Open Energy Transition
from the creators of PyPSA meets Earth

Maximize Impact with Open Energy Planning Solutions

OET energy modelling exchange

Dr. Maximilian Parzen
January 13th 2025

Introduction

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Maximilian Parzen
Co-Founder & CEO

PhD in Energy System Modelling
University of Edinburgh

Our Goal as Non-Profit Company:
Accelerating the energy transition by empowering energy planners through open-source software and open data solutions.

Our Approach:

- Perform **reproducible** energy planning **studies**
- Advance **open-source software** and **open data** for energy planning
- Provide reliable industry **support** and **training**

Our Clients and Partners:

- Transmission System Operators (e.g. ENTSO-E)
- Regulators (e.g. ACER)
- Non Governmental Organizations (e.g. Project Innerspace, EDF)
- Universities (e.g. Stanford University)
- Industries (e.g. Form Energy)
- Philanthropies (e.g. Breakthrough Energy, Google.org)

GOAL:

1. Learn about **Grid Modelling Landscape**
2. Learn about **Storage Modelling Challenges**
3. Learn about **PyPSA capabilities**

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Tools and Applications

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Relevant to TESLA Masterplan/ Autobidder team

Category	Real-time Models	Market Models	Investment Models
Applications	Operational feasibility, reliability and power quality assessments.	Production cost optimization, market simulation, resource adequacy.	Investment decisions, technology assessment, resource adequacy, decarbonization pathways.
Tools (proprietary)		PLEXOS	
	PowerFactory/ PSSE		
Tools (open-source)		**PyPSA/** GenX	
	PowSyBl/ Sienna		

System Models usually Minimise System Costs

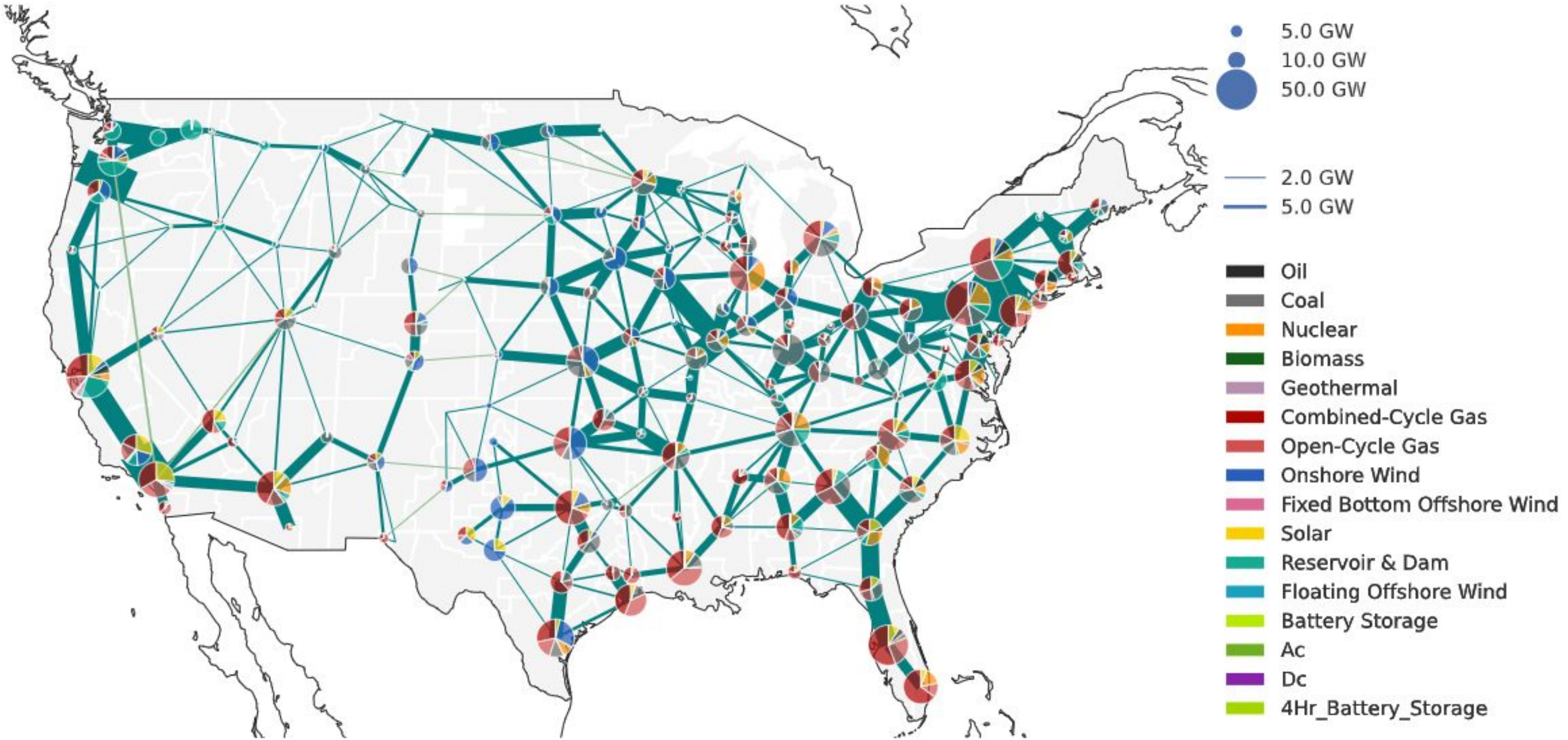
[3] Objective: minimise the total system cost that consist of

- investment costs in new generation projects
- investment costs in new storage capacity
- investment costs in new transmission line projects
- variable costs, such as costs for fuels or maintenance

$$\underset{G,H,F,g,h,e}{\text{minimize}}\ AC = \Bigg[\sum_{i,r}(c_{i,r} \cdot G_{i,r}) + \sum_{l}(c_l \cdot F_l) + \sum_{i,s}(c_{i,s}^{store} \cdot H_{i,s}^{store} + c_{i,s}^{-} \cdot H_{i,s}^{-} + c_{i,s}^{+} \cdot H_{i,s}^{+})$$

$$+ \sum_{i,r,t}(o_{i,r} \cdot g_{i,r,t} \cdot w_t) + \sum_{i,s,t}((o_{i,s}^{+} \cdot h_{i,s,t}^{+} + o_{i,s}^{-} \cdot h_{i,s,t}^{-}) \cdot w_t) + \sum_{i,s,t}(o_{i,s}^{store} \cdot e_{i,s,t} \cdot w_t)\Bigg]$$

Dispatch and investment co-optimization example - PyPSA-USA Model



What is Open Modelling?

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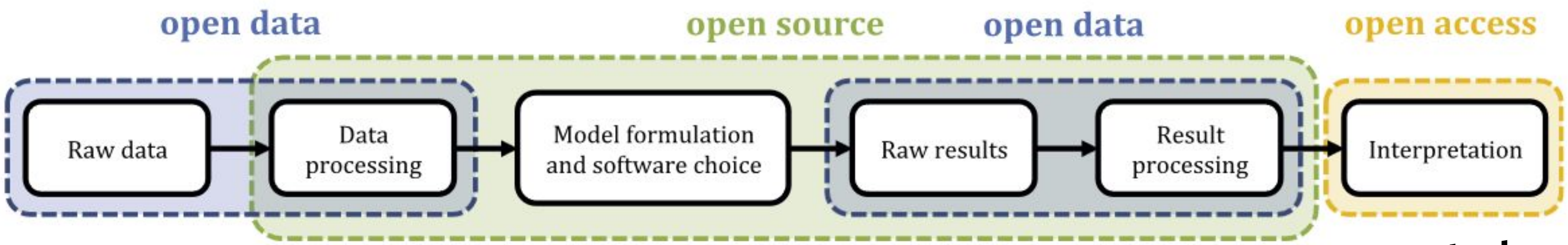


