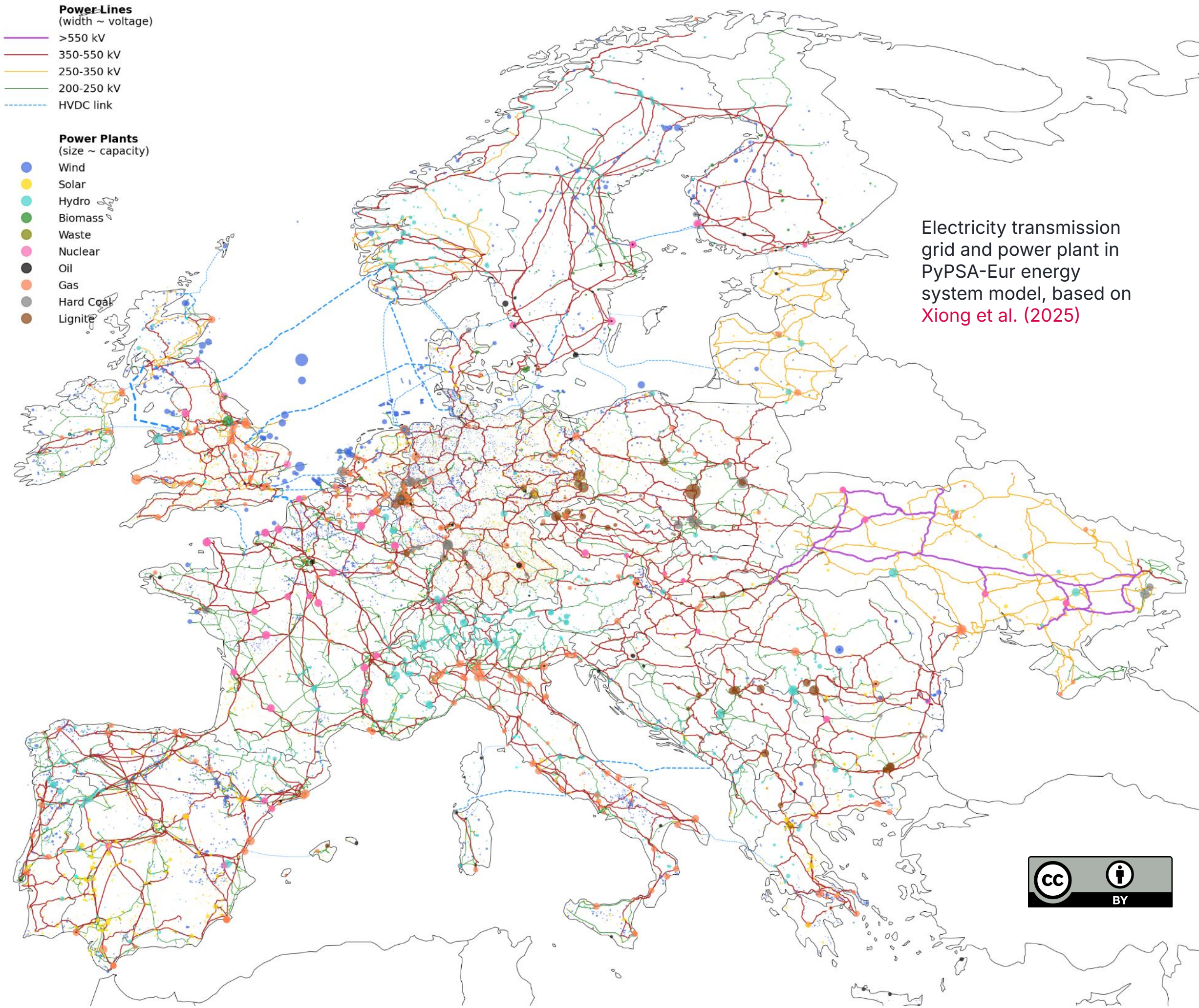
PyPSA Labs

PyPSA-Eur

Introduction

Fabian Neumann
Iegor Riepin

Birmingham
10-11 September 2026



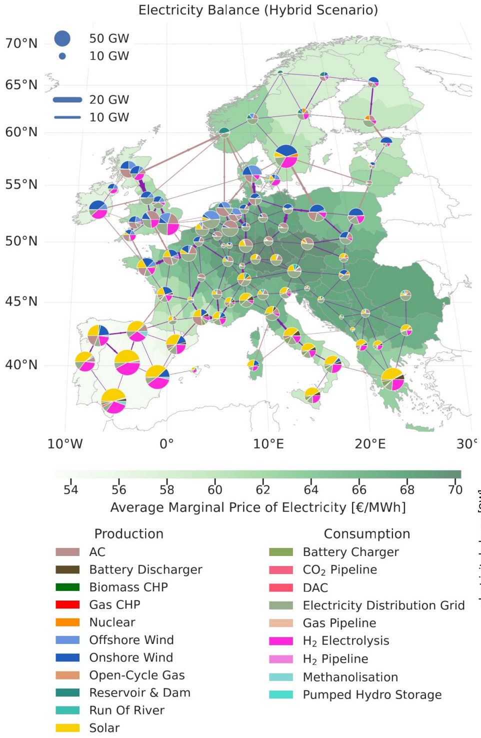
Electricity transmission grid and power plant in PyPSA-Eur energy system model, based on Xiong et al. (2025)

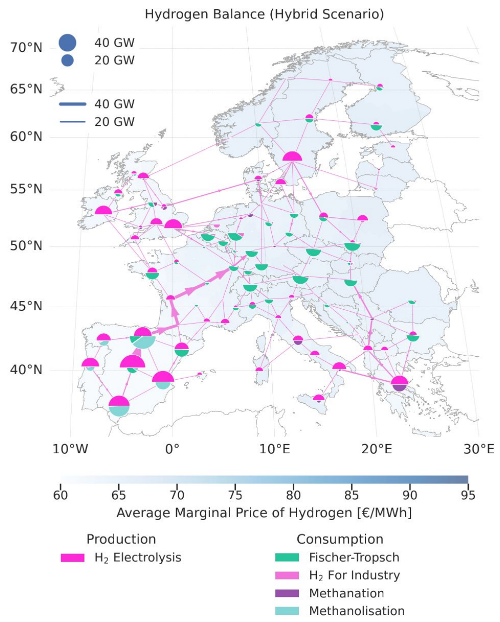
Introduction

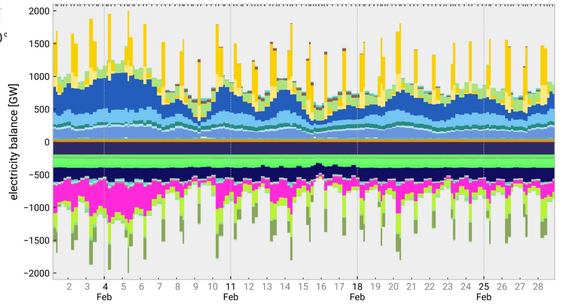
PyPSA-Eur: A sector-coupled open model of the European energy system

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

1. OSM power lines (>60 kV) + TYNDP
2. a database of existing power plants
3. time series for electricity demand
4. time series for wind/solar availability
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





