation
- test robustness of system

Carbon management, global trade, etc

- CO_2 network and sequestration sites
- imports of green energy and materials
- circular carbon economy and recycling
- biomass usage options

Industry transformation (FORECAST)

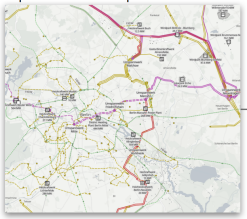
- fuel and process switching
- industry relocation
- carbon sources and feedstocks
- data on stock & investment cycles
- new technologies (oxyfuel cement, etc.)

Other developments

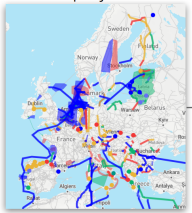
- Better and more extensive data sources
- Continuous improvements of data workflow
- Clustering techniques for time/regions
- New model features and functionality

Power grid topology

OpenStreetMap data



TYNDP projects



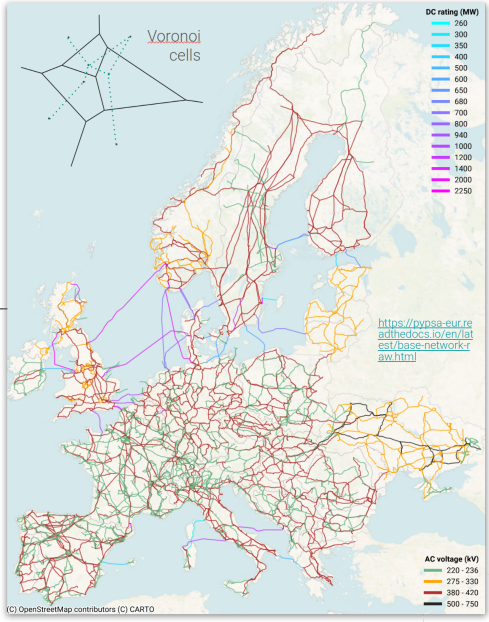
Apply **standard line types** for capacity and parameters.

Calculate **dynamic line rating** potential from weather data.

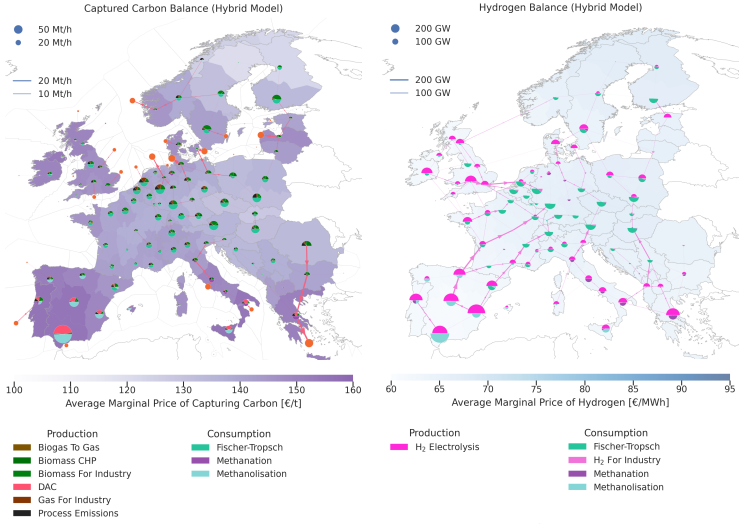
European network with

- ~5,800 buses
- ~7,300 AC lines (>220 kV)
- 36 HVDC links (+TYNDP)

