

Workshop

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

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Training program by Green Deal Ukraina team
25/26 February 2025

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

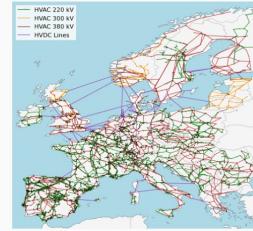
PyPSA



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

[Documentation »](#)

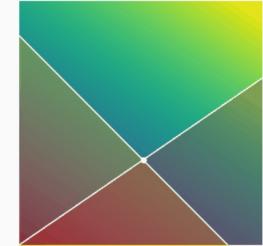
PyPSA-Eur



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

[Documentation »](#)

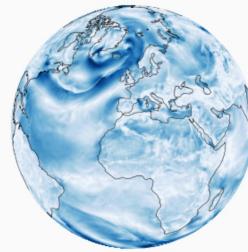
Linopy



Linear optimization interface for N-D labeled variables.

[Documentation »](#)

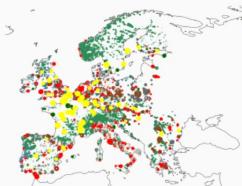
Atlite



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

[Documentation »](#)

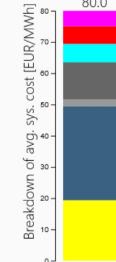
Powerplantmatching



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

[Documentation »](#)

Model Energy

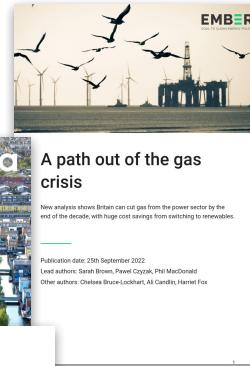
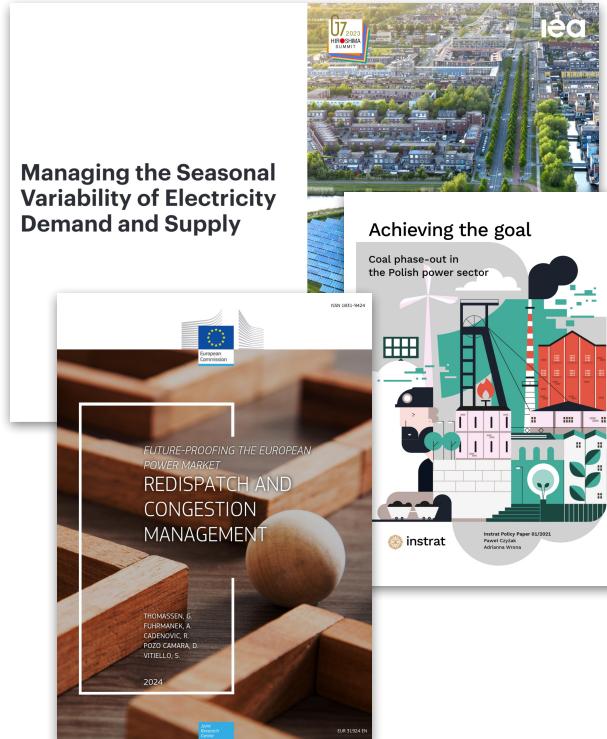


An online toolkit for calculating renewable electricity supplies.

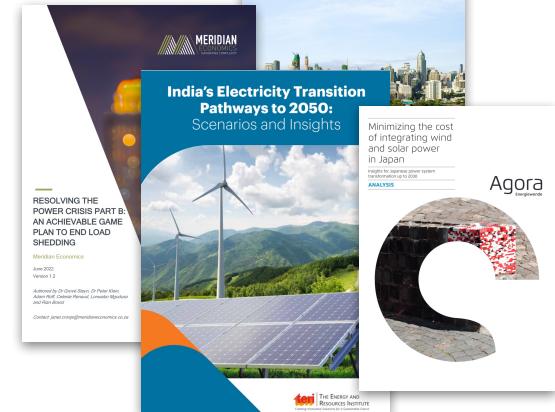


Application examples

NGOs and international organisations



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

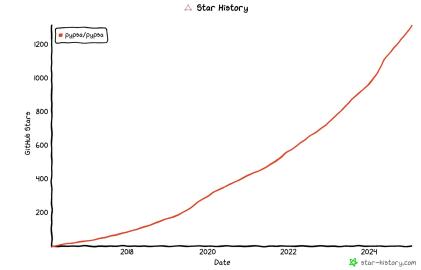
- Newton-Raphson

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

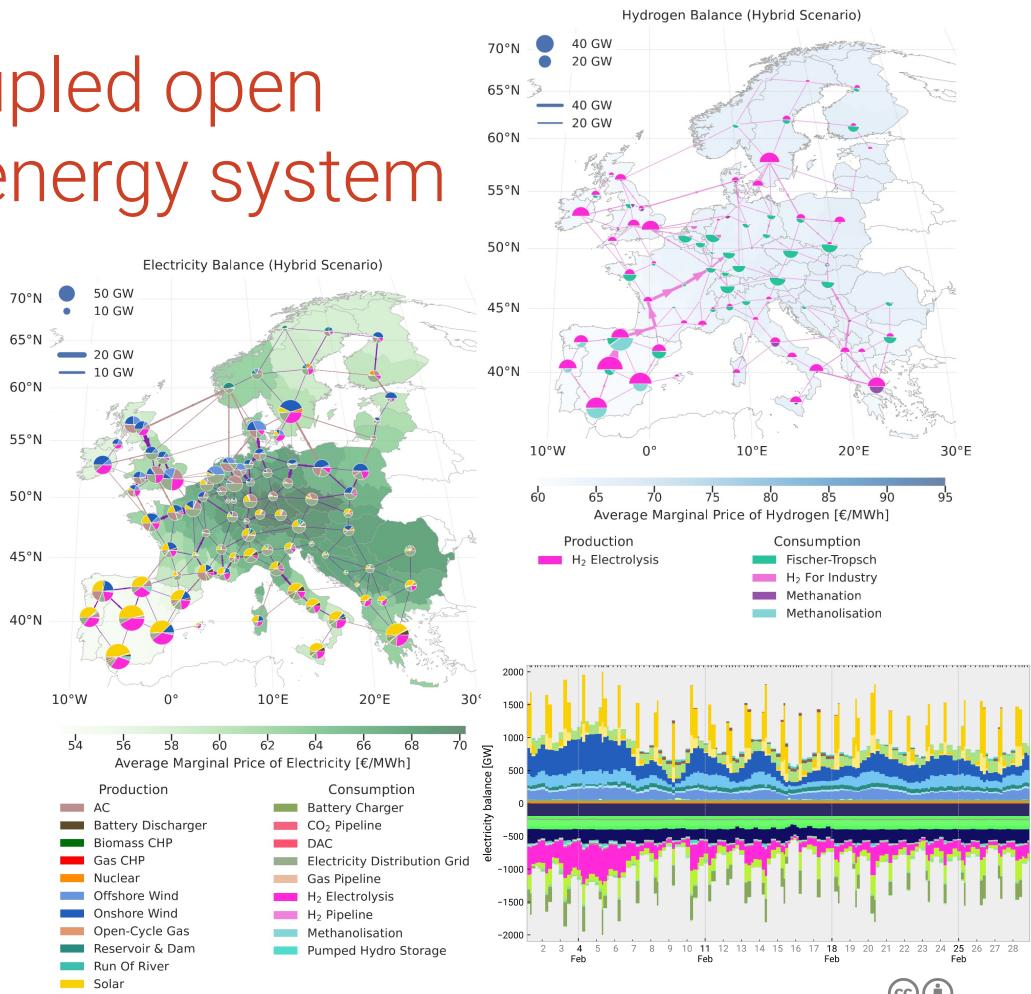
- all data stored in **pandas**
- framework built for performance with large networks and time series
- Interfaces to major **solvers** (Gurobi, CPLEX, HiGHS, Xpress), with **linopy** (by PyPSA devs)
- Highly **customisable**, but **no GUI**
- Suitable for greenfield, brownfield & pathway studies



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, ... (*later*)



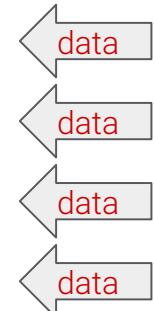
Energy infrastructure planning in PyPSA as an optimisation problem

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

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

subject to

- meeting energy demand at each node n (e.g. region) and time t (e.g. hour of year)
- transmission constraints between nodes and linearised power flow
- wind, solar, hydro (variable renewables) availability time series $\forall n, t$
- installed capacity \leq geographical potentials for renewables
- fulfilling CO₂ emission reduction targets
- Flexibility from gas turbines, battery/hydrogen storage, HVDC links

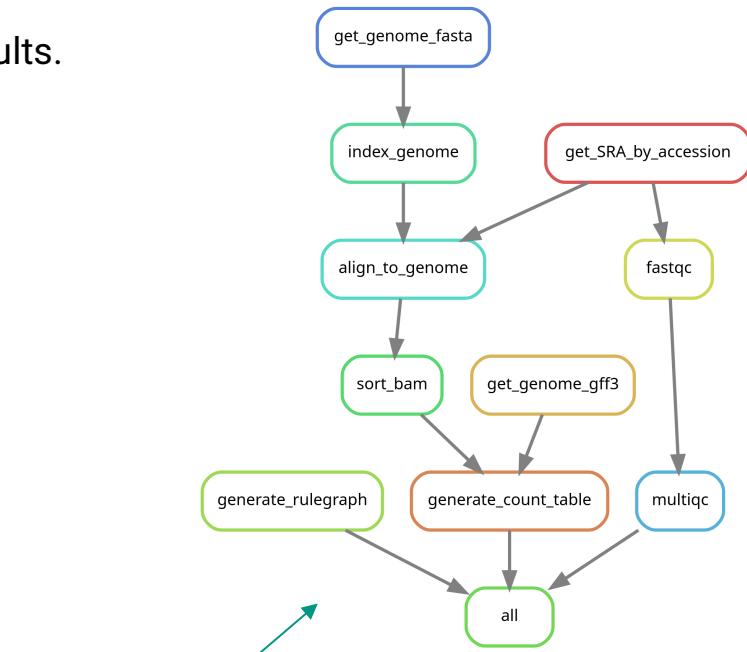


More on that later!

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:

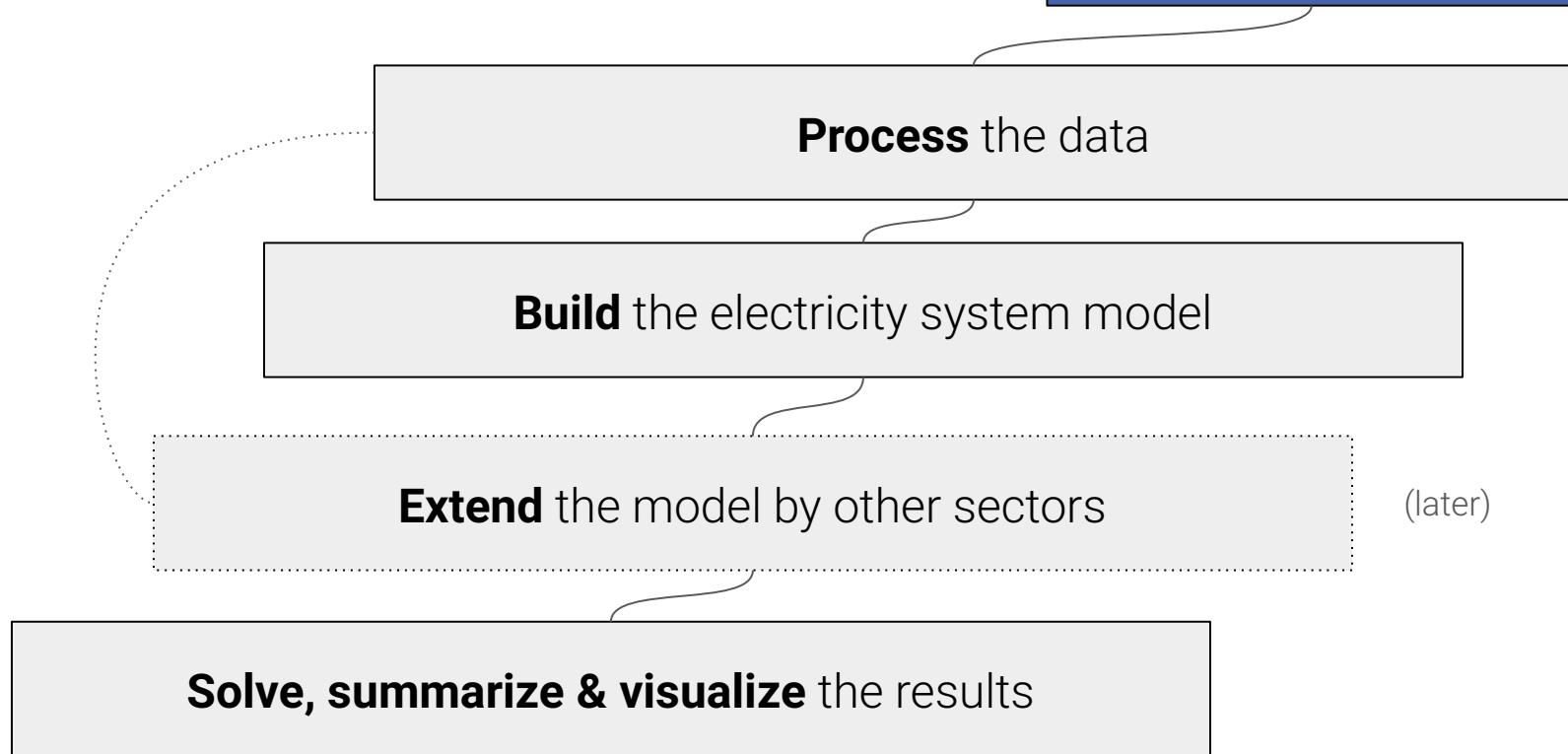
```
$ snakemake figures/myfigure.pdf
```

snakemake workflow for the electricity sector



Simplified workflow structure

Automated **downloads**

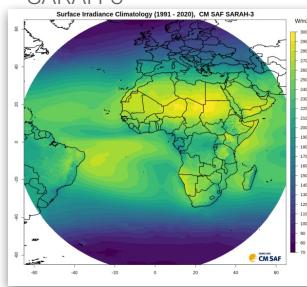


First, raw data is automatically downloaded.

