PyPSA: Free Software for Investment Planning in Sector-Coupled Energy Systems

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HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

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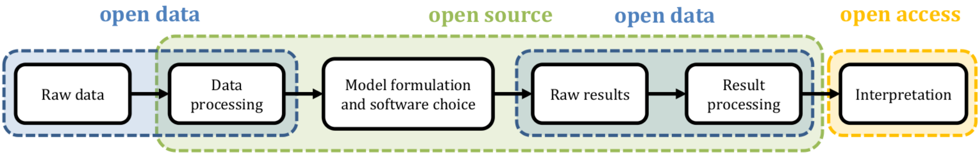
Our Group's Research

- **Cost-effective pathways** to reduce greenhouse gas emissions
- **Co-optimisation** of generation, storage and transmission infrastructure (trade-offs)
- **Power grid reinforcement** requirements with large shares of wind and solar generation
- **Algorithms** to increase the tractability of energy system optimisation (spatial, temporal clustering, model reduction)
- **Open Source** software development and open data

We aim to follow the Idea(l) of Open Energy Modelling

The whole chain from raw data to modelling results should be open:



open data + free software ⇒ transparency + reproducibility

There's an initiative for that! Sign up for the mailing list / come to the next (virtual) workshop:

openmod open energy modelling initiative

http://openmod-initiative.org/

Source: openmod initiative

Agenda

1 Power System Analysis in Python with

PyPSA: Python for Power System Analysis

pypi v0.17.0 | conda-forge v0.17.0 | build passing | docs passing | license GPLv3 | DOI 10.5281/zenodo.786605 | chat on gitter

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2 Data-Driven Modelling with

PyPSA-Eur: An Open Optimisation Model of the European Transmission System

release v0.2.0 | build passing | docs passing | repo size 25.9 MB | DOI 10.5281/zenodo.3520875 | chat on gitter

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3 Sector-Coupling with

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

release v0.1.0 | docs passing | license GPL-3.0 | repo size 743 kB | chat on gitter

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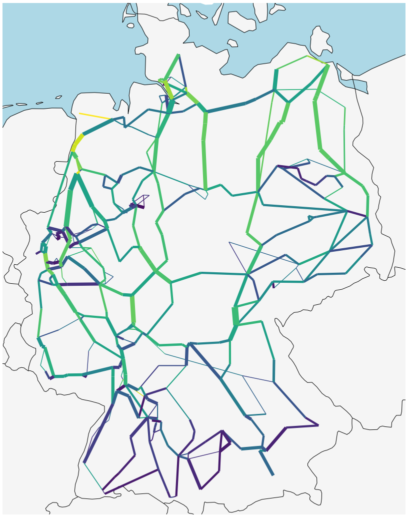
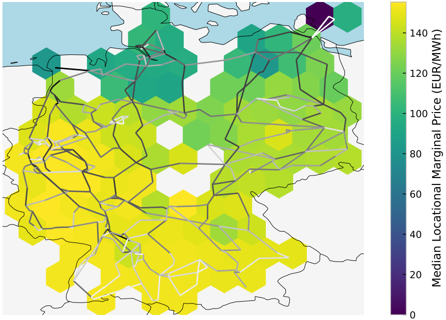
Python for Power System Analysis (PyPSA)

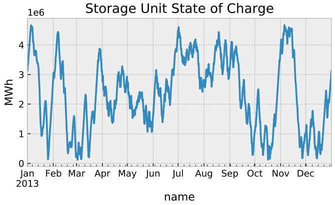
- **Open source** tool for modelling energy systems at **high resolution**.
- Fills missing gap between **load flow software** (e.g. PowerFactory, MATPOWER) and **energy system simulation software** (e.g. PLEXOS, TIMES, OSeMOSYS).
- Good grid modelling is increasingly important, for integration of **renewables** and **electrification** of transport, heating and industry.



PyPSA can do

- Static **power flow** (Newton-Raphson)
- **Linear optimal power flow** (LOPF)
  - multiple periods
  - unit commitment
  - storage units
  - coupling to other sectors
- **Security-constrained LOPF**
- Coordinated total energy system **capacity expansion optimisation**