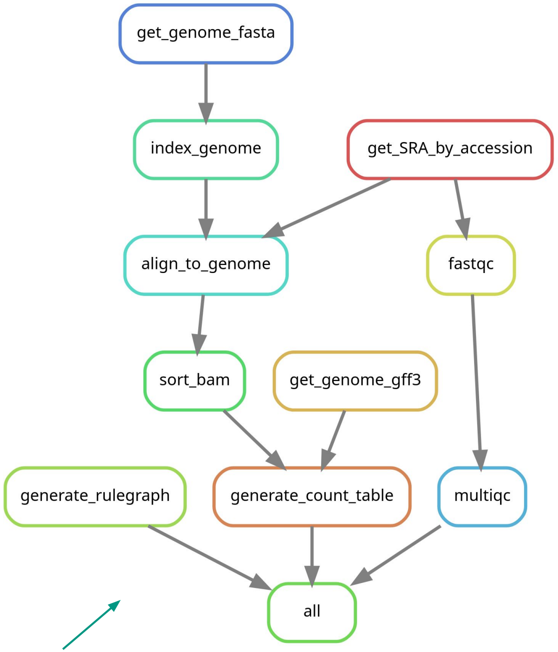


Challenges with data-driven modelling

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"
```

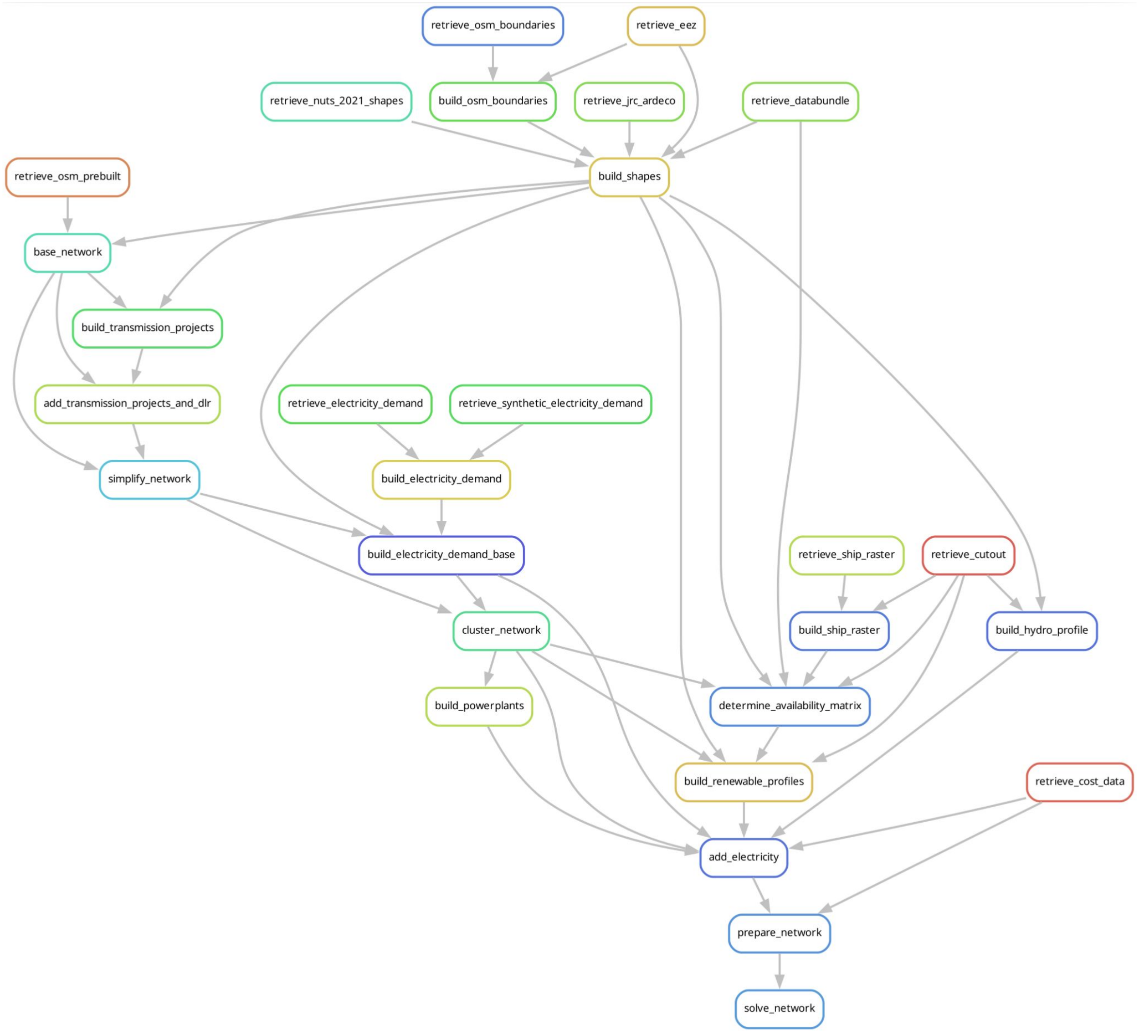
```
rule myplot:
    input:
        "result/{sample}.txt"
    output:
        "figures/{sample}.pdf"
    script:
        "scripts/myplot.py"
```

command:

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

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

Electricity System



snakemake
workflow for the electricity sector

Simplified workflow structure

Automated **downloads**

Process the data

Build the electricity system model

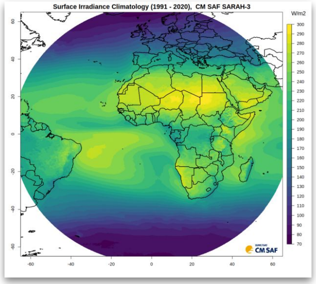
Extend the model by other sectors (later)

Solve, summarize & visualize the results

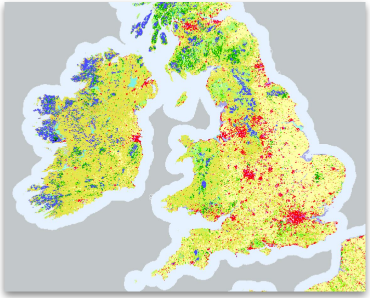
Raw data is automatically downloaded

WDPA

SARAH-3

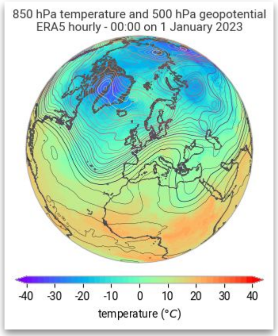


CORINE

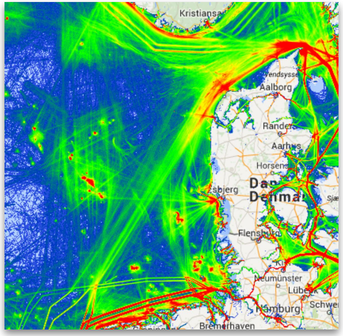


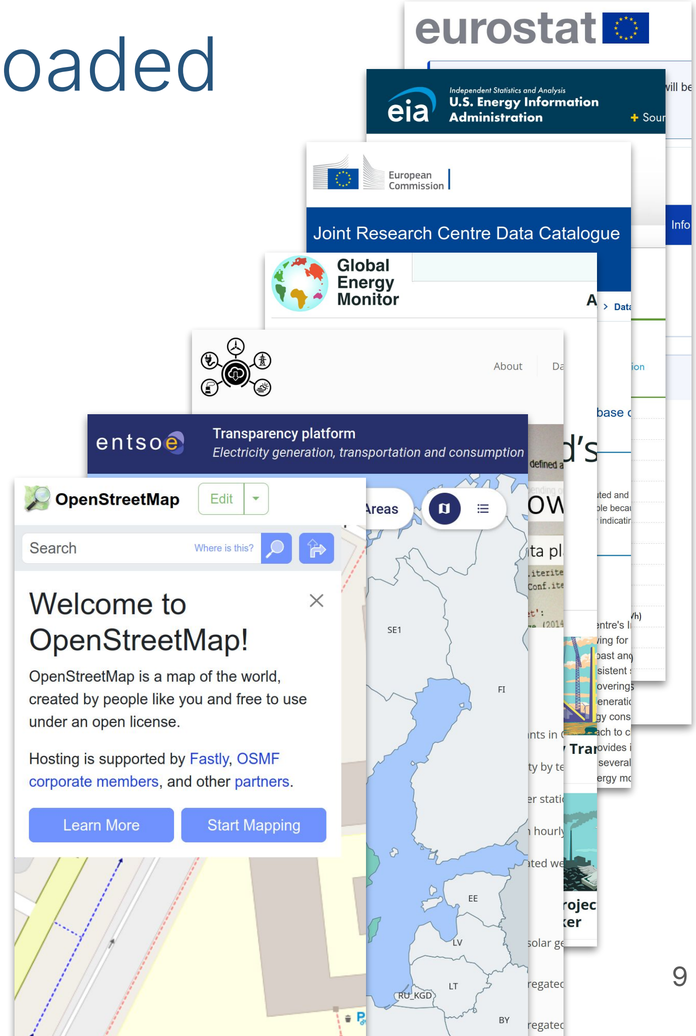
GEBCO

ERA5



World Bank





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

Simplified workflow structure

Automated **downloads**

Process the data

Build the electricity system model

Extend the model by other sectors

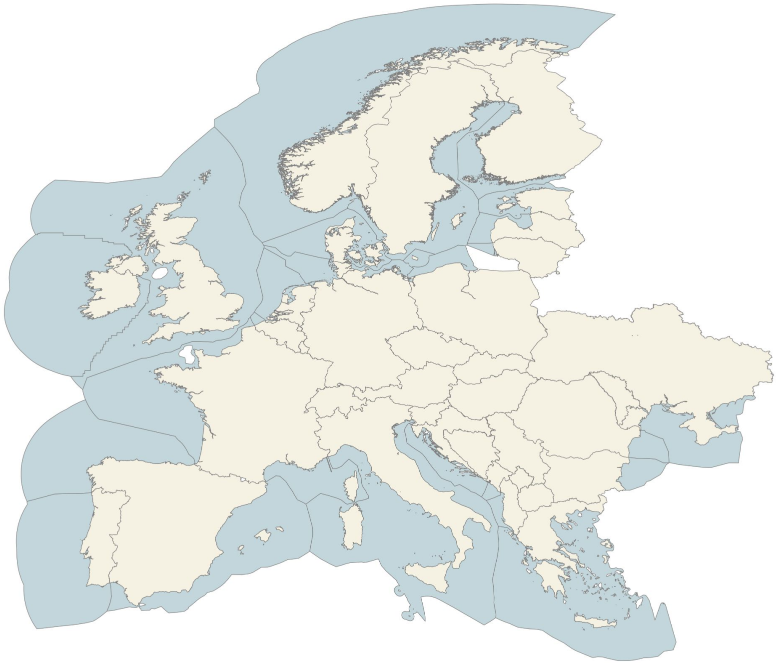
(later)

Solve, summarize & visualize the results

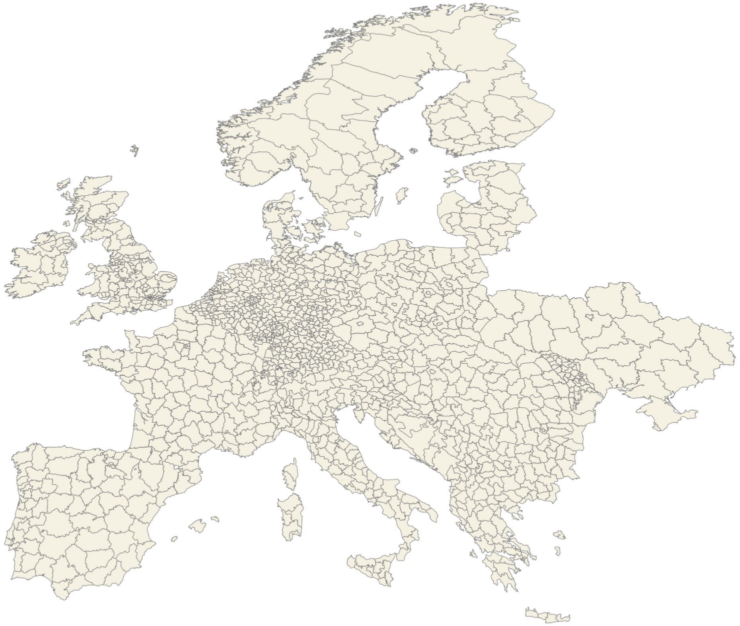
Steps to building PyPSA-Eur electricity system

Retrieve onshore & offshore polygons for each country	`build_shapes`

Country shapes & exclusive economic zones (EEZ)



NUTS administrative regions (NUTS3)

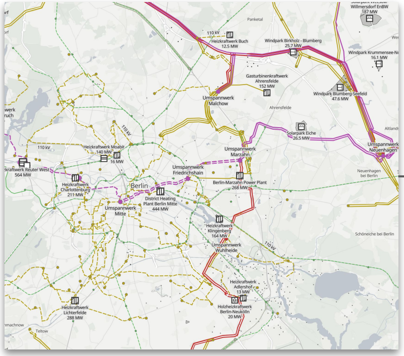


Steps to building PyPSA-Eur electricity system

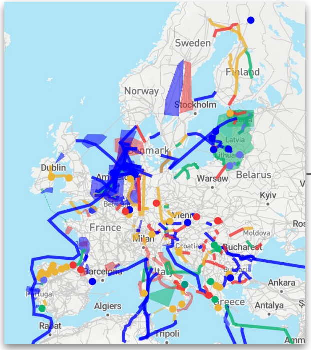
Retrieve onshore & offshore polygons for each country	`build_shapes`
Construct a base medium- to high-voltage network with buses, transformers, AC & DC lines with DLR & TYNDP	`base_network`, `build_transmission_projects`

Power grid topology

OpenStreetMap data



TYNDP projects



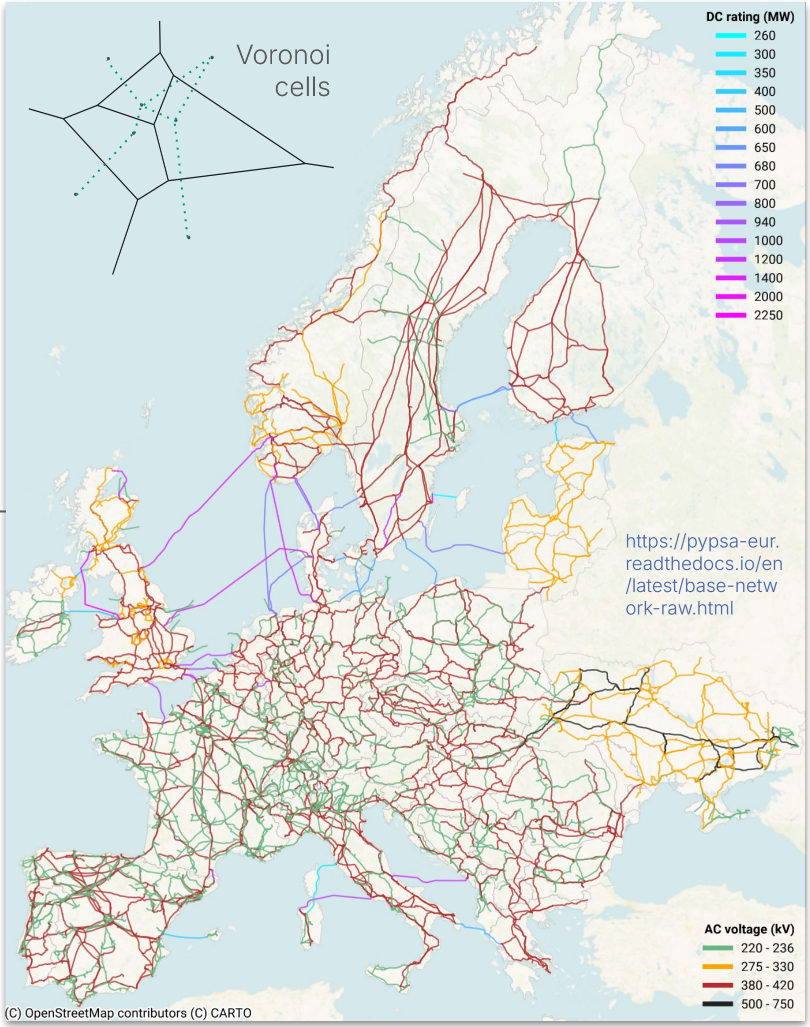
Apply **standard line types** for capacity and parameters.

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

European network with

- ~5,800 buses
- ~7,300 AC lines (>220 kV)
- 36 HVDC links (+TYNDP)
- Optionally down to 60 kV

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



Steps to building PyPSA-Eur electricity system

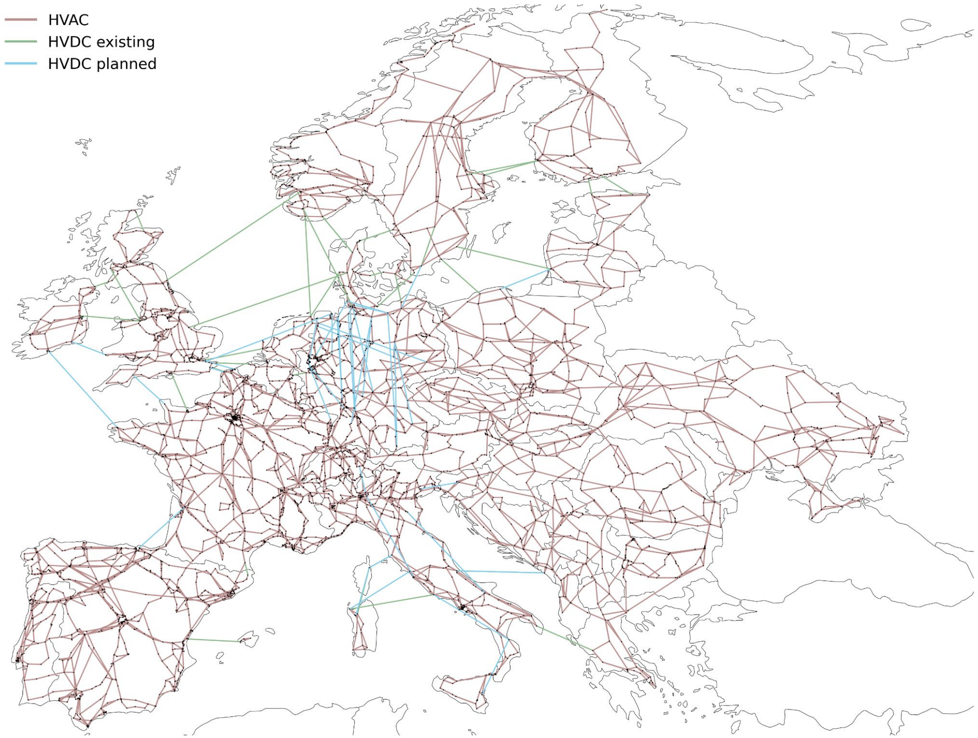
Retrieve onshore & offshore polygons for each country	`build_shapes`
Construct a base high-voltage network with buses, transformers, AC & DC lines with DLR & TYNDP	`base_network`, `build_transmission_projects`
Transform all transmission lines to 380 kV, remove dead ends & cluster with k-means or hierarchical 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-optimise generation, storage, PtX conversion and transmission infrastructure:

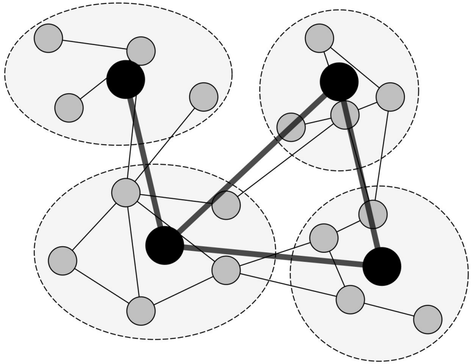
- Lift all lines to common voltage level of 380 kV.
- Remove dead ends.



Clustering the electricity network: `cluster_network`

Transformed **to 380 kV**

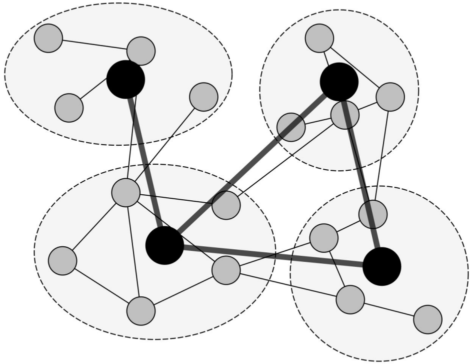
Clustered to **512 regions**

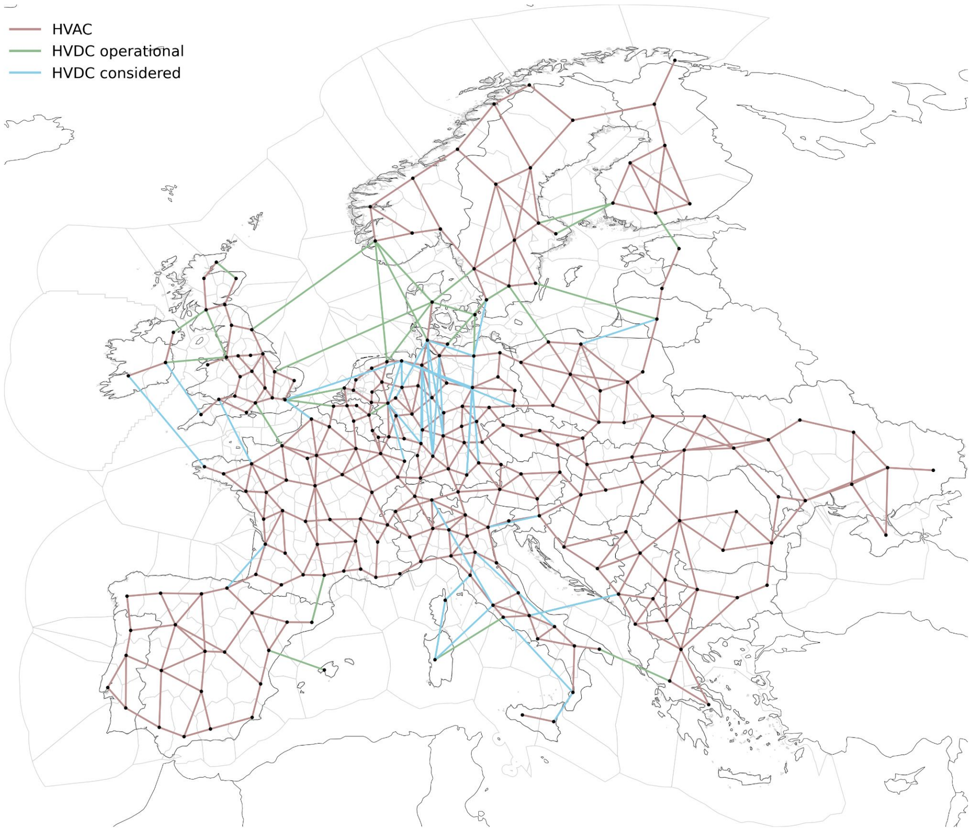


Clustering the electricity network: `cluster_network`

Transformed **to 380 kV**

Clustered to **256 regions**

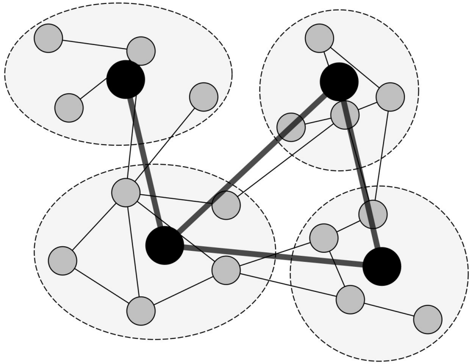




Clustering the electricity network: `cluster_network`

Transformed **to 380 kV**

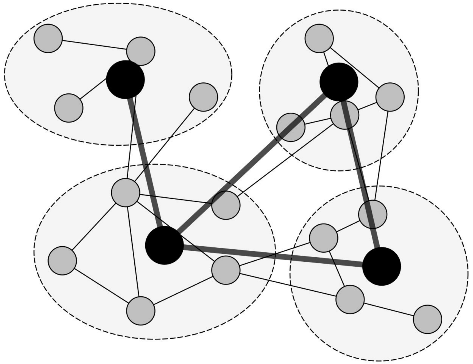
Clustered to **128 regions**