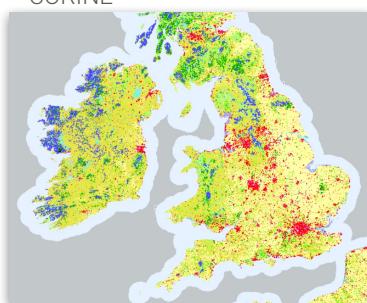
WDPA



SARAH-3



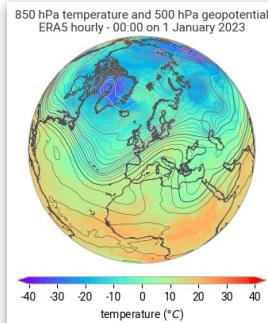
CORINE



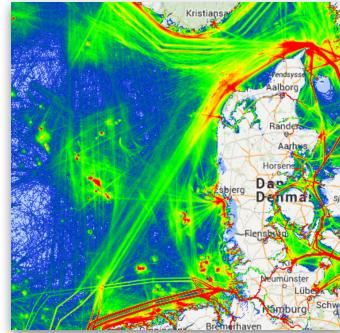
GEBCO



ERA5



World Bank



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

eurostat

eia
Independent Statistics and Analysis
U.S. Energy Information Administration

European Commission
Global Energy Monitor



Welcome to
OpenStreetMap!

OpenStreetMap is a map of the world,
created by people like you and free to use
under an open license.

Hosting is supported by [Fastly](#), [OSMF](#)
corporate members, and other partners.

Learn More

Start Mapping



11

Simplified workflow structure

Automated **downloads**

Process the data

Build the electricity system model

Extend the model by other sectors

(later)

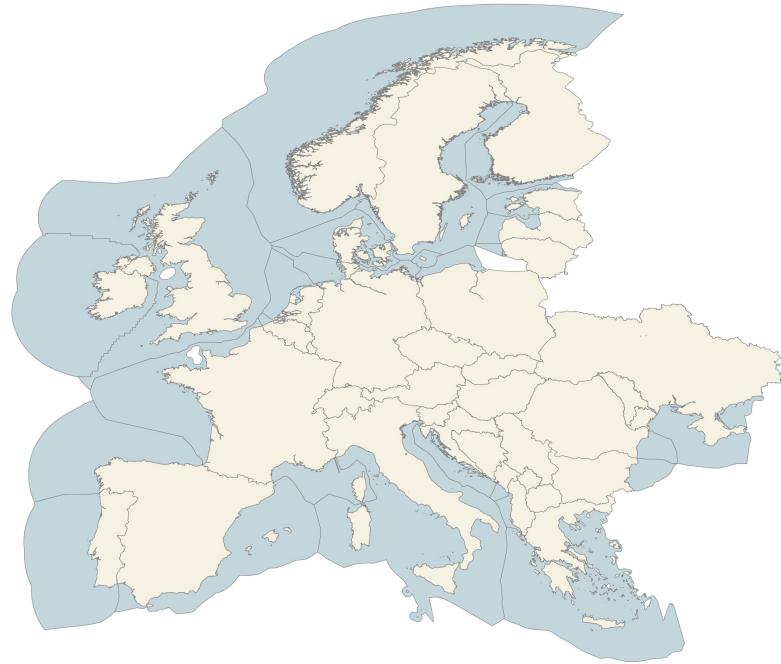
Solve, summarize & visualize the results

Steps to building PyPSA-Eur electricity system

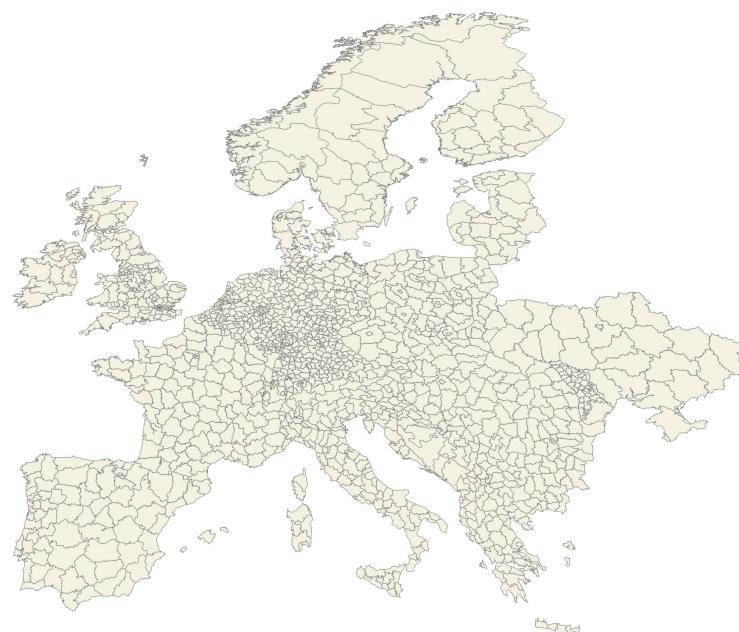
Retrieve onshore & offshore [polygons](#) for each country

build_shapes

Country shapes & exclusive economic zones (EEZ)



NUTS administrative regions (NUTS3)

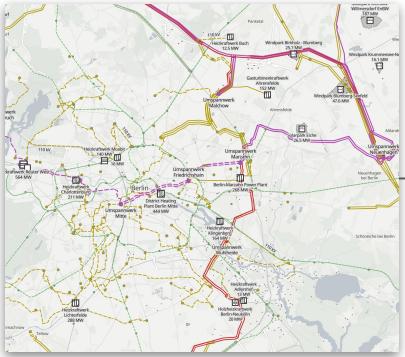


Steps to building PyPSA-Eur electricity system

Retrieve onshore & offshore polygons for each country	<code>build_shapes</code>
Construct a base high-voltage network with buses, transformers, AC & DC lines with DLR & TYNDP	<code>base_network,</code> <code>build_transmission_projects</code>

Power grid topology

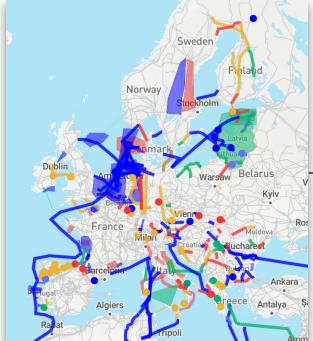
OpenStreetMap data



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

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

TYNDP projects

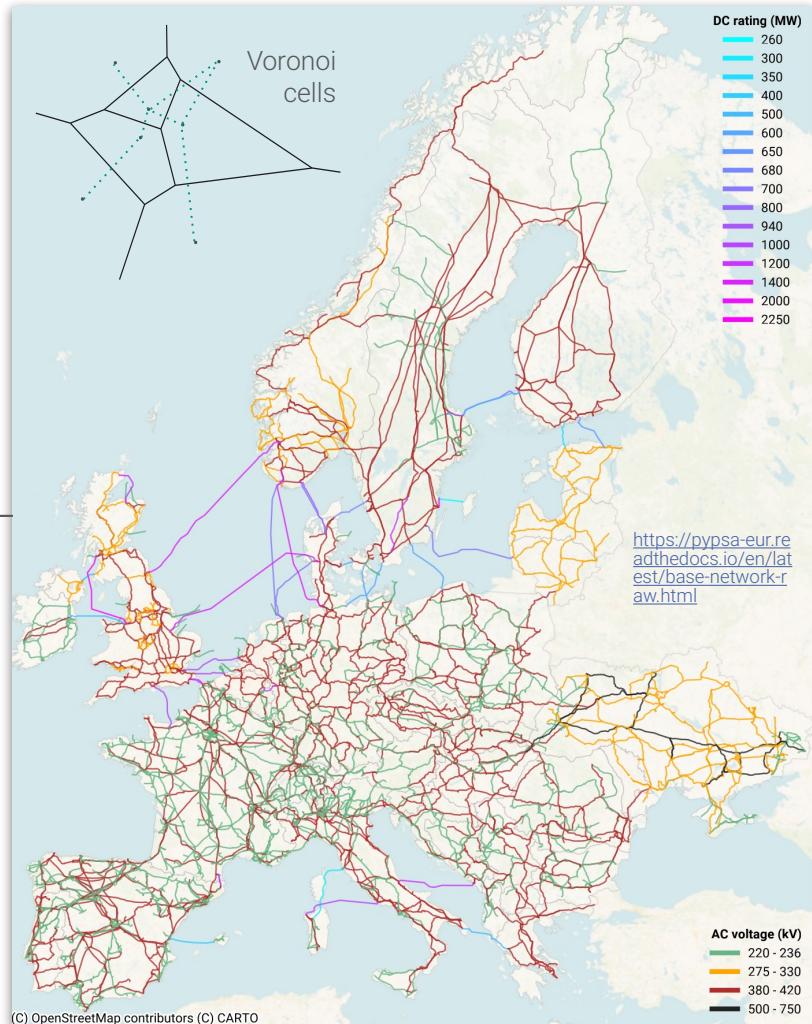


European network with

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

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

Voronoi cells



Steps to building PyPSA-Eur electricity system

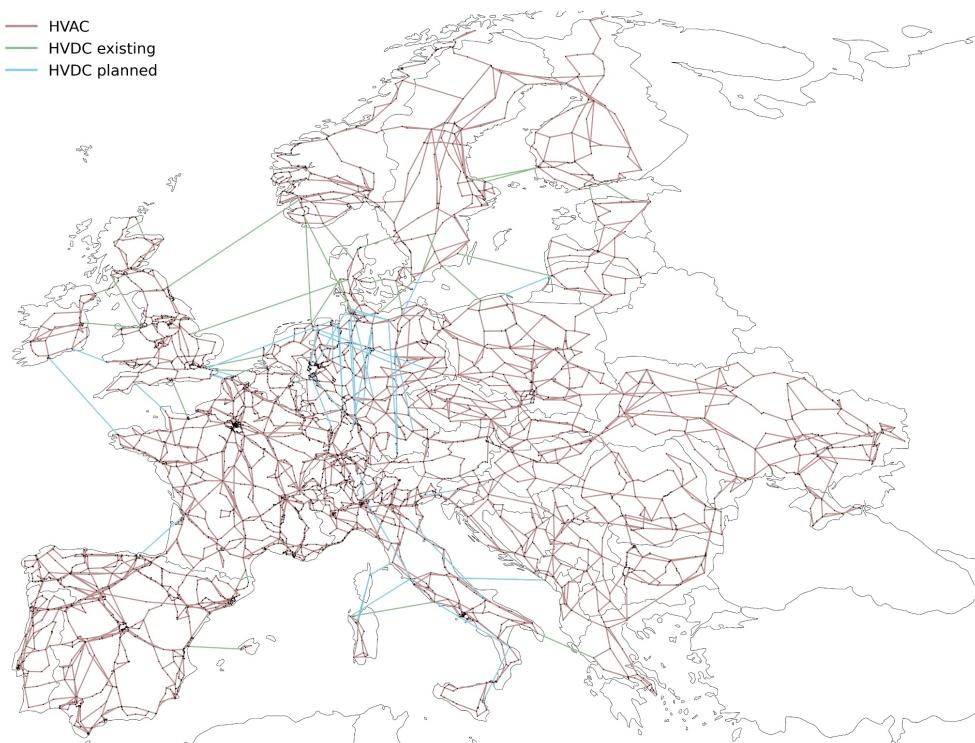
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Construct a base high-voltage network with buses, transformers, AC & DC lines with DLR & TYNDP	<code>base_network,</code> <code>build_transmission_projects</code>
Transform all transmission lines to 380kV, remove dead ends & cluster with k-means or hierarchical clustering	<code>simplify_network,</code> <code>cluster_network</code>

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:

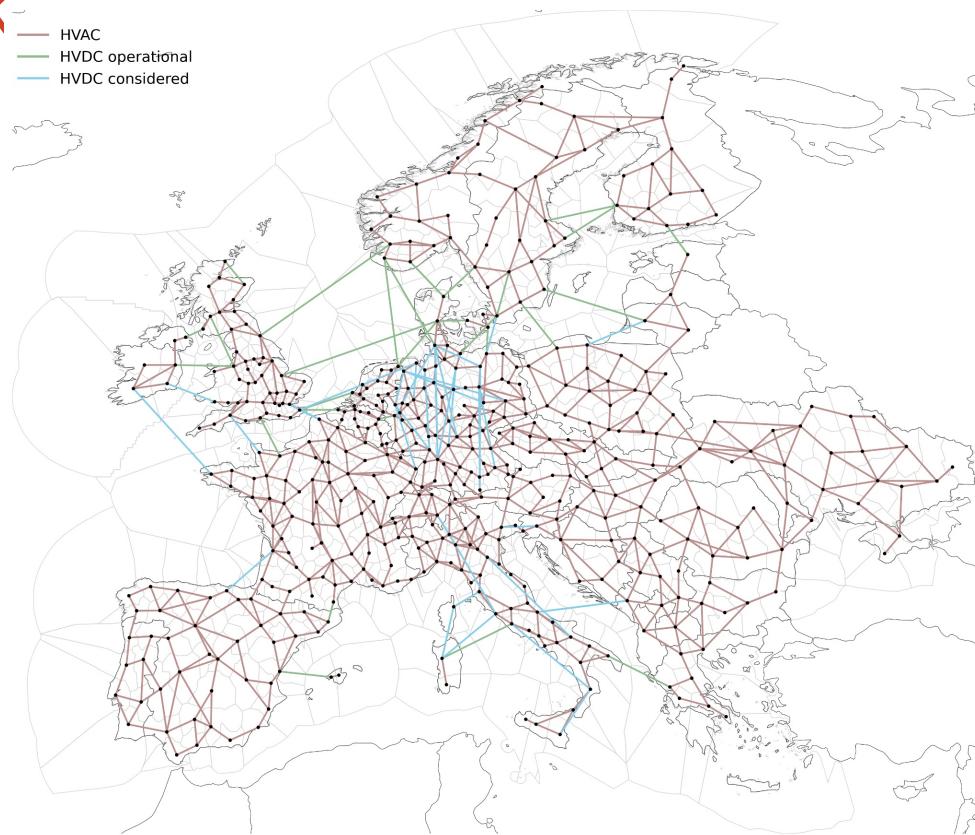
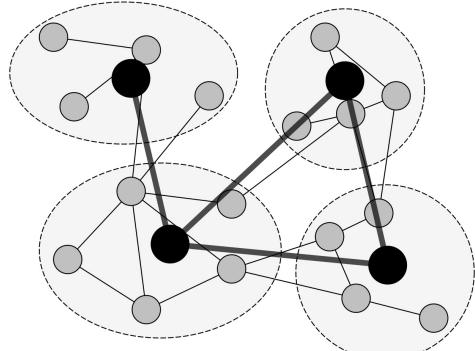
1. Lift all lines to **common voltage** level of 380 kV.
2. Remove **dead ends**.



