On 24/7 Carbon Free Energy research (& PyPSA: an open source energy modelling toolbox)

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Big Picture Breakfast @ Aurora Energy Research (Berlin)
2 April 2025

Send me an email: iegor.riepin@tu-berlin.de
Find this slide deck: `https://iriepin.com/uploads/AER_20250402.pdf`

Buying more than just energy

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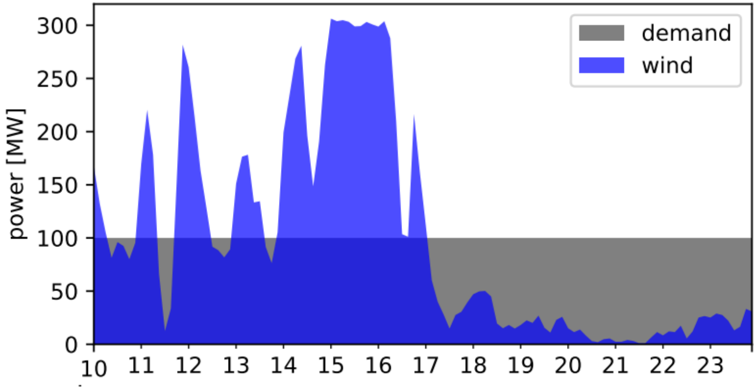
- Many companies claim to be "powered by clean energy". The meaning of these claims, however, **varies greatly**
- Some companies procure "unbundled certificates", such as Guarantees of Origin to **indicate sustainability** credentials
- Many buyers recognise limitations of the unbundled certificates and **turn towards Power Purchase Agreements** (PPAs)

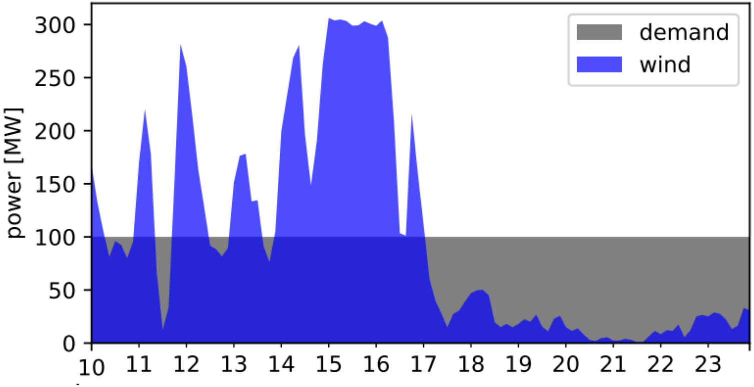
More than **400 companies** worldwide have pledged to match their electricity demand with renewable electricity on an **annual basis**

RE100



- **Temporal mismatch**: 100% RES PPAs result in periods of oversupply and deficit.
- Hours of deficit must be met by rest of system – grid supply may have high emissions and high prices
- Extended period of supply deficit is expensive to bridge with battery storage.

Great, so what's the problem? 2/2



There are even more challenges:

- No **simultaneity**
- Lack of **additionality**
- Displaced **location**
- Exposure to **market risk**
- Need for **backup**

24/7 carbon-free energy

- There is growing interest in voluntary clean electricity procurement to cover consumption with clean energy supply on a **hourly basis**.
- Achieving 24/7 Carbon-Free Energy (CFE) means that every kilowatt-hour of electricity consumption is met with carbon-free electricity sources, **round-the-clock**.
- 24/7 CFE matching principles necessarily require **additionality** and **geographical matching** of renewable generation.

The **24/7 Carbon-free Energy Compact** initiative was launched in 2021.
Now: 171 members.

Open questions

We want to find out:

- How can we achieve **hourly clean energy** matching?
- What is the **cost premium** of 24/7 CFE?
- Can **long-duration storage** or **new dispatchable clean** technologies help?
- If many companies take a 24/7 approach, how does this effect the **rest of the system**?
- What role can **demand flexibility** play for 24/7 CFE?

Open-source environment for energy system modelling

What is PyPSA?

Our research focus:

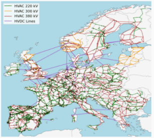
- Cost-effective pathways to reduce greenhouse gas emissions
- Evaluation of grid expansion, hydrogen strategies, carbon management strategies
- Co-optimisation of generation, storage, conversion and transmission infrastructure
- Algorithms to improve the tractability of models
- All open source and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

PyPSA

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

Documentation »

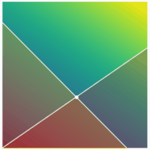
PyPSA-Eur



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

Documentation »

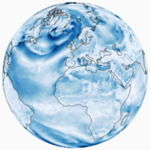
Linopy



Linear optimization interface for N-D labeled variables.