Clustering the electricity network: `cluster_network`

Transformed **to 380 kV**

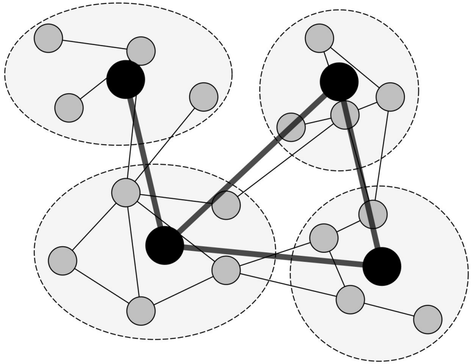
Clustered to **64 regions**



Clustering the electricity network: `cluster_network`

Transformed **to 380 kV**

Clustered to **41 regions**



Steps to building PyPSA-Eur electricity system

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

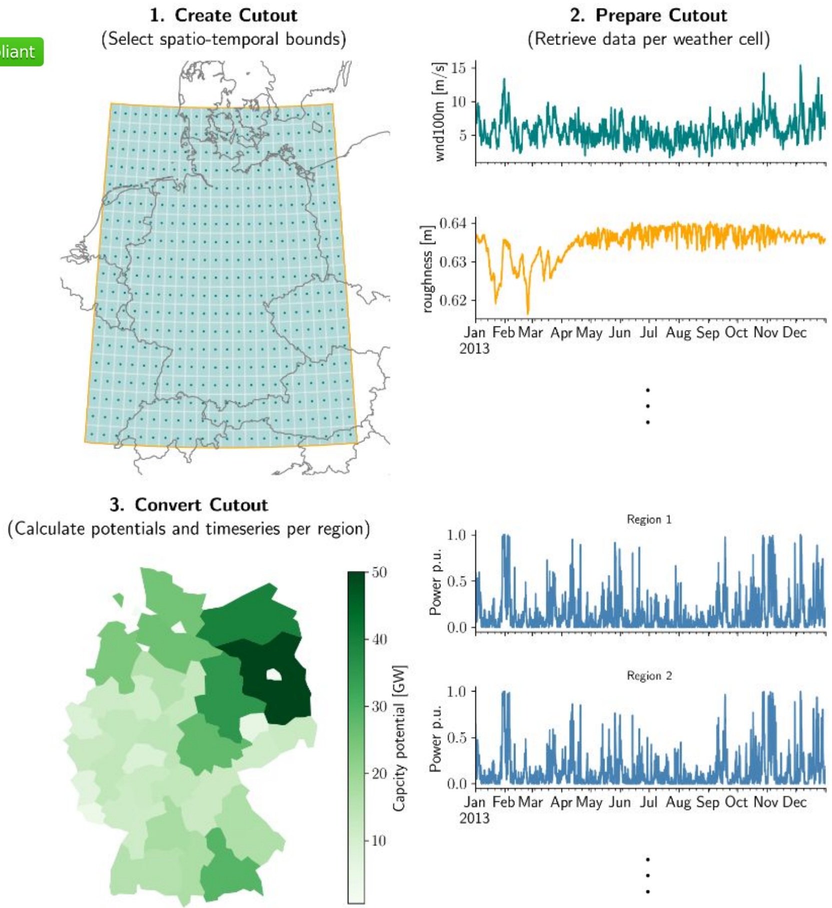
Rule: `build_renewable profiles`

pypi v0.4.1 | conda-forge v0.4.1 | Tests passing | codecov 72% | docs passing | license MIT | REUSE compliant
JOSS 10.21105/joss.03294 | chat 63 online | stackoverflow pypsa questions 38

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

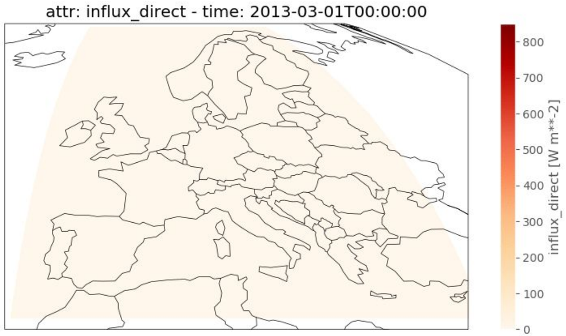
- solar photovoltaics
- solar thermal collectors
- wind turbines
- hydro run-off, reservoir, dams
- heat pump COPs
- dynamic line rating (DLR)
- heating and cooling demand (HDD/CDD)

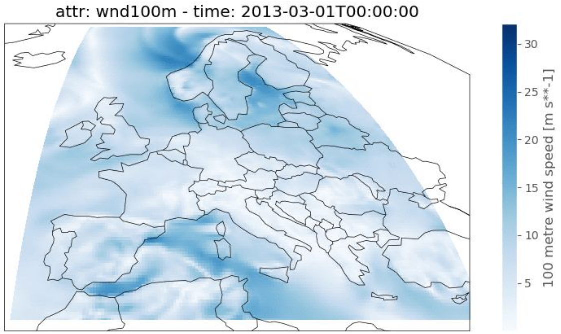
It can also perform land eligibility analyses.



Time series for renewables

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





Solar panel models
- orientation
- material

Wind turbine models
- power curve
- surface roughness

atlite: Convert weather data to energy systems data

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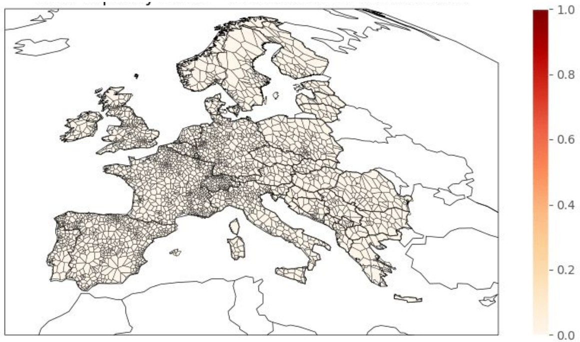
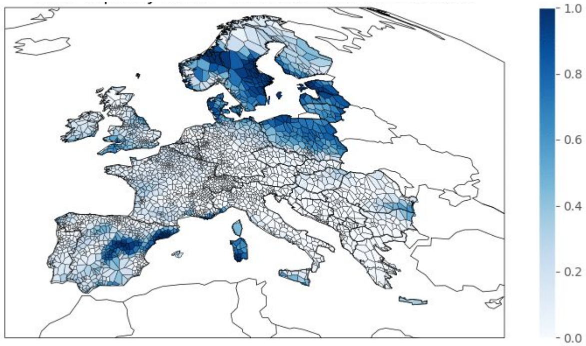
Wind and solar capacity factors





Land availability for renewables

atlite: Convert weather data to energy systems data

pypi v0.4.1 | conda-forge v0.4.1 | Tests passing | codecov 72% | docs passing | license MIT | REUSE compliant
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Example:
Onshore wind in one clustered region

- CORINE / LUISA land cover
  - eligible land types
  - distance requirements
- NATURA / WDPA natural protection areas
- GEBCO bathymetry data
- Shipping lanes
- Distance to shore

Steps to building PyPSA-Eur electricity system

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Prepare existing renewables and fossil power plants	`build_powerplants`

Welcome to powerplantmatching's documentation!

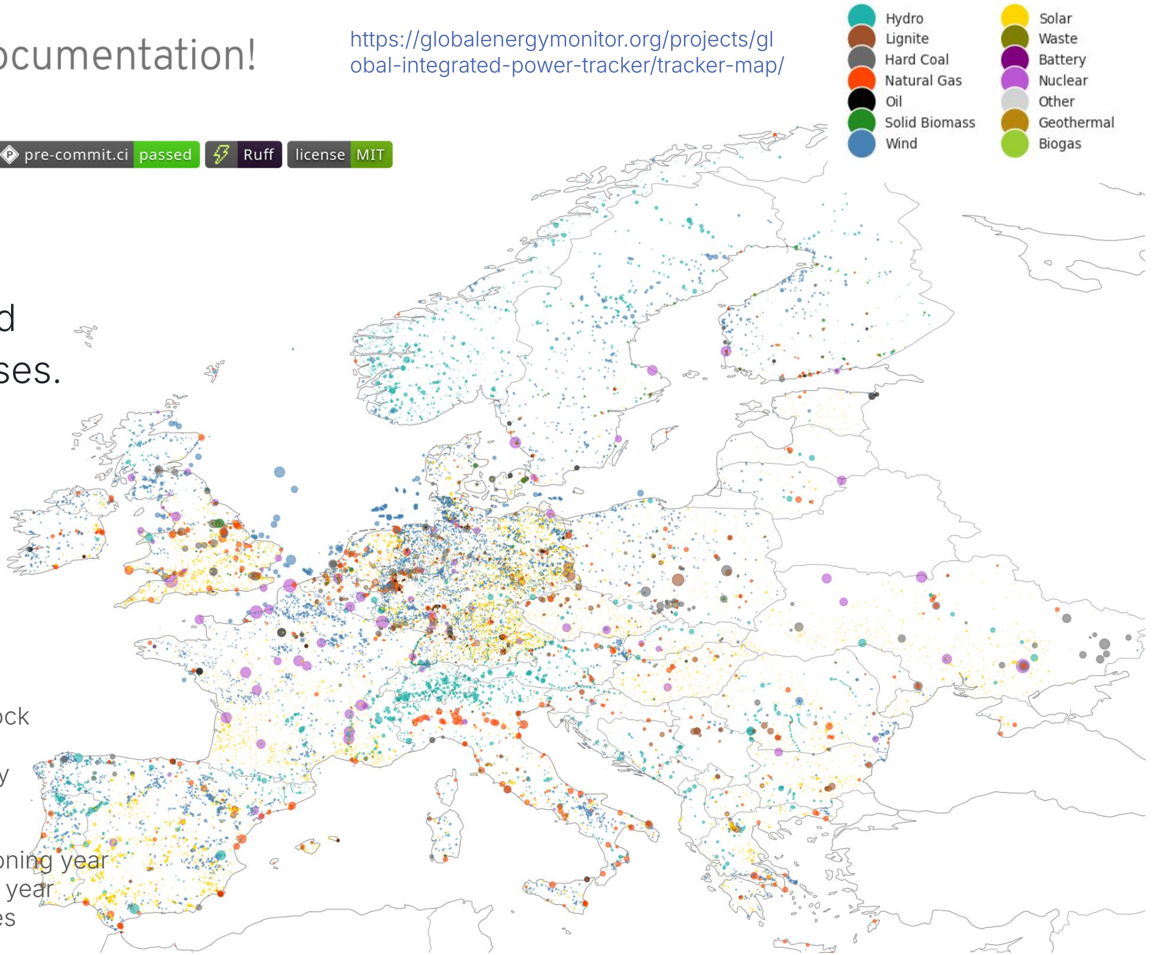
https://globalenergymonitor.org/projects/global-integrated-power-tracker/tracker-map/

pypi v0.8.1 | conda-forge v0.8.1 | python >=3.11 | Tests failing | docs passing | pre-commit.ci passed | Ruff | license MIT

DOI 10.5281/zenodo.3358985

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

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



Sources

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

Attributes

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

github.com/pypsa/powerplantmatching

Steps to building PyPSA-Eur electricity system

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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

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

Simplified workflow structure

Automated **downloads**

Process the data

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Extend the model by other sectors (later)

Solve, summarize & visualize the results

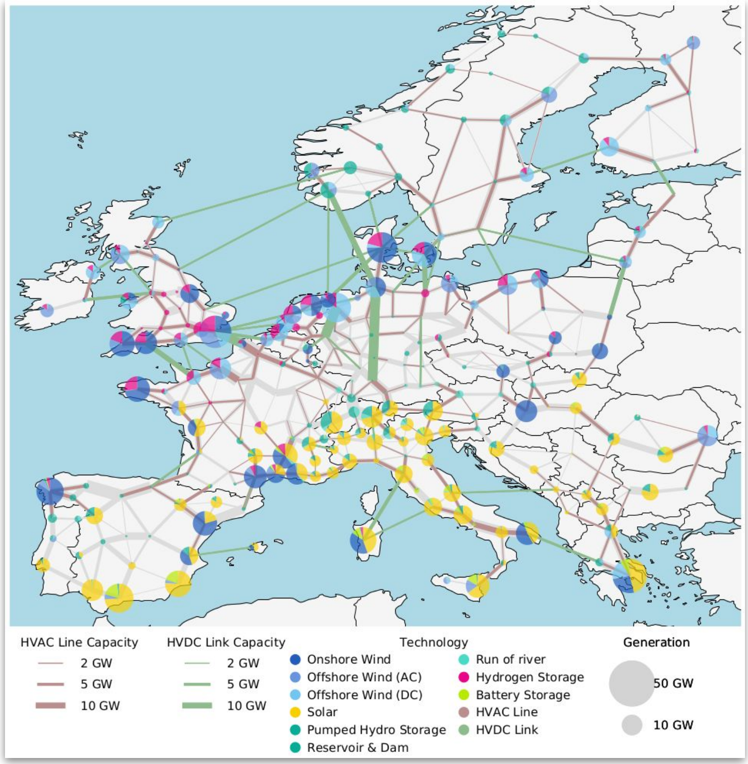
Solving and summarising networks

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.

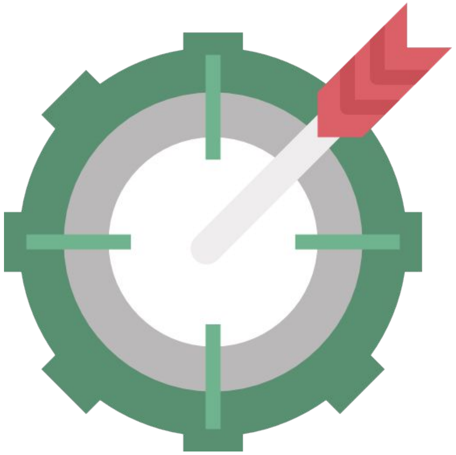
Example result without sector-coupling



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`

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

Icon made by surang from www.flaticon.com

Live Demo

Start with a dry-run:

```
$ pixi run snakemake -c1 solve_elec_networks --configfile
config/test/config.electricity.yaml -n
```

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

```
$ pixi run snakemake -call solve_elec_networks --configfile
config/test/config.electricity.yaml
```

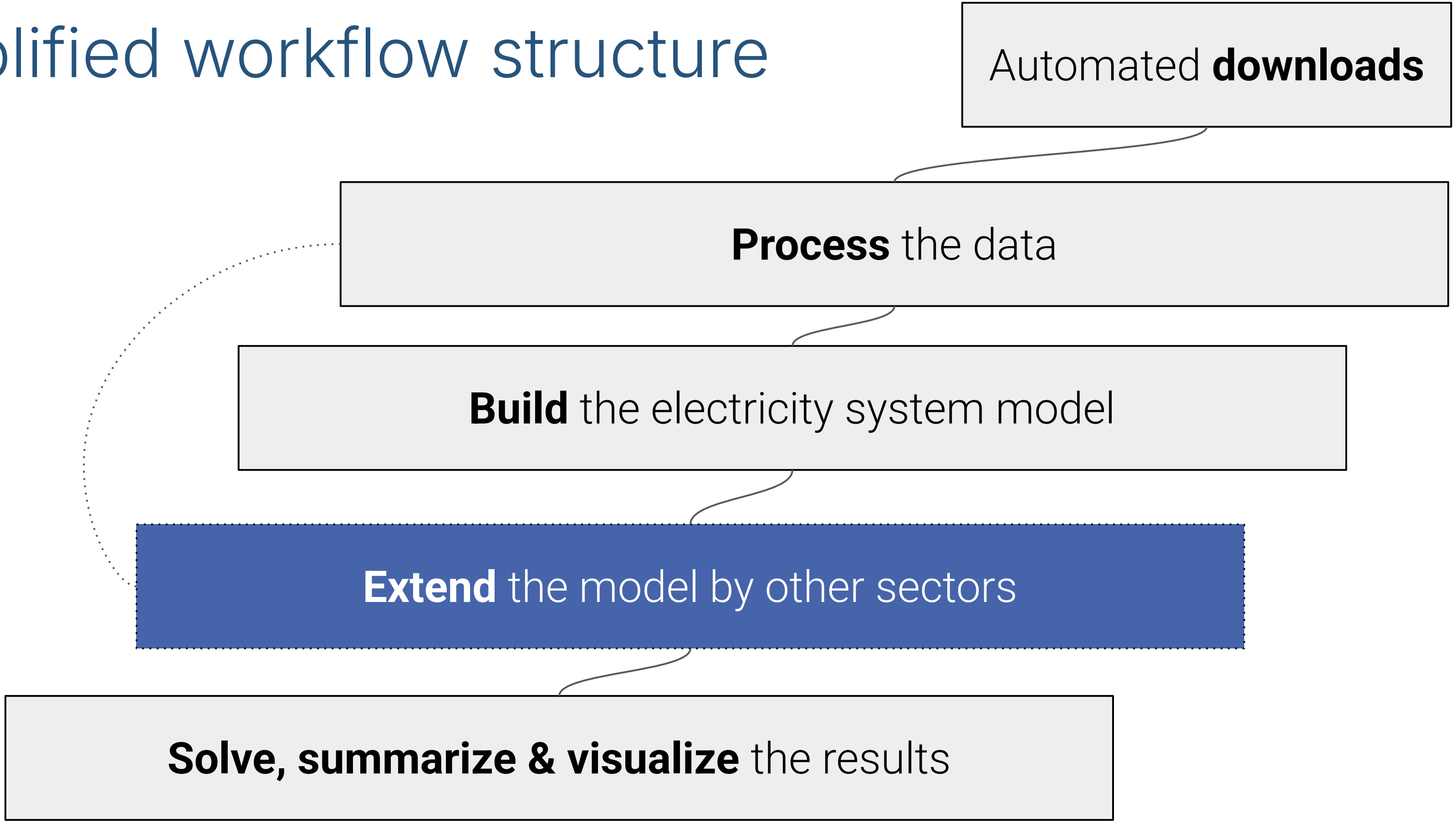
The “-c1” flag tells snakemake to run one job at a time; “-call” to use all cores.

To explore results, start a Jupyter notebook:

```
$ pixi run jupyter notebook
```

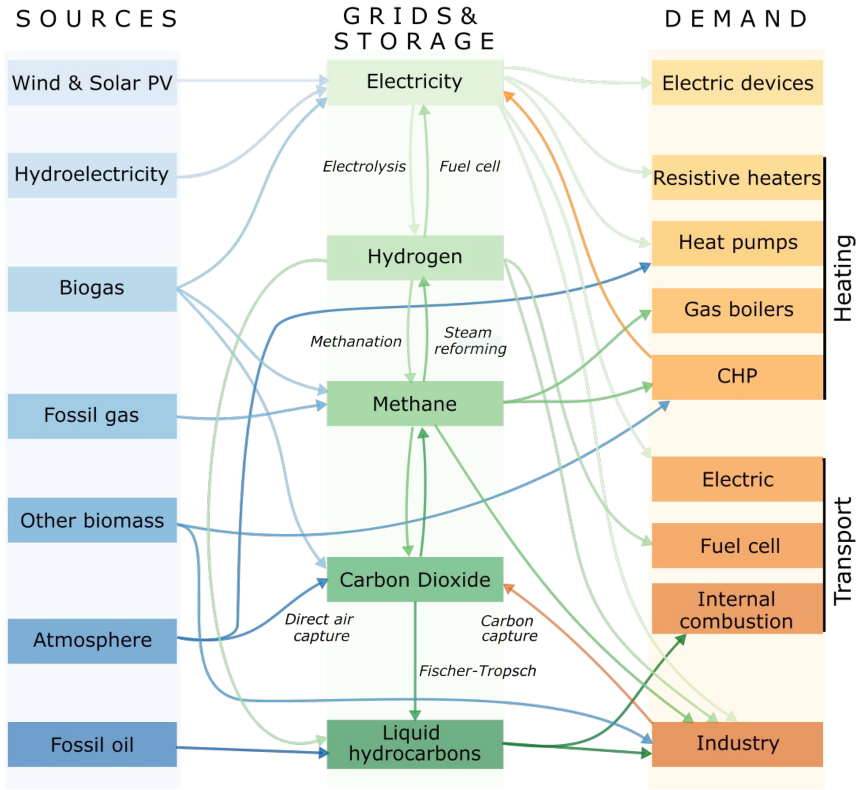
Energy System

Simplified workflow structure

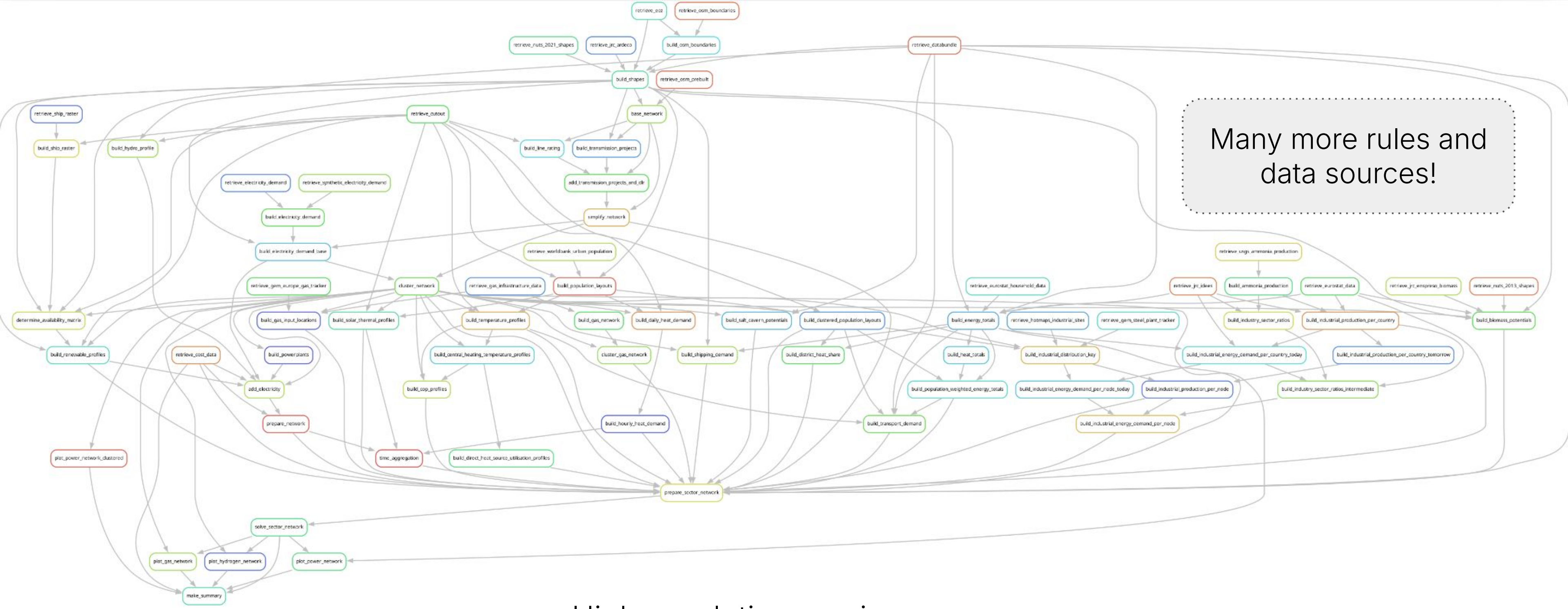


Coupling with other sectors

- 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



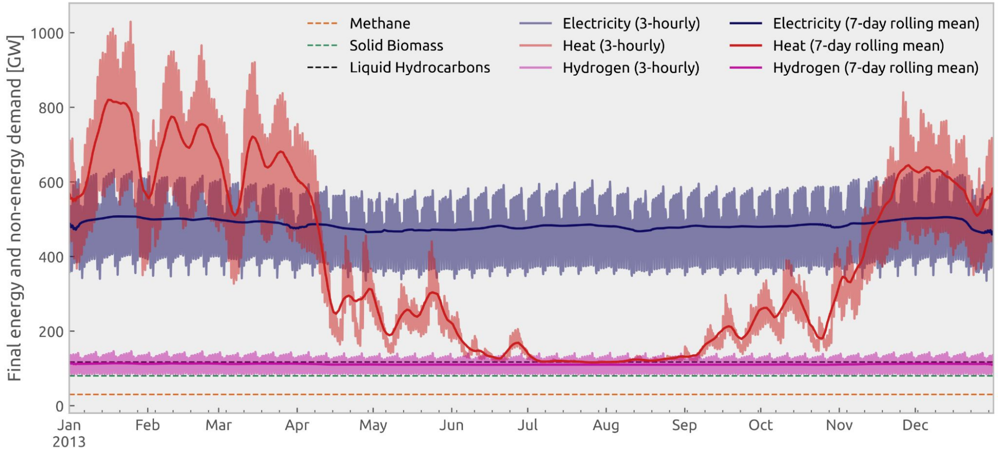
Extension by other sectors requires more data!



Many more rules and data sources!

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

Heating - Demand



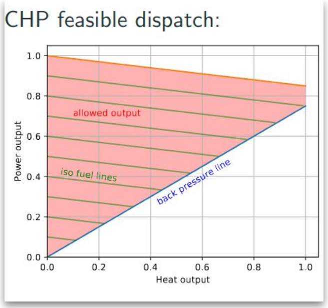
Heating demand time series created by :

- 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

Decentral individual heating
can be supplied by:

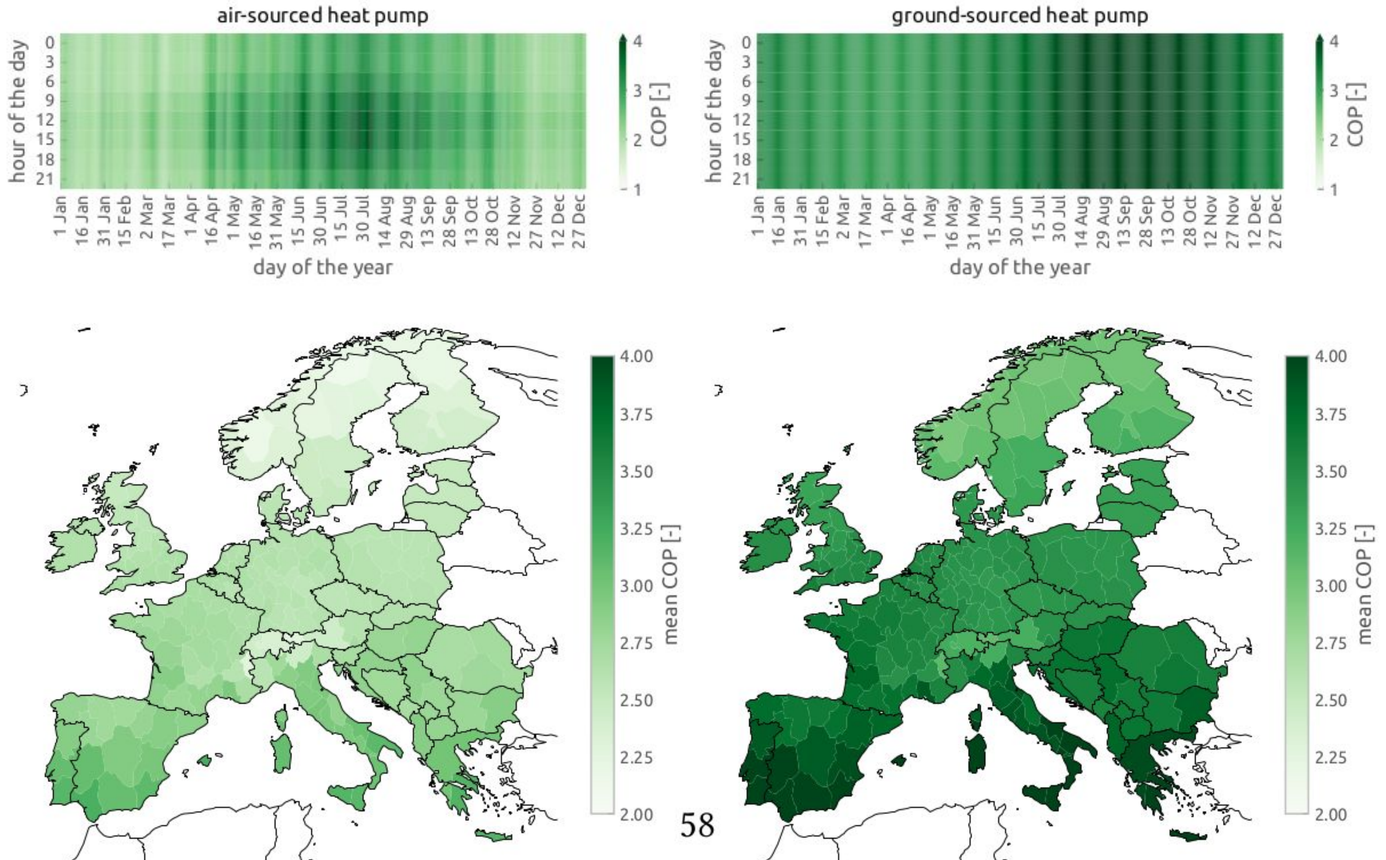
- air- or ground-source heat pumps
- resistive heaters
- gas / oil / biomass / hydrogen boilers
- solar thermal
- small water tanks



District heating systems
can be supplied in urban areas by:

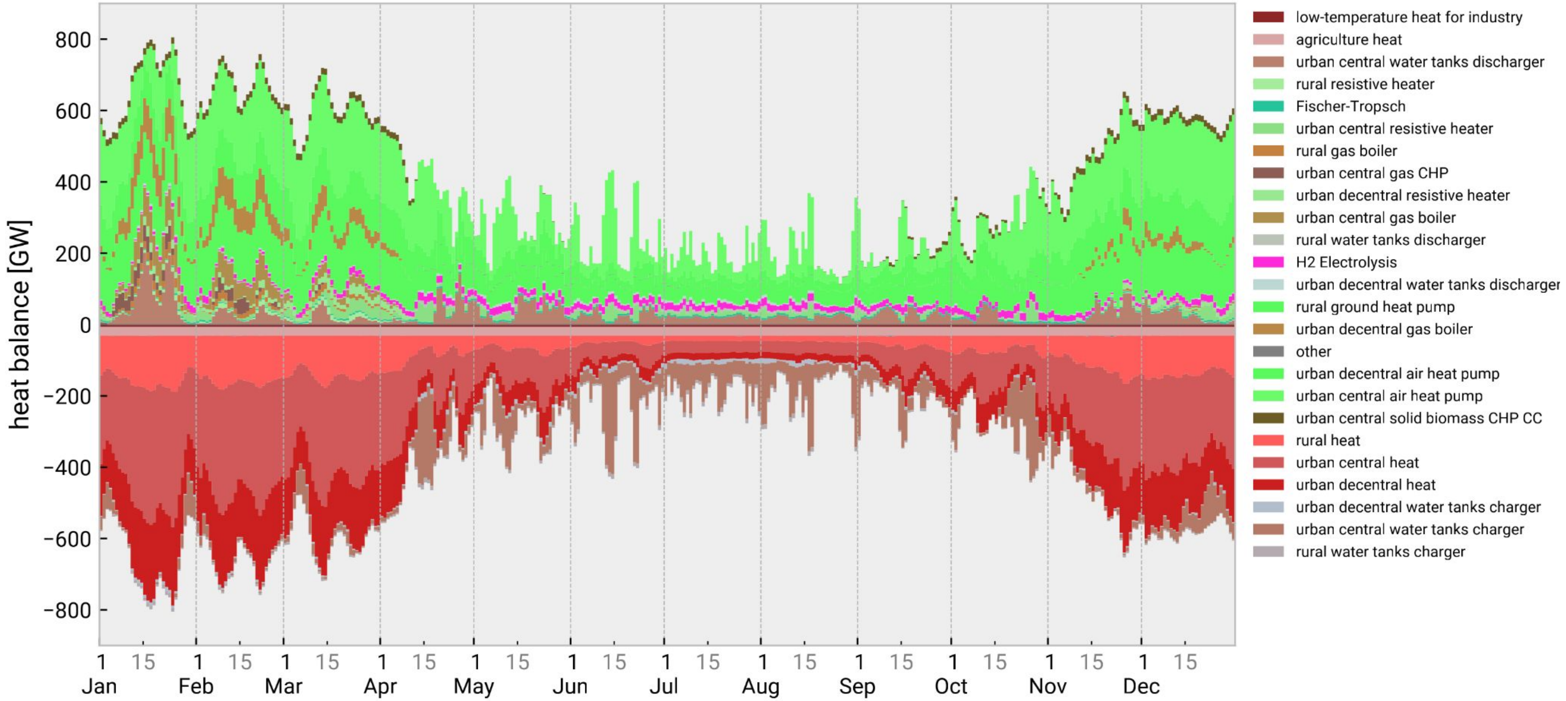
- air-source heat pumps + other
- resistive heaters
- gas / hydrogen / biomass / waste CHPs
- gas / oil / biomass / hydrogen boilers
- solar thermal
- long-duration hot water storage
- waste heat from industrial processes

Heating - Heat pumps as variable supply tech



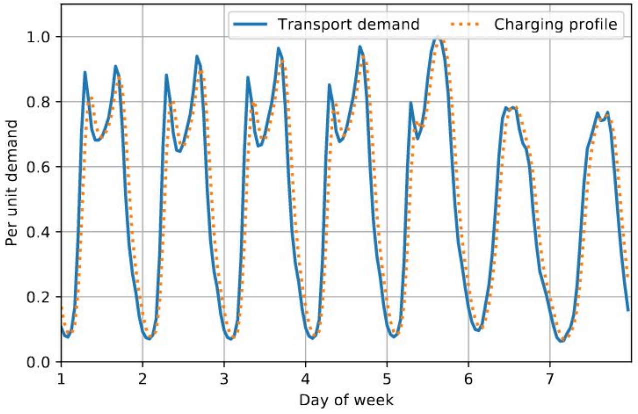
Geothermal and other heat sources are available as well!

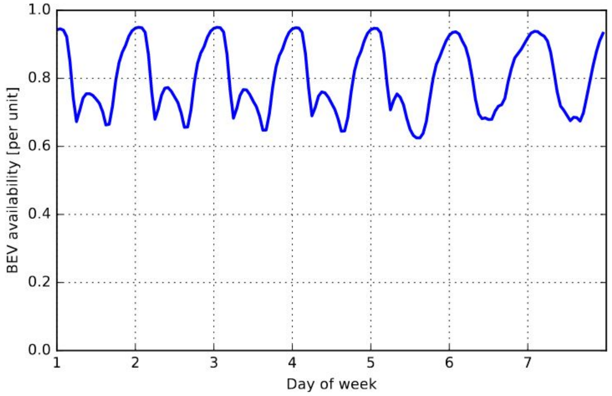
Heating - Example daily heat system balance



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.

Transport - Electrification of land transport

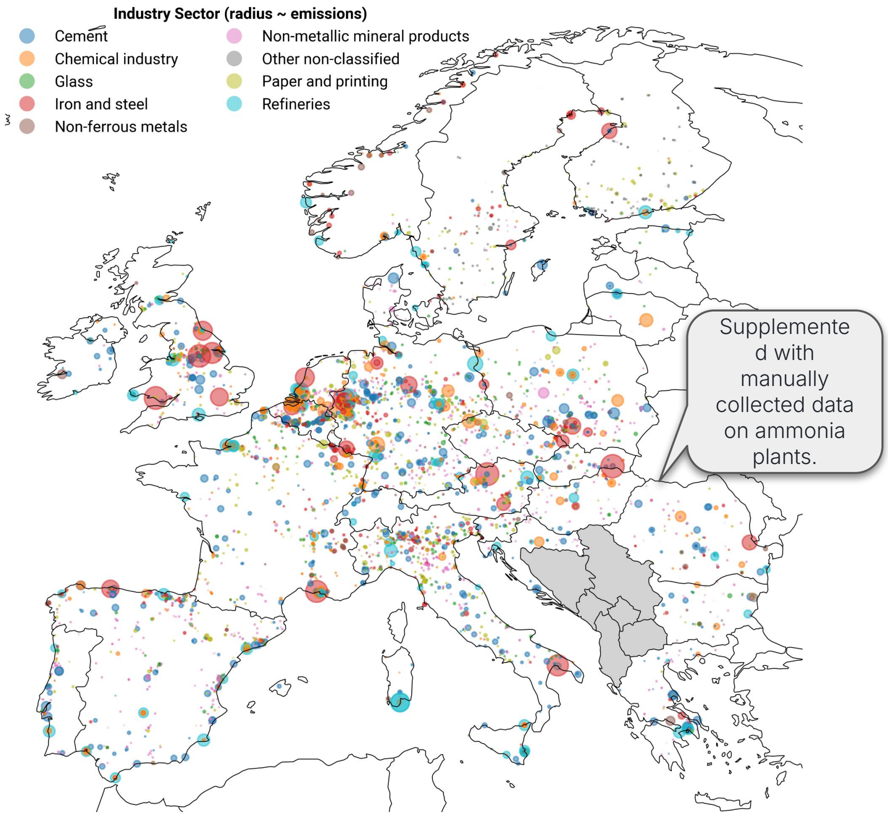




- Road and rail are largely electrified, ICE only during pathway to net-zero
- Time series from traffic counting
- Lumped representation of electric vehicles: a configurable share of them participates in demand-side management (DSM) or vehicle-to-grid (V2G)
