# Workshop

## PyPSA-Eur: A Sector-Coupled Open Optimisation Model of the European Energy System

Supported by:
Federal Ministry for Economic Affairs and Climate Action
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INDEPENDENT RESEARCH FUND DENMARK

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DTU, Copenhagen – 26-27 June 2025

github.com/pypsa/pypsa-eur
pypsa-eur.readthedocs.io
resilient-project.github.io

# What is PyPSA?

**Our research focus:**

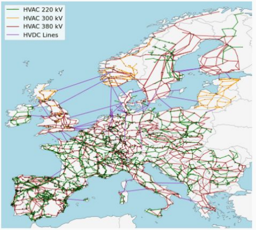
- Cost-effective pathways to reduce greenhouse gas emissions
- Evaluation of grid expansion, hydrogen strategies, carbon management strategies
- Co-optimisation of generation, storage, conversion and transmission infrastructure
- Algorithms to improve the tractability of models
- All open source and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

### PyPSA

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

Documentation »

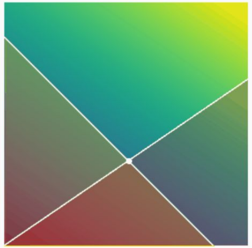
### PyPSA-Eur




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

Documentation »

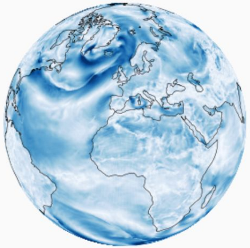
### Linopy



Linear optimization interface for N-D labeled variables.

Documentation »

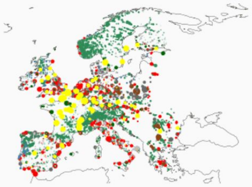
### Atlite



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

Documentation »

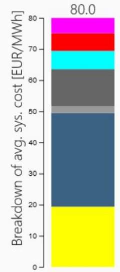
### Powerplantmatching



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

Documentation »

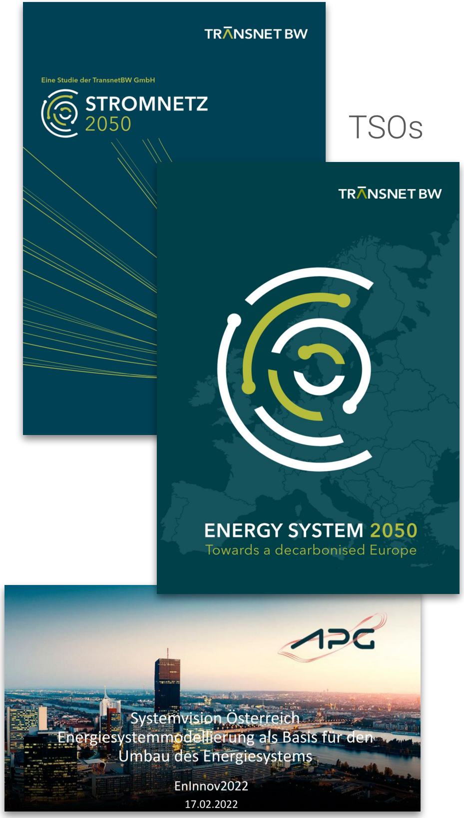
### Model Energy



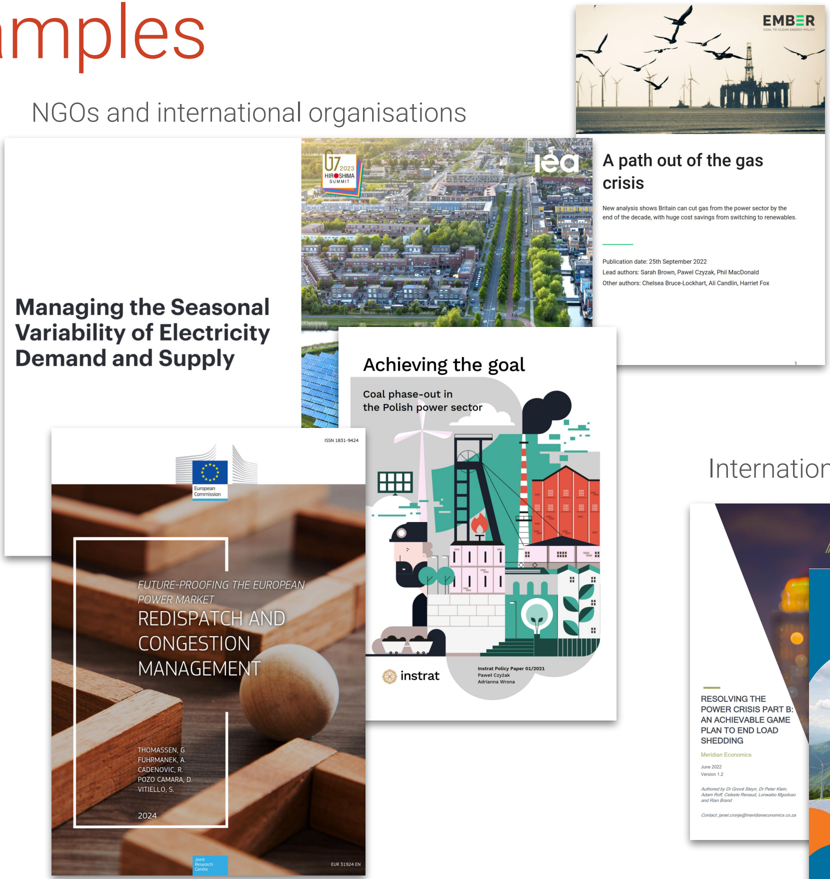

An online toolkit for calculating renewable electricity supplies.

# Application examples

TSOs




NGOs and international organisations

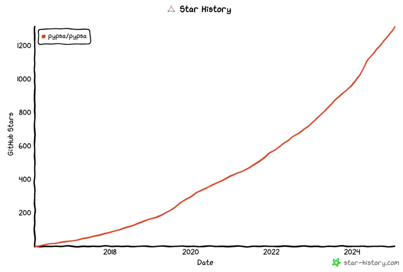



Regulators


International


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)

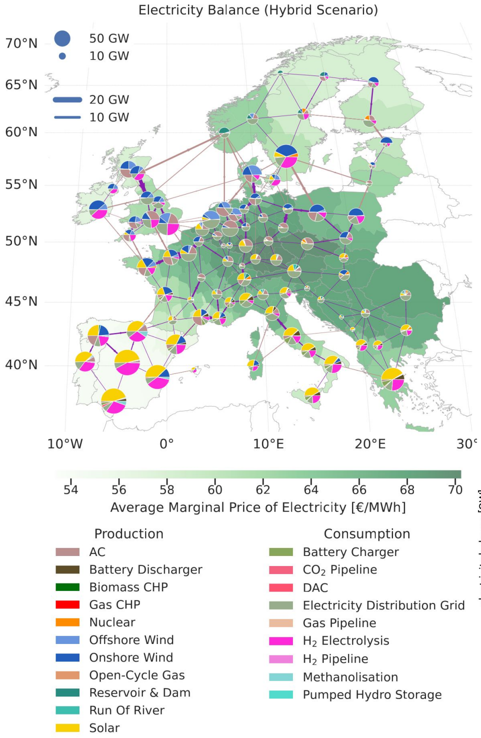
### Backend

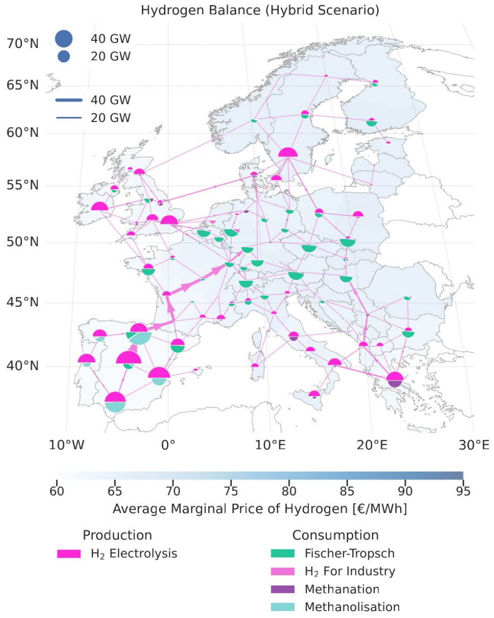
- all data stored in pandas
- framework built for performance with large networks and time series
- interfaces to major solvers (Gurobi, CPLEX, HiGHS, Xpress), with linopy (by PyPSA devs)
- highly customisable, but no GUI
- Suitable for greenfield, brownfield & pathway studies

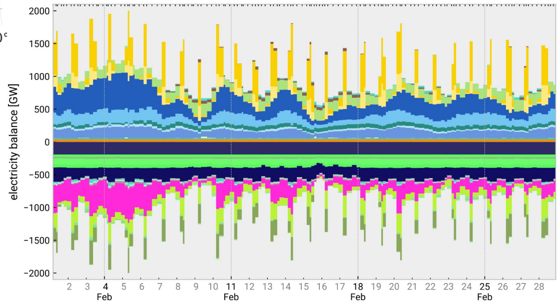
# PyPSA-Eur: A sector-coupled open model of the European energy system

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,



# Energy infrastructure planning in PyPSA as an optimisation problem

Find the long-term cost-optimal energy system, including investments and short-term costs:

$$\textbf{Min}\left[\begin{array}{c}\textbf{Yearly}\\ \textbf{system costs}\end{array}\right] = \textbf{Min}\left[\sum_{n}\left(\begin{array}{c}\textbf{Annualised}\\ \textbf{capital costs}\end{array}\right) + \sum_{n,t}\left(\begin{array}{c}\textbf{Marginal}\\ \textbf{costs}\end{array}\right)\right]$$

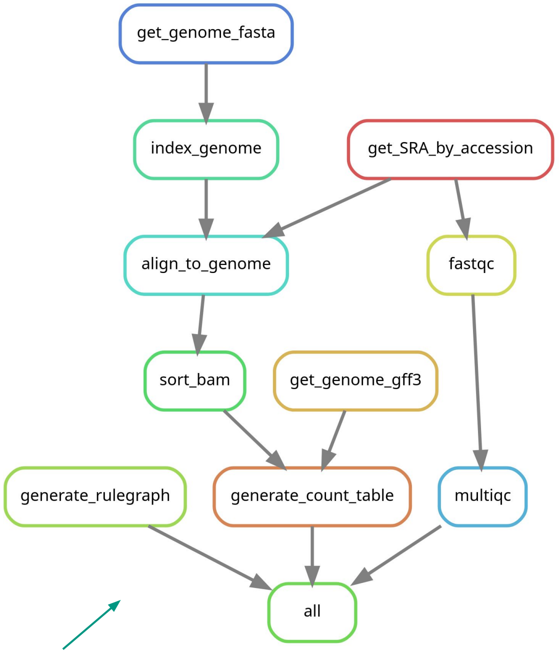
subject to

- meeting energy demand at each node $n$ (e.g. region) and time $t$ (e.g. hour of year) ⟸ data
- transmission constraints between nodes and linearised power flow ⟸ data
- wind, solar, hydro (variable renewables) availability time series $\forall\, n, t$ ⟸ data
- installed capacity $\leq$ geographical potentials for renewables ⟸ data
- fulfilling $CO_2$ emission reduction targets
- Flexibility from gas turbines, battery/hydrogen storage, HVDC links — More on that later!

# Challenges with data-driven modelling

Create a full pipeline of data processing from raw data to results.

- Many different data sources
- Many data sources need cleaning and processing
- Many intermediate scripts and datasets
- Data and software dependencies need to be managed
- Data and code change over time
- Want to be able to reproduce results
- Want to run many different scenarios




Requires a scalable workflow management tool! → snakemake

Originally comes from bioinformatics field.

# Miniature example of snakemake

Snakefile

```
rule mytask:
    input:
        "data/{sample}.txt"
    output:
        "result/{sample}.txt"
    script:
        "scripts/mytask.py"
```

```
rule myplot:
    input:
        "result/{sample}.txt"
    output:
        "figures/{sample}.pdf"
    script:
        "scripts/myplot.py"
```

command:

```
$ snakemake figures/myfigure.pdf
```

Example adapted from Johannes Köster,
https://slides.com/johanneskoester/snakemake-short#/


# **snakemake** workflow for the electricity sector

# Simplified workflow structure

Automated **downloads**

**Process** the data

**Build** the electricity system model

**Extend** the model by other sectors

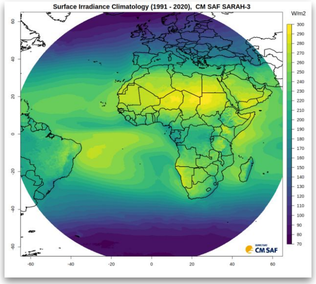
(later)

**Solve, summarize & visualize** the results

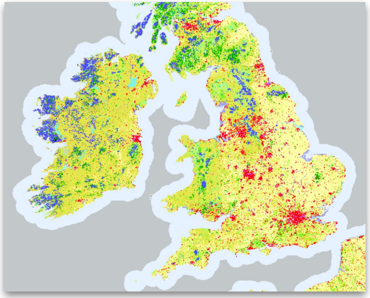
# First, raw data is automatically downloaded.