Clustering the electricity network: cluster_network

Transformed
to 380 kV

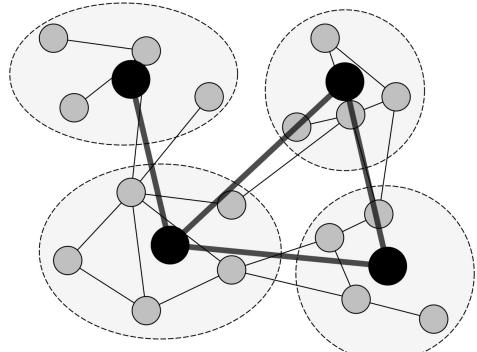
Clustered to
512 regions



Clustering the electricity network: cluster_network

Transformed
to **380 kV**

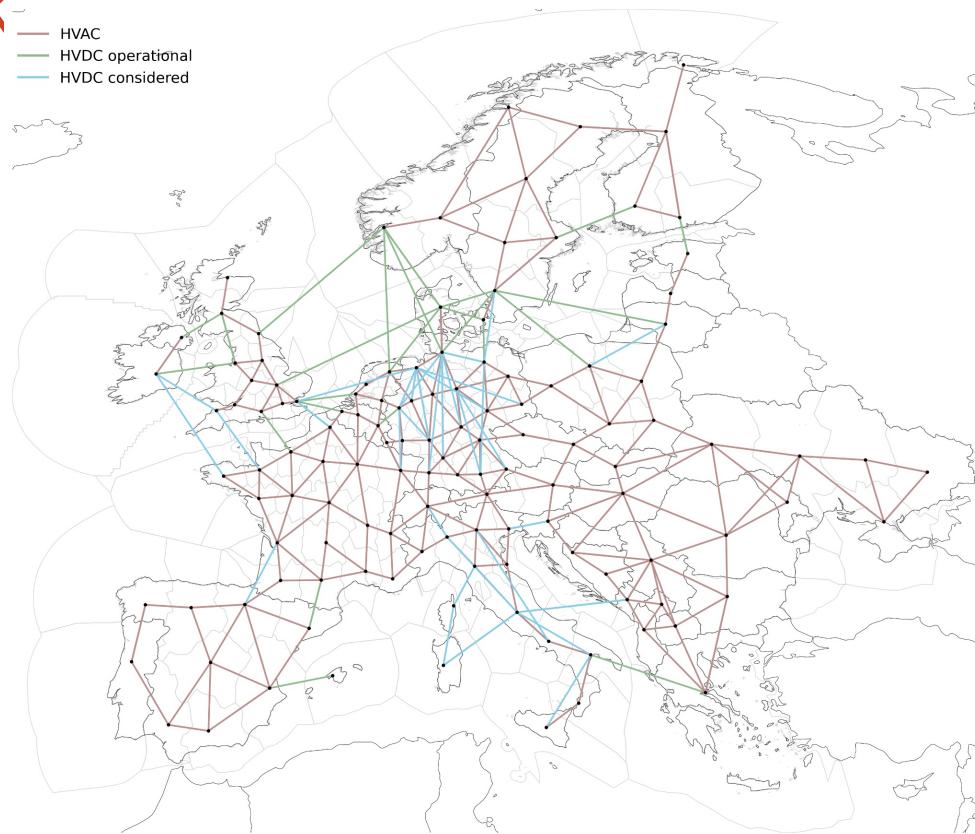
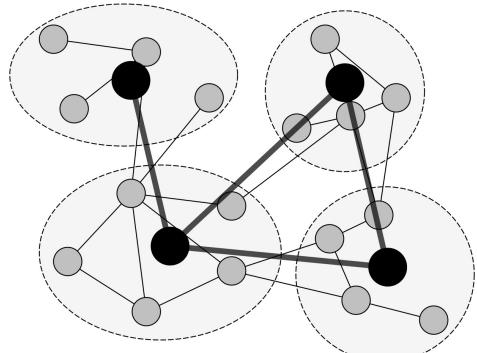
Clustered to
256 regions



Clustering the electricity network: cluster_network

Transformed
to 380 kV

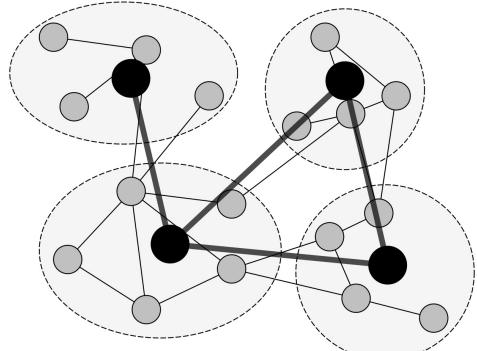
Clustered to
128 regions



Clustering the electricity network: cluster_network

Transformed
to 380 kV

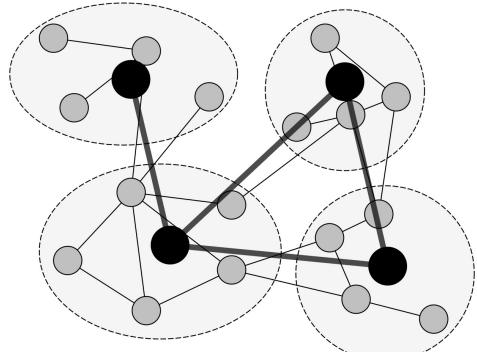
Clustered to
64 regions



Clustering the electricity network: cluster_network

Transformed
to 380 kV

Clustered to
41 regions



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Build renewable capacity factor profiles for each clustered region based on land availability	<code>build_renewable_profiles,</code> <code>build_hydro_profile</code>

atlite: Convert weather data to energy systems data



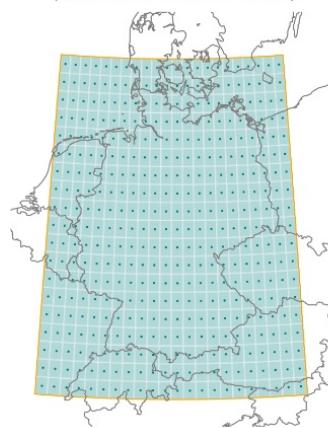
Python library for converting **weather data** (e.g. wind, solar radiation, temperature, precipitation) into **energy systems data**:

- 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)

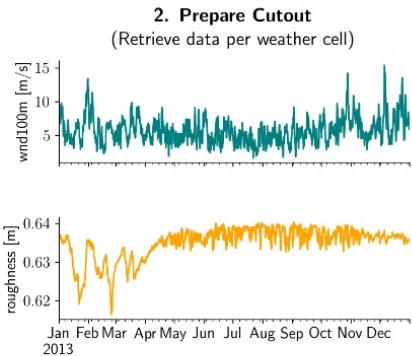
It can also perform **land eligibility analyses**.

Rule: build_renewable profiles

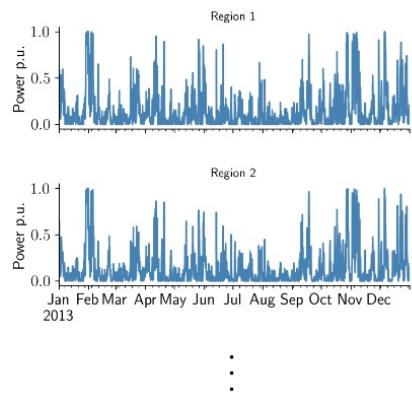
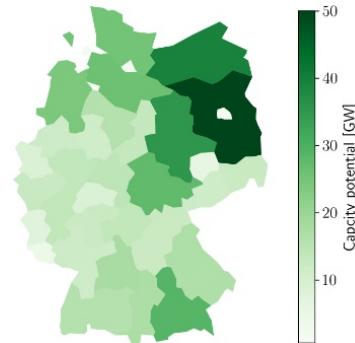
1. Create Cutout (Select spatio-temporal bounds)



2. Prepare Cutout (Retrieve data per weather cell)

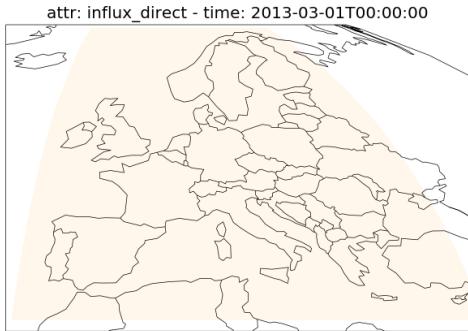


3. Convert Cutout (Calculate potentials and timeseries per region)

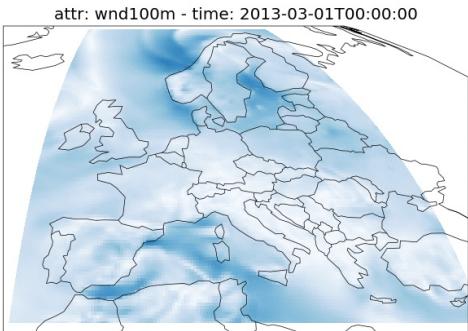


Time series for renewables

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



- Solar panel models
- orientation
 - material

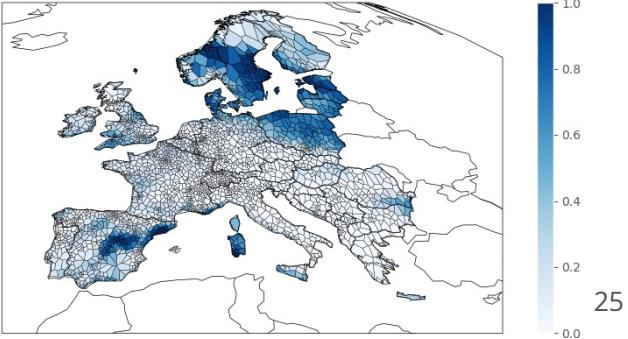
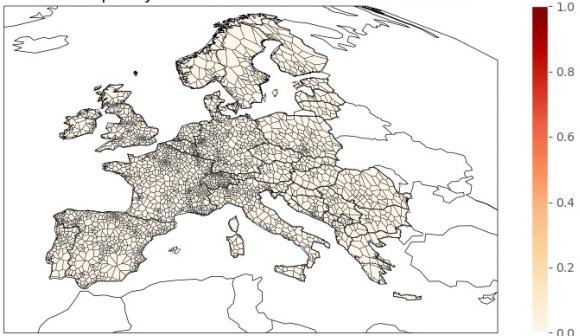


- Wind turbine models
- power curve
 - surface roughness

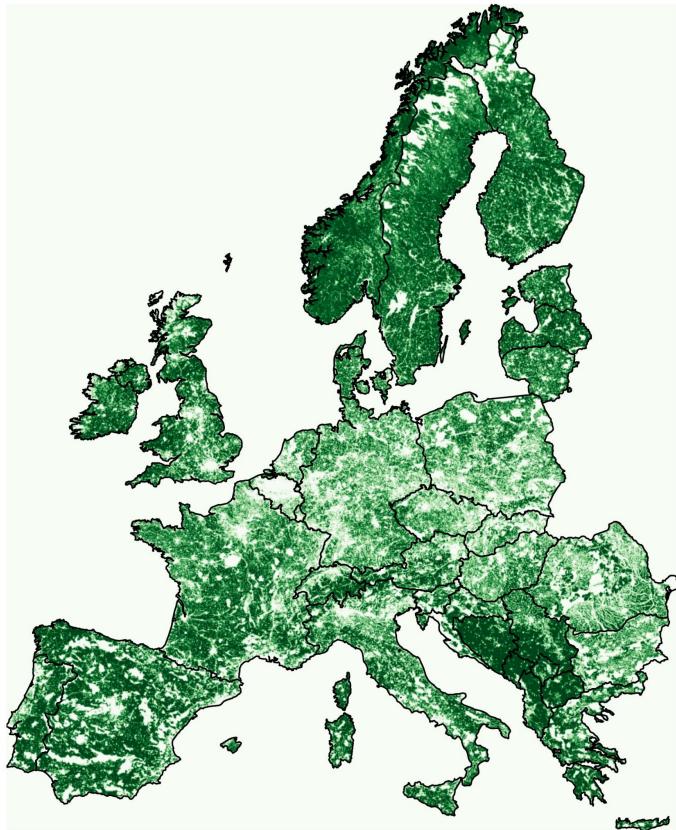
atlite: Convert weather data to energy systems data

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

Wind and solar capacity factors



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
REUSE compliant JOSS 10.21105/joss.03294 chat 52 online stackoverflow pypsa questions 44

- 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	<code>build_renewable_profiles,</code> <code>build_hydro_profile</code>
Prepare existing renewables and fossil power plants	<code>build_powerplants</code>