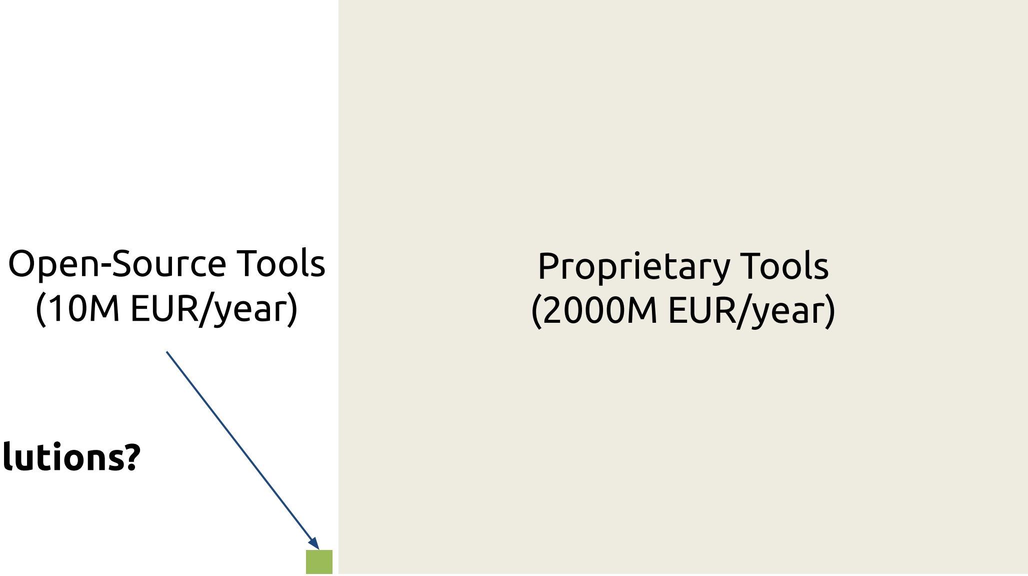
e.g. study

Benefits:

- + Transparency = Trust
- + No vendor lock-in = Freedom
- + No need to reinvent the wheel = Faster innovation
- + Faster insight generation (e.g. model generators like PyPSA-Earth save 10x time)

= Faster and better energy transition planning

Energy Planning Software Landscape in 2025



What was holding back open-source solutions?

- Missing commercial support
- Missing functional coverage
- Missing reference list
- Missing knowledge/ marketing
- …

OS energy planning is coming!

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- More than 500k downloads per year*
- Used by system operators, traders, regulators, manufacturers, universities
- People start implementing alternative solutions to proprietary software (e.g. OET enhances or replaces proprietary software tools with open-source solutions)

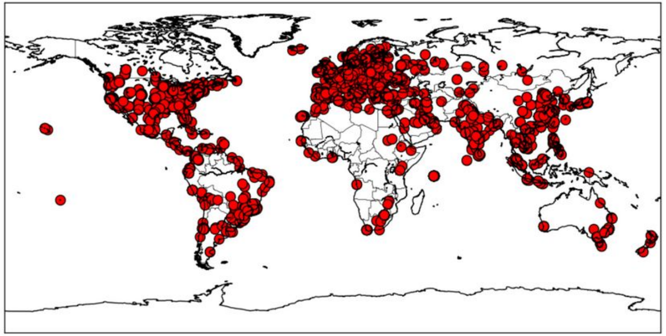

Fig. Showing PyPSA download locations @credit to Tom Brown

*based on PyPI estimates from PyPSA and pandapower

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

entsoe

BOSCH

iea International Energy Agency

Canada Energy Regulator

icct THE INTERNATIONAL COUNCIL ON CLEAN TRANSPORTATION

TATA STEEL

Stanford University

ACER European Union Agency for the Cooperation of Energy Regulators

Breakthrough Energy

TRANSNET BW

giz Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH

European Commission JOINT RESEARCH CENTRE

Rte

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Energy Storage Modelling Challenges

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  - Bad input assumptions (missing grid data etc.)
- Bad system modelling
  - Low spatial / temporal / technological resolution
  - Unintended storage cycling (=simultaneous charging/discharging)
  - Constrained energy storage sizes
  - Missing sector coupling

In total ~30% impact on total system cost and large impact on optimal tech mix

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PyPSA

An open source toolbox for simulating and optimising modern power and energy systems

PyPSA - Tool Adoption Indicators

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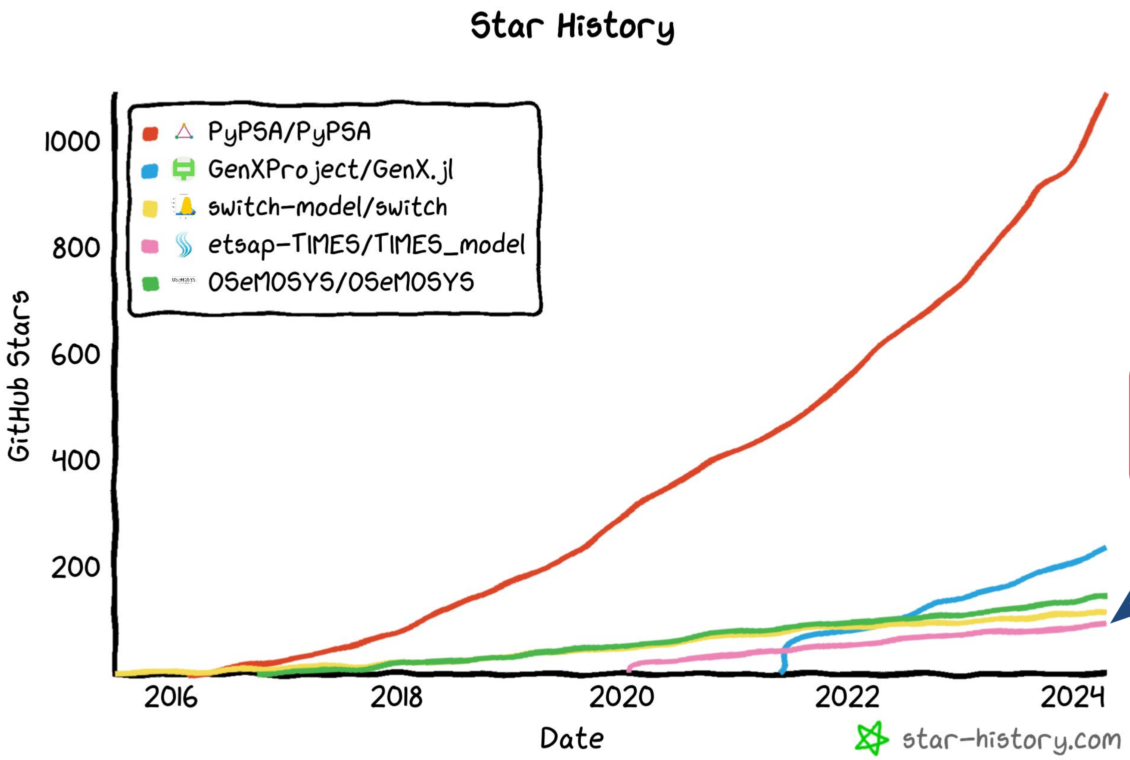

PyPSA,
>1200 stars

TIMES,
>98 stars

Performance example

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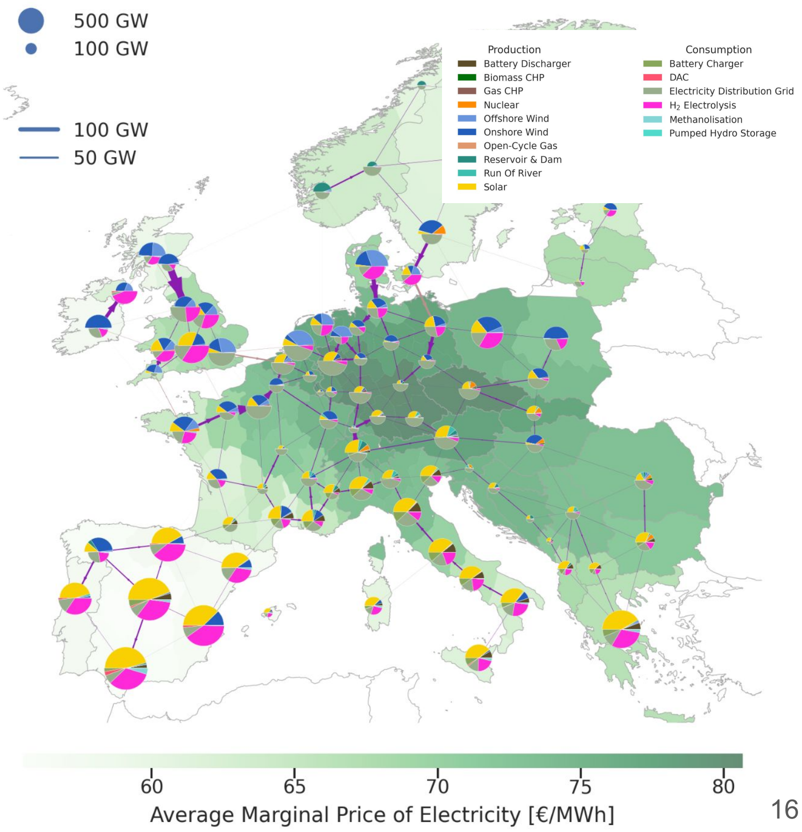
	Power Only	Sector Coupled
Type	Single year	Single year
Spatial Resolution	110 nodes	110 nodes
Temporal Resolution	3h	3h
# Constraints	11.4M	46M
# Variables	5.4M	21M
# Non-Zeros	23.3M	112M
Memory Peak	**11 GB**	**80 GB**
Solving time	**0.5h**	**29h**