WDPA


SARAH-3

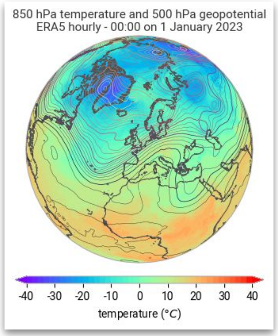



CORINE

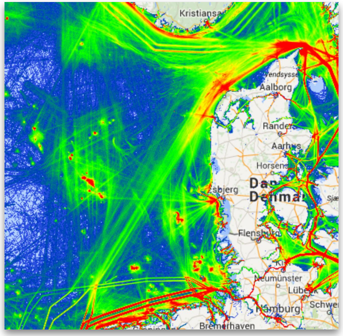


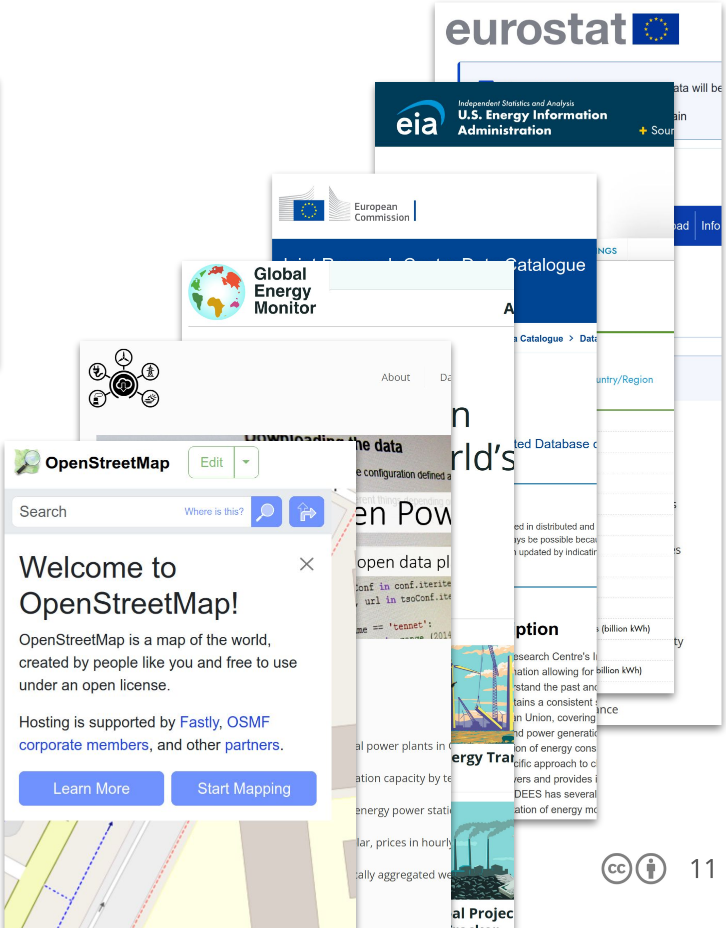
GEBCO


ERA5



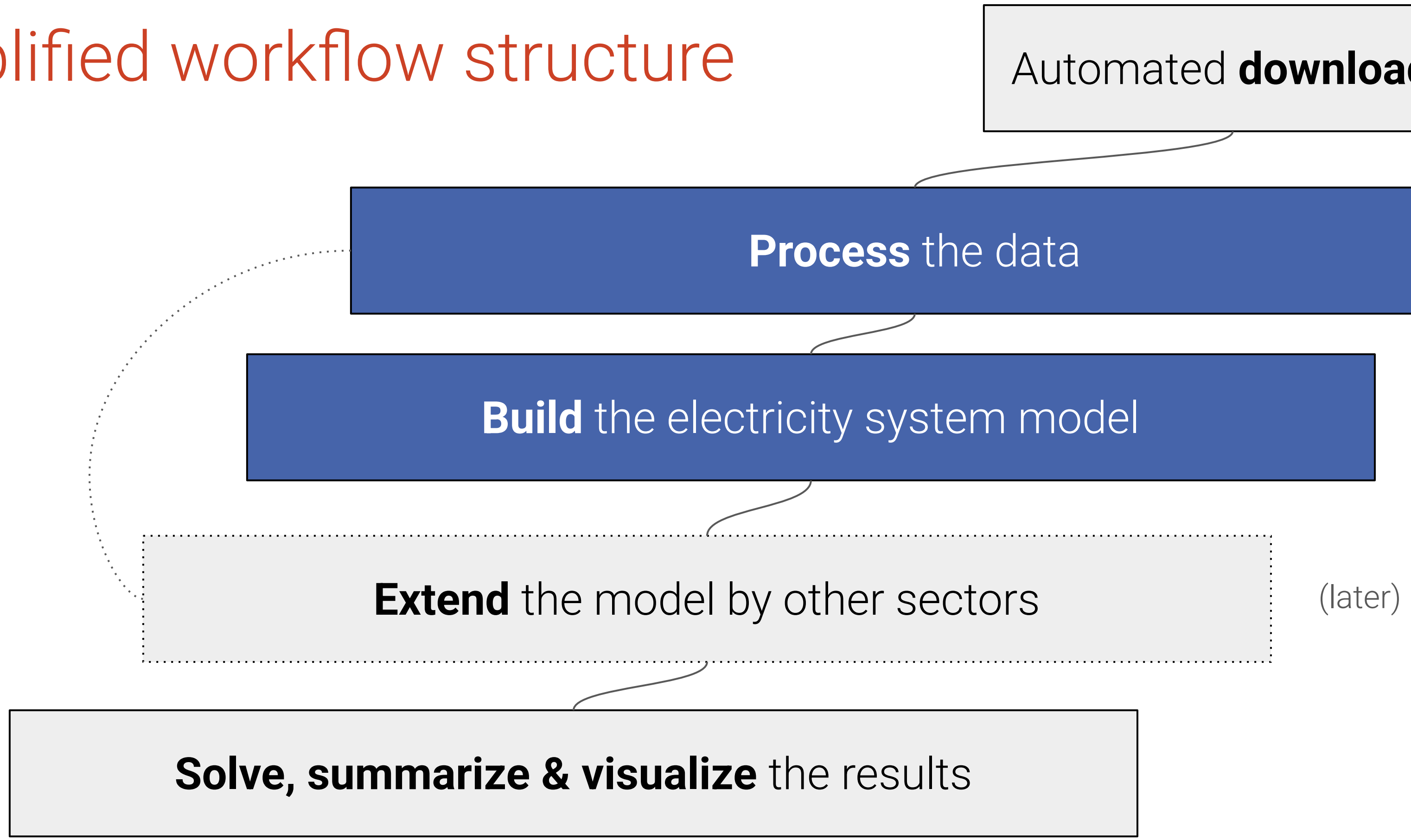

World Bank




https://pypsa-eur.readthedocs.io/en/latest/data_sources.html

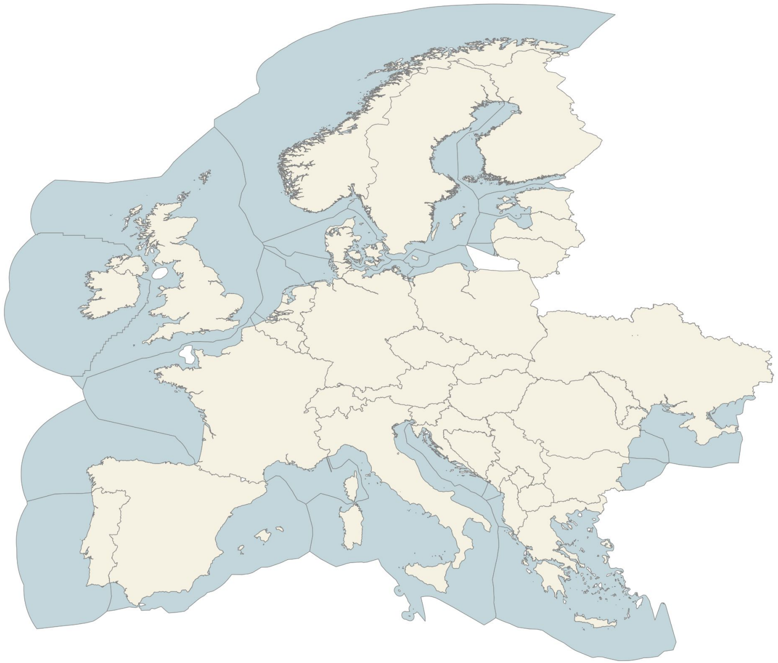
# Simplified workflow structure



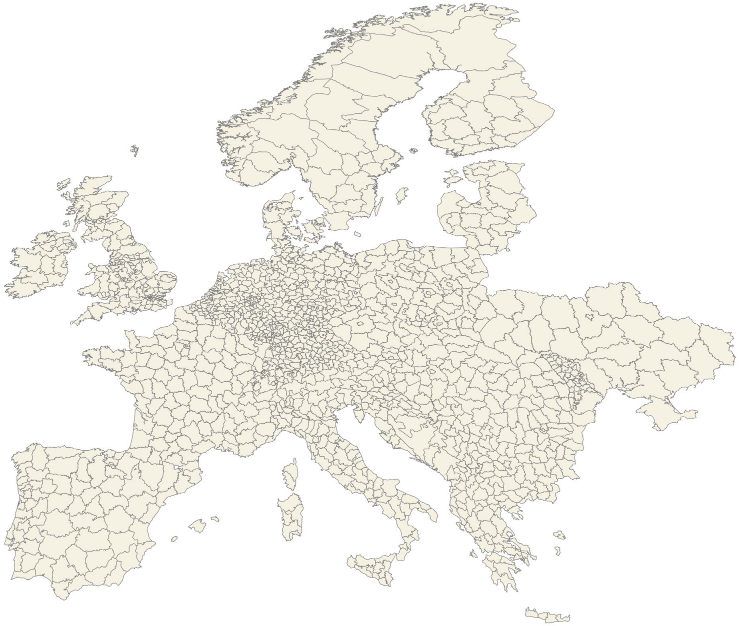
# Steps to building PyPSA-Eur electricity system

| | |
|---|---|
| Retrieve onshore & offshore polygons for each country | `build_shapes` |

Country shapes & exclusive economic zones (EEZ)



NUTS administrative regions (NUTS3)



# Steps to building PyPSA-Eur electricity system

| | |
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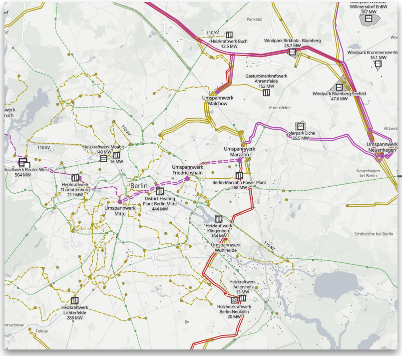
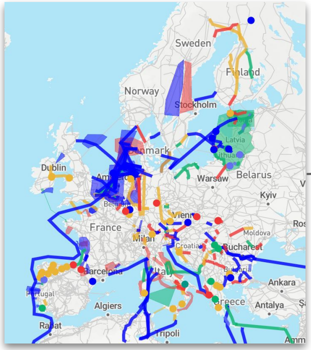
| Construct a base high-voltage network with buses, transformers, AC & DC lines with DLR & TYNDP | `base_network`, `build_transmission_projects` |

# Power grid topology

## OpenStreetMap data




## TYNDP projects



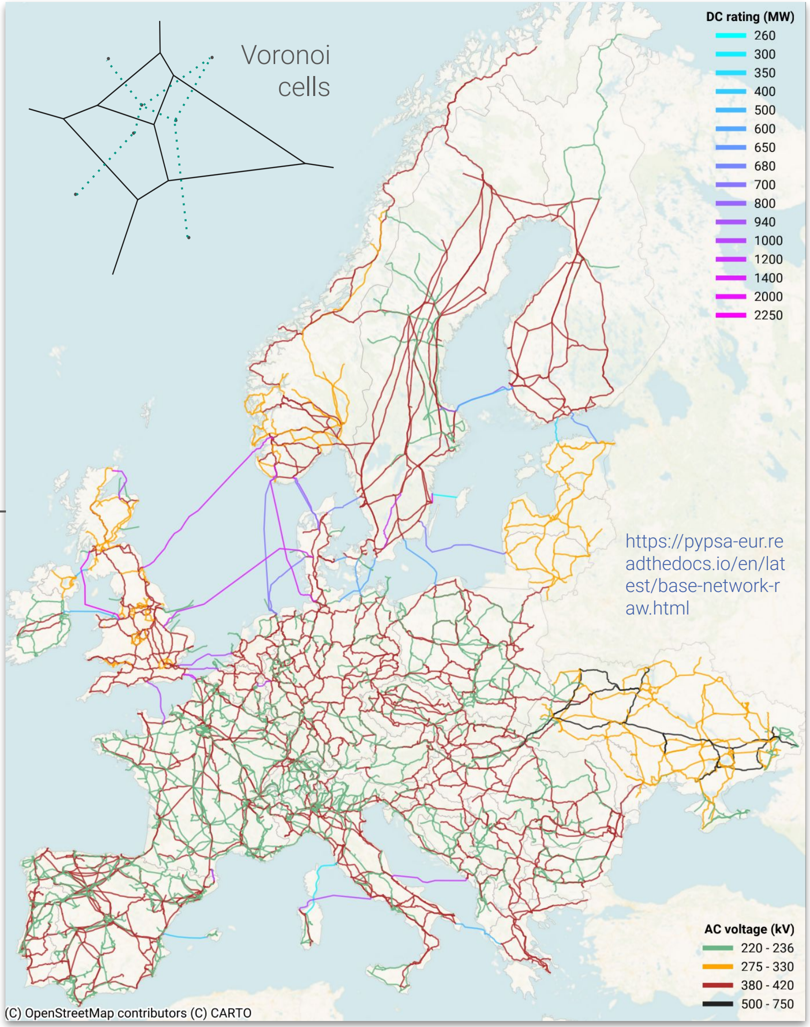

Apply **standard line types** for capacity and parameters.

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



# Steps to building PyPSA-Eur electricity system

| | |
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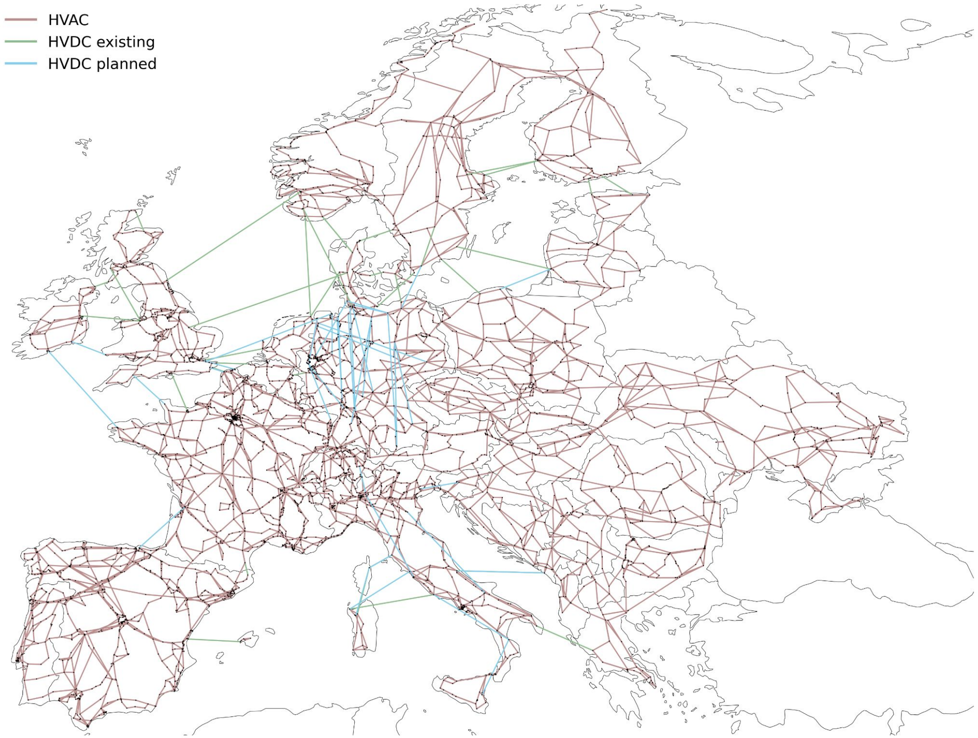
| Retrieve onshore & offshore polygons for each country | `build_shapes` |
| Construct a base high-voltage network with buses, transformers, AC & DC lines with DLR & TYNDP | `base_network`, `build_transmission_projects` |
| Transform all transmission lines to 380kV, remove dead ends & cluster with k-means or hierarchical clustering | `simplify_network`, `cluster_network` |

# Clustering the electricity network: `simplify_network`

Need to make the optimization problem less **computationally challenging**…

…if we want to **co-optimize** generation, storage, PtX conversion and transmission infrastructure:

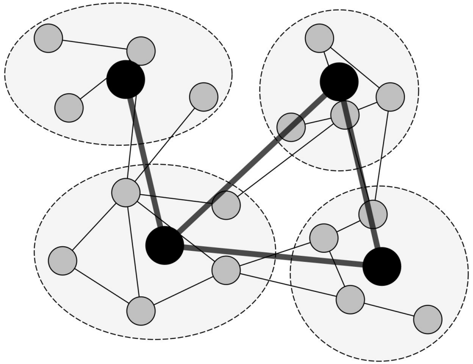
1. Lift all lines to common voltage level of 380 kV.
2. Remove dead ends.