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")
```

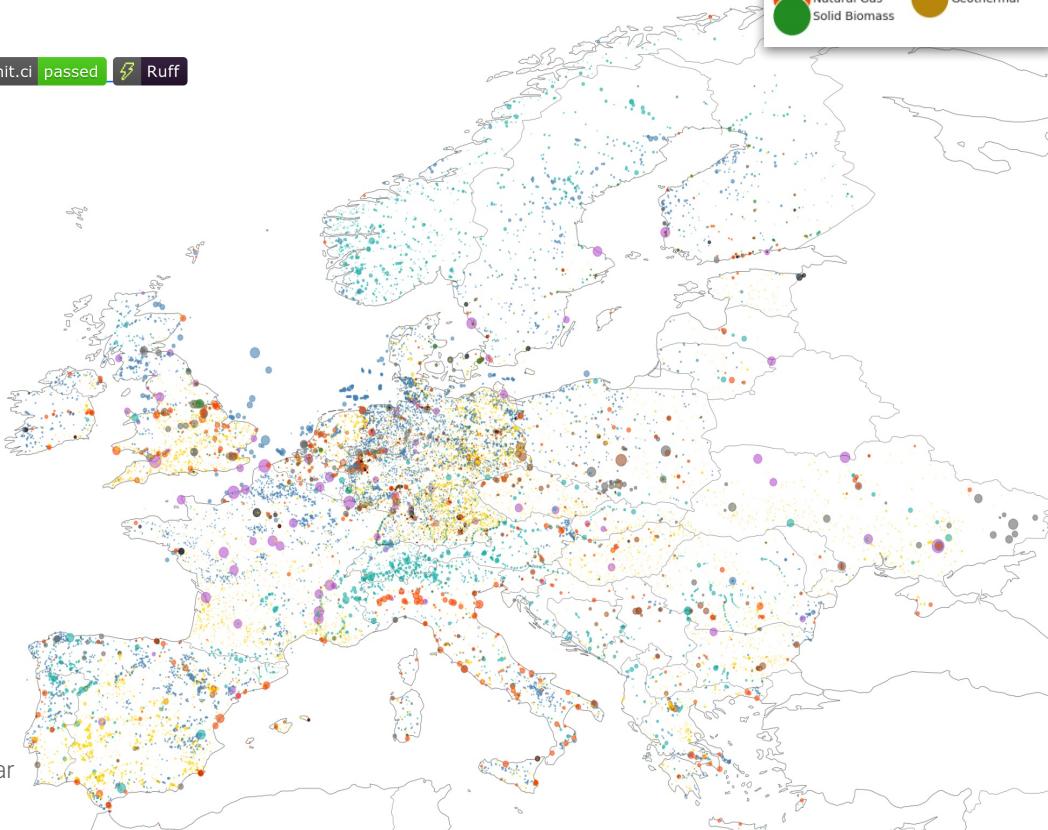
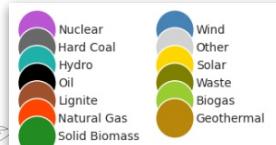
Sources

- 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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Prepare existing renewables and fossil power plants	<code>build_powerplants</code>
Add generation, storage and demand to the network with techno-economic assumptions on costs and efficiencies, ...	<code>add_electricity,</code> <code>prepare_network</code>

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

Q 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	10
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

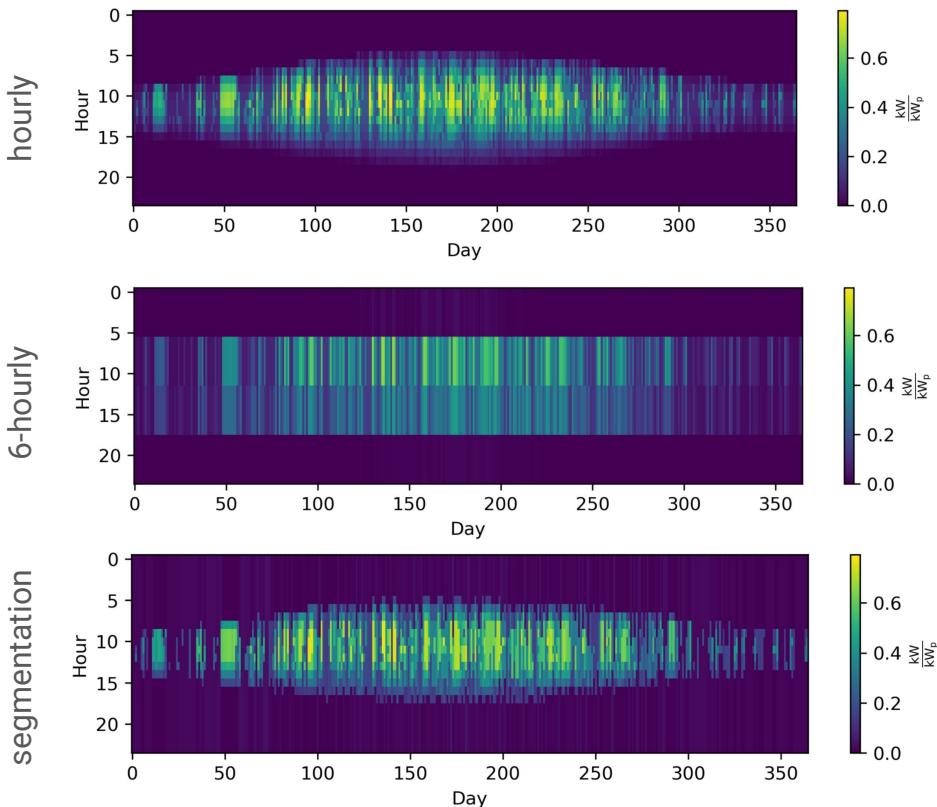
https://github.com/PyPSA/technology-data/blob/master/outputs/costs_2030.csv



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

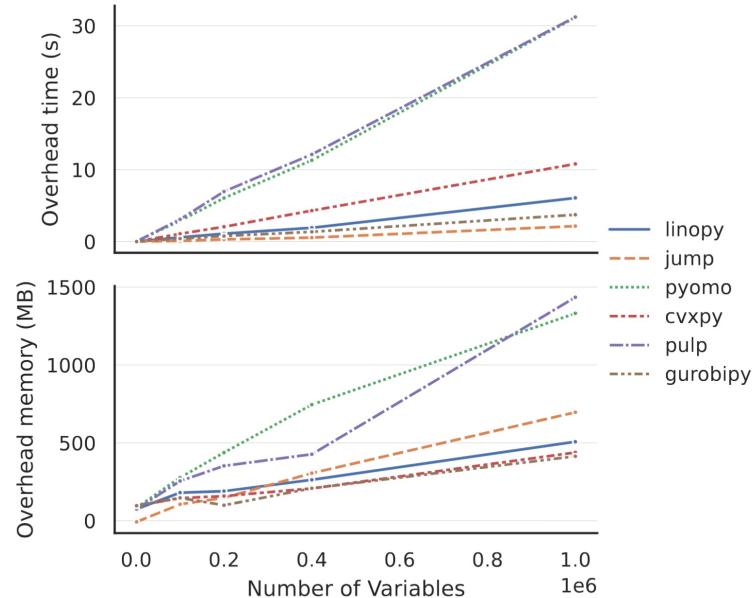


Python library that facilitates **optimization** with real-world, large-scale data.

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**.



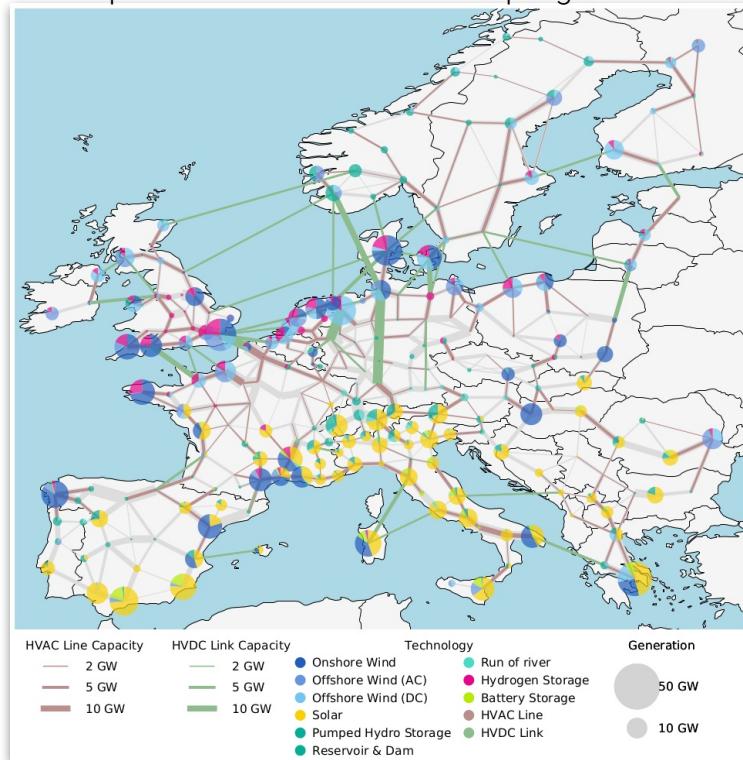
Solving and summarising networks

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.

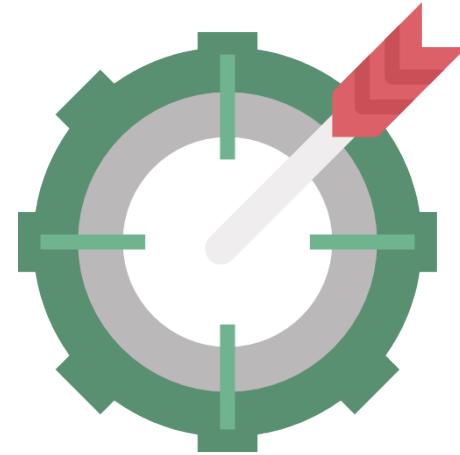
Example result without sector-coupling



What is configurable?

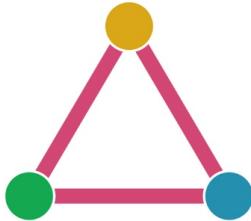
electricity-only examples

- Select subset of countries and focus countries (e.g. only DE)
- Select weather year (1940 - 2024 for ERA5)
- Specify CO₂ 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!



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.

```
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

Top-level configuration

- run
- foresight
- scenario
- countries
- snapshots
- enable
- co2 budget
- electricity
- atlite
- renewable
- conventional
- lines
- links
- transmission projects
- transformers
- load
- energy
- biomass
- solar_thermal
- existing_capacities
- sector
- industry
- costs
- clustering

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



Live Demo – Belgium / electricity-only / few days

Start with a dry-run:

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

Don't forget to activate your conda environment first!

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)

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
```

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()
```

1) Download the repository

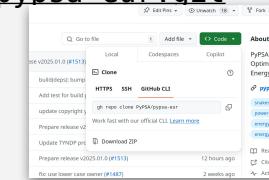
Open a terminal / CMD and type:

```
$ 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.



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
```

Users of Windows, add two lines to YAML:

```
run:  
  use_shadow_directory: false
```



Small exploratory configuration tasks

(electricity-only)

Go to <https://pypsa-eur.readthedocs.io/en/latest/configuration.html> 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

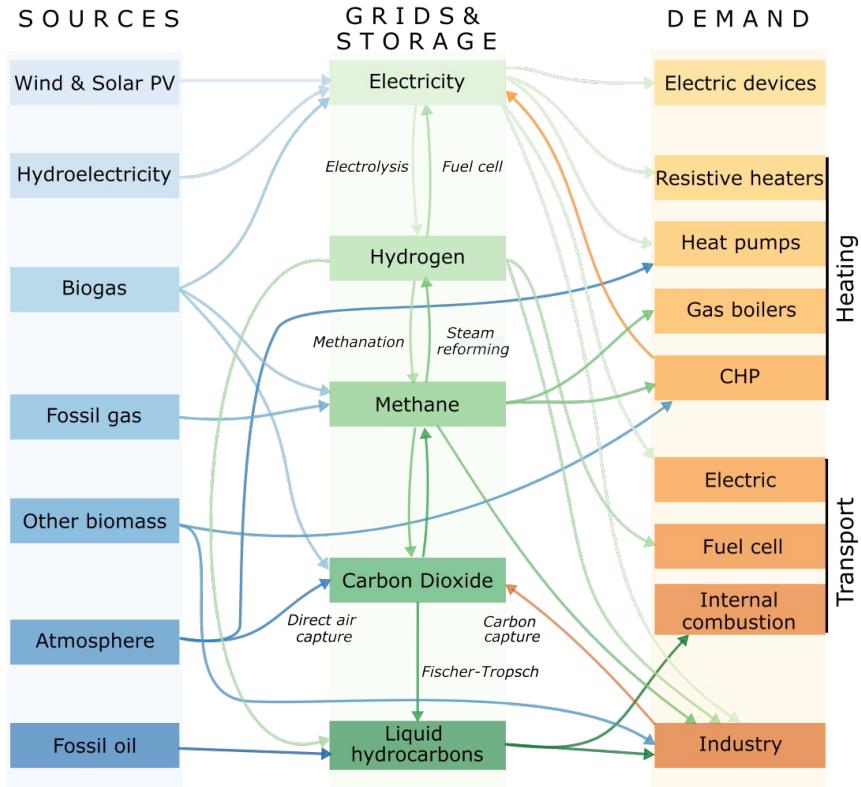
Solve, summarize & visualize the results

Coupling with other sectors

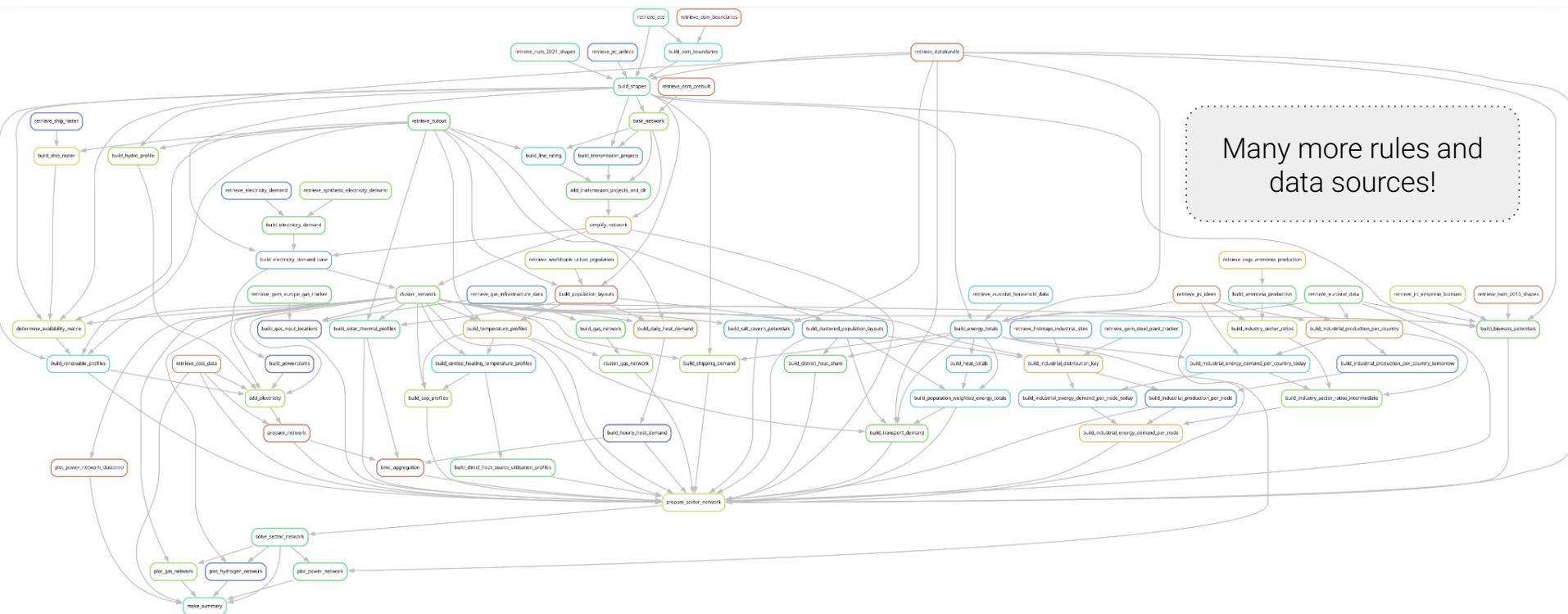
Need to decarbonise **all sectors** in Europe obeying spatial and temporal constraints.