Electricity Balance (CO_2-Grid Model)



Model type + Existing Technical Capabilities Part I

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Optimization Problems

Capacity expansion (linear)

- Co-optimization of invest+operations
- Single-horizon (single-year, myopic)
- Multi-horizon (perfect foresight)
- Modeling to Generate Alternatives (MGA), Monte-Carlo Sampling
- Solve LP, MILP and QP problems

Market modelling (linear)

- Linear optimal power flow (LOPF)
- Security-constrained LOPF (N-1, N-X)
- Unit commitment
- Dispatch & redispatch

Non-linear power flow

- Newton-Raphson

+

Components

- **Generators:** with unit commitment and hourly time series
- **Transmission**: Meshed AC-DC networks (Transmission)
- **Storage**: Includes efficiency losses and inflow/spillage for hydro
- **Conversion** between energy carriers & materials (enables PtX, CHP, BEV, DAC, CO2 networks, material/data flows, …)

Planned Technical Capabilities

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- **Uncertainty:**
  - Stochastic single stage optimization (Ongoing dev)
  - Bender-decomposition (Maybe, screening of literature especially GenX)
- **Feature:**
  - Linearised gas pipeline flow (Concept done)
  - Disaggregation methods from low to high-res networks (Done, but not in main branch)
  - Add missing power flow components for better interoperability (Concept done)
- **Backend:**
  - Pydantic for stable interfaces/type checking (Maybe)
  - Polars instead of Pandas for slight performance increase (Maybe)
  - Solver callbacks implementation in Linopy (Maybe)
  - PyOptInterface for solver interface acceleration (Maybe)

Interoperability

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Converters that import and/or export the PyPSA network file.

- PyPOWER
- Pandapower
- Switch
- EnergyRT
- GenX (not public)
- Sienna-Invest (planned)
- Others …

Speed and **memory** matters.
PyPSA is build on top of solver interface **Linopy.**

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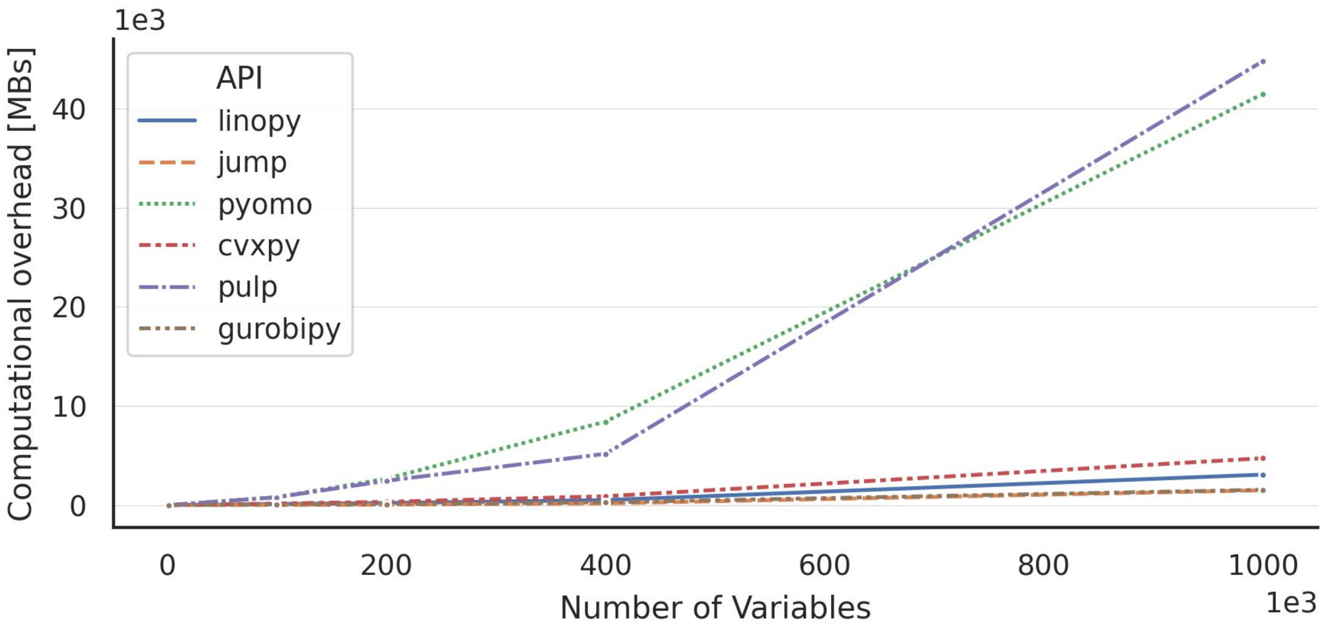
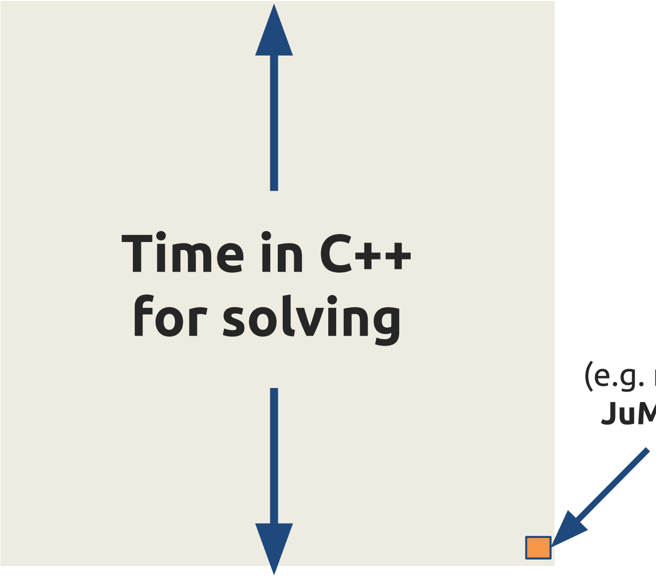


pyomo/ pulp

jump/ **linopy**/
cvxpy/ gurobipy

The **programming language** is <u>**not**</u> the **speed bottleneck** for capacity expansion and market modelling

<u>Time spent for each optimization:</u>



Time in other programming language
(e.g. mainly solver interface like **JuMP for Julia** or **Linopy for Python**, GAMS)

NEWS - "Python solver interfaces can be faster than other options"

Solver interface benchmark

Time (second) to generate model and pass it to Gurobi optimizer.

Model	Variables	C++	PyOptInterface	JuMP	gurobipy	Pyomo
fac-25	67651	0.2	0.2	0.2	1.2	4.1
fac-50	520301	0.8	1.2	1.8	9.7	32.7
fac-75	1732951	2.7	4.1	6.6	32.5	119.3
fac-100	4080601	6.3	10.0	17.8	79.1	286.3
lqcp-500	251501	0.9	1.5	1.3	6.3	23.8
lqcp-1000	1003001	3.7	6.0	6.1	26.7	106.6
lqcp-1500	2254501	8.3	14.0	17.7	61.8	234.0
lqcp-2000	4006001	14.5	24.9	38.3	106.9	444.1
			Python	Julia		