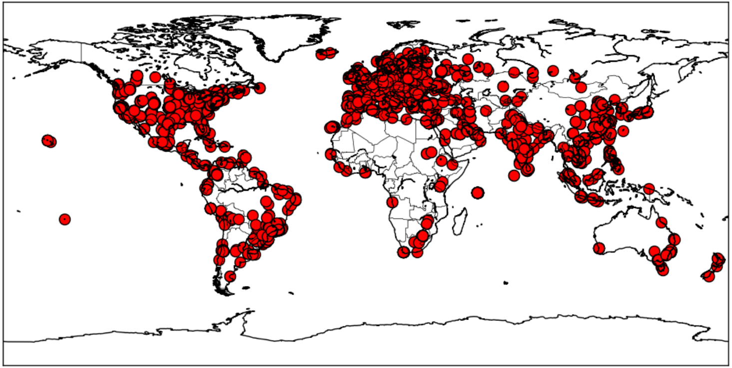
PyPSA has models for

- meshed **AC and DC networks**, with controllable converters
- **standard types** for lines and transformers following the implementation in pandapower
- conventional **dispatchable generators** with **unit commitment**
- generators with **time-varying power availability**, such as wind and solar generators
- **storage units** with efficiency losses; simple **hydroelectricity** with inflow and spillage
- coupling of **other energy carriers**, e.g. P2G, P2L, P2H, DAC, district heating, gas networks, electric vehicles, carbon capture and usage/sequestration (CCU/S)
- **easy to extend**: build complicated assets out of basic components

Worldwide Usage

PyPSA is used worldwide by **dozens of research institutes and companies**, e.g.

- TU Delft
- TransnetBW (TSO)
- Fraunhofer ISE
- Fraunhofer IEG
- DLR Oldenburg
- Shell
- Saudi Aramco
- Reiner Lemoine Institute
- HS Flensburg
- Aarhus University
- Jülich Research Centre
- Chalmers University of Technology
- Frankfurt Institute of Advanced Studies
- Karlsruhe Institute of Technology



Comparison to Other Software Tools

	Software	Language	Version	Free Software	Grid Analysis: Power Flow	Grid Analysis: Continuation Power Flow	Grid Analysis: Dynamic Analysis	Economic Analysis: Transport Model	Economic Analysis: Linear OPF	Economic Analysis: N-1 OPF	Economic Analysis: Nonlinear OPF	Economic Analysis: Multi-Period Optimisation	Economic Analysis: Unit Commitment	Economic Analysis: Investment Optimisation	Economic Analysis: Other Energy Sectors
Power system tools	NEPLAN	–	5.5.8		✓		✓	✓	✓	✓	✓				✓
Power system tools	PowerFactory	–	2017		✓		✓		✓	✓	✓				
Power system tools	PowerWorld	–	19		✓		✓	✓	✓	✓	✓				
Power system tools	PSS/E	–	33.10		✓		✓		✓	✓	✓				
Power system tools	PSAT	MATLAB	2.1.11	✓	✓	✓	✓		✓		✓	✓	✓		
Power system tools	MATPOWER	MATLAB	7.0	✓	✓	✓		✓	✓		✓				
Power system tools	PYPOWER	Python	5.1.4	✓	✓			✓	✓		✓				
Power system tools	pandapower	Python	2.2.2	✓	✓			✓	✓		✓				
Power system tools	PowerDynamics.jl	Julia	2.3.1	✓			✓								
Power system tools	PowerSimulations.jl	Julia	0.5.5	✓				✓	✓		✓	✓	✓		
Power system tools	PowerModels.jl	Julia	0.17.2	✓	✓				✓		✓	(✓)	✓		
	PyPSA	Python	0.17.0	✓	✓			✓	✓	✓		✓	✓	✓	✓
Energy system tools	calliope	Python	0.5.2	✓				✓				✓		✓	✓
Energy system tools	oemof	Python	0.4.0	✓				✓				✓	✓	✓	✓
Energy system tools	OSeMOSYS	various	2020	✓				✓				✓		✓	✓
Energy system tools	PowerGAMA	Python	1.1	✓				✓	✓			✓			
Energy system tools	TIMES	GAMS	4.4.2	(✓)				✓	✓			✓	✓	✓	✓
Energy system tools	PLEXOS	–	8.1					✓	✓	✓		✓	✓	✓	✓
Energy system tools	PRIMES	–	2017					✓	✓			✓	✓	✓	✓

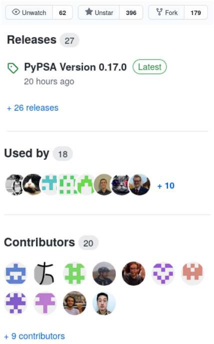
Technical Details

PyPSA leans heavily on

- **pandas** for storing data about components and time series
- **numpy** and **scipy** for linear algebra and sparse matrices
- **networkx** for some network calculations
- **pyomo** for preparing optimisation problems
- **cartopy** for plotting networks on a map
- **py.test** for unit testing (PYPOWER and pandapower)