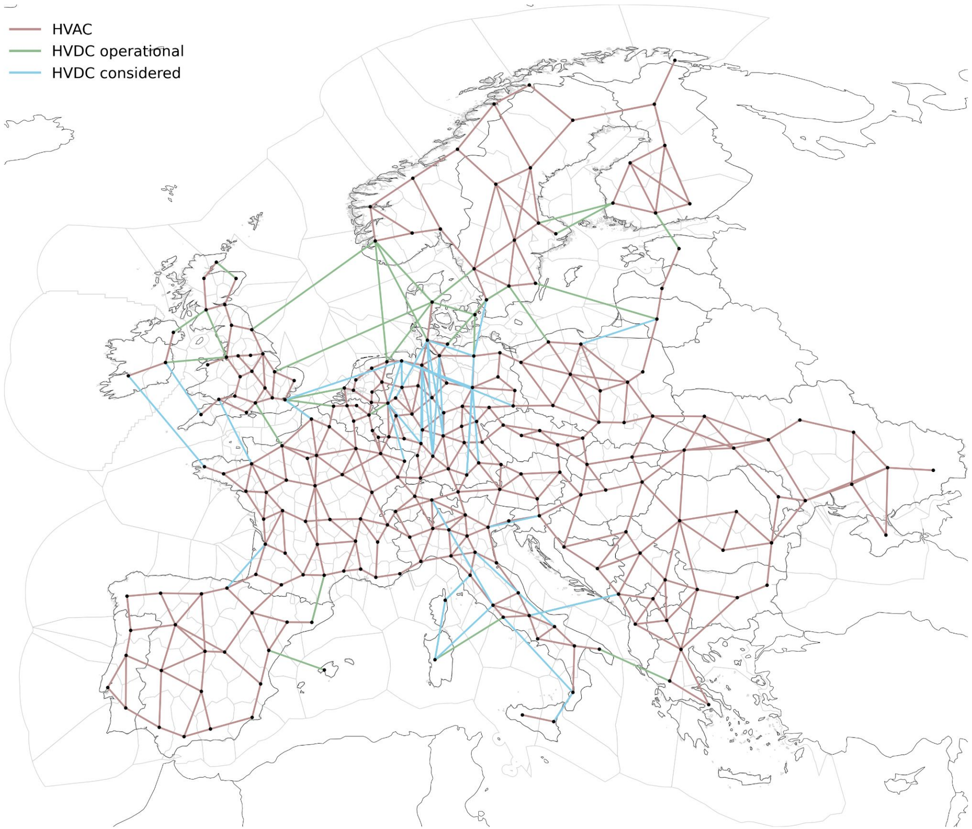
# Clustering the electricity network: `cluster_network`

Transformed
**to 380 kV**

Clustered to
**512 regions**

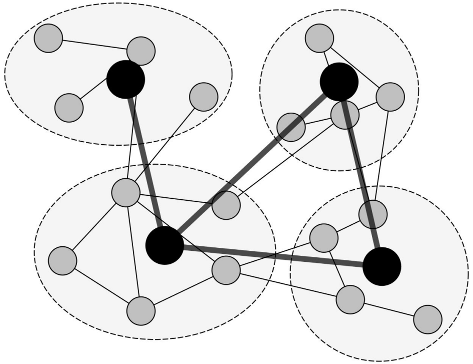


# Clustering the electricity network: `cluster_network`




Transformed **to 380 kV**

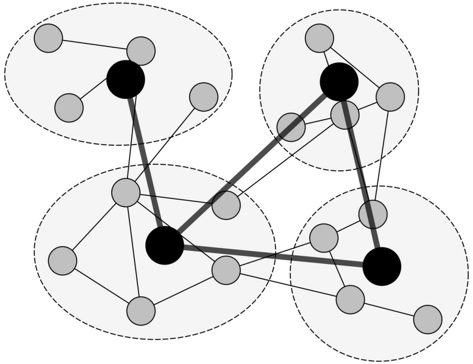
Clustered to **256 regions**



# Clustering the electricity network: `cluster_network`

Transformed **to 380 kV**

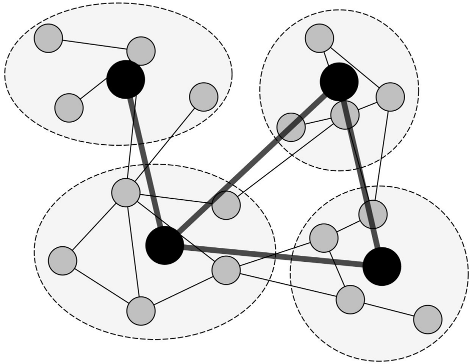
Clustered to **128 regions**



# Clustering the electricity network: `cluster_network`

Transformed **to 380 kV**

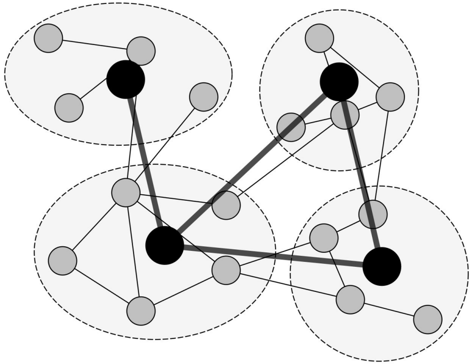
Clustered to **64 regions**



# Clustering the electricity network: `cluster_network`

Transformed **to 380 kV**

Clustered to **41 regions**



# Steps to building PyPSA-Eur electricity system

| | |
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| Retrieve onshore & offshore polygons for each country | `build_shapes` |
| Construct a base high-voltage network with buses, transformers, AC & DC lines with DLR & TYNDP | `base_network`, `build_transmission_projects` |
| Transform all transmission lines to 380kV, remove dead ends & cluster with k-means or hierarchical clustering | `simplify_network`, `cluster_network` |
| Determine eligible areas for utility-scale PV & onshore/offshore wind park development | `determine_availability_matrix` |
| Build renewable capacity factor profiles for each clustered region based on land availability | `build_renewable profiles`, `build_hydro_profile` |

# atlite: Convert weather data to energy systems data

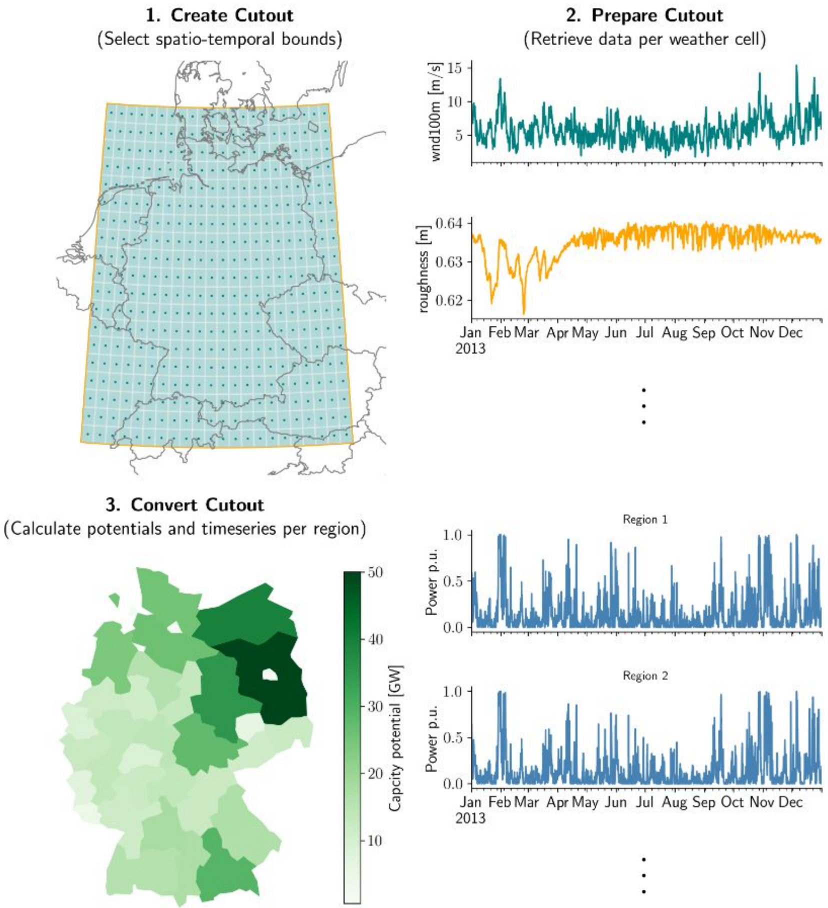
**Rule:** `build_renewable profiles`

pypi v0.3.0 | conda-forge v0.3.0 | Tests passing | codecov 72% | docs passing | license MIT
REUSE compliant | JOSS 10.21105/joss.03294 | chat 52 online | stackoverflow pypsa questions 44

Python library for converting weather data (e.g. wind, solar radiation, temperature, precipitation) into energy systems data:

- solar photovoltaics
- solar thermal collectors
- wind turbines
- hydro run-off, reservoir, dams
- heat pump COPs
- dynamic line rating (DLR)
- heating and cooling demand (HDD/CDD)

It can also perform land eligibility analyses.

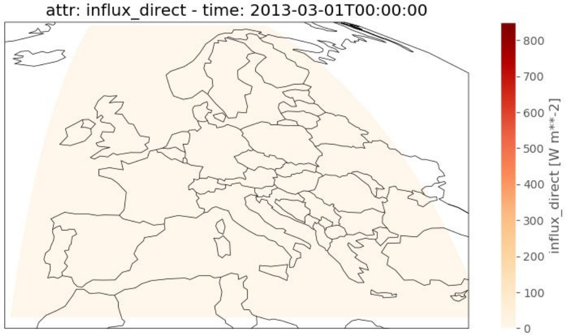


# Time series for renewables

atlite: Convert weather data to energy systems data

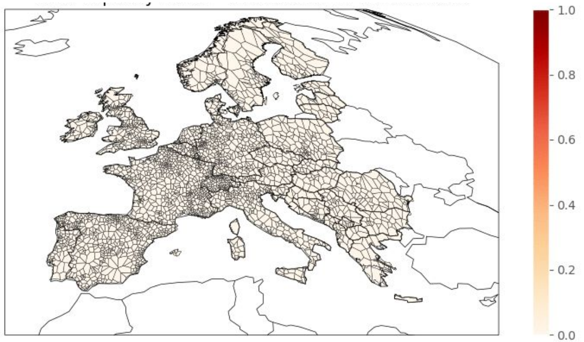
pypi v0.3.0 | conda-forge v0.3.0 | Tests passing | codecov 72% | docs passing | license MIT | REUSE compliant | JOSS 10.21105/joss.03294 | chat 52 online | stackoverflow pypsa questions 44

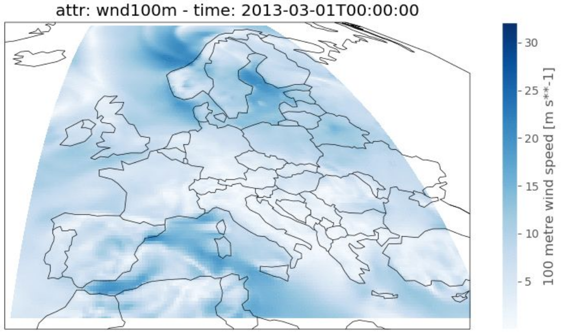
Historical meteorological weather data from ERA5 and SARAH-3
(up to 84 years, 30x30 km)



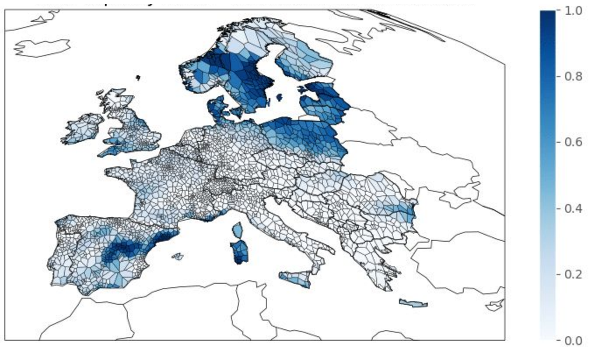

Solar panel models
- orientation
- material

Wind and solar capacity factors




Wind turbine models
- power curve
- surface roughness



# Land availability for renewables

**Example:**
Onshore wind
in one clustered
region


## atlite: Convert weather data to energy systems data

pypi v0.3.0 | conda-forge v0.3.0 | Tests passing | codecov 72% | docs passing | license MIT
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- CORINE / LUISA land cover
  - eligible land types
  - distance requirements
- NATURA / WDPA natural protection areas
- GEBCO bathymetry data
- Shipping lanes
- Distance to shore

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| Build renewable capacity factor profiles for each clustered region based on land availability | `build_renewable profiles`, `build_hydro_profile` |
| Prepare existing renewables and fossil power plants | `build_powerplants` |

# Welcome to powerplantmatching's documentation!

pypi v0.7.0 | conda-forge v0.7.0 | python >=3.9 | Tests failing | docs passing | pre-commit.ci passed | Ruff

license GPLV3+ | DOI 10.5281/zenodo.3358985 | stackoverflow pypsa questions 44

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

```
import powerplantmatching as pm
df = pm.powerplants(from_url=True)
df.query("DateIn > 2000")
```

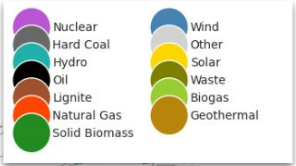
**Sources**

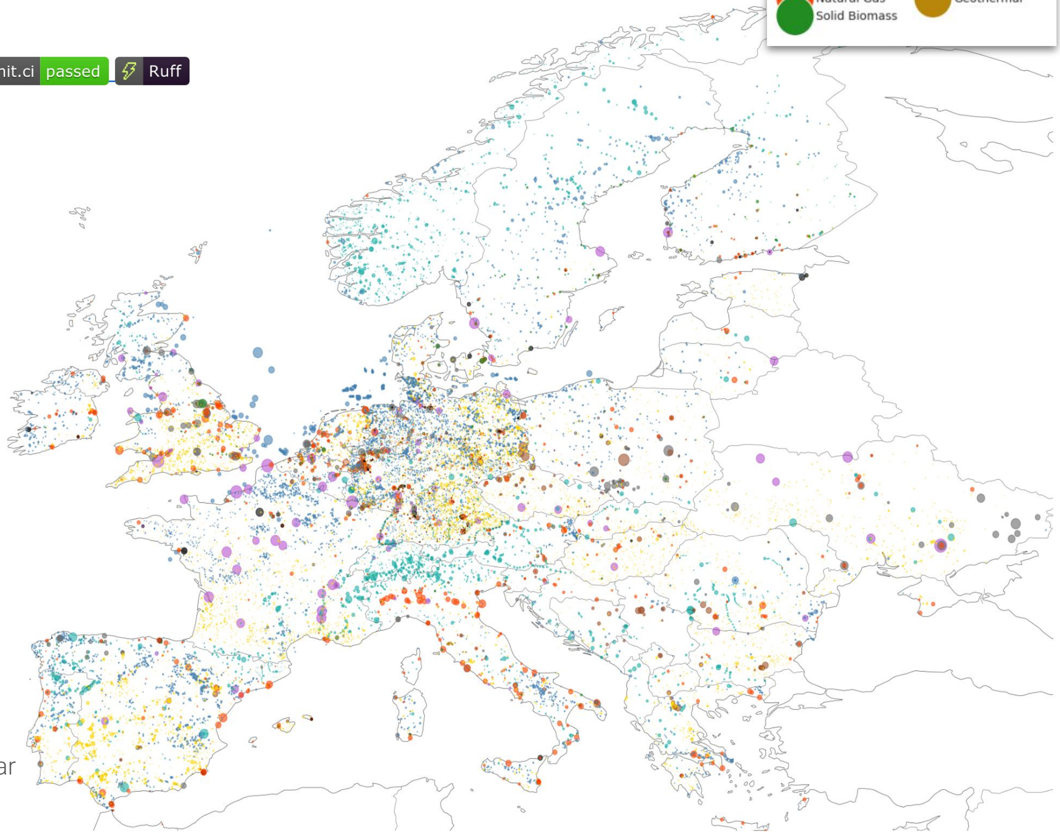
- Global Energy Monitor (GEM)
- Open Power System Data (OPSD)
- Global Energy Observatory
- World Resources Institute
- Marktstammdatenregister (MaStR)
- CARMA
- ENTSO-E, BNetzA, UBA, IRENA
- JRC for hydro power plants