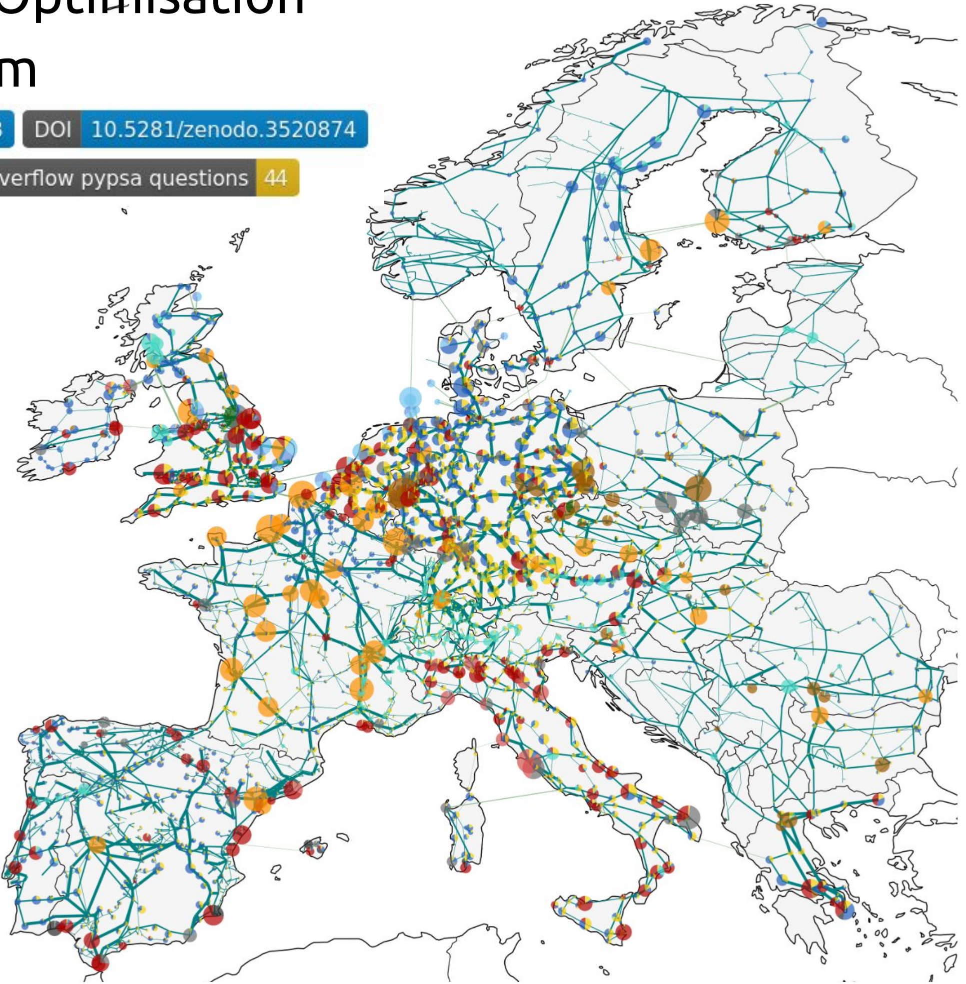
https://www.linkedin.com/posts/maximilian-parzen-b047a1126_python-pytoptinterface-optimization-activity-7185910141442043905-3Mqy

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

release v0.13.0 | Test workflows passing | docs passing | repo size 109.3 MiB | DOI 10.5281/zenodo.3520874 | DOI 10.5281/zenodo.3938042 | snakemake ≥8.14.0 | REUSE compliant | stackoverflow pypsa questions 44

Automated workflow to build **European PyPSA networks** from open data. The network includes:

- all AC lines at and above 220 kV, substations and (planned) HVDC links,
- a database of existing power plants,
- time series for electrical demand,
- time series for wind/solar availability, and geographic potentials
- methods for model simplification



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

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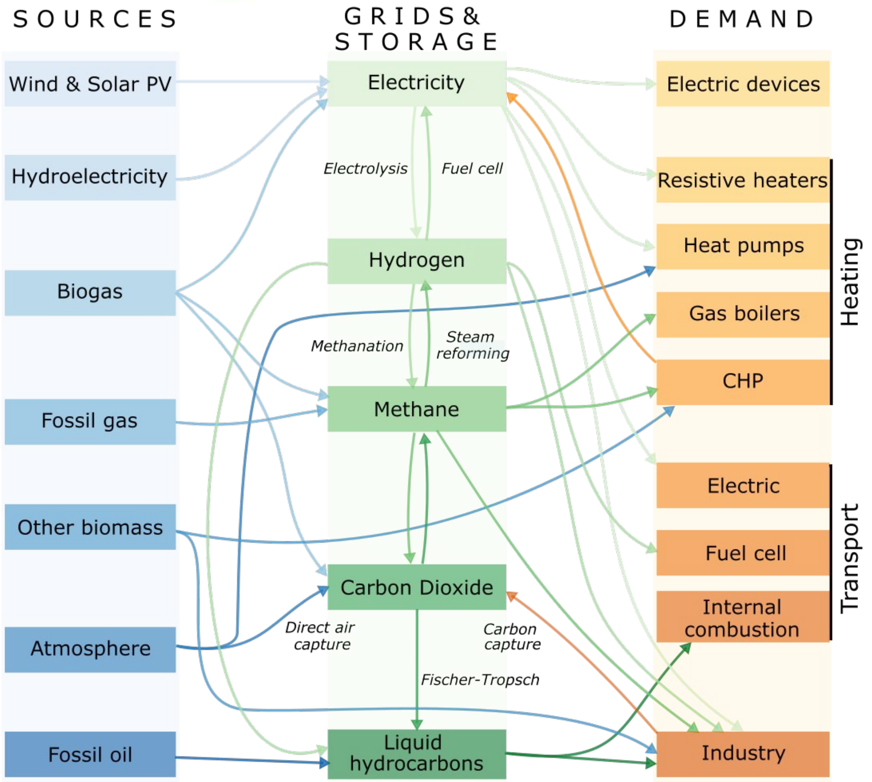
Need to decarbonise all sectors obeying spatial and temporal constraints.

Sector-coupled power system model, including

- transport sector
- heating sector
- industry sector
- international shipping and aviation
- industrial feedstocks and biomass
- better carbon management
- hydrogen and gas networks
- pathway optimisation (myopic)



PyPSA-Earth. A Flexible Python-based Open Optimisation Model to Study Energy System Futures

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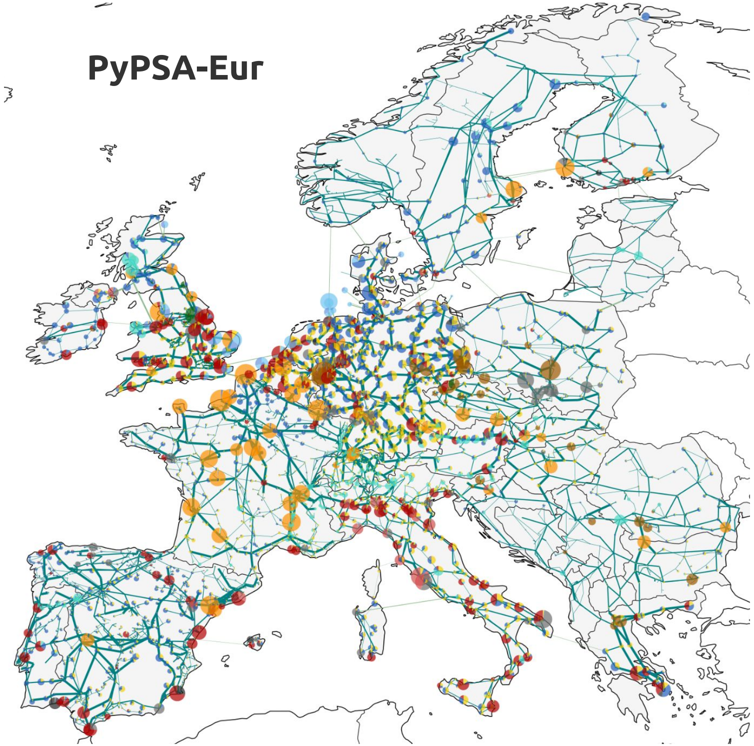
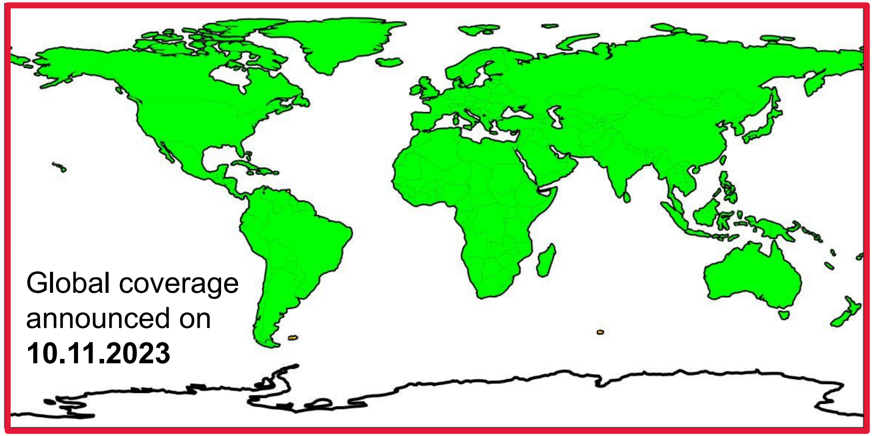
Test workflows passing | docs passing | repo size 26.5 MiB | License AGPLv3 | REUSE compliant | code style black