- transport sector (EVs, shipping, aviation)
- heating sector (district heating, individual)
- industry sector (steel, chemicals, ammonia, ...)
- industrial feedstocks
- biomass resources
- carbon management (CCUTS)
- hydrogen, CO₂ and gas networks
- pathway optimisation (myopic, perfect)

Boundaries between energy and material model blur.



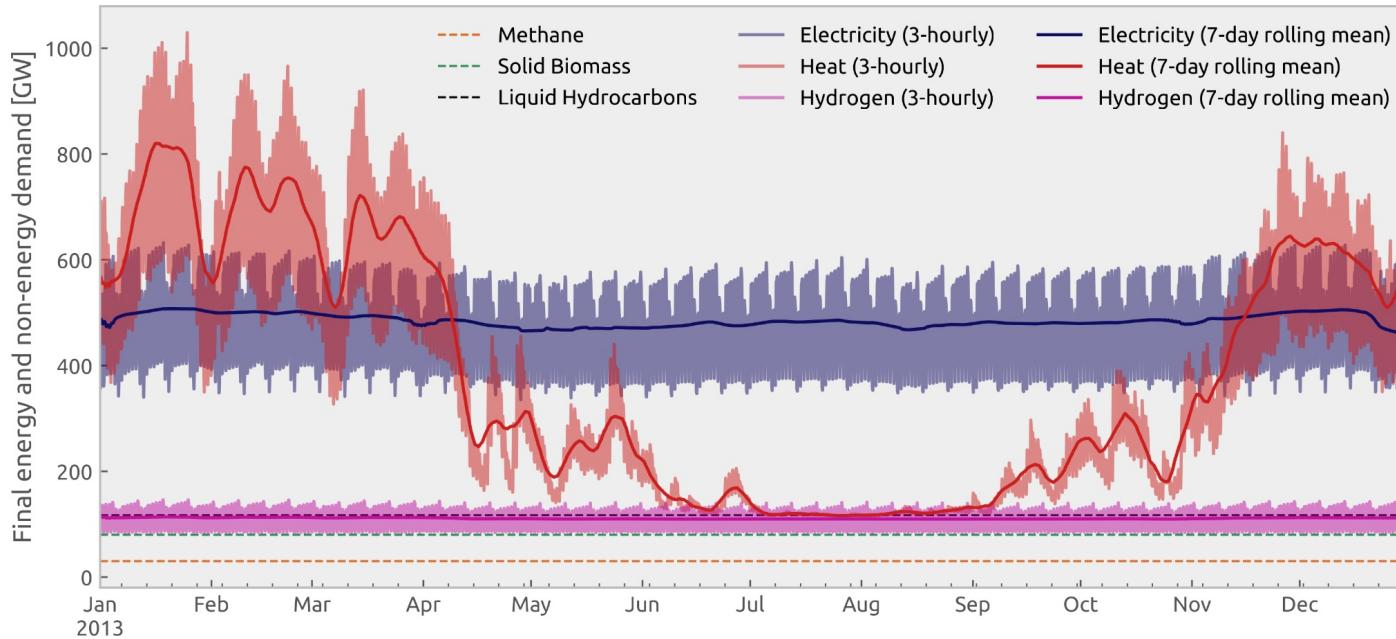
Extension by other sectors requires more data!



High-resolution version:
<https://tubcloud.tu-berlin.de/s/E7tx3BaqXsKXLre>

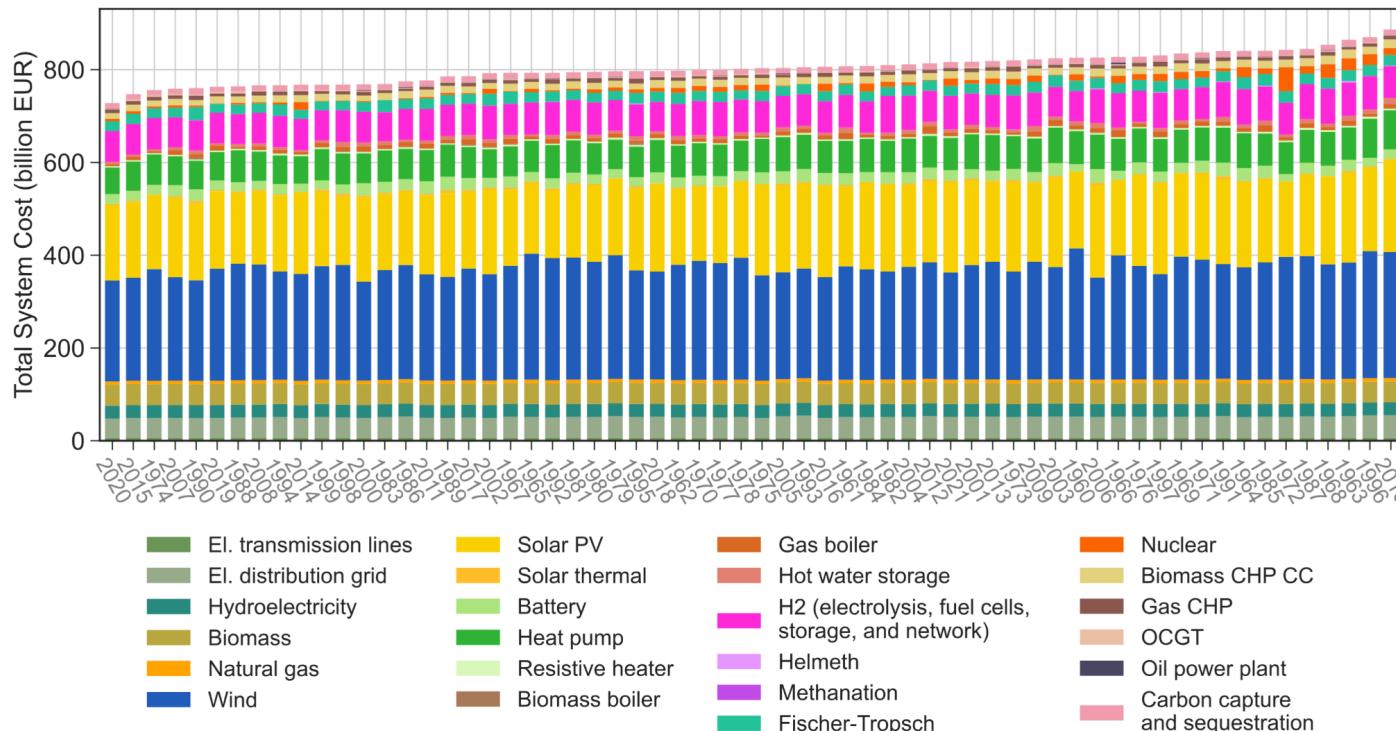


Temporal distribution of energy demands



From a temporal perspective, the **seasonal variation of heat demand** adds a challenge – it can coincide **periods of low wind and solar availability** and **varies from year to year**.

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

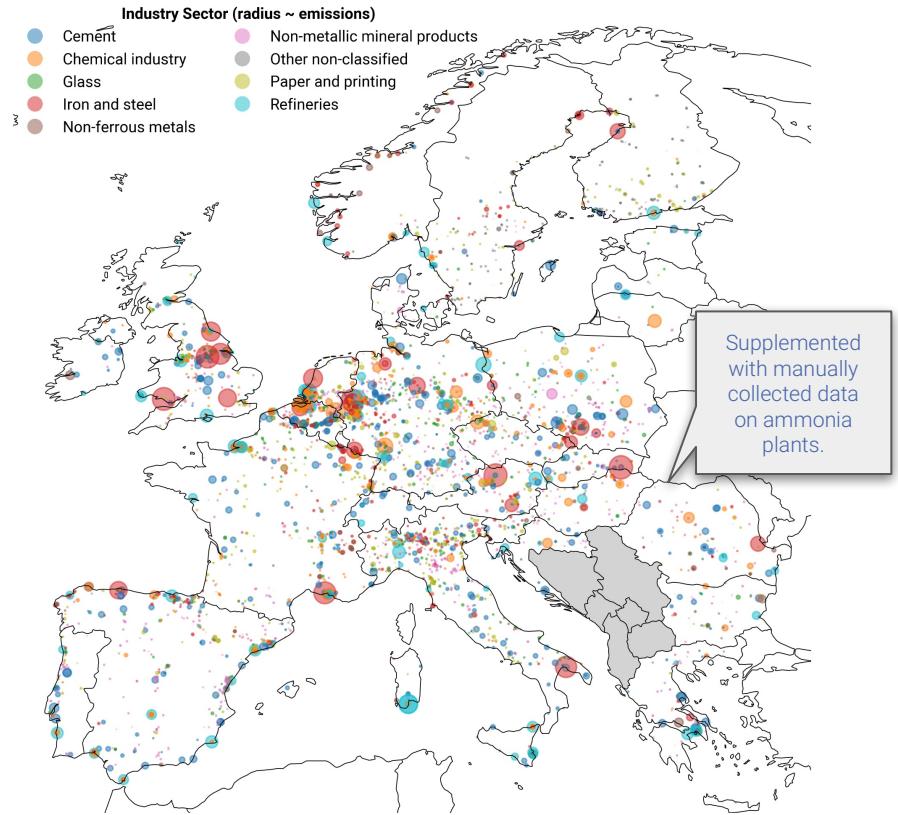


The years **2010, 2013, 2019** and **2023** are currently available "out of the box".

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

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

Industry - Regionalisation based on Hotmaps



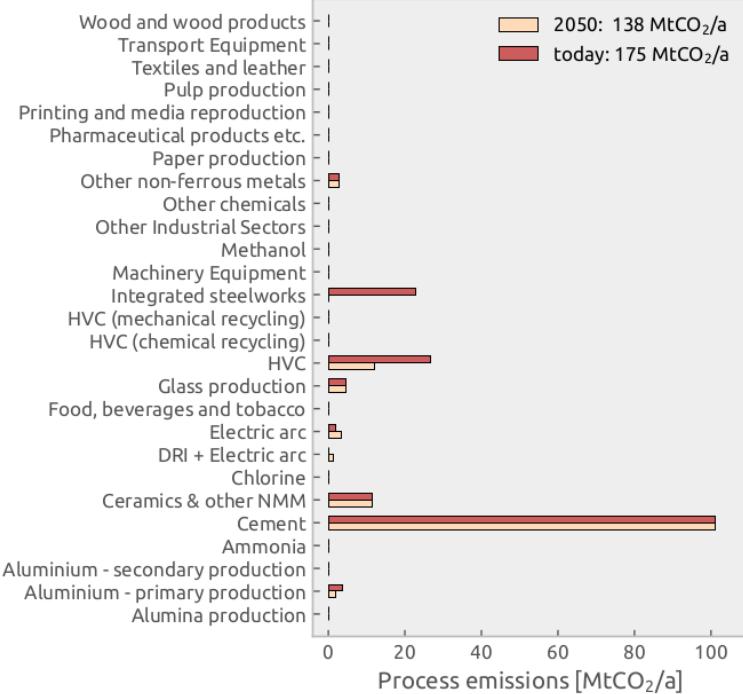
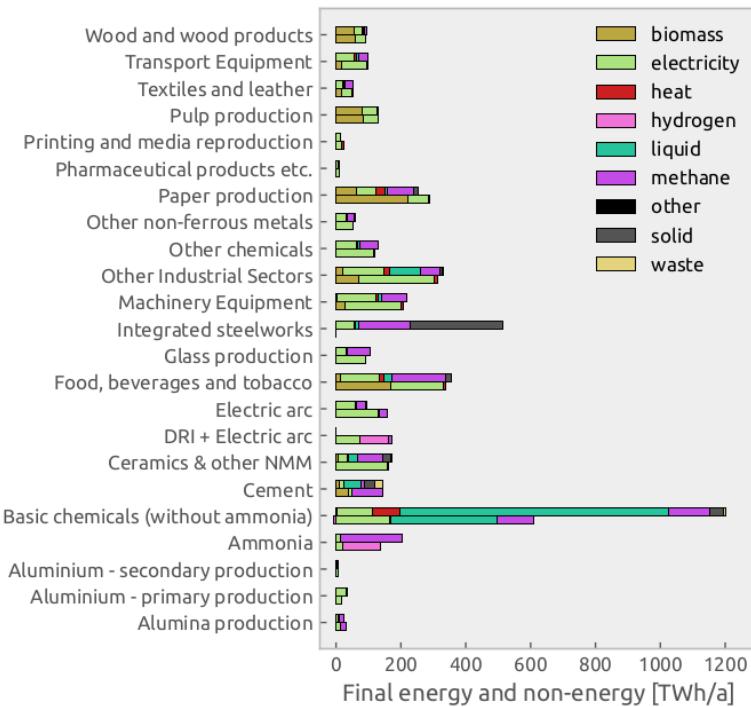
https://gitlab.com/hotmaps/industrial_sites/industrial_sites_Industrial_Database

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!