**Attributes**

- name
- fuel type
- technology
- country
- capacity
- commissioning year
- retirement year
- coordinates

https://globalenergymonitor.org/projects/global-integrated-power-tracker/tracker-map/



github.com/pypsa/powerplantmatching

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| Determine eligible areas for utility-scale PV & onshore/offshore wind park development | `determine_availability_matrix` |
| Build renewable capacity factor profiles for each clustered region based on land availability | `build_renewable profiles`, `build_hydro_profile` |
| Prepare existing renewables and fossil power plants | `build_powerplants` |
| Add generation, storage and demand to the network with techno-economic assumptions on costs and efficiencies, … | `add_electricity`, `prepare_network` |

# Open database of techno-economic assumptions

- compiles **techno-economic assumptions** on energy system components
  - investment costs, FOM/VOM costs, efficiencies, lifetimes
  - for given years, e.g. 2020, 2030, 2040, 2050
  - from mixed sources, but prioritising **Danish Energy Agency** where available (and sensible)

Preview Code Blame 1097 lines (1097 loc) · 213 KB Raw

fischer-tropsch

| 1 | technology | parameter | value | unit | source | fu |
|---|---|---|---|---|---|---|
| 217 | Fischer-Tropsch | FOM | 3.0 | %/year | Agora Energiewende (2018): The Future Cost of Electricity-Based Synthetic Fuels (https://www.agora-energiewende.de/en/publications/the-future-cost-of-electricity-based-synthetic-fuels-1/), section 6.3.2.1. | |
| 218 | Fischer-Tropsch | VOM | 4.4663 | EUR/MWh_FT | Danish Energy Agency, data_sheets_for_renewable_fuels.xlsx | 1( |
| 219 | Fischer-Tropsch | capture rate | 0.9 | per unit | Assumption based on doi:10.1016/j.biombioe.2015.01.006 | |
| 220 | Fischer-Tropsch | carbondioxide-input | 0.326 | t_CO2/MWh_FT | DEA (2022): Technology Data for Renewable Fuels (https://ens.dk/en/our-services/projections-and-models/technology-data/technology-data-renewable-fuels), Hydrogen to Jet Fuel, Table 10 / pg. 267. | Ir |
| 221 | Fischer-Tropsch | efficiency | 0.799 | per unit | Agora Energiewende (2018): The Future Cost of Electricity-Based Synthetic Fuels (https://www.agora-energiewende.de/en/publications/the-future-cost-of-electricity-based-synthetic-fuels-1/), section 6.3.2.2. | |
| 222 | Fischer-Tropsch | electricity-input | 0.007 | MWh_el/MWh_FT | DEA (2022): Technology Data for Renewable Fuels (https://ens.dk/en/our-services/projections-and-models/technology-data/technology-data-renewable-fuels), Hydrogen to Jet Fuel, Table 10 / pg. 267. | 0. |
| 223 | Fischer-Tropsch | hydrogen-input | 1.421 | MWh_H2/MWh_FT | DEA (2022): Technology Data for Renewable Fuels (https://ens.dk/en/our-services/projections-and-models/technology-data/technology-data-renewable-fuels), Hydrogen to Jet Fuel, Table 10 / pg. 267. | 0. |
| 224 | Fischer-Tropsch | investment | 703726.4462 | EUR/MW_FT | Agora Energiewende (2018): The Future Cost of Electricity-Based Synthetic Fuels (https://www.agora-energiewende.de/en/publications/the-future-cost-of-electricity-based-synthetic-fuels-1/), table 8: "Reference scenario". | W |
| 225 | Fischer-Tropsch | lifetime | 20.0 | years | Danish Energy Agency, Technology Data for Renewable Fuels (04/2022), Data sheet "Methanol to Power". | |
| 956 | methanation | lifetime | 20.0 | years | Guesstimate. | B |

https://github.com/PyPSA/technology-data/blob/master/outputs/costs_2030.csv

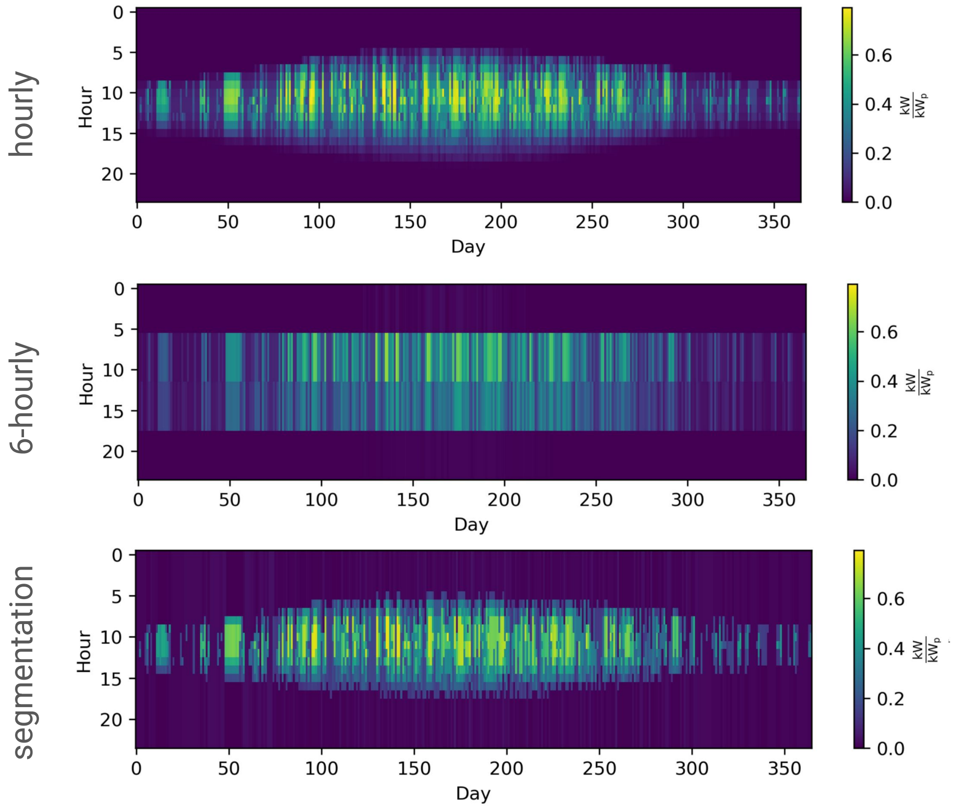
# Temporal aggregation

Multiple options:

1. **averaging** of every Nth hour

2. **sampling** every Nth hour (e.g. 3-hourly)

3. Non-equidistant **segmentation** with pre-defined number of segments using the **`tsam`** Python library from **FZ Jülich**




Introduction

tsam - time series aggregation module

https://tsam.readthedocs.io/en/latest/newsDoc.html

# Simplified workflow structure

Automated **downloads**

**Process** the data

**Build** the electricity system model

**Extend** the model by other sectors (later)

**Solve, summarize & visualize** the results

# linopy: Linear optimization with N-D labeled variables

pypi v0.5.0 CI license MIT

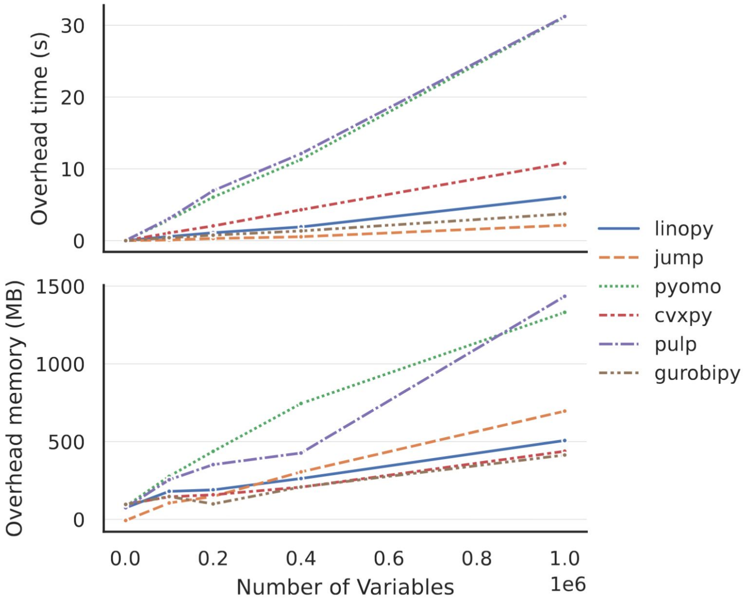
linopy

Python library that facilitates **optimization** with real-world, large-scale data.

It supports:

- Linear (LP),
- Mixed-Integer (MILP),
- Quadratic programming (QP).

It has been developed to make linear programming in Python easy, highly-flexible and – most importantly – **highly performant**.




https://joss.theoj.org/papers/10.21105/joss.04823

# Solving and summarising networks

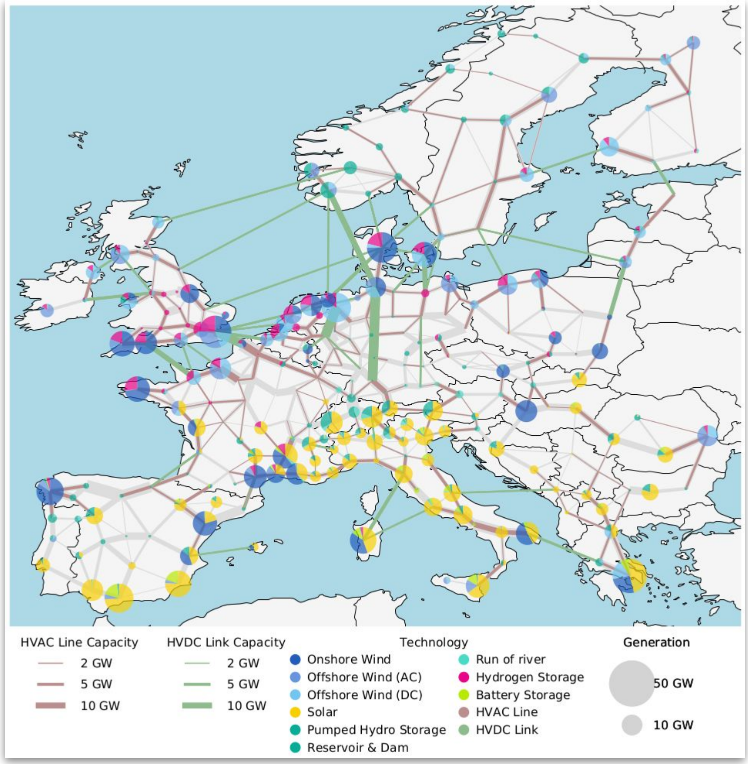
## Hardware requirements:

- Building the model **can run locally** on most modern laptops. Very simple models can run with HiGHS solver.

- But access to a **commercial solver** and a larger **cluster/workstation** is required for solving problems (~250 GB RAM per scenario if resolution is very high)!

There is a **statistics module in PyPSA** designed to help with analysing solved networks and several **figures/maps are created automatically**.

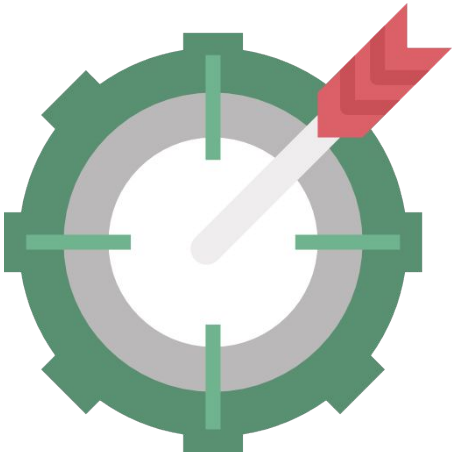
Example result without sector-coupling



# What is configurable?

electricity-only examples

- Select subset of countries and focus countries (e.g. only DE)
- Select weather year (1940 - 2024 for ERA5)
- Specify $CO_2$ constraint and gas usage limit
- Tweak spatial resolution (between 41 and >1000 nodes)
- Tweak temporal resolution (from hourly to N-hourly)
- Customize cost assumptions (e.g. 2020, 2030, 2050)
- Parametrize technologies (e.g. wind turbine type, panel orientation)
- Define land use eligibility criteria (e.g. distance requirements)
- Pick a solver (HiGHS, Gurobi, CPLEX, Xpress…)
- Choose between greenfield or brownfield expansion



`config.yaml`

Let's look at this in more detail!

Icon made by surang from www.flaticon.com

Search Ctrl + K

**Getting Started**

- Introduction
- Installation
- Tutorial: Electricity-Only
- Tutorial: Sector-Coupled

**Configuration**

- Wildcards
- **Configuration**
- Foresight Options
- Techno-Economic Assumptions

**Rules Overview**

- Retrieving Data
- Building Electricity Networks
- Building Sector-Coupled Networks
- Solving Networks
- Plotting and Summaries

# Configuration

PyPSA-Eur has several configuration options which are documented in this section and are collected in a `config/config.yaml` file. This file defines deviations from the default configuration (`config/config.default.yaml`); confer installation instructions at Handling Configuration Files.

## Top-level configuration

"Private" refers to local, machine-specific settings or data meant for personal use, not to be shared. "Remote" indicates the address of a server used for data exchange, often for clusters and data pushing/pulling.

```yaml
version: v2025.01.0
tutorial: false

logging:
  level: INFO
  format: '%(levelname)s:%(name)s:%(message)s'

private:
  keys:
    entsoe_api:

remote:
  ssh: ""
  path: ""
```

| | Unit | Values | Description |
|---|---|---|---|
| version | – | 0.x.x | Version of PyPSA-Eur. Descriptive only. |
| tutorial | bool | {true, false} | Switch to retrieve the tutorial data set instead of the full data set. |
| logging | | | |

Contents



https://pypsa-eur.readthedocs.io/en/latest/configuration.html

# Live Demo – Belgium / electricity-only / few days

Start with a dry-run:

Don't forget to activate your conda environment first!

```
$ snakemake -j1 solve_elec_networks --configfile config/test/config.electricity.yaml -n
```

Then execute the same command "for real" by dropping "-n" flag:

The "-j1" flag tells snakemake to run one job at a time.

```
$ snakemake -j1 solve_elec_networks --configfile config/test/config.electricity.yaml
```

To explore results, start a Jupyter notebook:

```
$ jupyter notebook
```

# Practical Phase

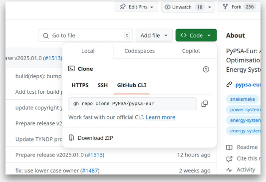
(electricity-only)

## 1) Download the repository

Open a terminal / CMD and type:

```
$ cd ~/path/to/my/directory
$ git clone https://github.com/PyPSA/pypsa-eur.git
$ cd pypsa-eur
```

You can also download the repository as a ZIP by hand.



## 2) Install conda environment

Installation links:

- Anaconda (bigger download):
- Miniconda (recommended):

```
$ conda update conda
$ conda env create -f envs/environment.yaml
$ conda activate pypsa-eur
```

## 3) Run PyPSA-Eur tutorial with `snakemake`

Guide:
https://pypsa-eur.readthedocs.io/en/latest/tutorial.html

```
$ snakemake solve_elec_networks
  --configfile
  config/test/config.electricity.yaml -j1
```

Users of Windows, add two lines to YAML:

```
run:
  use_shadow_directory: false
```

## 4) Explore PyPSA network in a Jupyter notebook

```
import pypsa
fn = “results/test-elec/networks/base_s_5_elec_.nc”
n = pypsa.Network(fn)
n.statistics()
n.plot()
```

# Small exploratory configuration tasks

(electricity-only)

Go to https://pypsa-eur.readthedocs.io/en/latest/configuration.html and https://github.com/PyPSA/pypsa-eur/blob/master/config/config.default.yaml and try to find out how to configure some of the settings for **electricity-only models** listed below:

1. Increase the maximum line loading from 70% to 100%.
2. Disable power transmission grid reinforcements.
3. Activate dynamic line rating with default settings.
4. Activate linearised transmission loss approximation.
5. Deactivate the estimation of existing renewable capacities.
6. Change the techno-economic assumptions to the year 2020.
7. Remove the option to build hydrogen or battery storage.