pre-commit.ci passed | chat 90 online | Google Drive



PyPSA-Earth extends the **automated model workflow** for the **rest of the world.**



workflow runs

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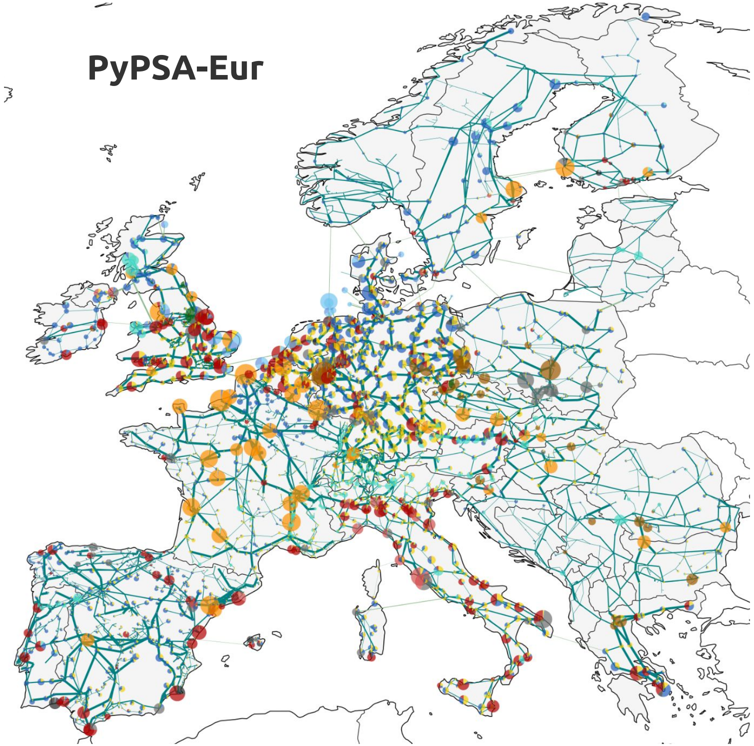

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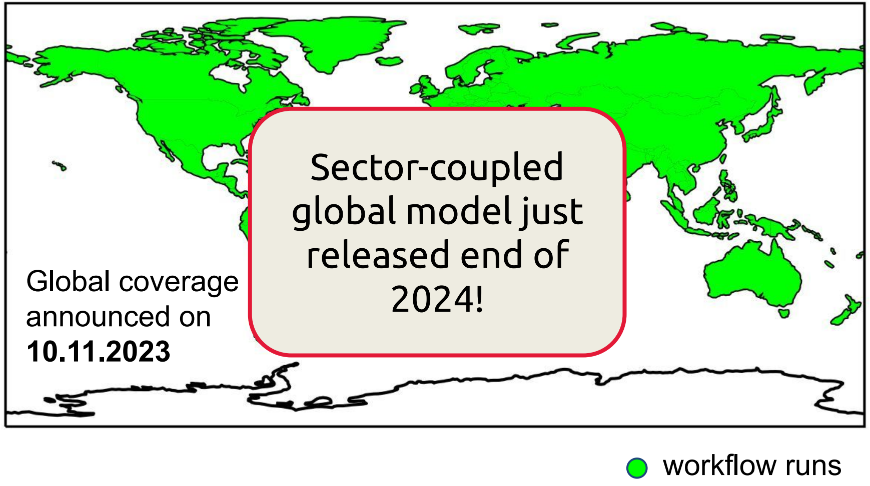


“DATA IS THE NEW GOLD”

Data tools maintained in the PyPSA universe

ENERGY
DATA

- **atlite.** A Python package to convert weather data to energy system data
- **powerplantmatching.** A Python package for creating a more complete power plant database
- **earth-osm.** A Python package to extract large amounts of OpenStreetMap energy infrastructure data
- **technology-data.** Python package to compile techno-economic assumptions for energy system models

Atlite: A Python Package for Calculating Renewable Power Potentials and Time Series

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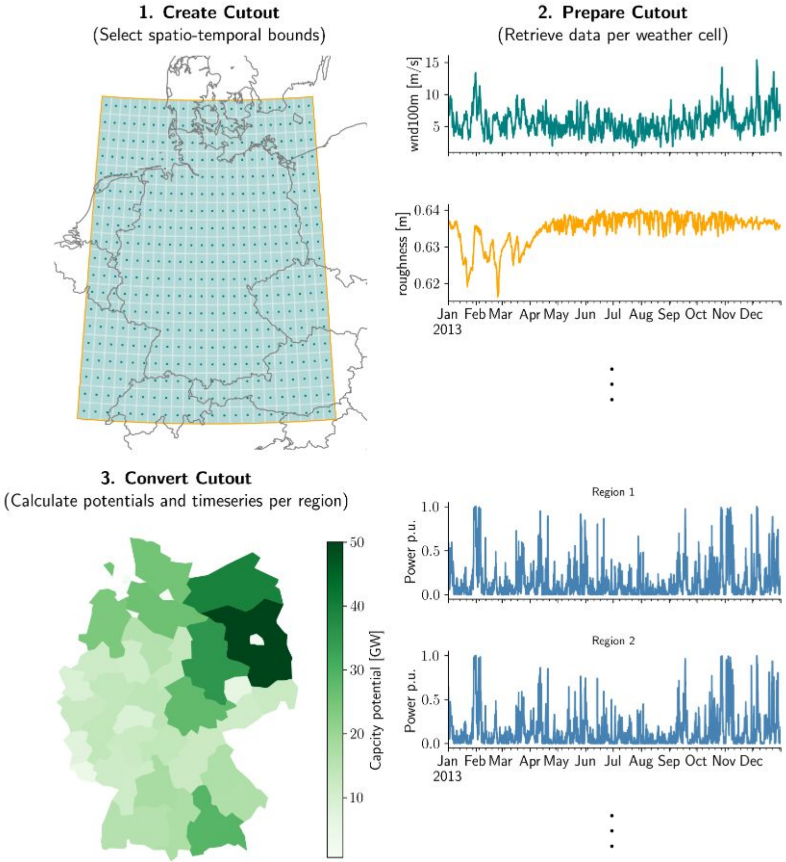
pypi v0.2.12 | conda-forge v0.2.12 | docs passing | CI passing | codecov 72% | readme style sta
REUSE compliant | code style black | pre-commit.ci passed | JOSS 10.21105/joss.03294 | chat 33
stackoverflow pypsa questions 14

Atlite can also perform **land eligibility analyses**, differentiating between conflicting land use options:

- Exclude protected and reserved areas
- Exclude farm land
- Exclude cities for certain technologies
- Increase potential in deserts

It can also convert **global weather data** into **energy systems data**:

- solar photovoltaics & thermal collectors
- wind turbines
- hydro run-off, reservoir, dams
- heat pump COPs
- dynamic line rating
- heat demand (HDD)



Big open data efforts in 2025!

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1. Improve globally **open grid data** coverage and quality!

2. Create a global **open electricity time series** database!

3. Improve existing **open-source data tools!**

THANK YOU!