- Electric vehicles have time-varying availability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

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

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 high-temperature heat source & shipping fuels endogenously is currently under development!

Infrastructure - Gas network with H_2 retrofitting

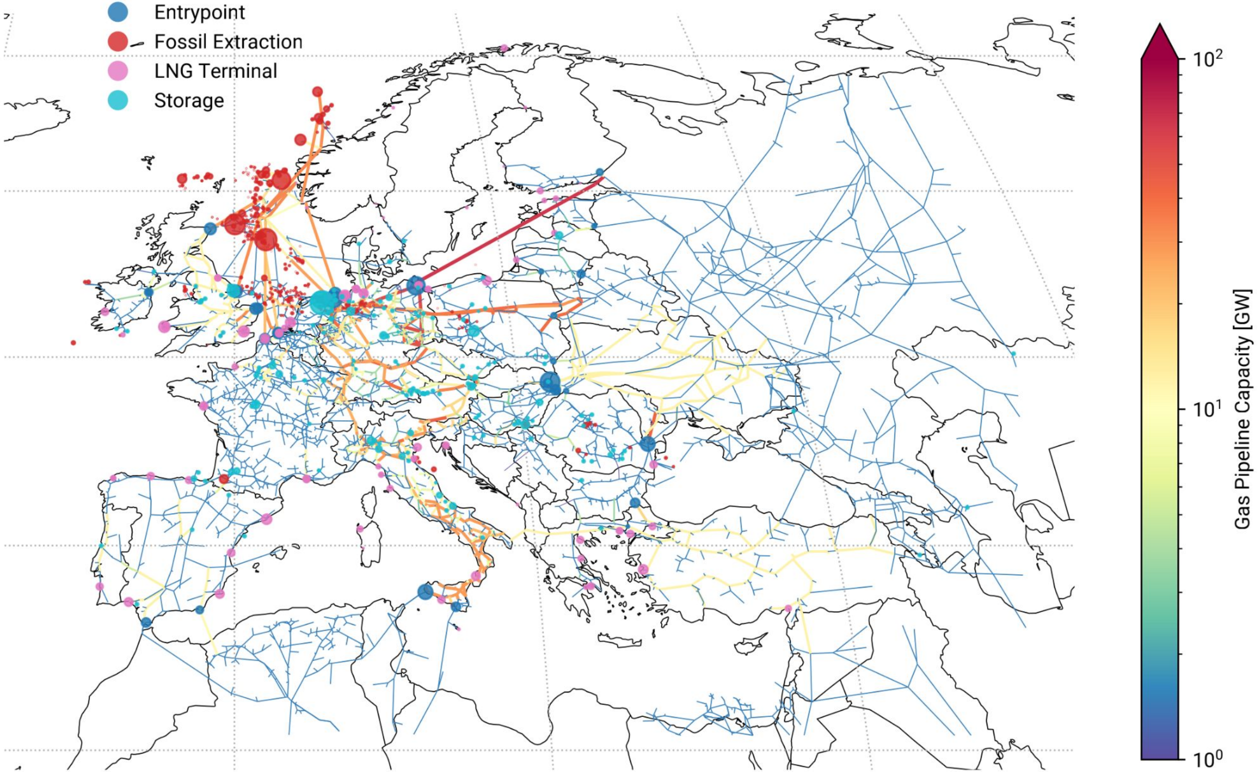
Compiled from open **SciGRID_gas** dataset.

Fossil gas enters at LNG terminals or gas fields.

Gas flow physics and valve control neglected transport model.

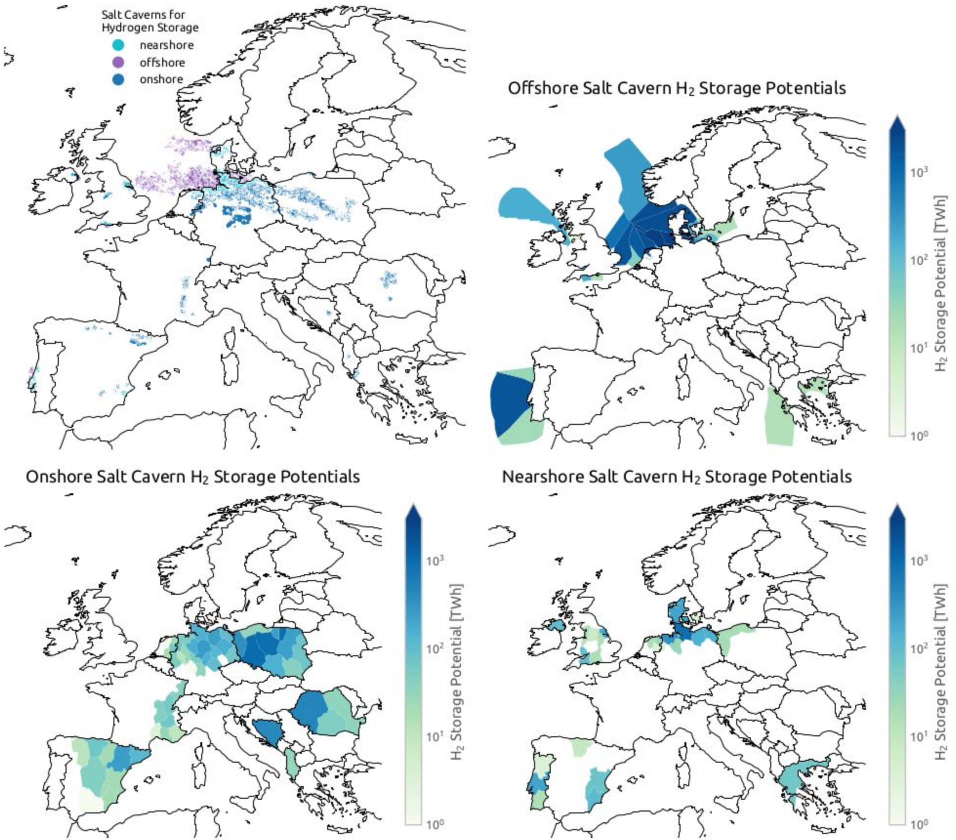
Electricity demand for compression and leakage configurable.

Pipelines can be retrofitted to H_2 with costs from EHB.



https://zenodo.org/records/4767098

Infrastructure - Hydrogen storage potentials

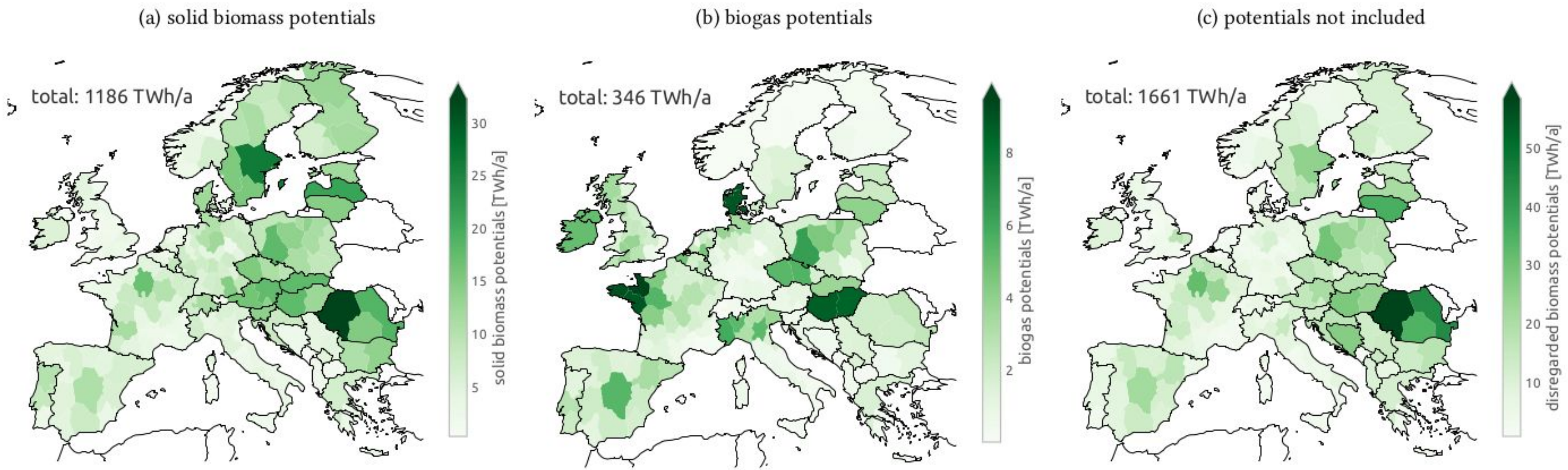


The regional distribution of geological potential to store hydrogen in salt caverns is considered.

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



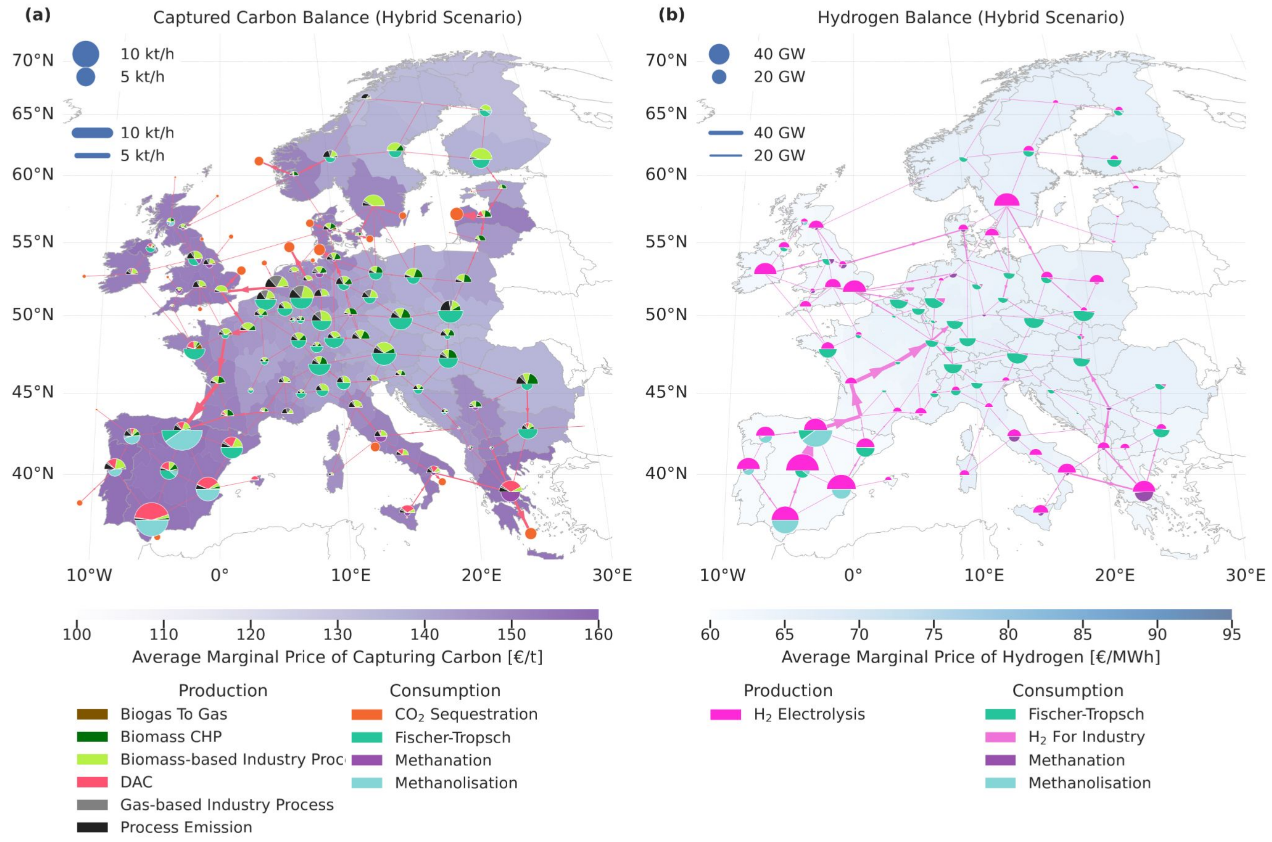
Biomass potentials are split between solid biomass and biogas (which can be, for instance, upgraded).

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

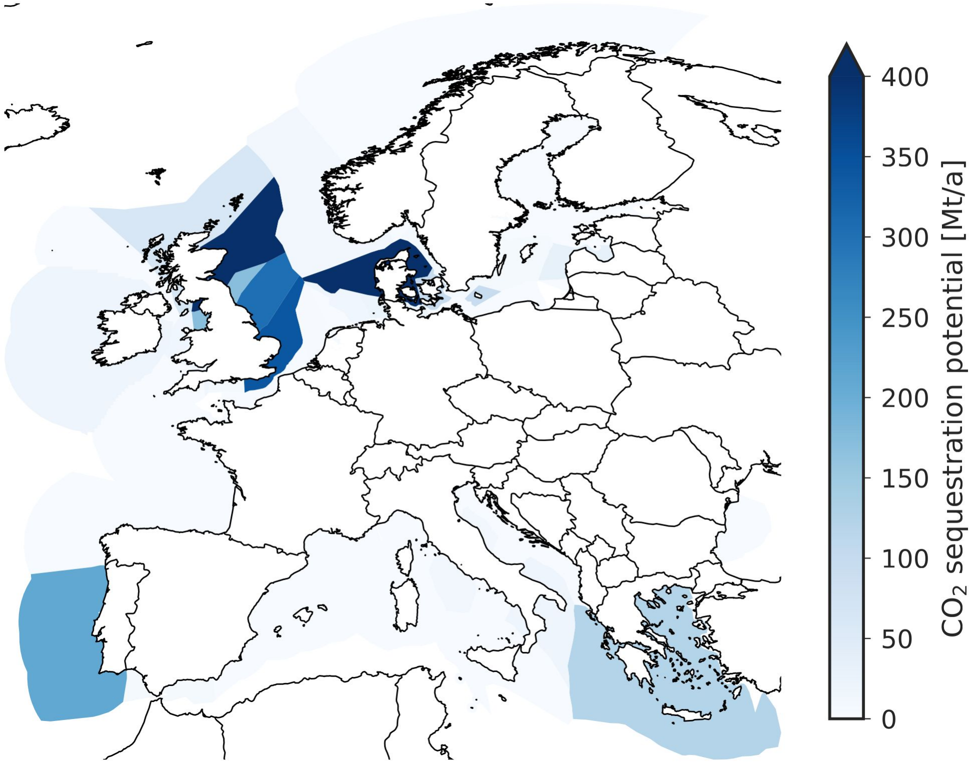


Built-in carbon flows:

- **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

Example: Offshore carbon sequestration potentials



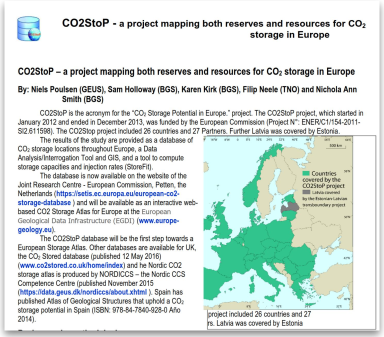
The user can **configure**

- 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.

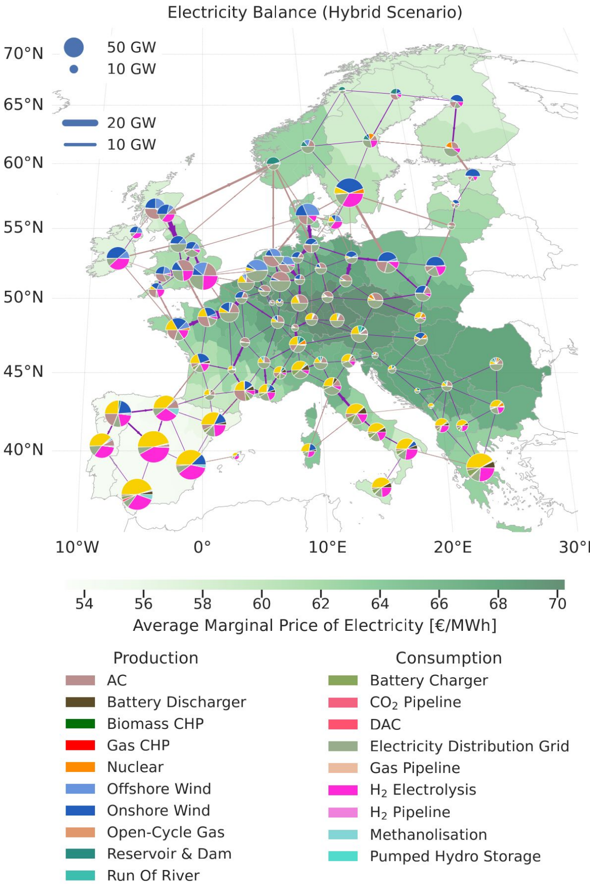
The results of the study are provided as a database of CO_2 storage locations throughout Europe, a Data Analysis/Interrogation Tool and GIS, and a tool to compute storage capacities and injection rates (StoreFit).