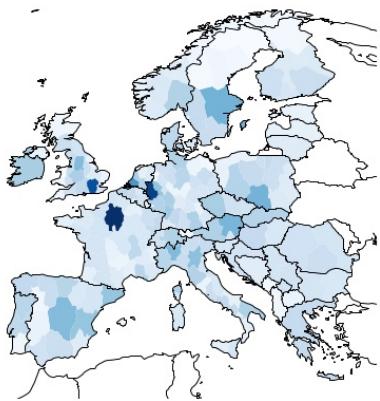
Industry - Fuel & process switching / process emissions



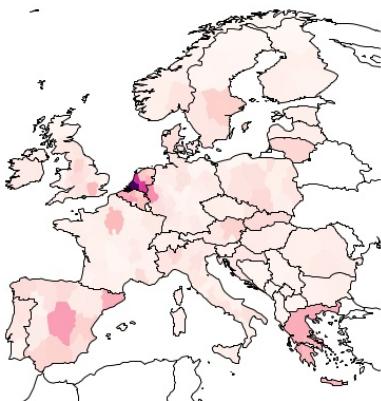
Currently, the most fuel & process switching in different industrial sectors is **exogenously configured** by the user. We're working to make these decisions **endogenous** to the model.

Spatial distribution of energy demands

(a) electricity demand



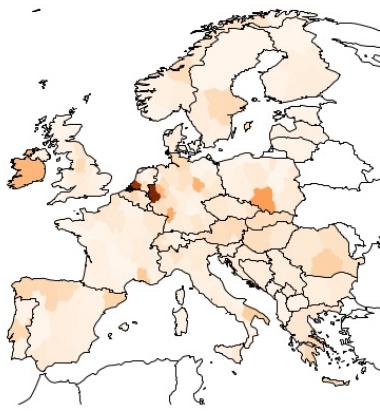
(b) hydrogen demand



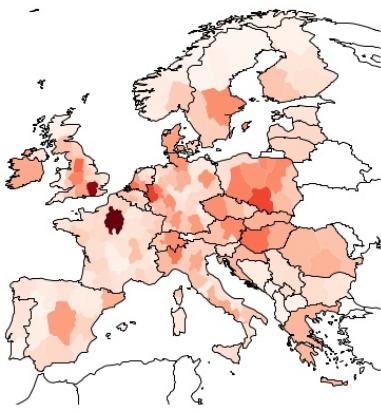
(e) oil-based product demand



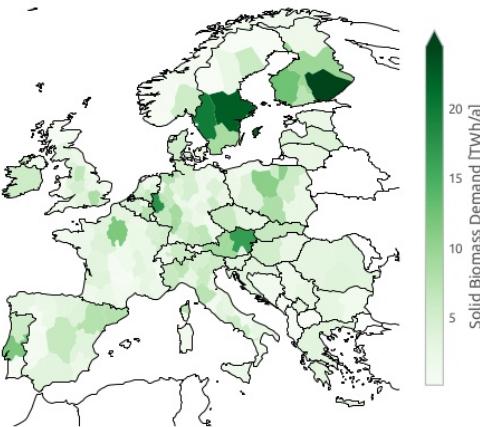
(c) methane demand



(d) heat demand



(f) solid biomass demand



Infrastructure - Gas network with H₂ retrofitting

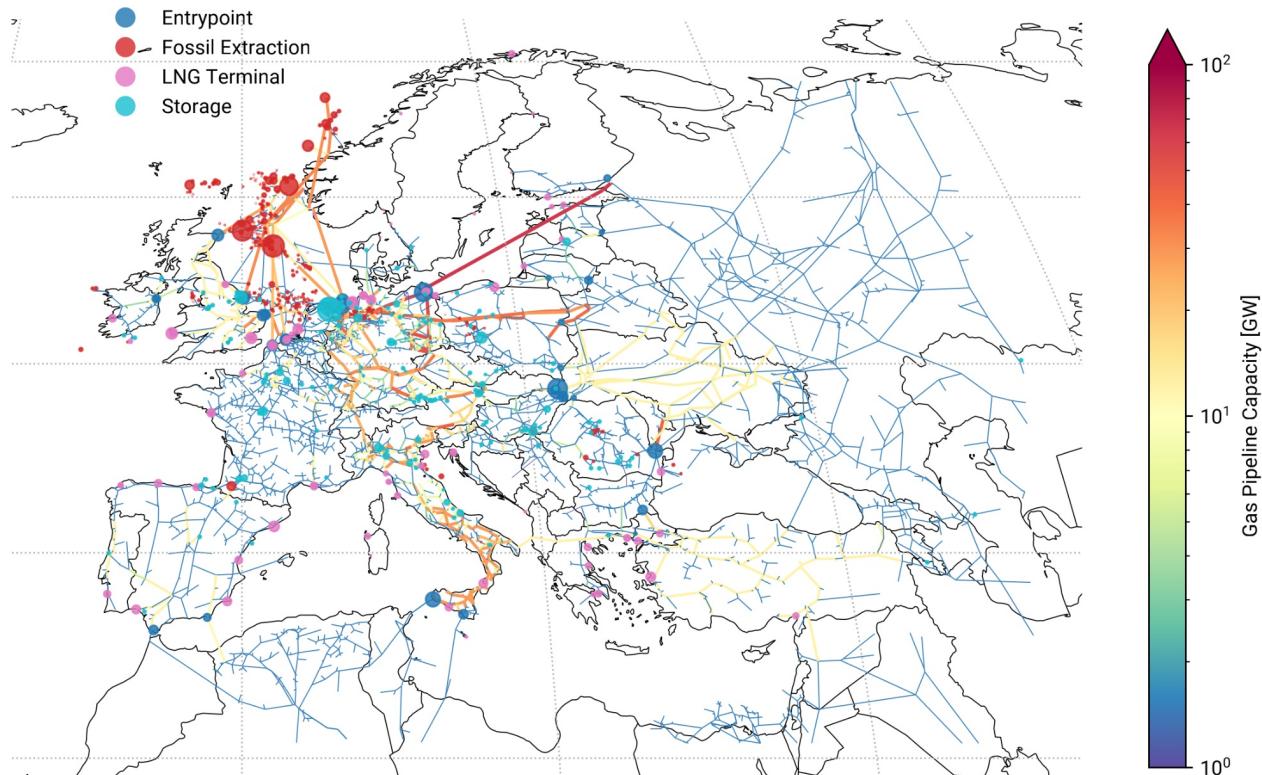
Compiled from open
SciGRID_gas dataset.

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.

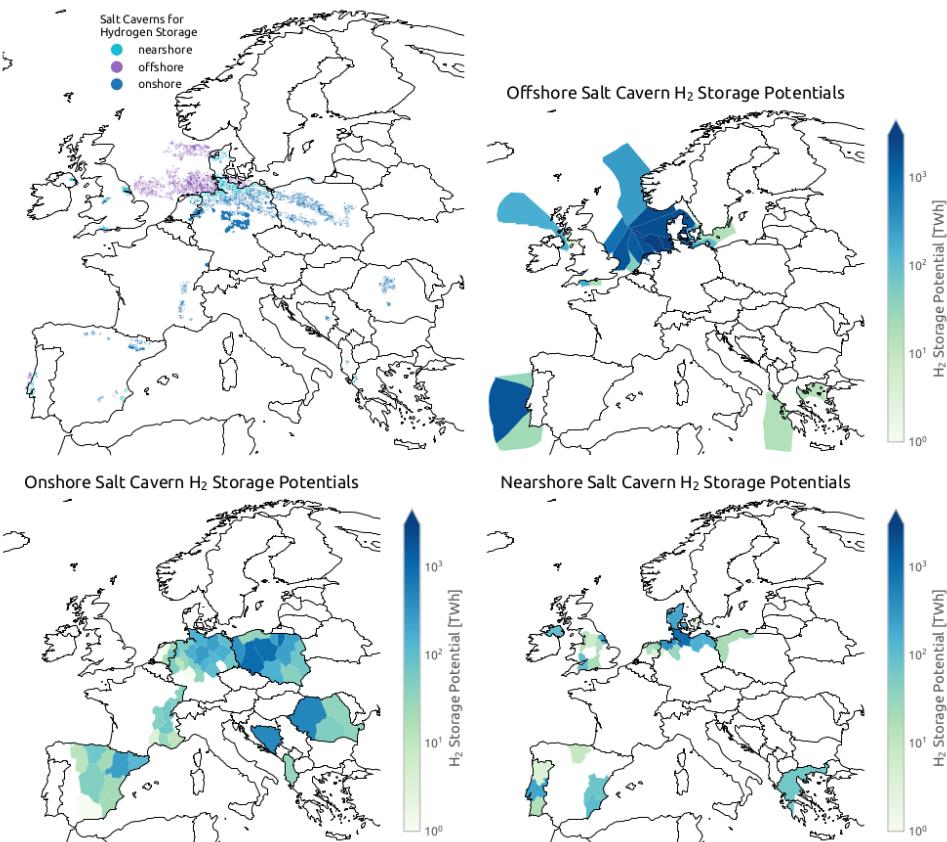
Pipelines can be **retrofitted** to H₂ with costs from [EHB](#).



<https://zenodo.org/records/4767098>



Infrastructure - Hydrogen storage potentials



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

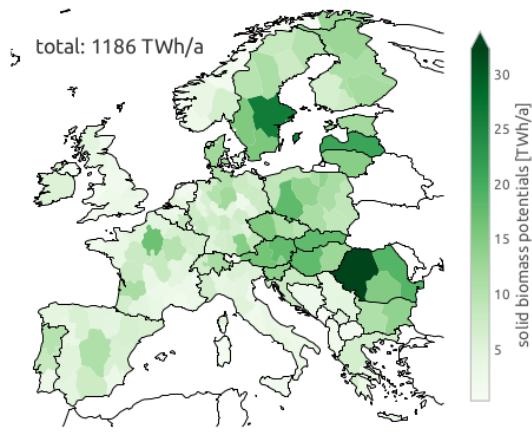
The user can **configure** if onshore and/or offshore potentials can be used.

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>

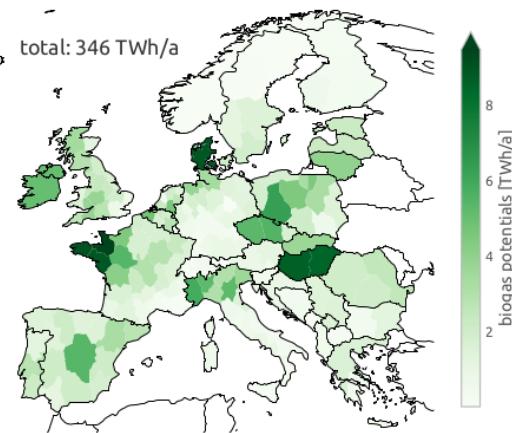


Infrastructure - Biomass from JRC ENSPRESO

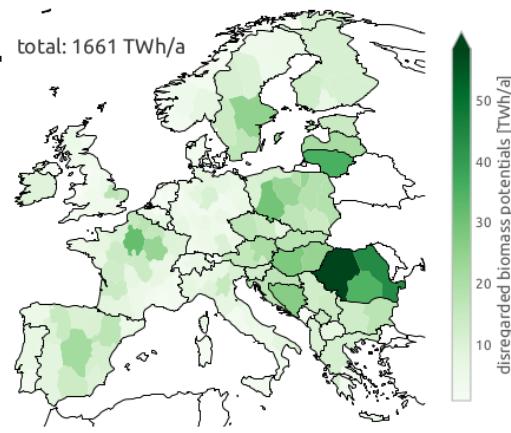
(a) solid biomass potentials



(b) biogas potentials



(c) potentials not included

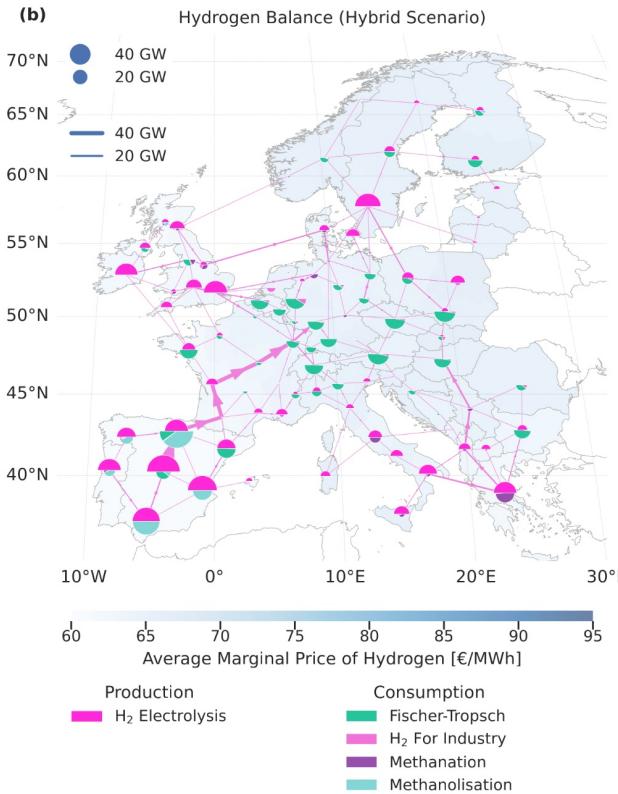
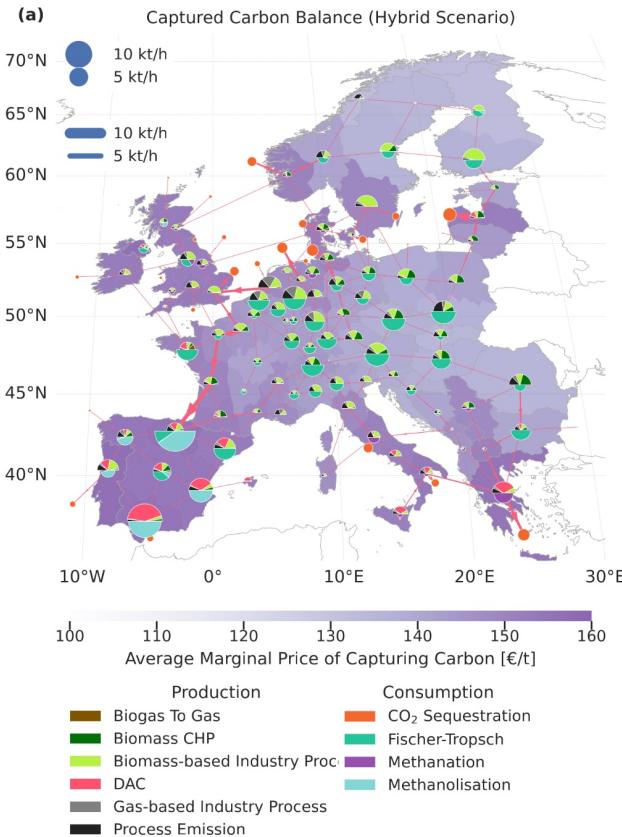


Biomass potentials are split between **solid biomass** and **biogas** (which can be, for instance, upgraded).