APPENDIX

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Energy Storage Modelling Challenges

- Bad system data
    - Bad input assumptions (missing grid data etc.)
- Bad system modelling
    - Low spatial / temporal / technological resolution
        - Models with high-resolution capacity placement for wind and solar **reduce total system costs by up to 10%.**
        - Models with high network resolution that better consider congestion, **increase total system costs by 23%.**
        - Models that include a mix of affordable long-term/ short-term storages options **reduce total system costs by 20%.**

Source: Frysztacki, Brown, et al. (2021), The strong effect of network resolution on electricity system models with high shares of wind and solar, Applied Energy, https://doi.org/10.1016/j.apenergy.2021.116726, Parzen et al. (2023) . "The Value of Competing Energy Storage in Decarbonized Power Systems". arXiv, https://doi.org/10.48550/arXiv. 2305.0979

Energy Storage Modelling Challenges

- Bad system data
  - Bad input assumptions (missing grid data etc.)
- Bad system modelling
  - Low spatial / temporal / technological resolution
  - Unintended storage cycling (=simultaneous charging/discharging)
    - Models with USC misleadingly show **increased full load hours by up to 23% for energy storage and 5% for RES**
  - Constrained energy storage sizes
  - Missing sector coupling

Source: Parzen et al. (2023), Reducing energy system model distortions from unintended storage cycling through variable costs, iScience, https://doi.org/10.1016/j.isci.2022.105729

Energy Storage Modelling Challenges

- Bad system data
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- Bad system modelling
  - Low spatial / temporal / technological resolution
  - Unintended storage cycling (=simultaneous charging/discharging)
  - Constrained energy storage sizes
    - Models with flexible energy storage energy to power ratios **reduces the total system costs by 10%.**
  - Missing sector coupling

Source: Parzen et al. (2022), Beyond cost reduction: improving the value of energy storage in electricity systems, Carbon Neutrality, https://doi.org/10.1007/s43979-022-00027-3

Energy Storage Modelling Challenges

- Bad system data
  - Bad input assumptions (missing grid data etc.)
- Bad system modelling
  - Low spatial / temporal / technological resolution
  - Unintended storage cycling (=simultaneous charging/discharging)
  - Constrained energy storage sizes
  - Missing sector coupling
    - Models with sector coupling can **reduce total system costs by up to 28%.**

Source: Brown et al. (2018), Synergies of sector coupling and transmission reinforcement in a cost-optimised, highly renewable European energy system, Energy, https://doi.org/10.1016/j.energy.2018.06.222

PyPSA - Tool Adoption Indicators

downloads 292k

downloads/month 7k

Forks (Code Copies): 429

Issues (Ideas/Bugs):

- 83 Open
- 233 Closed

Pull Requests (Code changes):

- 22 Open
- 514 Closed

Discord members: ~1000

Google Groups members: 749

Questions per month: 70

Total questions answered: ~1500

More than **2000 closed Pull Request** in the models PyPSA-Earth, PyPSA-USA, PyPSA-Eur

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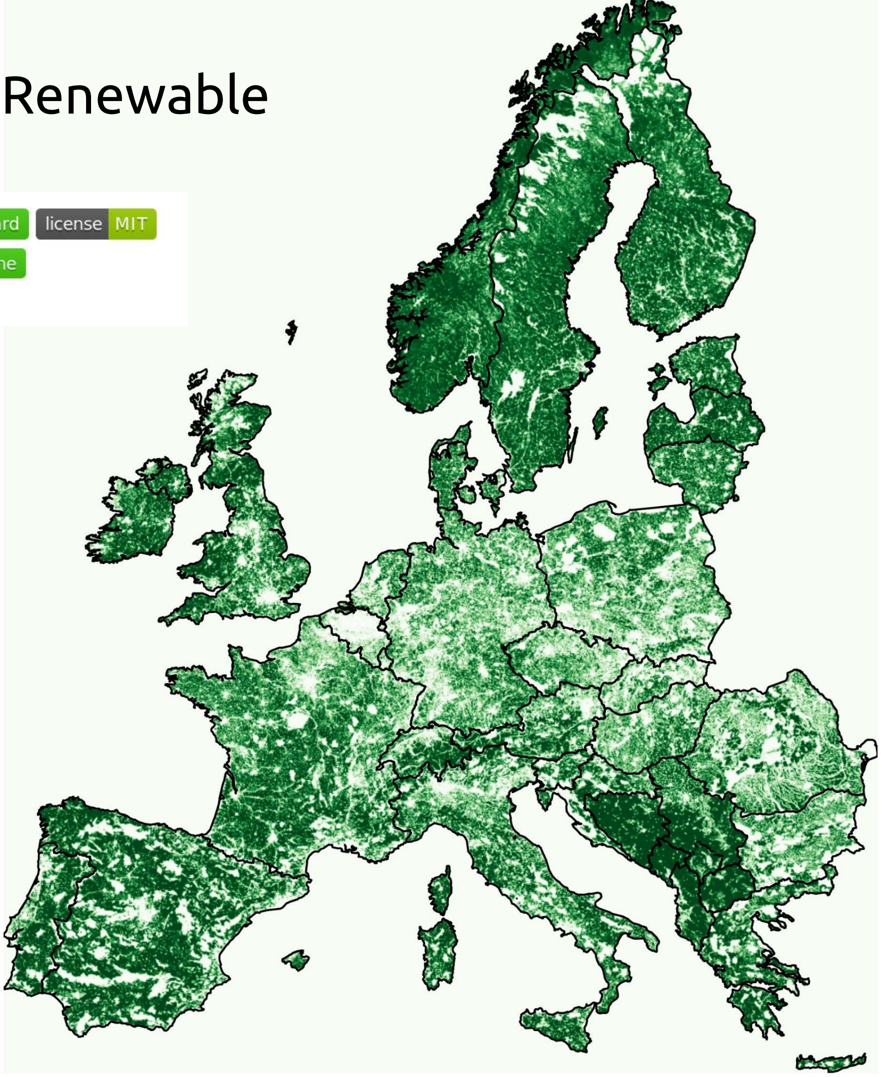


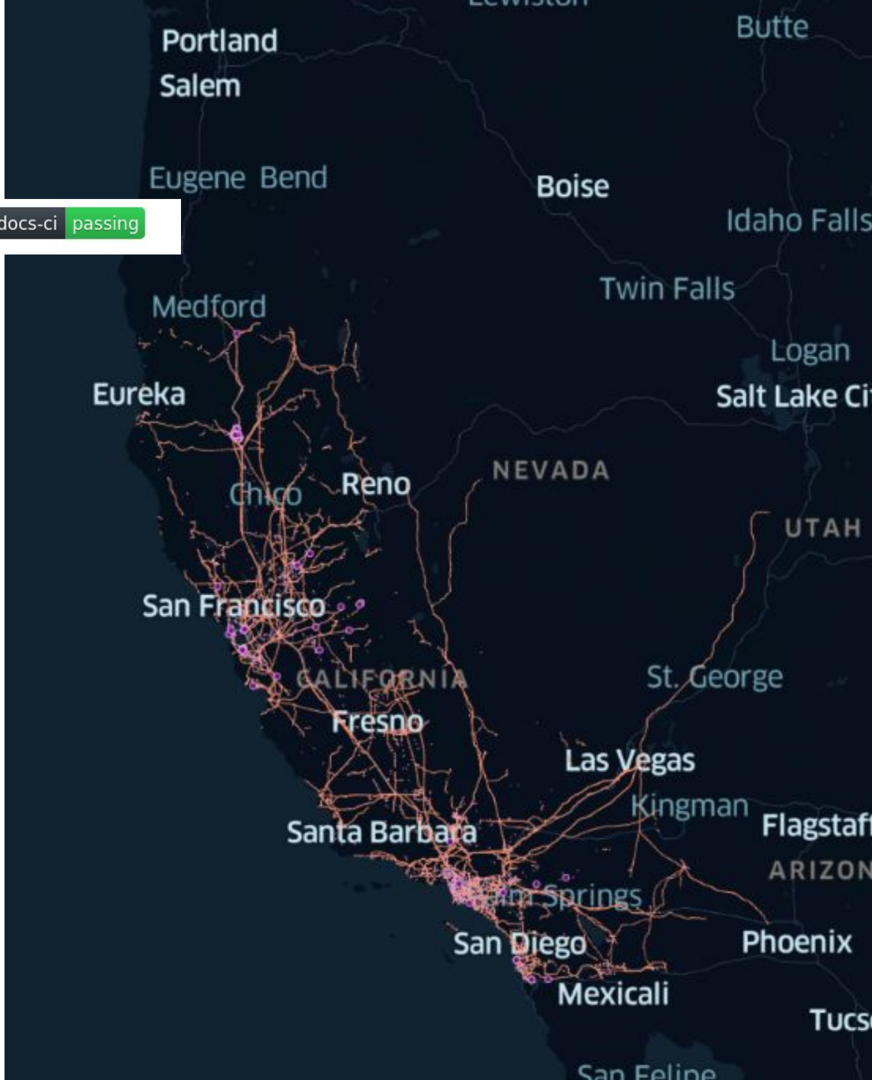
earth-osm. Python tool to extract large amounts of OSM data

pypi v0.1.0 | conda-forge v0.1.0 | codecov 59% | CI passing | License MIT | chat 38 online | docs-ci passing

Python package for extracting **power infrastructure data** from **openstreetmap (OSM)**:

- substations
- transmission lines
- distribution lines
- gas pipelines
- generators
- buildings

and more … **thanks to the OS community!**



OSM Data Quality Check: Europe

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- OpenStreetMap data is great in many cases!
- Potential to get better than anything else! (e.g. real routing, accurate line parameters)
- OET working with Breakthrough Energy to improve OSM grid data worldwide

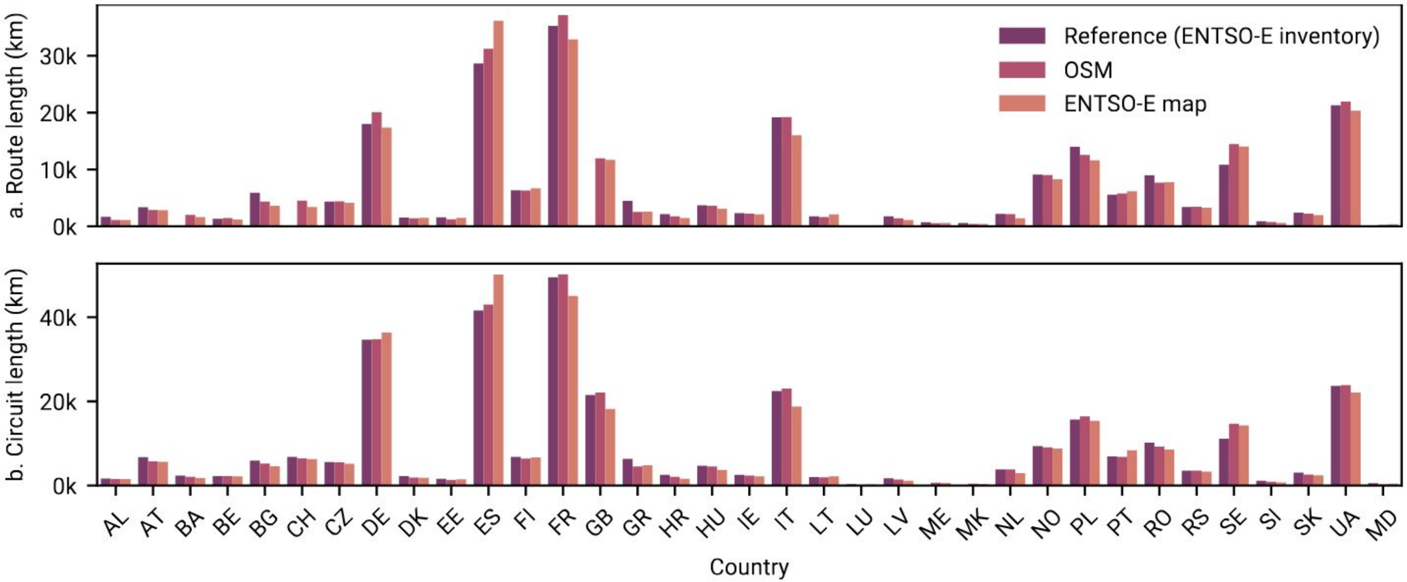

Figure 6. Comparison of total route and circuit lengths per country.

Full paper: https://arxiv.org/pdf/2408.17178

technology-data

release v0.6.2 | docs failing | license GPL-3.0 | repo size 85.8 MB | DOI 10.5281/zenodo.3994163 | chat on gitter

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- compiles techno-economic assumptions on energy system components
  - investment costs, FOM costs, efficiencies, lifetimes
  - for given years, e.g. 2030, 2040, 2050
  - from mixed sources (e.g. Danish Energy Agency, **NREL ATB**, PNNL)
  - outputs have standardized cost years, technology names, and units

531 lines (531 sloc) | 73.1 KB — Raw | Blame

Search this file…

	technology	parameter	value	unit	source
1	**technology**	**parameter**	**value**	**unit**	**source**
2	Ammonia cracker	FOM	4.3	%/year	Ishimoto et al. (2020): 10.1016/j.ijhydene.2020.09.017 , table 7.
3	Ammonia cracker	investment	1062107.74	EUR/MW_H2	Ishimoto et al. (2020): 10.1016/j.ijhydene.2020.09.017 , table 6.
4	Ammonia cracker	lifetime	25.0	years	Ishimoto et al. (2020): 10.1016/j.ijhydene.2020.09.017 , table 7.

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

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Impactful Outputs with PyPSA

(full list available at: https://pypsa.readthedocs.io/en/latest/references/users.html and **https://openenergytransition.org/projects.html)**

Example - Modeling future European requirements

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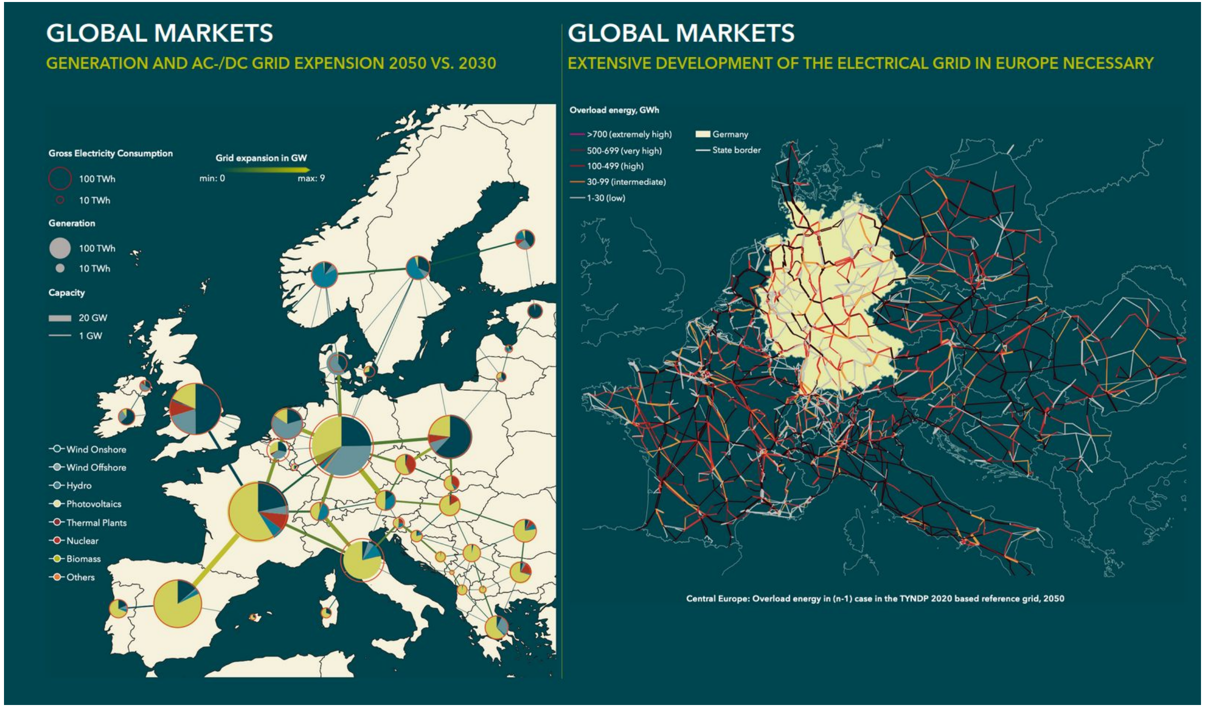
TransnetBW, a German Transmission System Operator, uses PyPSA to explore future continental infrastructure requirements to meet decarbonisation targets in all sectors by 2050.



Example - Supporting Transmission System Operators

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OET works with **German TSO, TransnetBW,** to improve their open energy system modelling setup. **Why?** Our work lead to quicker updates, better software quality, easier OS contributions and costs savings.

Example - Supporting Openmod and Training People

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OET was invited for a training at **Stanford University**. Why? We have more than a handful "world-class" **open-source maintainers and creators**. We took the opportunity to also revive openmod in US.