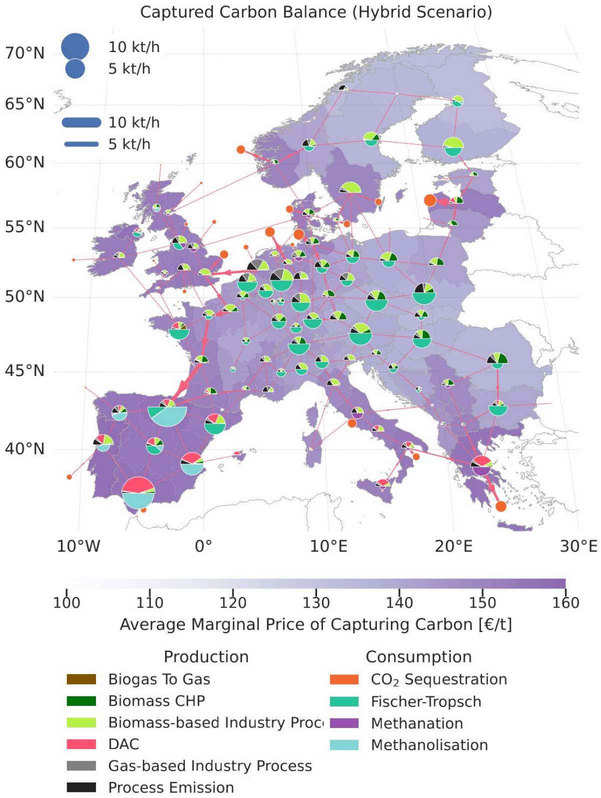
The database is now available on the website of the Joint Research Centre - European Commission, Petten, the Netherlands (https://setis.ec.europa.eu/european-co2-storage-database) and will be available as an interactive web-based CO2 Storage Atlas for Europe at the European Geological Data Infrastructure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

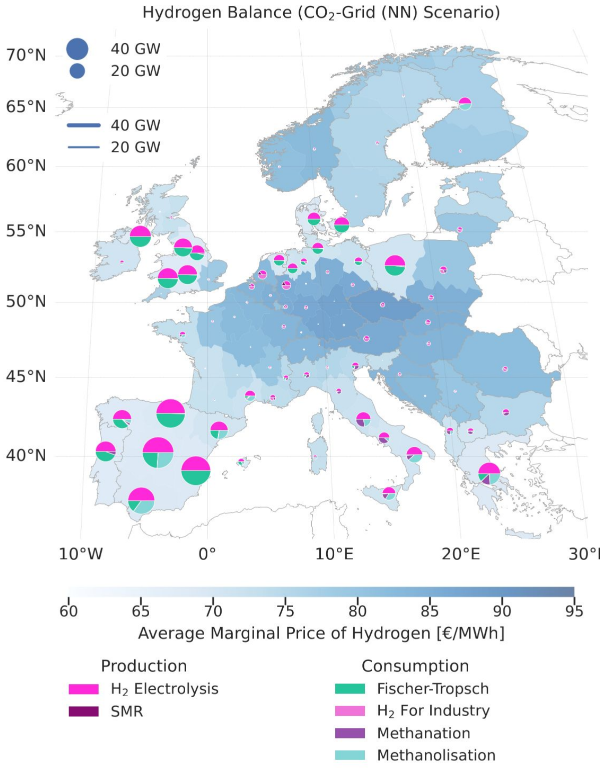
The CO2StoP database will be the first step towards a European Storage Atlas. Other databases are available for UK, the CO_2 Stored database (published 12 May 2016) (www.co2stored.co.uk/home/index) and he Nordic CO2 storage atlas is produced by NORDICCS – the Nordic CCS Competence Centre (published November 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

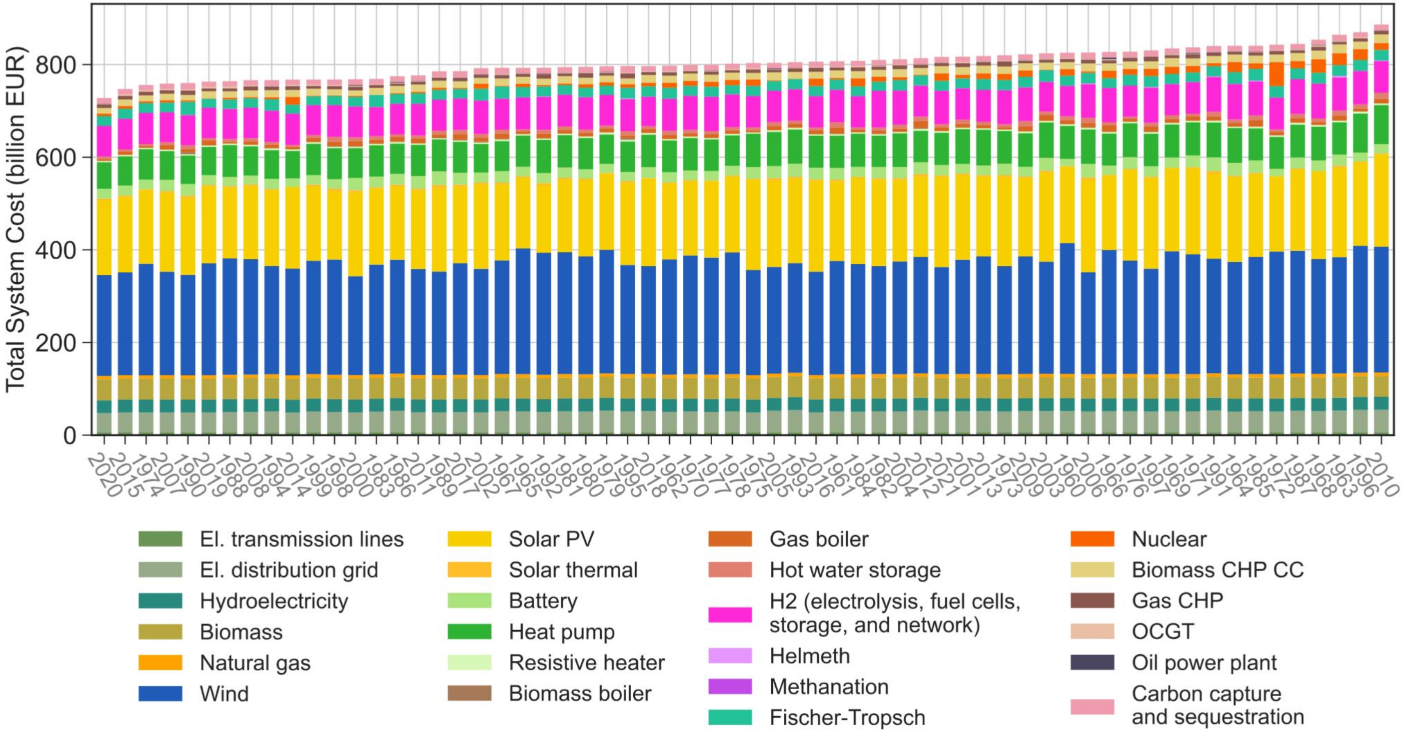
Examples of sector-coupled results







PyPSA-Eur can be run on multiple **weather years**!



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

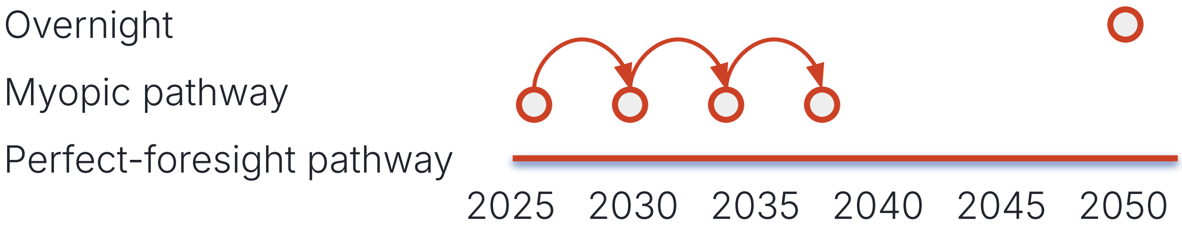
Other years **1940-2025** require a few more steps.

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

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

Overnight and pathway optimisation

- **Overnight:** Optimisation builds the complete system in one go.
    - Already existing capacities can be included (**brownfield**) or
    - the system can be built from scratch (**greenfield**)
- **Myopic foresight pathway**: The CO_2 emission **reduction path** is exogenous.
- **Perfect foresight pathway:** The CO_2 budget is distributed endogenously.



Integrated scenario management

config/config.demo.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:

```
$ pixi run snakemake all
-n --configfile
config/config.demo.yaml
```

and

```
$ pixi run snakemake all
```

config/scenarios123.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

Start with a dry-run:

```
$ pixi run snakemake -call --configfile config/test/config.overnight.yaml -n
```

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

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

And for myopic pathway optimisation:

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

To explore results, start a Jupyter notebook:

```
$ pixi run jupyter notebook
```

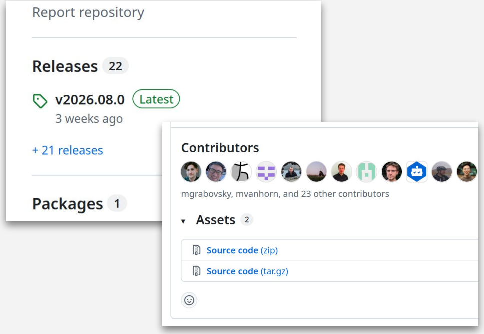
Practical Phase
(electricity-only)

1) Download the repository

Open a terminal and type:

```
$ cd ~/path/to/my/directory
$ git clone https://github.com/PyPSA/pypsa-eur.git
$ cd pypsa-eur
$ git checkout v2026.08.0
```

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



2) Install pixi by following instructions:

https://pixi.prefix.dev/latest/installation/

3) Run PyPSA-Eur tutorial with snakemake

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

```
$ pixi run snakemake -call solve_elec_networks --configfile config/test/config.electricity.yaml
```

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.explore()
```

Practical Phase
(sector-coupled)

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

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

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

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

Go to the documentation and try to find out how to configure some of the settings 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.

Backup

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)

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