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.

Infrastructure - Carbon management



Built-in carbon flows:

- Capture:**
DAC, process emissions, fossil / biomass CHP
- Transport:**
CO₂ 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:

 CO2Stop - a project mapping both reserves and resources for CO₂ storage in Europe

By: Niels Poulsen (EUUS), Sam Holloway (BGS), Karen Kirk (BGS), Filip Neeli (TNO) and Nicola Ann Smith (BGS)

CO2Stop is the acronym for the "CO₂ 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/CT/1154-2011-SI2-01104). The CO2Stop project has mapped both reserves and resources for CO₂ storage in Europe. Further Latvia was covered by Estonia.

The results of the study are provided as a database of CO₂ storage locations throughout Europe, a Database of Geological Data Infrastructure (GeDI) and a Database of Compute storage capacities and injection rates (StoreP).

The database is now available on the website of the Joint Research Centre (JRC) (<http://geodi.jrc.ec.europa.eu/european-co2-storage-database>) and will be available as an interactive web-based application (<http://www.eurogeopedia.org/>) in the future.

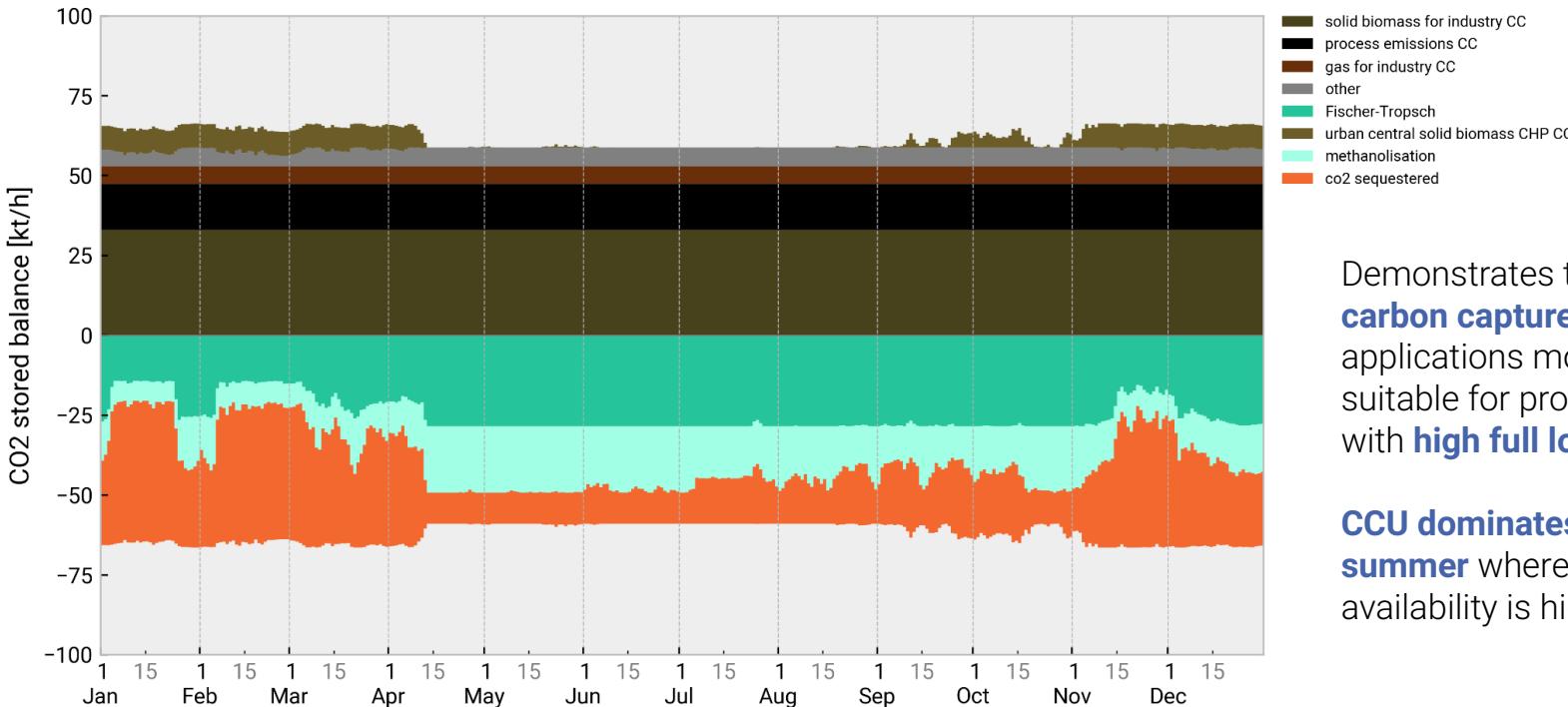
Geological Data Infrastructure (GeDI) (<http://www.eurogeopedia.org/>)

The CO2Stop database will be the first step towards a European Storage Atlas. Other databases are available for UK, Ireland, Norway, Sweden, Denmark, and the Netherlands (www.co2storeden.co.uk/home/index.html) and the Nordic CO₂ storage atlas is produced by NORCCS – the Nordic CCS Consortium (<http://www.nordicccslabut.htm>). Spain has published Atlas of Geological Structures that uphold a CO₂ storage potential in Spain (ISBN: 978-84-7840-928-0 Mayo 2013).

88 Countries covered by the CO2Stop project
32 Countries covered by the CO2StorageAtlas project
The boundary project included 26 countries and 27
Latvia was covered by Estonia



Examples - Carbon management on a time axis



Heating - Tech for individual & district heating

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

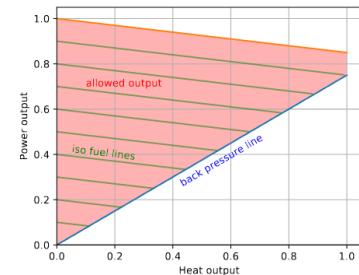
Building renovations can be co-optimized to reduce space heating demand.

District heating systems

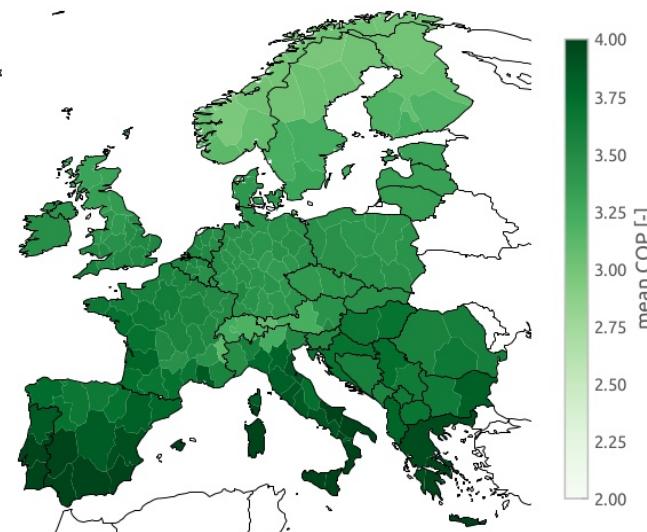
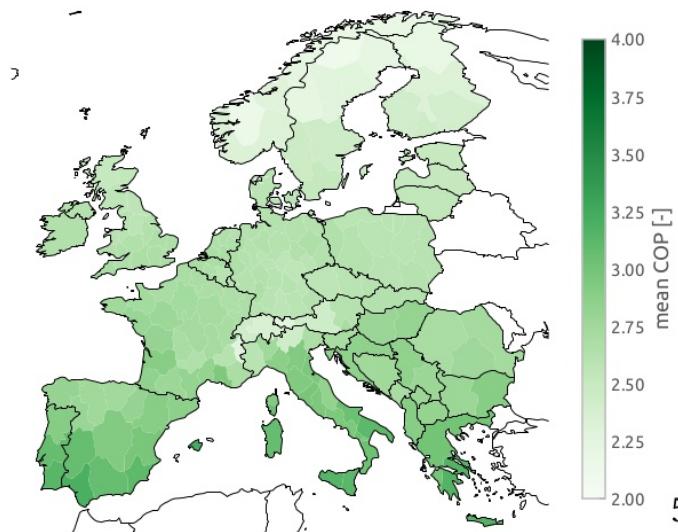
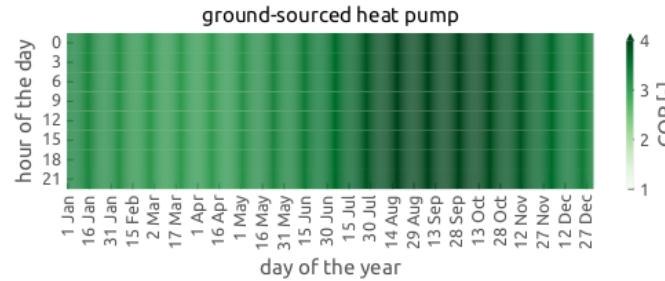
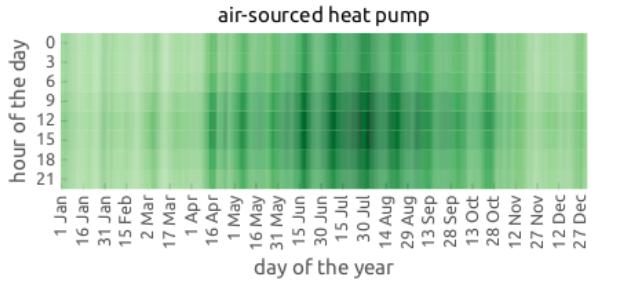
can be supplied in urban areas by:

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

CHP feasible dispatch:

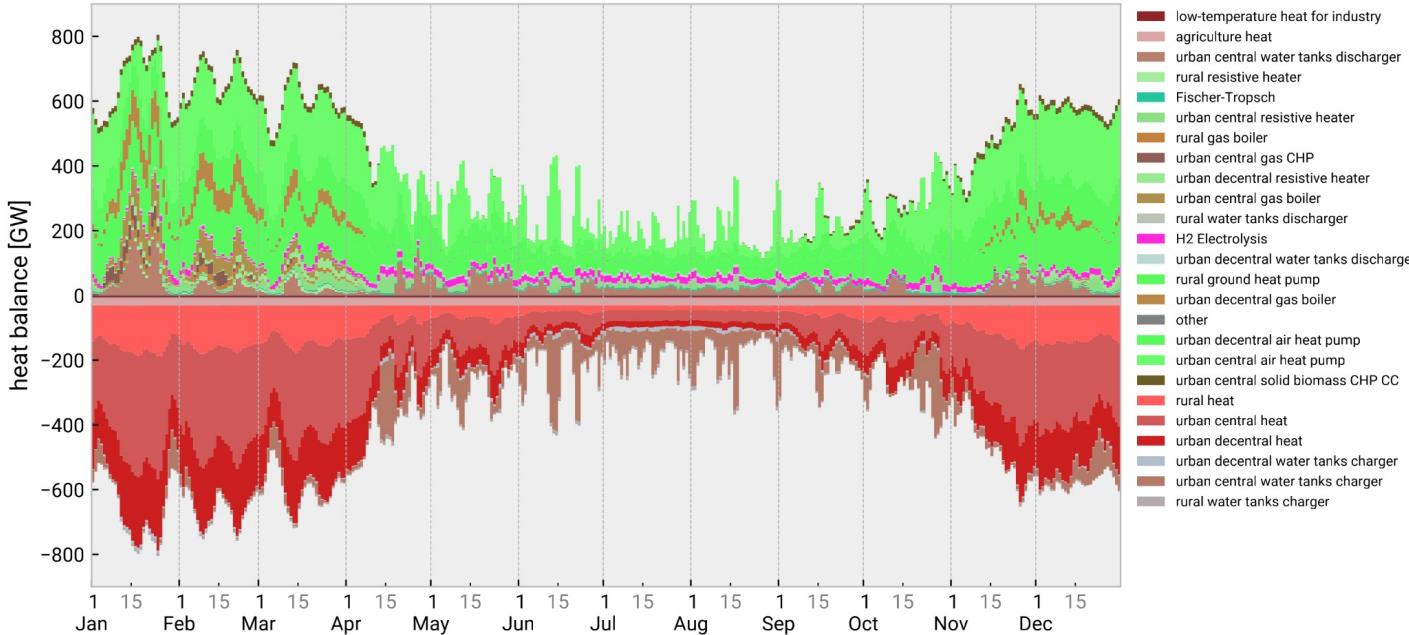


Heating - Heat pumps as new variable supply tech



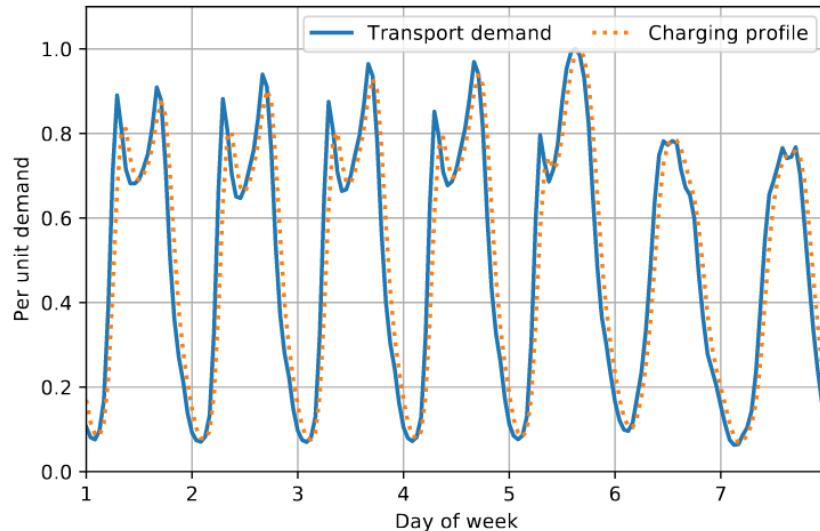
Geothermal heat
sources have
been integrated
very recently!