https://www.nature.com/articles/s41597-025-04550-7

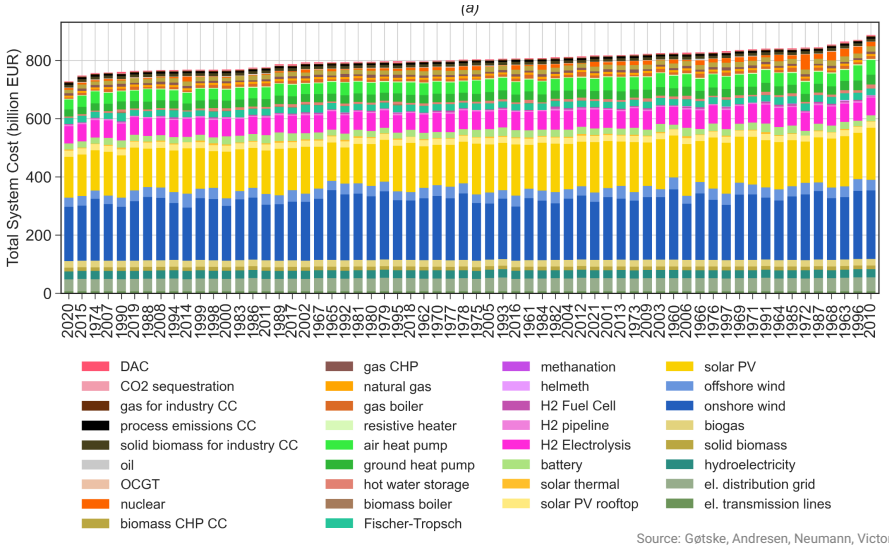


Transporting CO_2 to H_2 or transporting H_2 to CO_2?



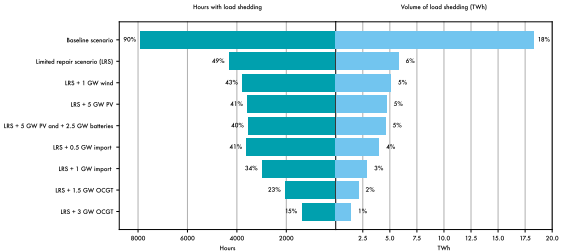
Source: Hofmann, Tries, Neumann, Zeyen, Brown, 2024; https://arxiv.org/abs/2402.19042

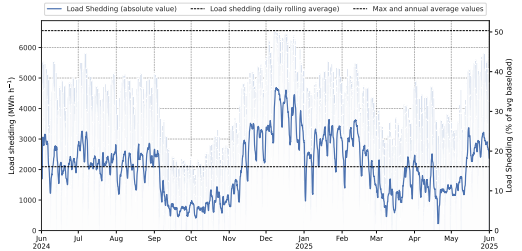
System cost variations for different underlying **weather years**

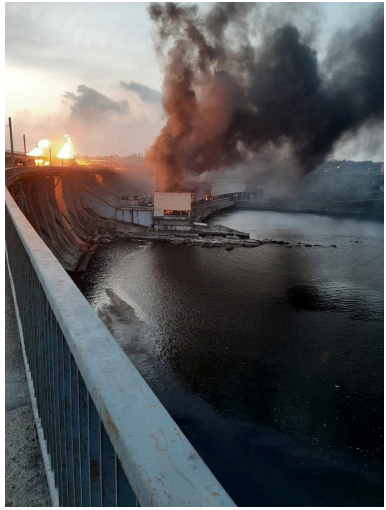


Source: Gøtske, Andresen, Neumann, Victoria, 2024;
https://www.nature.com/articles/s41467-024-54853-3

Mitigating Ukraine's Looming Electricity Crisis







Source: Photo by Reuters (credit: Denys Shmyhal); graphs from https://ssrn.com/abstract=4930511

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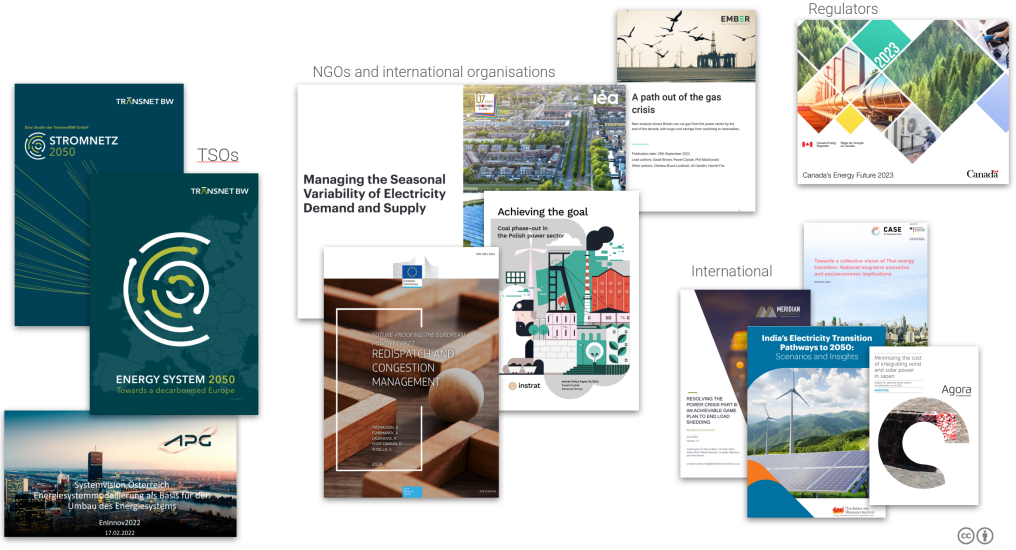
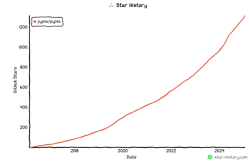
Info PyPSA: https://pypsa.org/