# Simplified workflow structure

Automated **downloads**

**Process** the data

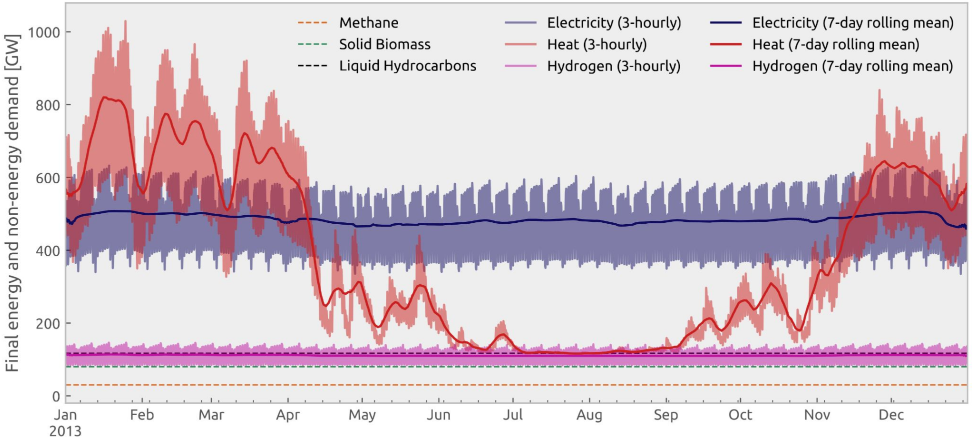
**Build** the electricity system model

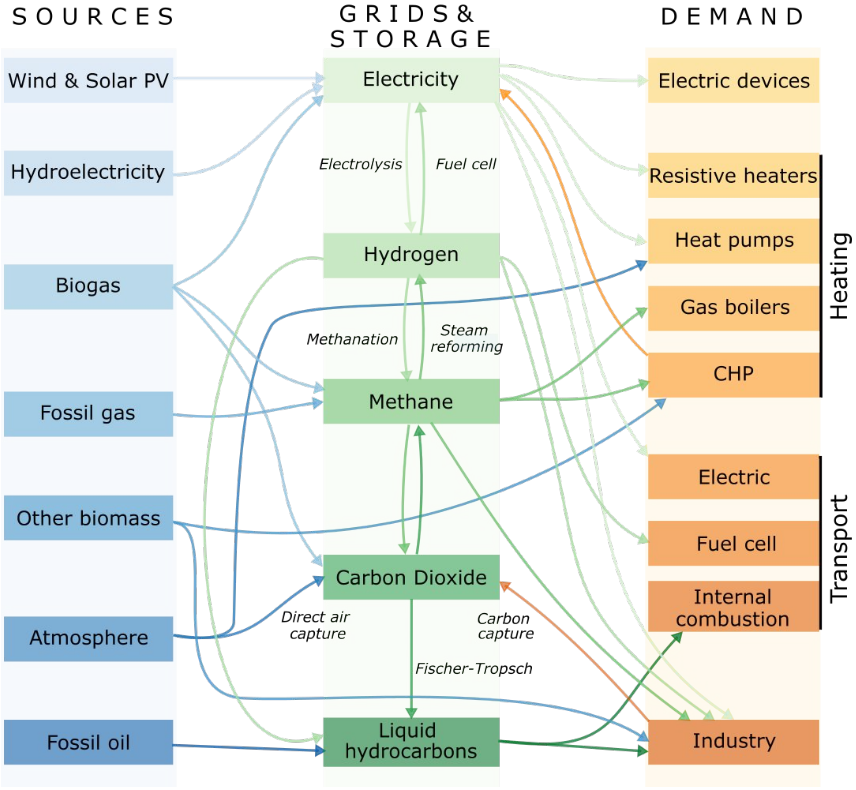
**Extend** the model by other sectors

**Solve, summarize & visualize** the results

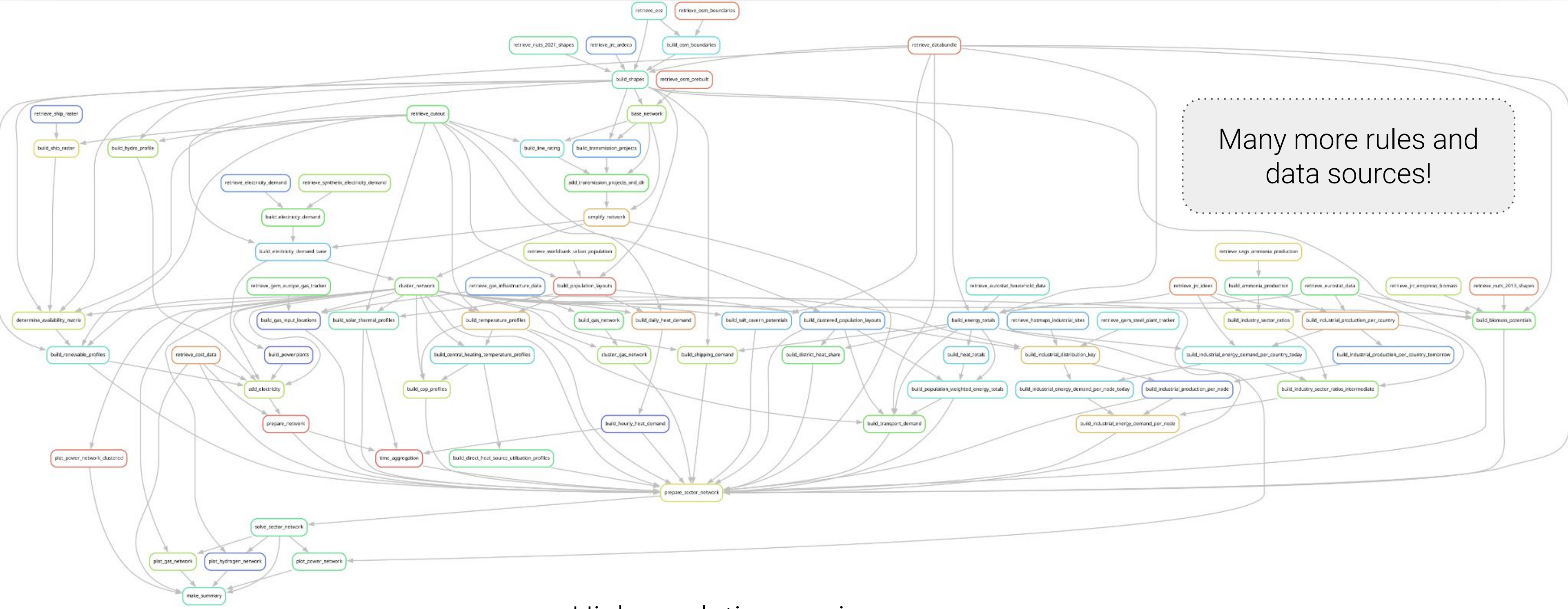
# Coupling with other sectors

- transport sector (EVs, shipping, aviation)
- heating sector (district heating, individual)
- industry sector (steel, chemicals, ammonia, ...)
- carbon management (CCUTS) + biomass
- hydrogen, $CO_2$ and gas networks



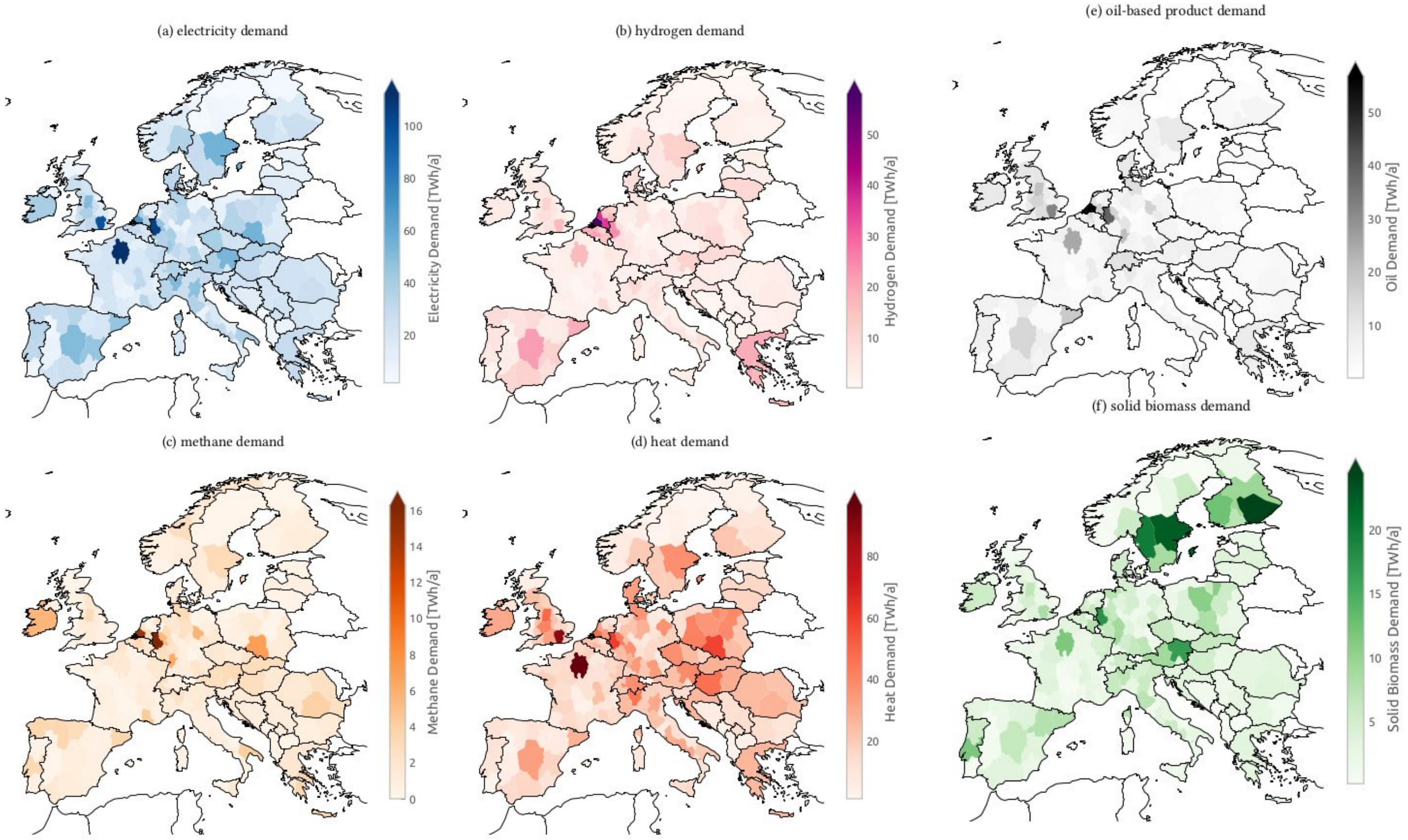
# Extension by other sectors requires more data!




Many more rules and
data sources!

High-resolution version:
https://tubcloud.tu-berlin.de/s/E7tx3BagXsKXLre

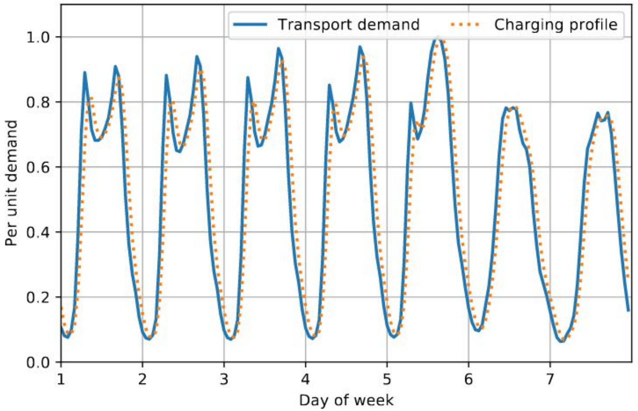
# **Spatial** distribution of energy demands

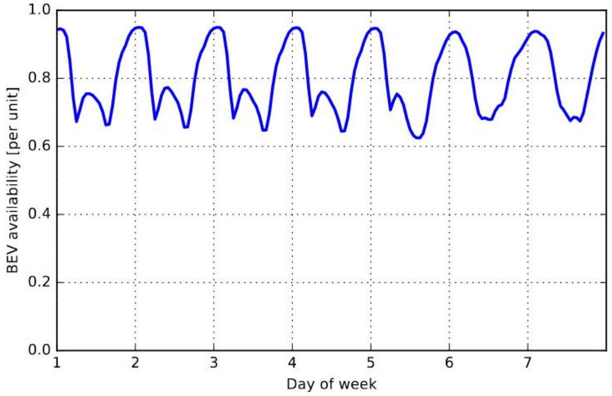


# Use of PyPSA components

- **Buses** impose energy balances for different energy carriers (heat, hydrogen, methane), and account for $CO_2$ emitted/absorbed from the atmosphere.
- **Links** represent **energy converters**, e.g. a heat pump that withdraws energy from the electricity bus and supplies heat to the heating bus with a certain efficiency.
- **Multilinks** represent more **elaborated conversion processes**, e.g. a biomass-fired CHP that withdraws biomass and supplies electricity, heat and $CO_2$ emissions.
- **Stores** can represent available potential (if allowed to discharge throughout the modelled period) or relax the hourly energy balancing constraint to annual (when a free store is added).

# Transport - Electrification of land transport

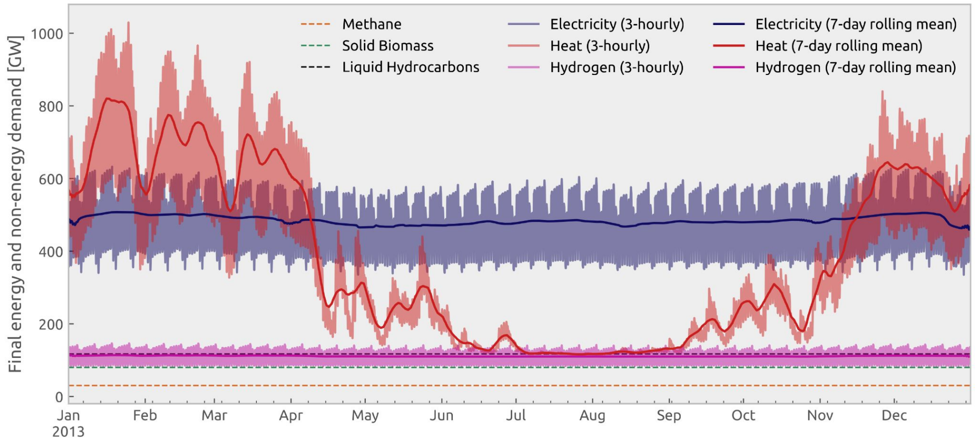



- Road and rail are **largely electrified**, ICE only during pathway to net-zero
- Time series from traffic counting
- Lumped representation of electric vehicles: a configurable share of them participates in demand-side management (**DSM**) or vehicle-to-grid (**V2G**)
- Electric vehicles have **time-varying availability** for charging depending on driving profiles
- EV battery almost fully charged in the

Modelling **land transport transformation** endogenously is currently under development!