Recent and current developments include

- **custom optimisation framework** as alternative to pyomo
- **multi-horizon** investment optimisation



Simple Example

```
import pypsa

n = pypsa.Network("mynetwork.nc")

n.lopf(solver_name="cbc", pyomo=False, solver_options={"primalT": 1e-4})

n.generators.p_nom_opt                      # static attributes

n.generators_t.p                            # time-dependent attributes

n.plot(geomap=True, line_colors=n.lines_t.p0.abs().mean())

n.pf()                                      # AC power flow
```

Example Problem: Greenfield Power System Investment Planning

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

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

subject to

- meeting energy demand at each node n (e.g. region) and time t (e.g. hour of year)
- 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 CO_2 emission reduction targets

Challenges of Data-Driven Modelling

- Many different data **sources**
- Many data sources need **cleaning** and processing before they can be used
- Many **intermediate scripts** and datasets
- Often **dependencies** are not clear (both data and software)
- Data and code **change** over time
- Want to be able to **reproduce** results
- Want to run many **parametric scenarios** for same model

Workflow Management Tool `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/greatstuff.pdf`

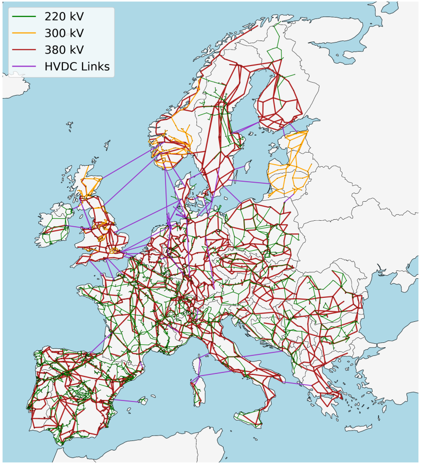
Support for Bash, Python, Julia, and R scripts. Neat cluster integration.

What is PyPSA-Eur?

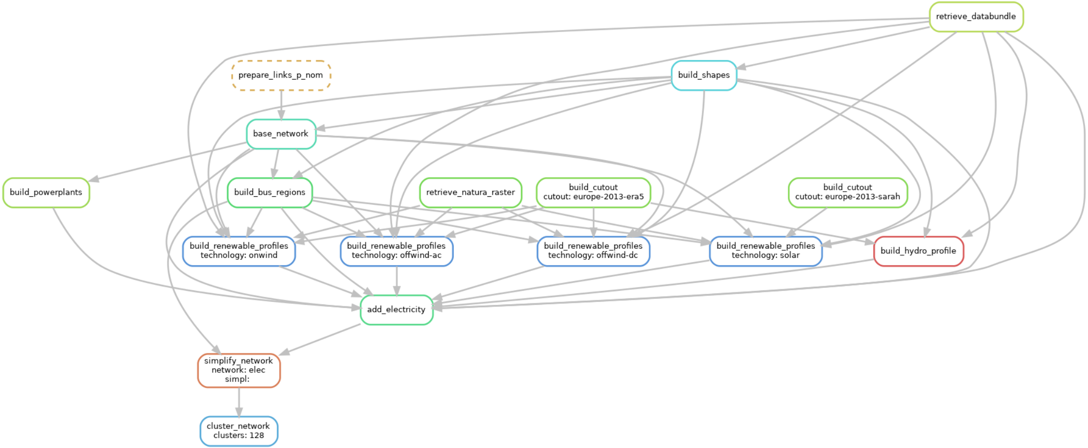
An automated and configurable workflow to build a model of the European power system from open data.

Covers the ENTSO-E area and contains

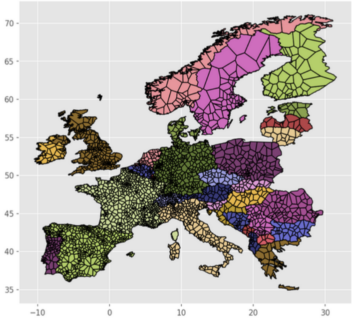
- all AC lines at and above 220 kV, substations and HVDC links,
- a database of conventional power plants,
- time series for electrical demand,
- time series for variable renewable generator availability, and
- geographic potentials for the expansion of wind and solar power.