Source: https://pypsa.readthedocs.io/en/latest/references/users.html

PyPSA:
Python for Power System Analysis



Capabilities

Capacity expansion (linear)
- single-horizon
- multi-horizon

Market modelling (linear)
- Linear optimal power flow
- Security-constrained LOPF
- Unit commitment
- Dispatch & redispatch

Non-linear power flow
- Newton-Raphson

With components for

- Electricity transmission networks and pipelines.
- Generators with unit commitment constraints
- Variable generation with time series (e.g. wind and solar)
- Storage with efficiency losses and inflow/spillage for hydro
- Conversion between energy carriers (PtX, CHP, BEV, DAC)

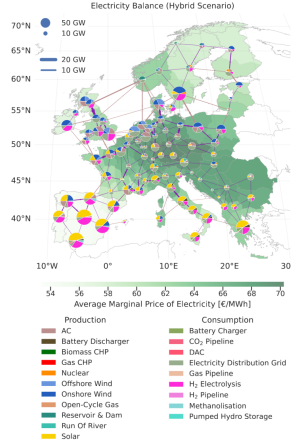
Backend

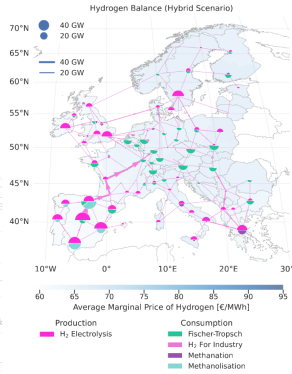
- all data stored in pandas
- framework built for performance with large networks and time series
- interfaces to major solvers (Gurobi, CPLEX, HiGHS, Xpress), with linopy (by PyPSA devs)
- highly customisable, but no GUI
- Suitable for greenfield, brownfield & pathway studies

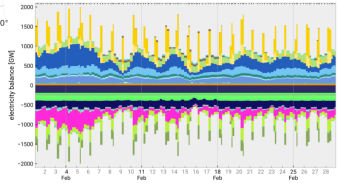
PyPSA-Eur: A sector-coupled open model of the European energy system

Automated workflow to build energy system model of Europe from raw open data with high spatial and temporal resolution:

1. OSM transmission lines (>220 kV) + TYNDP
2. a database of existing power plants,
3. time series for electricity demand,
4. time series for wind/solar availability, and
5. geographic wind/solar potentials
6. cost and efficiency assumptions
7. methods for model simplification
8. more for sector-coupled networks like pipelines, LNG terminals, electric vehicles, industry locations, …







Supply, consumption and storage options by carrier

Electricity (115 regions)

Supply	Withdrawal
rooftop solar	industry electricity
utility-scale solar	residential electricity
onshore wind	services electricity
offshore wind (fixed-pole/floating, AC/DC-connected)	agriculture electricity
nuclear	air-sourced heat pump
hydro reservoirs	ground-sourced heat pump
pumped-hydro	resistive heater
run-of-river	electric vehicle charger
import by HVDC link	battery charger
gas CHP (w/wo CC)	pumped-hydro
biomass CHP (w/wo CC)	hydrogen pipeline (compression)
gas turbine (OCGT)	direct air capture
methanol turbine (OCGT)	Haber-Bosch
hydrogen turbine (OCGT)	electric arc furnace
hydrogen fuel cell CHP	direct iron reduction
battery discharger	distribution grid losses
vehicle-to-grid	transmission grid losses
	methanolisation
	electrolysis

Grids & Storage
distribution grid
transmission grid
battery storage
pumped-hydro storage
electric vehicles

Hydrogen (115 regions)

Supply	Withdrawal
import by pipeline	Fischer-Tropsch
import by ship	methanolisation
electrolysis	electrobiofuels
chlor-alkali electrolysis (exogenous)	direct iron reduction
steam methane reforming (w/wo CC)	Haber-Bosch
ammonia cracker	hydrogen turbine (OCGT)
	hydrogen fuel cell CHP
	methanol-to-kerosene
	Sabatier