# Heating - Demand



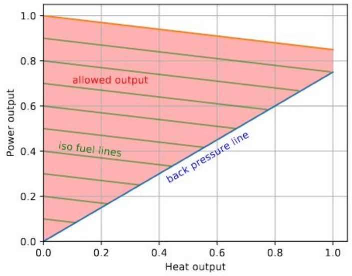

**Heating demand time series** created by :

- space heating based on degree-day and daily profiles, weighted by population
- constant water heating demand
- scaled to historical annual demand
- split into individual and central systems

(cooling demand already electrified)

# Heating - Tech for individual & district heating

CHP feasible dispatch:




**Decentral individual heating**
can be supplied by:

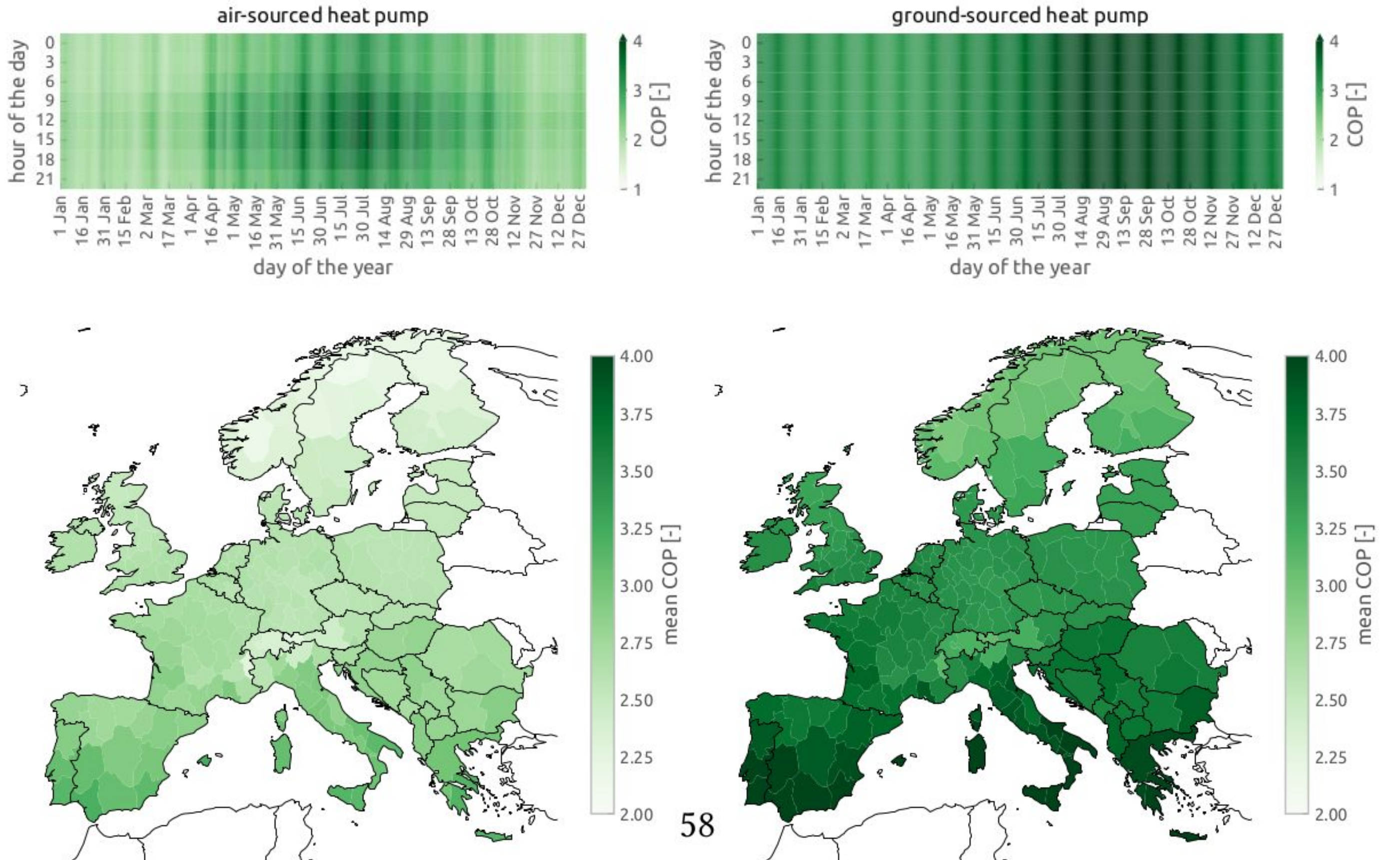
- air- or ground-sourced heat pumps
- resistive heaters
- gas / oil / biomass / hydrogen boilers
- solar thermal
- small water tanks

Building renovations can be co-optimized to reduce space heating demand.

**District heating systems**
can be supplied in urban areas by:

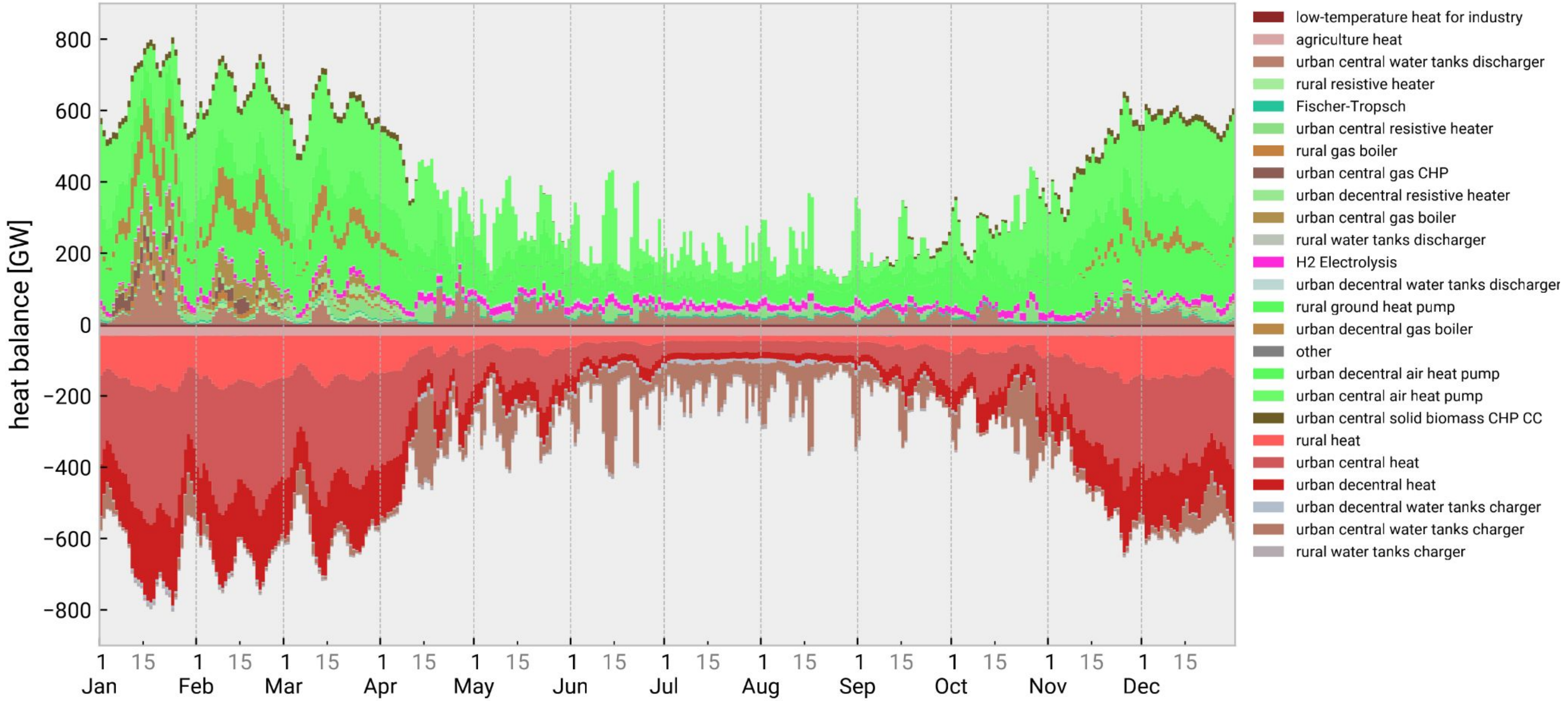
- air-sourced heat pumps + other
- resistive heaters
- gas / hydrogen / biomass / waste CHPs
- gas / oil / biomass / hydrogen boilers
- solar thermal
- long-duration hot water storage
- waste heat from industrial processes

# Heating - Heat pumps as new variable supply tech




**Geothermal heat** sources have been integrated very recently!

# Heating - Example daily heat system balance




There are difficult periods in winter with low wind and solar, high space heating demand and low air temperatures, which are bad for air-sourced heat pump performance. In this case **gas boilers** and **CHP plants** jump in as backup.

# Synthetic fuels - Power-to-X

**Carbonaceous fuels** produced synthetically:

- Synthetic methane using Sabatier reaction

  $CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$

- Synthetic oil via Fischer-Tropsch

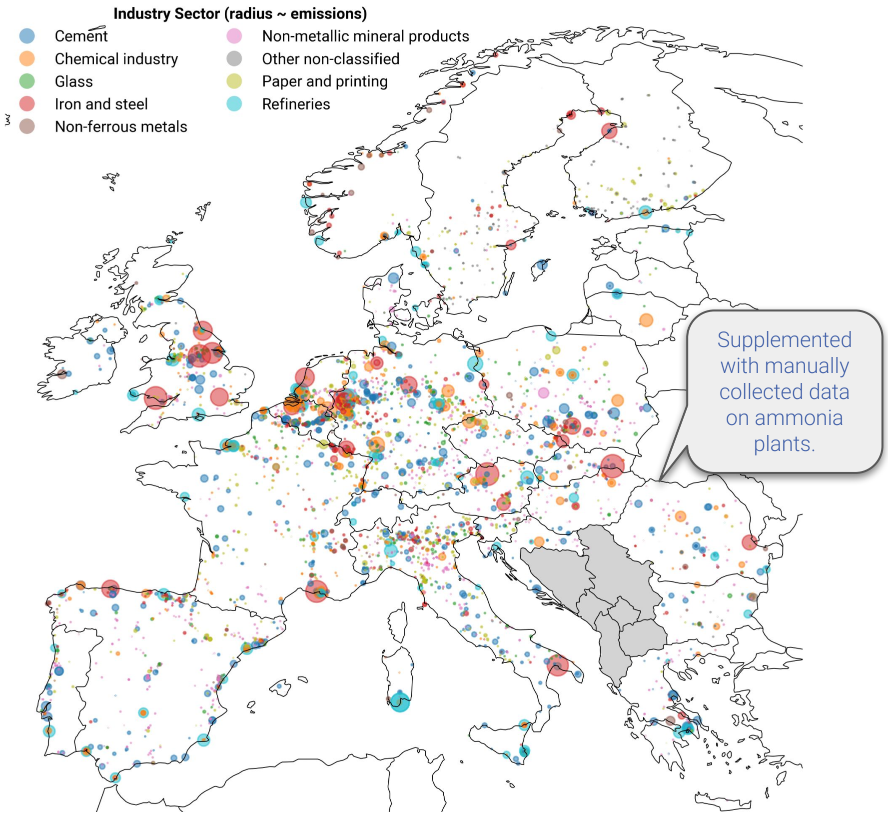
  $(2n + 1)\ H_2 + n\ CO \rightarrow C_nH_{2n+2} + n\ H_2O$

- Synthetic methanol in methanolisation plants

  $CO_2 + 3H_2 \rightarrow CH_3OH + H_2O$

Conversion efficiencies read from open database of techno-economic assumptions
`https://github.com/PyPSA/technology-data/blob/master/outputs/costs_2030.csv`

# Industry - Regionalisation based on Hotmaps




https://gitlab.com/hotmaps/industrial_sites/industrial_sites_Industrial_Database

| | |
|---|---|
| Iron & Steel | Phase-out integrated steelworks; increased recycling; rest from $H_2$-DRI + EAF |
| Aluminium | Methane for high-enthalpy heat; increased recycling |
| Cement | Solid biomass; capture of $CO_2$ emissions |
| Ceramics | Electrification |
| Ammonia | Gray, blue, green hydrogen |
| Plastics | Synthetic naphtha; MtO/MtA, increased recycling |
| Other industry | Electrification; process heat from biomass |
| Shipping | Methanol, (oil), (liquid hydrogen), (LNG) |
| Aviation | Kerosene from Fischer-Tropsch or methanol |

Modelling **industry relocation, high-temperature heat source & shipping fuels** endogenously is currently under development!

# Infrastructure - Gas network with $H_2$ retrofitting

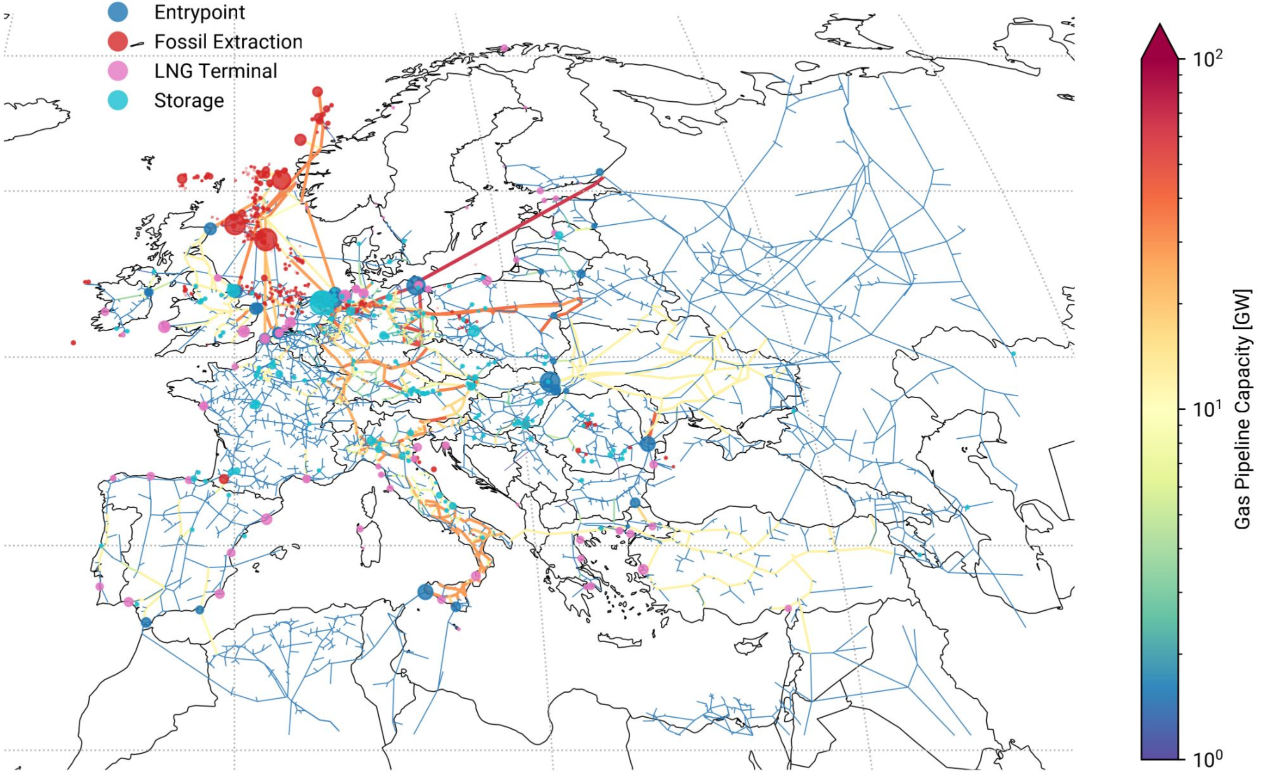
Compiled from open **SciGRID_gas** dataset.

Fossil gas enters at **LNG terminals** or **gas fields**.

Gas flow **physics** and **valve control** neglected transport model.