Snakemake for PyPSA-Eur: Building Model



Installable Potential and Land Eligibility



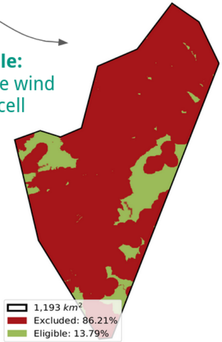
example:
onshore wind
in one cell

Geospatial Land Availability for Energy Systems (GLAES)

JÜLICH FORSCHUNGSZENTRUM

DOI 10.5281/zenodo.1122558

Severin Ryberg
github.com/FZJ-IEK3-VSA/glaes



- **CORINE 2018** land cover
  - eligible codes
  - distances
- **NATURA 2000** natural protection areas
- **GEBCO 2018** bathymetry dataset
- **Density:** capacity per km²

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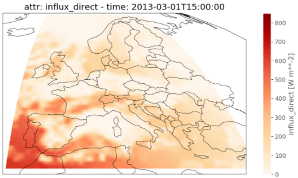
Derivation of Time Series of Variable Renewables

Reanalysis weather data
from **ERA-5** and **SARAH-2**
(up to 40 years, 30x30 km)

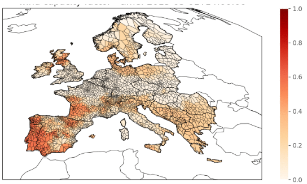
https://atlite.readthedocs.io/
https://github.com/PyPSA/atlite

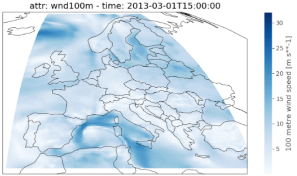
Atlite: Convert weather data to energy systems data

pypi v0.0.2 | conda-forge v0.0.2 | docs passing | license GPLv3

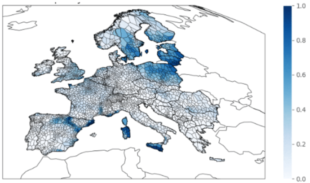


Solar panel models
- orientation
- material





Wind turbine models
- power curve
- surface roughness



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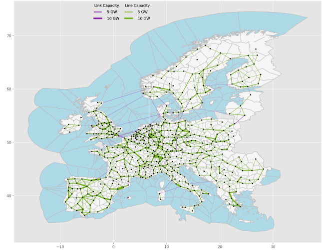
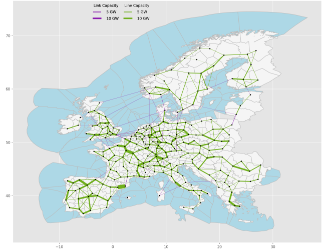
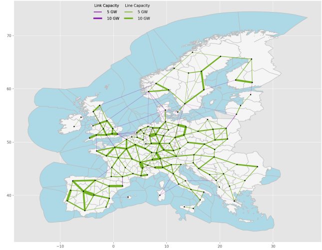
Network Clustering



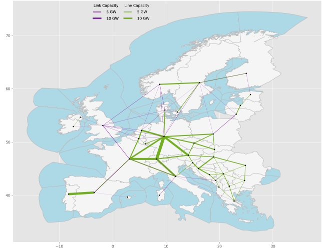
512 nodes



256 nodes



128 nodes



37 nodes

Snakemake for PyPSA-Eur: Managing Scenarios

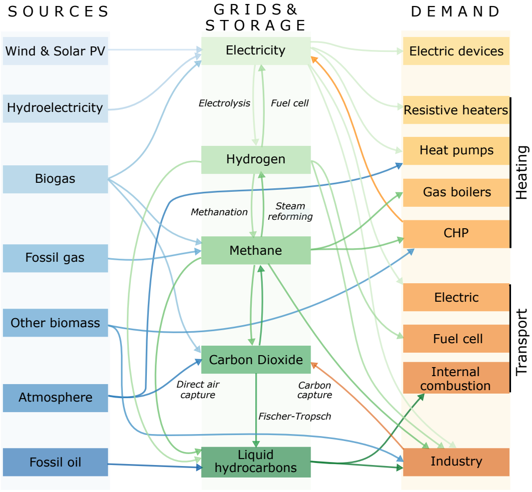
What is PyPSA-Eur-Sec?

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

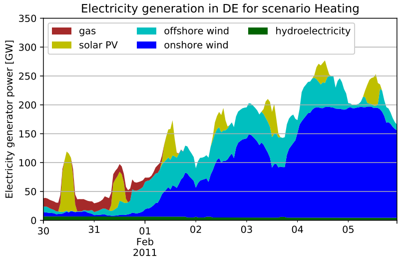
Extends **PyPSA-Eur** power system model with

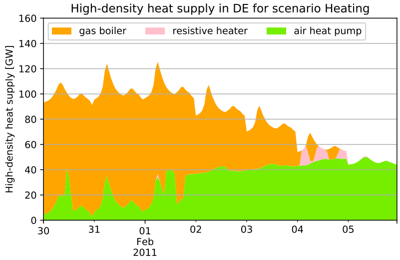
- transport sector
- heating sector
- industry sector
- aviation
- shipping
- industrial feedstocks
- biomass
- better carbon management
- carbon capture and usage/sequestration
- gas networks