Grids & Storage
new pipelines
retrofitted pipelines
storage in salt caverns
storage in steel tanks

Methane (not spatially resolved)

Supply	Withdrawal
import by ship	gas for high-T industry heat (w/wo CC)
fossil gas	steam methane reforming (w/wo CC)
biogas upgrading (w/wo CC)	gas boiler (rural/urban)
Sabatier	gas CHP
	gas turbine (OCGT)

Storage	hydrocarbon storage

Liquid Hydrocarbons (not spatially resolved)

Supply	Withdrawal
import by ship	kerosene for aviation
fossil oil refining	naphtha for industry
Fischer-Tropsch	diesel for agriculture
electrobiofuels	

Storage	hydrocarbon storage

Methanol (not spatially resolved)

Supply	Withdrawal
import by ship	methanol turbine (OCGT)
methanolisation	methanol for shipping
	methanol for industry
	methanol-to-kerosene

Storage	hydrocarbon storage

Ammonia (not spatially resolved)

Supply	Withdrawal
import by ship	ammonia cracker
Haber-Bosch	ammonia for fertilizer

Storage	ammonia tank

Supply, consumption and storage options by carrier

Heat (115 regions)

Supply	Withdrawal
air-sourced heat pump	residential heat
ground-sourced heat pump (only rural)	services heat
resistive heater	agriculture heat
gas boiler	low-T industry heat
biomass boiler	direct air capture
solar thermal	water tank charger
water tank discharger	
biomass CHP (w/wo CC, only DH)	
gas CHP (w/wo CC, only DH)	
hydrogen fuel cell CHP (only DH)	
electrolysis (only DH)	
Haber-Bosch (only DH)	
Sabatier (only DH)	
Fischer-Tropsch (only DH)	
methanolisation (only DH)	

Storage	long-duration thermal storage (only DH) hot water tank

CO2 atmosphere (not spatially resolved)

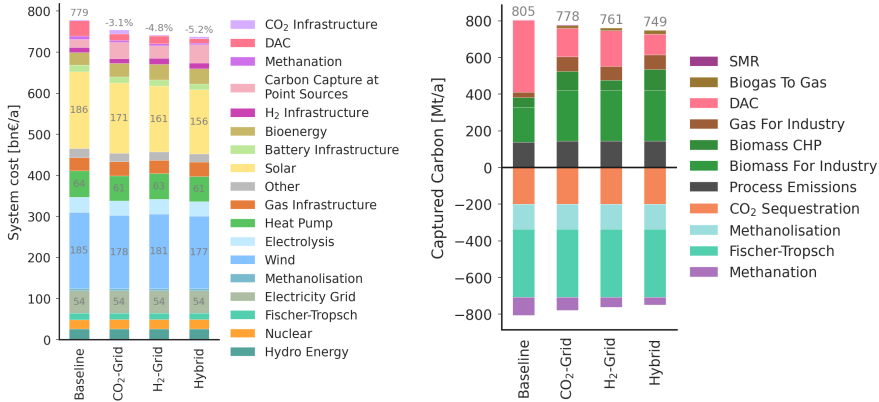
Supply	Withdrawal
kerosene for aviation	solid biomass for industry (w CC)
diesel for agriculture	solid biomass CHP (w CC)
methanol for shipping	biogas upgrading (w CC)
methanol for industry	direct air capture
naphtha for industry	electrobiofuels
gas boiler	
gas CHP (w/wo CC)	
gas turbine (OCGT)	
methanol turbine (OCGT)	
process emissions (w/wo CC)	
fossil oil refining	
gas for high-T industry heat (w/wo CC)	
steam methane reforming (w/wo CC)	

CO2 commodity (not spatially resolved)

Supply	Withdrawal
direct air capture	Fischer-Tropsch
biogas upgrading (w CC)	methanolisation
gas CHP (w CC)	sequestration
biomass CHP (w CC)	Sabatier
steam methane reforming (w CC)	
process emissions (w CC)	
solid biomass for industry (w CC)	
gas for high-T industry heat (w CC)	

Storage	intermediate storage in steel tank long-term geological sequestration

Carbon management: capture, use, transport and sequestration



- **CCS** for process emissions (for instance, in cement industry)
- **CCU** for e-synfuels and e-chemicals (in particular, shipping, aviation, plastics)
- **CDR** for unabatable and negative emissions (to offset imperfect capture rates)

Source: Hofmann, Tries, Neumann, Zeyen, Brown, 2024; https://arxiv.org/abs/2402.19042

Electricity infrastructure