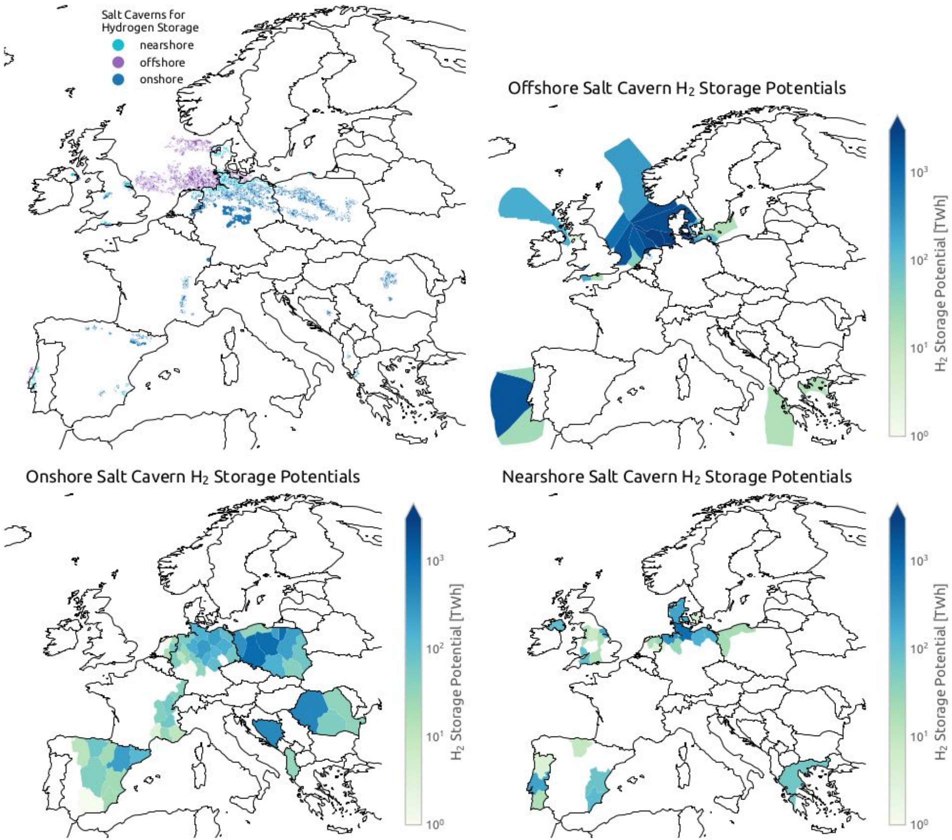
Electricity demand for **compression** and **leakage** configurable.

Pipelines can be **retrofitted** to $H_2$ with costs from EHB.




https://zenodo.org/records/4767098

# Infrastructure - Hydrogen storage potentials

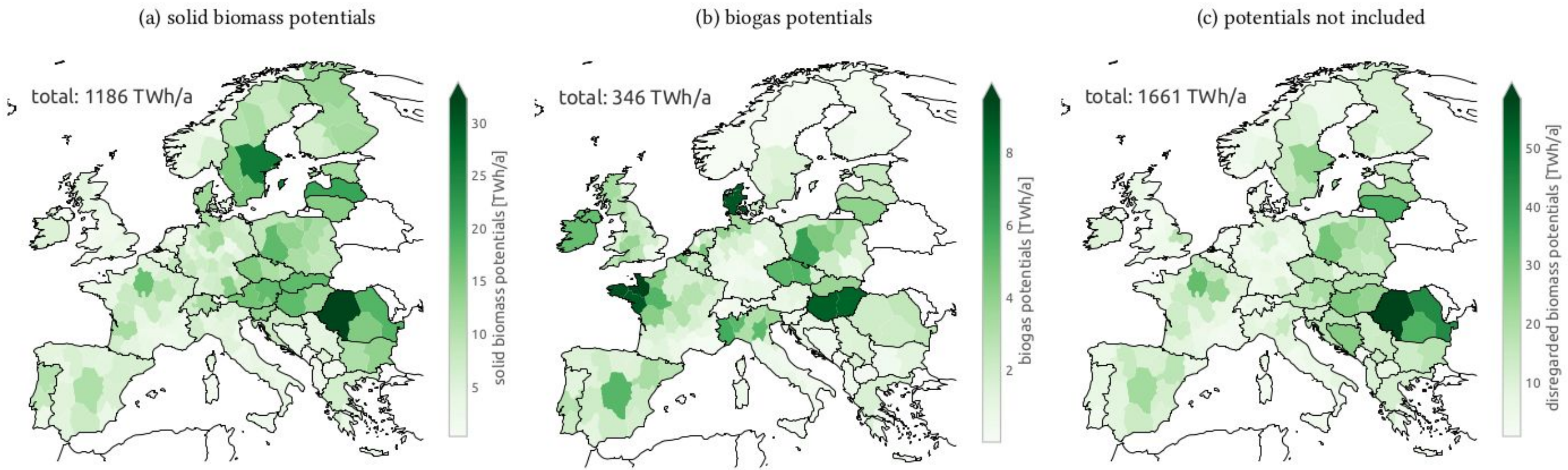



The regional distribution of **geological potential** to store hydrogen in **salt caverns** is considered.

The user can **configure** if onshore and/or offshore potentials can be used.

Dilara Gulcin Caglayan, Nikolaus Weber, Heidi U. Heinrichs, Jochen Linßen, Martin Robinius, Peter A. Kukla, Detlef Stolten, *Technical potential of salt caverns for hydrogen storage in Europe*, **International Journal of Hydrogen Energy**, Volume 45, Issue 11, 2020, 6793-6805, https://doi.org/10.1016/j.ijhydene.2019.12.161

# Infrastructure - Biomass from JRC ENSPRESO



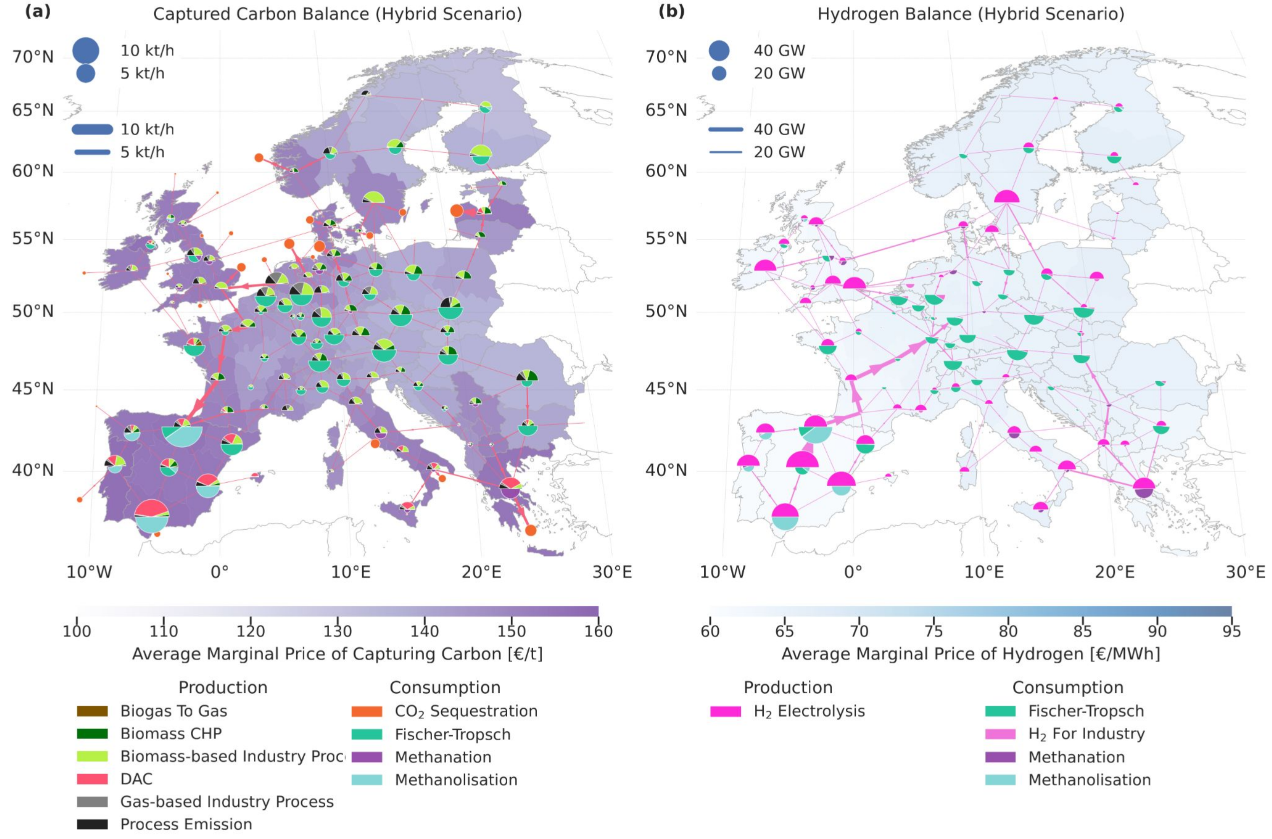

Biomass potentials are split between **solid biomass** and **biogas** (which can be, for instance, upgraded).

The user can configure low/medium/high potentials and what categories of biomass to consider (e.g. forest residues).

The default configuration only considers **residual biomass**, no energy crops.

https://data.jrc.ec.europa.eu/dataset/74ed5a04-7d74-4807-9eab-b94774309d9f

# Infrastructure - Carbon management

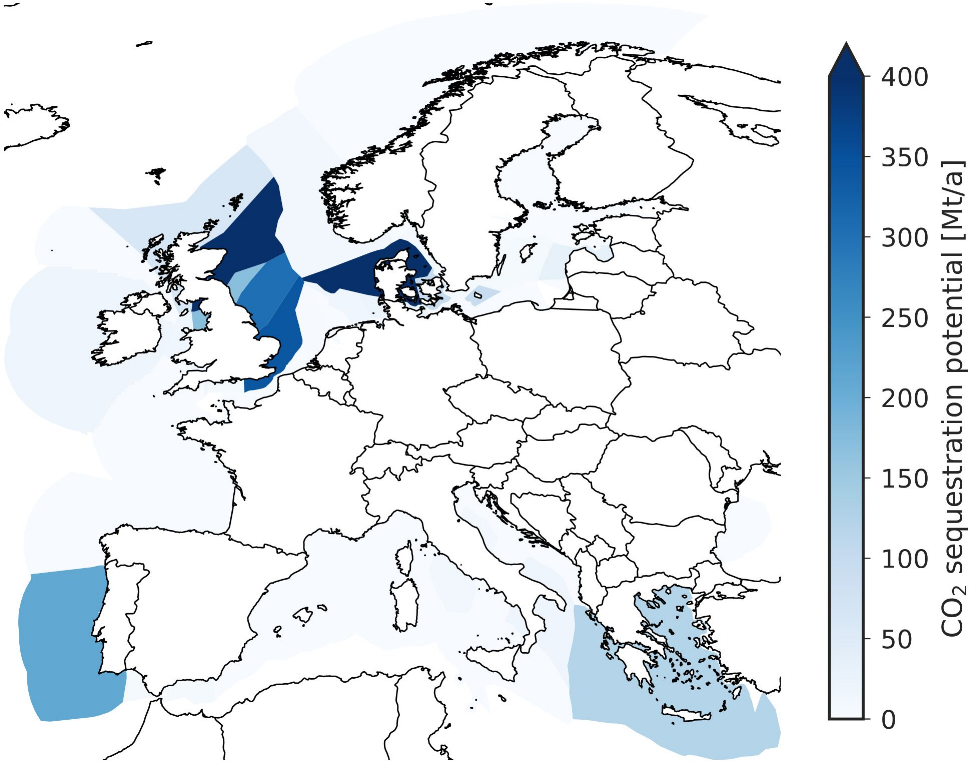



**Built-in carbon flows:**

- **Capture:** DAC, process emissions, fossil / biomass CHP
- **Transport:** $CO_2$ pipelines
- **Storage:** intermediate storage and long-term geological sequestration
- **Utilization:** for synthetic carbonaceous fuels

# Infrastructure - Carbon sequestration potentials

Example: Offshore carbon sequestration potentials



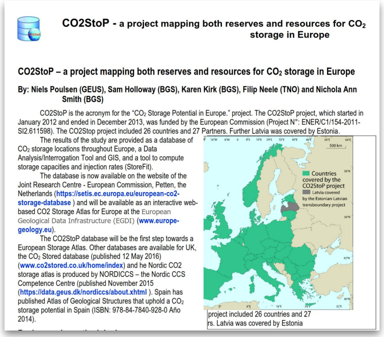

The user can **configure**

- onshore/offshore sequestration,
- gas fields/oil fields/aquifer, and
- low/medium/high potentials,

as well as a **total limit** on the annual sequestration, e.g. 250 Mt per year.

Data source:

https://energy.ec.europa.eu/publications/assessment-co2-storage-potential-europe-co2stop_en



**CO2StoP - a project mapping both reserves and resources for $CO_2$ storage in Europe**

**CO2StoP – a project mapping both reserves and resources for $CO_2$ storage in Europe**

**By: Niels Poulsen (GEUS), Sam Holloway (BGS), Karen Kirk (BGS), Filip Neele (TNO) and Nichola Ann Smith (BGS)**

CO2StoP is the acronym for the "$CO_2$ Storage Potential in Europe." project. The CO2StoP project, which started in January 2012 and ended in December 2013, was funded by the European Commission (Project N°: ENER/C1/154-2011-SI2.611598). The CO2Stop project included 26 countries and 27 Partners. Further Latvia was covered by Estonia.

The results of the study are provided as a database of $CO_2$ storage locations throughout Europe, a Data Analysis/Interrogation Tool and GIS, and a tool to compute storage capacities and injection rates (StoreFit).

The database is now available on the website of the Joint Research Centre - European Commission, Petten, the Netherlands (https://setis.ec.europa.eu/european-co2-storage-database ) and will be available as an interactive web-based CO2 Storage Atlas for Europe at the European Geological Data Infrastructure (EGDI) (www.europe-geology.eu).