Stanford Doerr School of Sustainability

Stanford | ENERGY Bits & Watts Initiative

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openmod open energy modelling initiative

Example - Reproducing the Kazakh power system

Open Energy Transition

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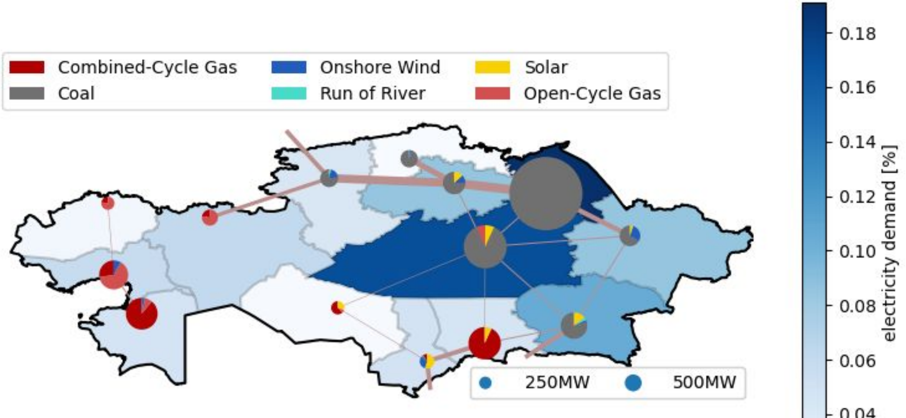
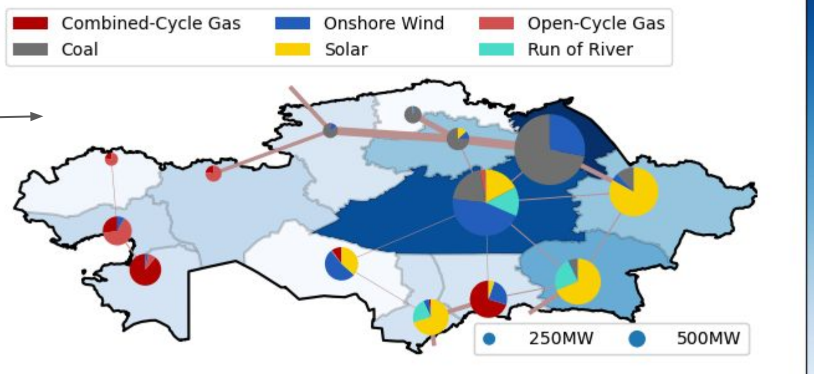
OET built a tailored PyPSA-KZ model based on PyPSA-Earth to demonstrate that PyPSA can **replicate todays operation** of the electricity grid. Why? A validated open-source model **builds trust** and is the perfect start to model future projections.

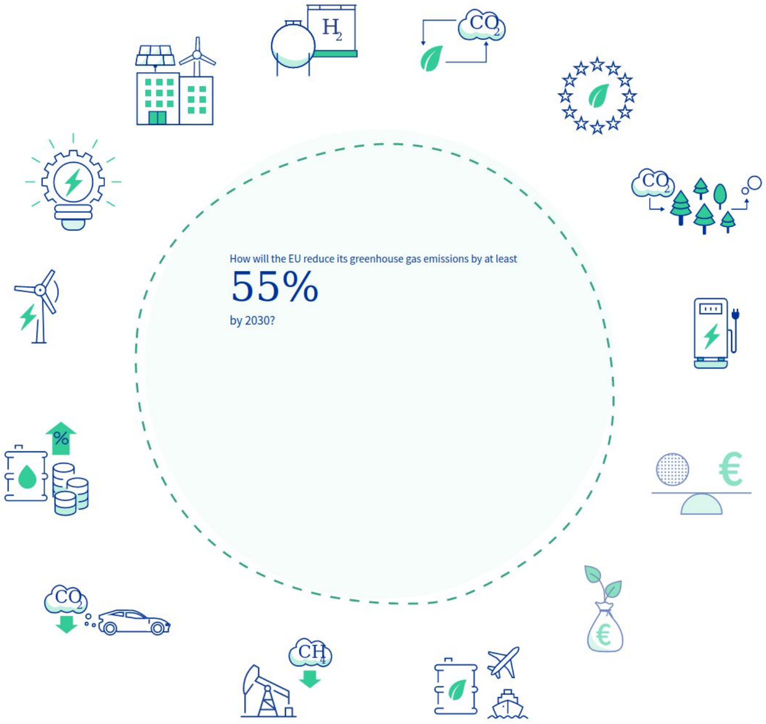
carrier	PyPSA [TWh]	national report [TWh]	error [TWh]	PyPSA [%]	national report [%]	error [%]
gas	20.358883	21.73	1.371117	18.753352	20.103617	1.350265
coal	74.573022	74.47	0.103022	68.692087	68.896290	0.204203
onwind	1.718037	1.08	0.638037	1.582550	0.999167	0.583383
hydro	10.862888	9.51	1.352888	10.006225	8.798224	1.208001
solar	1.048470	1.30	0.251530	0.965786	1.202701	0.236915

carrier	installed capacity [GW]	capacity projection (2030) [GW]
Combined-Cycle Gas	3.48000	3.480000
Open-Cycle Gas	1.62540	1.625400
Coal	12.96700	12.967000
Onshore Wind	0.64870	8.239741
Run of River	0.06278	2.132999
Solar	0.82182	4.568450





Example - Modeling the European Fit for 55 Project

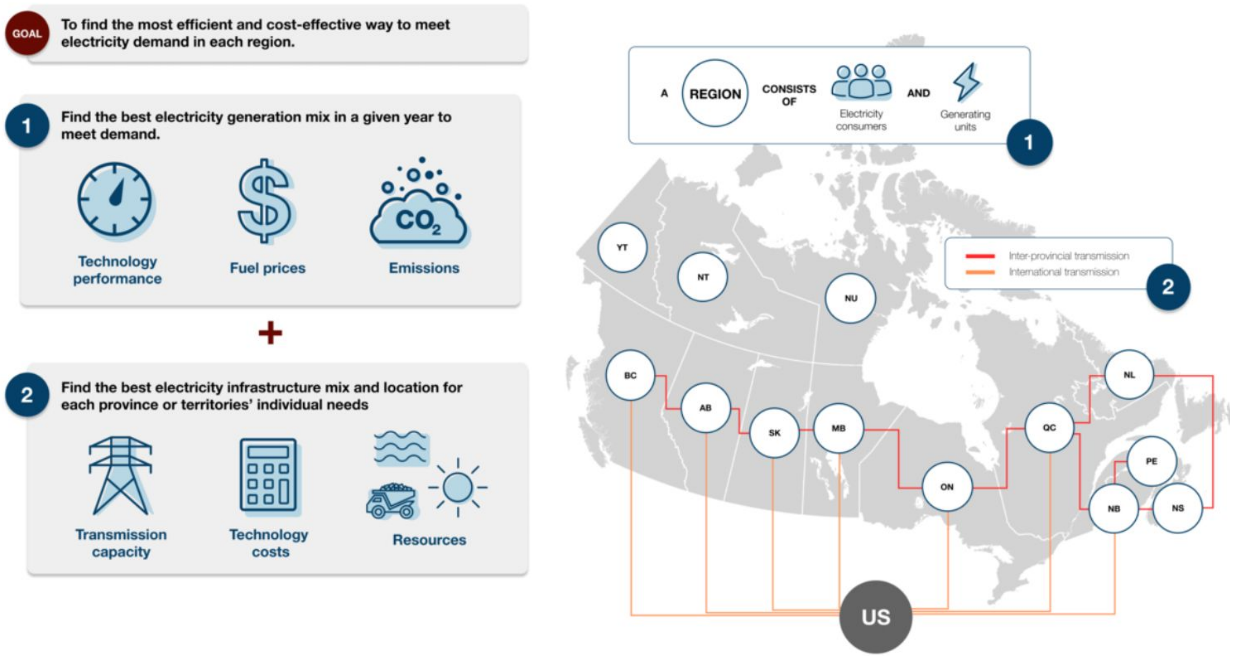


The **Joint Research Centre (JRC)** of the European Commission re-build modeling scenarios to model the European **Fit for 55 Project** using PyPSA. Why? To convince Bruxelles that the EU should move to open modelling. Initially, they were using an energy model developed by Artelys for the European Commission.

Example - Modeling future Canadian requirements

Open Energy Transition
from the creators of PyPSA meets Earth

The **Canada Energy Regulator,** the agency of the Government of Canada under its Natural Resources Canada portfolio, used PyPSA to explore future continental infrastructure requirements to meet decarbonisation targets by 2050.



Disclosure

Open Energy Transition
from the creators of PyPSA meets Earth

#NO #PYPSA #FANATICS
We have multiple open source **core** maintainers in the team:

- **PyPSA** (Max, Martha, Fabian, Katia, Davide, Hazem, Jonas, Johannes)
- **TIMES** (Sid)
- **Temoa** (Daniel, Gianvito)

… our goal is to **help people** to adopt good OS solutions!