⟶ multiple inputs/outputs



Example problem with balancing: Cold week in winter





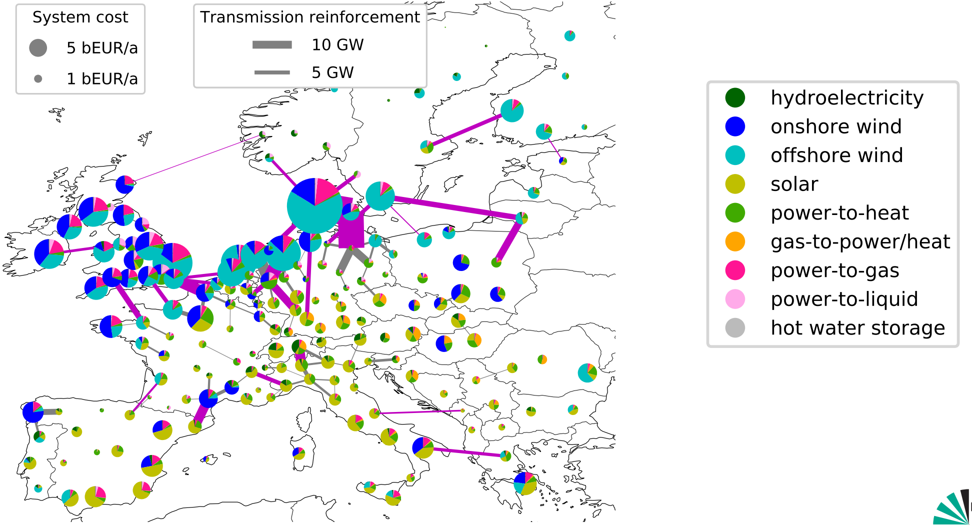
There are difficult periods in winter with:

- **Low** wind and solar generation
- **High** space heating demand
- **Low** air temperatures, which are bad for air-sourced heat pump performance

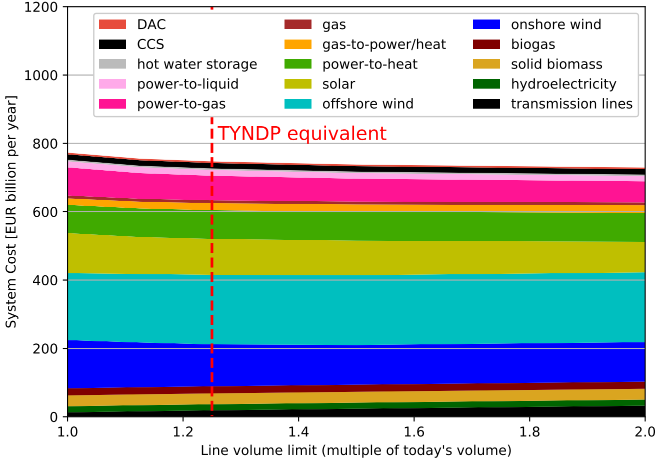
Less-smart solution: **backup gas boilers** burning either natural gas, or synthetic methane.

Smart solution: **long-term thermal energy storage** in **district heating networks** and efficient **combined-heat-and-power plants**.

Preliminary: Zero Emissions – 25% more grid volume (TYNDP)



Preliminary: Benefit of grid expansion for sector-coupled system



- Direct system costs **bit higher than today's system**
- Systems **without grid expansion** are feasible, but more costly
- As grid is expanded, **costs reduce** from solar and P2G; more offshore wind
- Total cost benefit of extra grid: $\sim$ € 47 billion per year
- **Over half of benefit available at 25% expansion** (like TYNDP)
- easy to implement with `snakemake`

Conclusion

PyPSA is for researchers, planners and utilities who need an easy-to-use tool for power system analysis.

Not so useful for

- dynamic analysis (differential equations)
- short-circuit calculations
- multiphase and unbalanced load flow
- low-voltage distribution grids

Useful for

- investment planning with high spatial and temporal scope and detail
- electricity market analysis
- coupling to other sectors
- adding custom constraints and components

PyPSA-Eur and PyPSA-Eur-Sec

Configurable workflows to build detailed power/energy system models from open data that can be used for both operational and investment planning studies.

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Resources

Find the slides:

https://neumann.fyi/files/pesgm2020.pdf

Reach out:

fabian.neumann@kit.edu

Find the energy system model:

Code: https://github.com/pypsa/pypsa-eur

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

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