The CO2StoP database will be the first step towards a European Storage Atlas. Other databases are available for UK, the $CO_2$ Stored database (published 12 May 2016) (www.co2stored.co.uk/home/index) and he Nordic CO2 storage atlas is produced by NORDICCS – the Nordic CCS Competence Centre (published November 2015 (https://data.geus.dk/nordiccs/about.xhtml ). Spain has published Atlas of Geological Structures that uphold a $CO_2$ storage potential in Spain (ISBN: 978-84-7840-928-0 Año 2014).



project included 26 countries and 27 rs. Latvia was covered by Estonia

# Technology choices - endogenous vs. exogenous

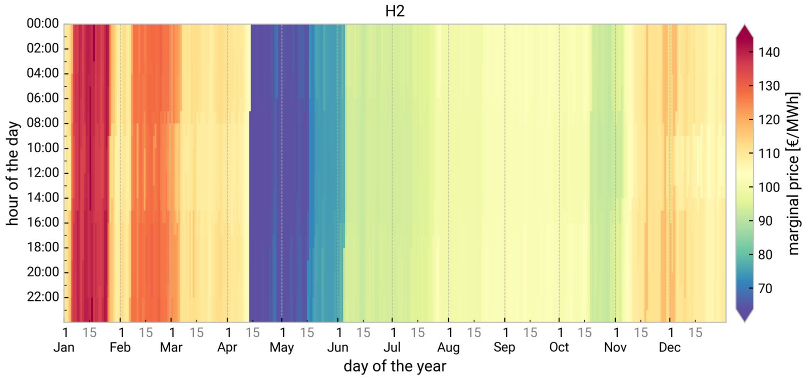
**Exogenous assumptions (modeller chooses):**

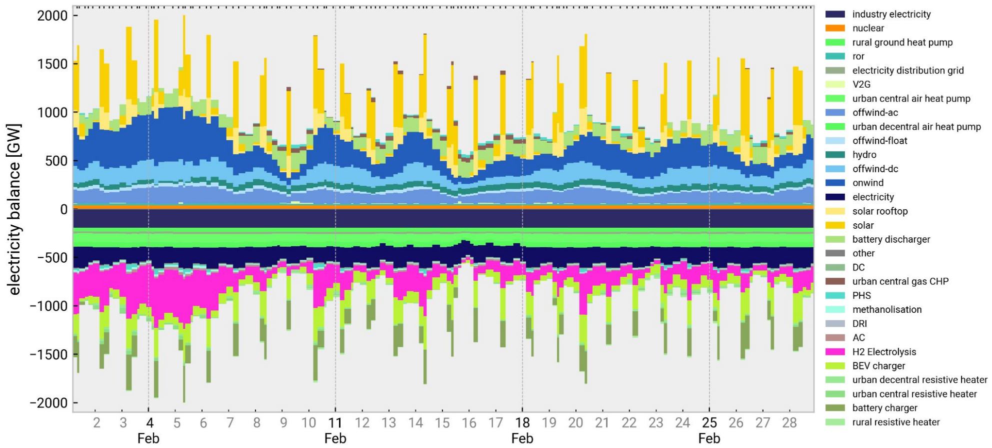
- energy services demand (e.g. heat)
- district heating shares
- energy carrier shares for road transport
- kerosene for aviation
- methanol for shipping
- electrification & recycling in industry
- steel production with DRI + EAF

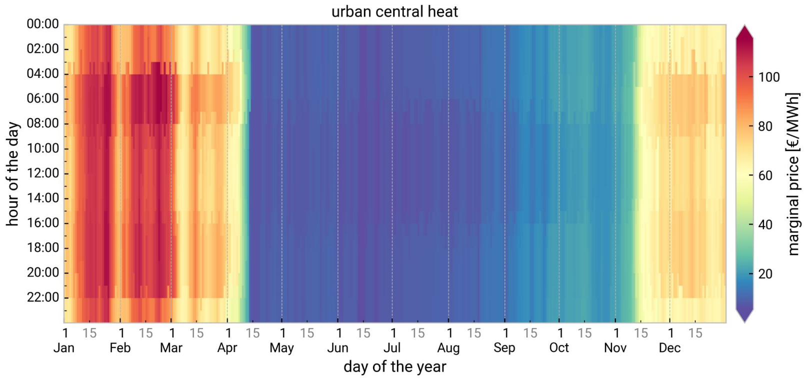
**Endogenous choices (model optimizes):**

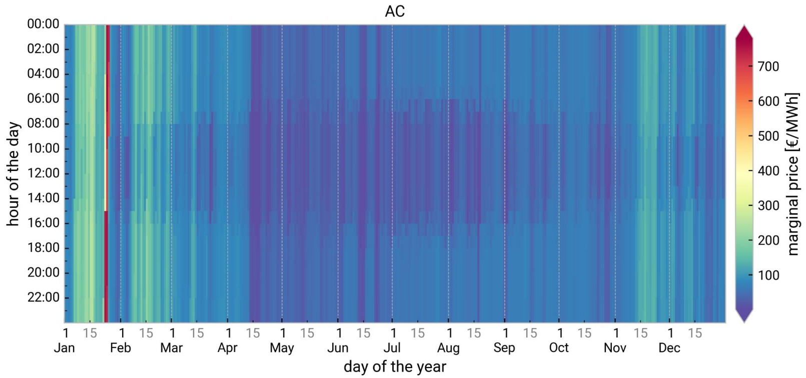
- change in electricity generation fleet
- transmission reinforcement
- capacities and locations of short and long-duration energy storage
- space and water heating technologies (including building renovations)
- all P2G/L/H/C
- supply of process heat for industry
- carbon capture (e.g. CHP, industry, DAC)

# Prices in the model

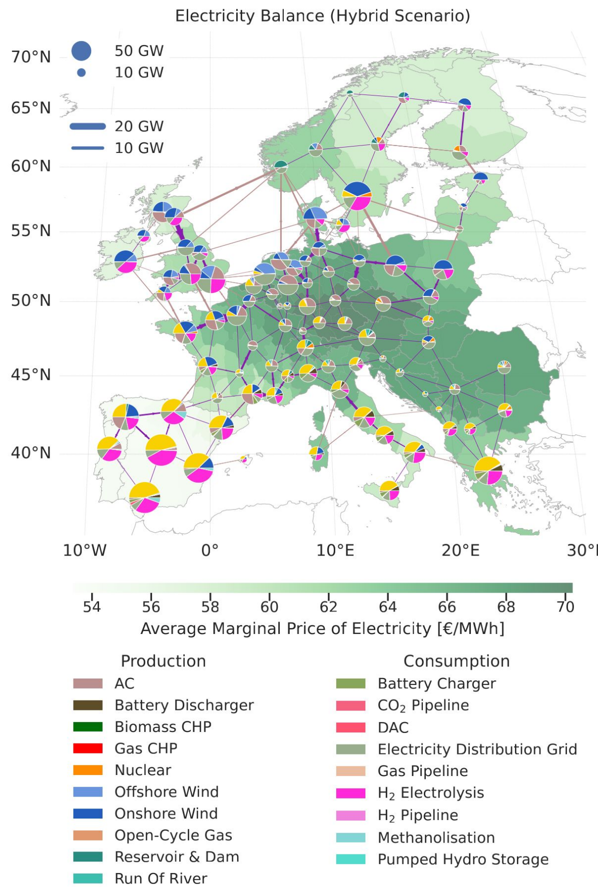


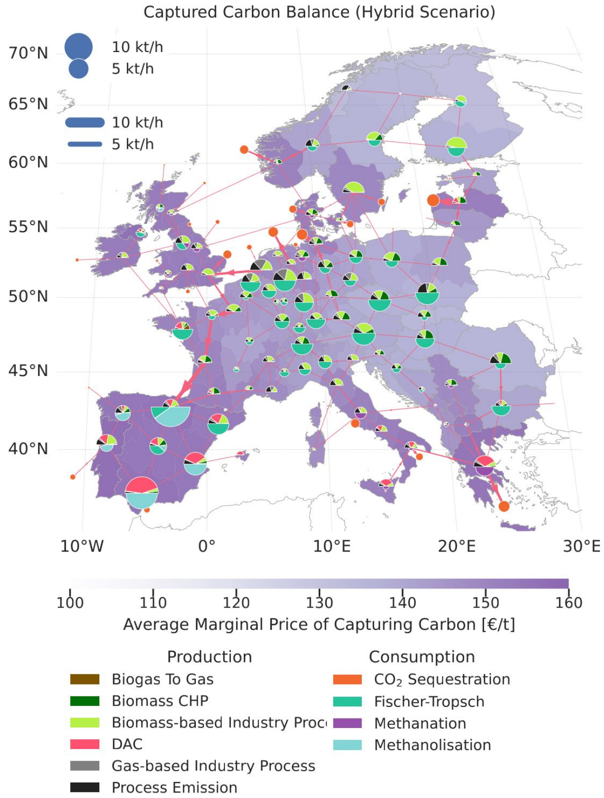



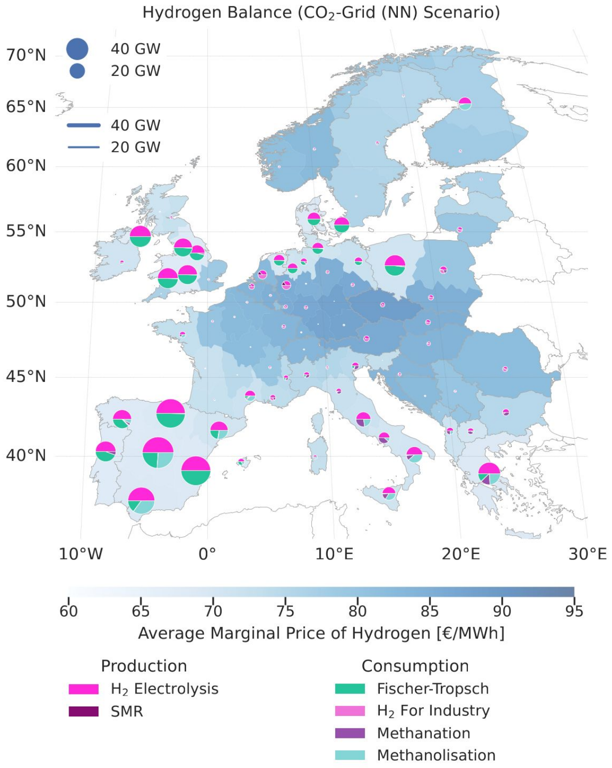



# Prices in the model



# 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)

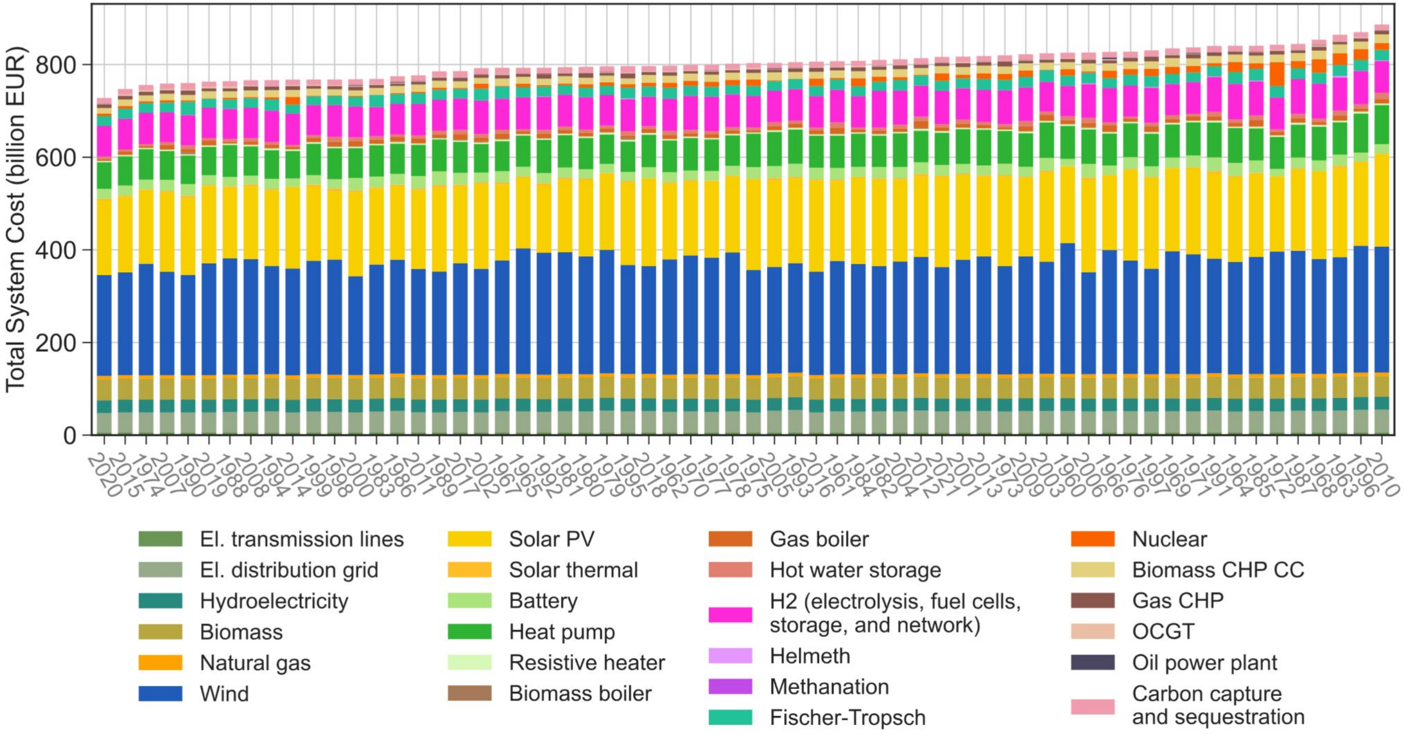
| Supply | Withdrawal |
|---|---|
| kerosene for aviation | solid biomass for industry (w CC) |
| diesel for agriculture | solid biomass CHP (w CC) |
| methanol for shipping | biogas upgrading (w CC) |
| methanol for industry | direct air capture |
| naphtha for industry | electrobiofuels |
| gas boiler | |
| 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

# PyPSA-Eur can be run on different **weather years**!




The years **2010**, **2013**, **2019** and **2023** are currently available "out of the box".

Other years **1940-2024** require a few more steps.

We are planning to expand the number of "plug-and-play" years.

https://www.nature.com/articles/s41467-024-54853-3

# Overnight and pathway optimization

- **Overnight** optimization builds the complete system in one go. Already existing capacities can be included (**brownfield**) or the system can be built from scratch (**greenfield**)

- The choice of **investment years** is arbitrary.

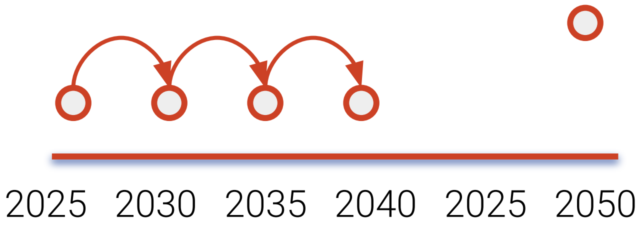
- **Pathway optimization with myopic foresight** (next slide). The $CO_2$ emission **reduction path** is exogenous.

- **Perfect foresight pathway planning** is currently experimental (i.e. use the $CO_2$ budget endogenously).

Overnight

Myopic pathway

Perfect-foresight pathway



# Myopic pathway optimization

- The $CO_2$ emission **reduction path** is exogenous.
- Optimise **start network** for e.g. 2025, starting with existing energy infrastructure.
- Take results from **2025 as input** for 2030 infrastructure optimisation, take 2030 results for next iteration, etc.
- Infrastructure decommissioned when reaching end of lifetime
- Configurable social discount rate and number of planning horizons

# Scenario management

**PyPSA-Eur** has integrated & scalable scenario management.

config/config.yaml

```yaml
run:
  name: all
  scenarios:
    enable: true

scenario:
  clusters: [90]

sector:
  H2_network: true
  gas_network: true
  H2_retrofit: true

electricity:
  transmission_limit: vopt
```

With these two files configured, run:

```
$ snakemake all -n
```

and

```
$ snakemake all
```

config/scenarios.yaml

```yaml
no-h2-network:
  sector:
    H2_network: false

no-grid-expansion:
  electricity:
    transmission_limit: v1.0

no-to-both:
  sector:
    H2_network: false
  electricity:
    transmission_limit: v1.0

yes-to-both:
  sector:
    H2_network: true
  electricity:
    transmission_limit: vopt
```

# Live Demo – very similar to electricity-only case

Start with a dry-run:

```
$ snakemake all --configfile config/test/config.overnight.yaml -n
```

Then execute the same command “for real” by dropping “-n” flag:

```
$ snakemake -call all --configfile config/test/config.overnight.yaml
```

And for myopic pathway optimisation:

```
$ snakemake -call all --configfile config/test/config.myopic.yaml
```

To explore results, start a Jupyter notebook:

```
$ jupyter notebook
```

# Practical Phase

(sector-coupled)

1) Run PyPSA-Eur sector-coupling tutorial with `snakemake`

   **Guide:**
   https://pypsa-eur.readthedocs.io/en/latest/tutorial_sector.html

```
snakemake -call all --configfile config/test/config.overnight.yaml
```

Users of Windows, add two lines to YAML:

```
run:
  use_shadow_directory: false
```

2) Explore CSV files and images in `results` directory.

Go to https://pypsa-eur.readthedocs.io/en/latest/configuration.html and try to find out how to configure some of the settings for **sector-coupled models** listed below:

1. Disable vehicle-to-grid discharging.
2. Disable hydrogen network expansion.
3. Increase the carbon sequestration potential to 800 Mt/a.
4. Allow hydrogen underground storage also onshore.
5. Reduce the primary production of plastics by increasing recycling rates.