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.

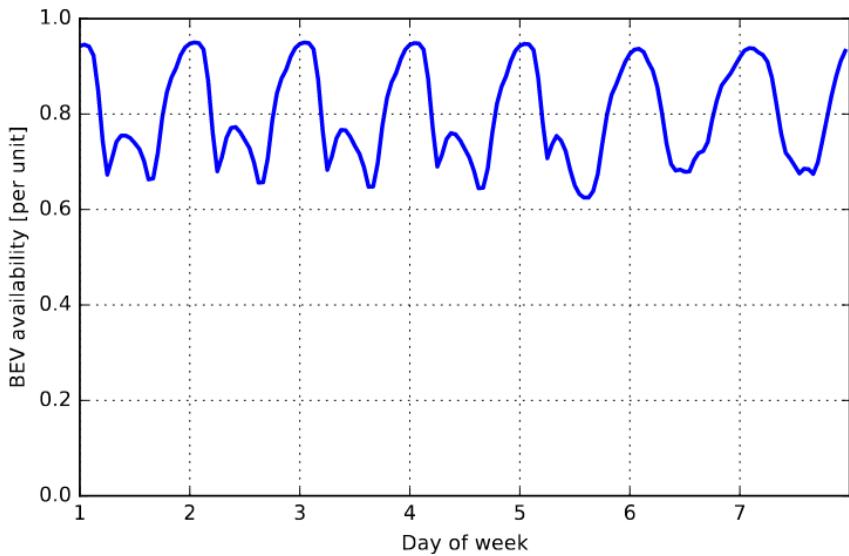
Transport - Electrification of land transport



Weekly profile for the transport demand based on statistics gathered by the German Federal Highway Research Institute (BASt).

- Road and rail transport is fully electrified (vehicle costs are not considered)
- Because of higher efficiency of electric motors, final energy consumption 3.5 times lower than today at 1100 TWh_{el}/a for Europe
- In model can replace Battery Electric Vehicles (BEVs) with Fuel Cell Electric Vehicles (FCEVs) consuming hydrogen. Advantage: hydrogen cheap to store. Disadvantage: efficiency of fuel cell only 60%, compared to 90% for battery discharging.

Transport - BEVs



Availability (i.e. fraction of vehicles plugged in)
of Battery Electric Vehicles (BEV).

- Passenger cars to Battery Electric Vehicles (BEVs), 50 kWh battery available and 11 kW charging power
- Can participate in DSM and V2G, depending on scenario (state of charge returns to at least 75% every morning)
- All BEVs have time-dependent availability, averaging 80%, max 95% (at night)
- No changes in consumer behaviour assumed (e.g. car-sharing/pooling)
- BEVs are treated as exogenous (capital costs NOT included in calculation)

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)

Supply, consumption and storage options by carrier

Electricity (115 regions)		Hydrogen (115 regions)		Liquid Hydrocarbons (not spatially resolved)	
Supply	Withdrawal	Supply	Withdrawal	Supply	Withdrawal
rooftop solar	industry electricity	import by pipeline	Fischer-Tropsch	import by ship	kerosene for aviation
utility-scale solar	residential electricity	import by ship	methanolisation	fossil oil refining	naphtha for industry
onshore wind	services electricity	electrolysis	electrobiofuels	Fischer-Tropsch	diesel for agriculture
offshore wind (fixed-pole/floating, AC/DC-connected)	agriculture electricity	chlor-alkali electrolysis (exogenous)	direct iron reduction	electrobiofuels	
nuclear	air-sourced heat pump	steam methane reforming (w/wo CC)	Haber-Bosch		
hydro reservoirs	ground-sourced heat pump	ammonia cracker	hydrogen turbine (OCGT)		
pumped-hydro	resistive heater		hydrogen fuel cell CHP		
run-of-river	electric vehicle charger		methanol-to-kerosene		
import by HVDC link	battery charger		Sabatier		
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	Methane (not spatially resolved)		Methanol (not spatially resolved)	
	transmission grid	Supply	Withdrawal	Supply	Withdrawal
	battery storage	import by ship	gas for high-T industry heat (w/wo CC)	import by ship	methanol turbine (OCGT)
	pumped-hydro storage	fossil gas	steam methane reforming (w/wo CC)	methanolisation	methanol for shipping
	electric vehicles	biogas upgrading (w/wo CC)	gas boiler (rural/urban)		methanol for industry
		Sabatier	gas CHP		methanol-to-kerosene
			gas turbine (OCGT)		
Storage		Storage		Storage	
hydrocarbon storage		hydrocarbon storage		hydrocarbon storage	
		Ammonia (not spatially resolved)		Ammonia (not spatially resolved)	
Supply	Withdrawal	Supply	Withdrawal	Supply	Withdrawal
		import by ship	ammonia cracker	import by ship	ammonia for fertilizer
Storage		Storage		Storage	
ammonia tank		ammonia tank		ammonia tank	

Supply, consumption and storage options by carrier

Heat (115 regions)		CO2 atmosphere (not spatially resolved)		CO2 commodity (not spatially resolved)					
Supply	Withdrawal	Supply	Withdrawal	Supply	Withdrawal				
air-sourced heat pump	residential heat	kerosene for aviation	solid biomass for industry (w CC)	direct air capture	Fischer-Tropsch				
ground-sourced heat pump (only rural)	services heat	diesel for agriculture	solid biomass CHP (w CC)	biogas upgrading (w CC)	methanolisation				
resistive heater	agriculture heat	methanol for shipping	biogas upgrading (w CC)	gas CHP (w CC)	sequestration				
gas boiler	low-T industry heat	methanol for industry	direct air capture	biomass CHP (w CC)	Sabatier				
biomass boiler	direct air capture	naphtha for industry	electrobiofuels	steam methane reforming (w CC)					
solar thermal	water tank charger	gas boiler		process emissions (w CC)					
water tank discharger		gas CHP (w/wo CC)		solid biomass for industry (w CC)					
biomass CHP (w/wo CC, only DH)		gas turbine (OCGT)		gas for high-T industry heat (w CC)					
gas CHP (w/wo CC, only DH)		methanol turbine (OCGT)							
hydrogen fuel cell CHP (only DH)		process emissions (w/wo CC)							
electrolysis (only DH)		fossil oil refining							
Haber-Bosch (only DH)		gas for high-T industry heat (w/wo CC)							
Sabatier (only DH)		steam methane reforming (w/wo CC)							
Fischer-Tropsch (only DH)									
methanolisation (only DH)									
Storage		long-duration thermal storage (only DH) hot water tank							
				intermediate storage in steel tank long-term geological sequestration					

Myopic pathway optimization

- Provide exogenous CO₂ emission **reduction path**.
- 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.
- The choice of **investment years** is arbitrary.
- **Perfect foresight pathway planning** is currently experimental (i.e. endogenous CO₂ budget).

Running many different scenarios with alternative configurations is straightforward and scalable in **snakemake!**



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

And for myopic pathway optimisation:

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

- 2) Explore CSV files and images in **results** directory.

Users of Windows, add two lines to YAML:

```
run:  
  use_shadow_directory: false
```

Small exploratory configuration tasks

(sector-coupled)

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 methanation as technology option.
3. Increase the carbon sequestration potential to 500 Mt/a.
4. Allow hydrogen underground storage also onshore.
5. Reduce the primary production of plastics by increasing recycling rates.
6. Change the settings of all transmission so that they are lossless.
7. Disable the use of PtX waste heat.

Scenario management

PyPSA-Eur has integrated & scalable scenario management!

config/config.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

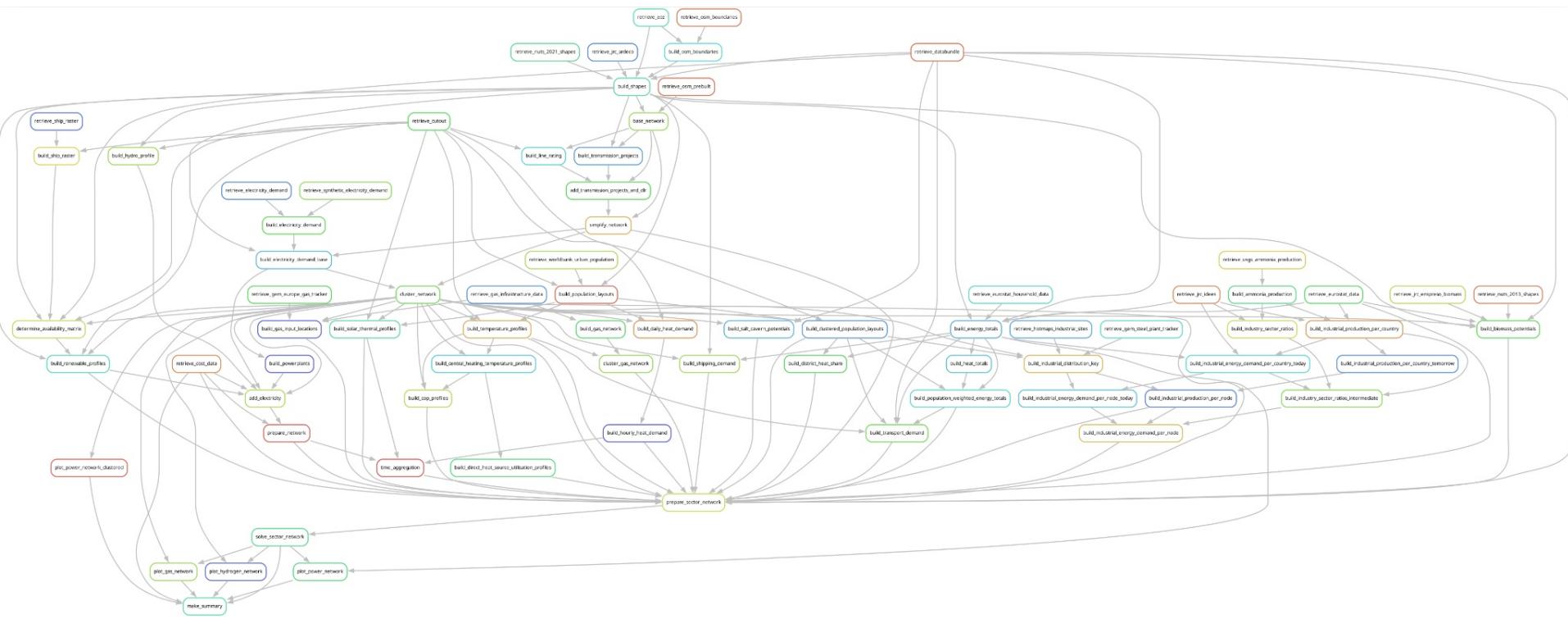
```
no-h2-network:
    sector:
        H2_network: false

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

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

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

Closing remark – There is much more to explore!



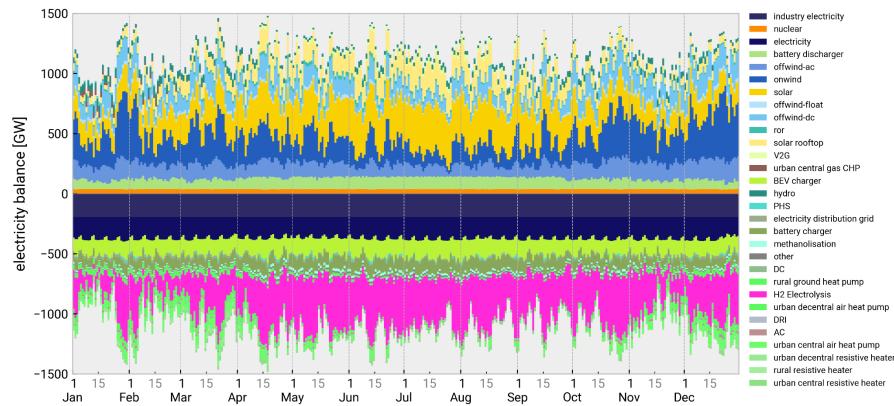
Additional Resources

Documentation

<https://pypsa-eur.readthedocs.io/>

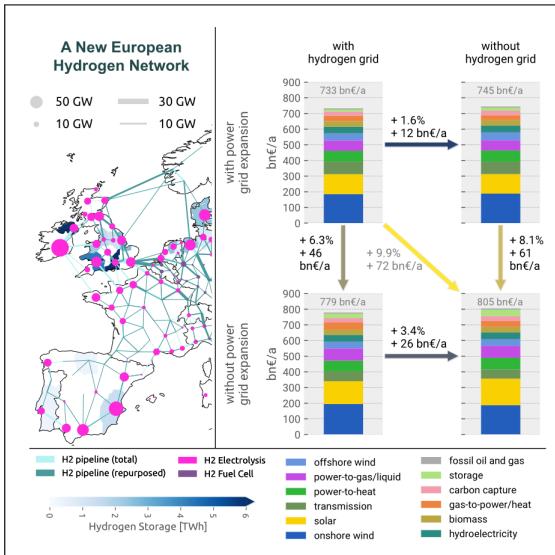
Supplementary Material

[https://www.cell.com/joule/pdfExtended/S2542-4351\(23\)00266-0](https://www.cell.com/joule/pdfExtended/S2542-4351(23)00266-0)



Article

The potential role of a hydrogen network in Europe



We examine the interplay between a continent-wide hydrogen network and electricity grid expansion in Europe to help balance variations in wind and solar energy supply. By adapting existing natural gas pipelines for hydrogen transport, energy system costs can be reduced, especially when power grid reinforcements are not possible. Both types of transmission infrastructure offer cost-effective options for achieving a European energy system with net-zero CO₂ emissions. However, with a 10% cost increase, it is possible to build neither.

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Highlights

Examination of the cost benefit of a European hydrogen network in net-zero emission scenarios

H₂ network reduces system costs by up to 3.4%, highest without power grid expansion

Between 64% and 69% of the hydrogen network uses retrofitted gas network pipelines

Power grid expansion saves more than hydrogen network, but strongest savings with both