Documentation »

Atlite



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

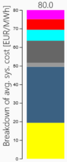
Documentation »

Powerplantmatching

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

Documentation »

Model Energy



An online toolkit for calculating renewable electricity supplies.

https://pypsa.readthedocs.io/en/latest/references/users.html

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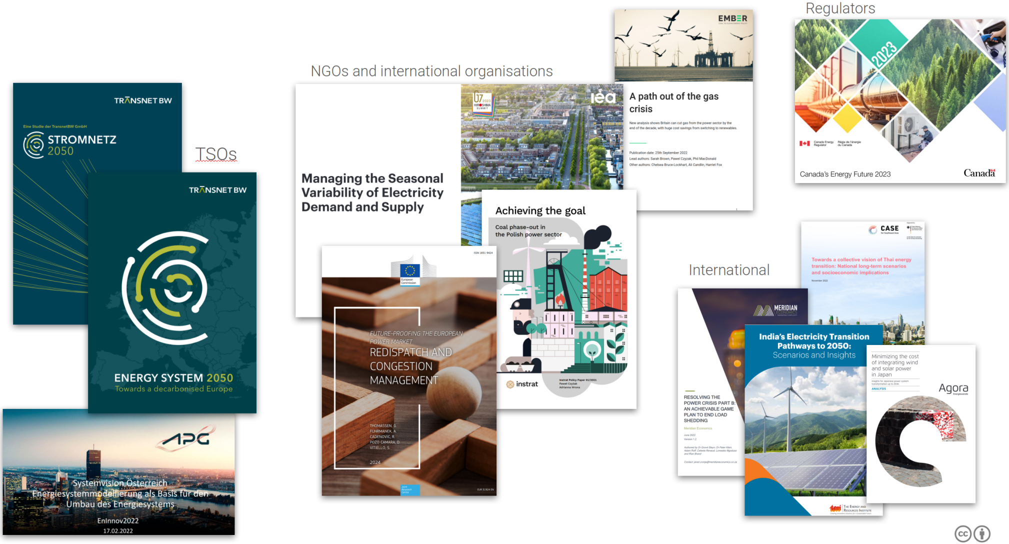
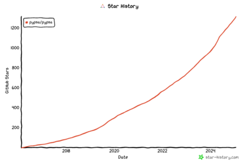


PyPSA:
Python for Power System Analysis



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)

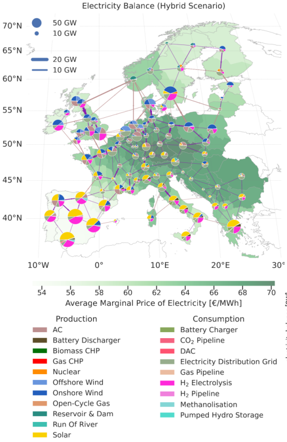
Backend

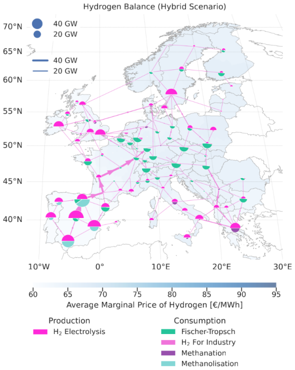
- all data stored in pandas
- framework built for performance with large networks and time series
- interfaces to major solvers (Gurobi, CPLEX, HiGHS, Xpress), with linopy (by PyPSA devs)
- highly customisable, but no GUI
- Suitable for greenfield, brownfield & pathway studies

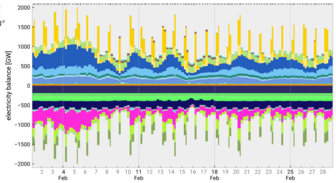
PyPSA-Eur: A sector-coupled open model of the European energy system

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, …



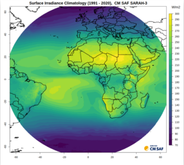




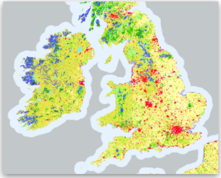
Raw data is automatically downloaded

WDPA

SARAH-3

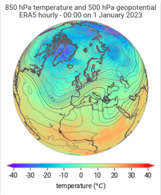


CORINE

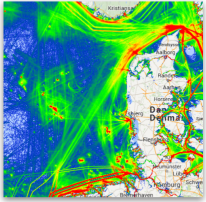


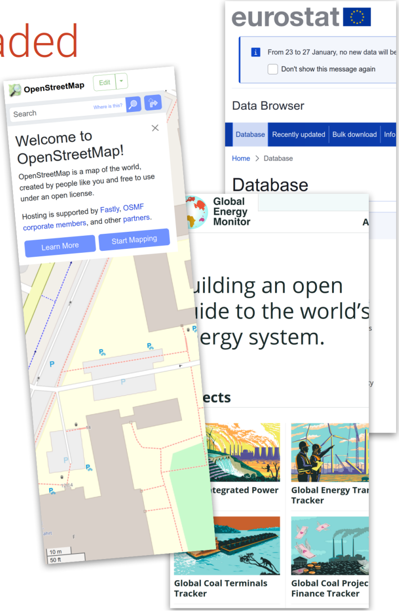
GEBCO

ERA5



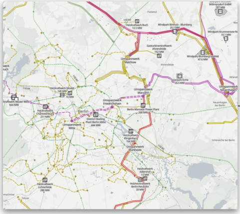
World Bank



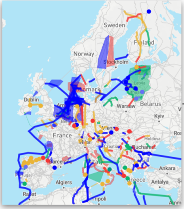


Power grid topology

OpenStreetMap data



TYNDP projects



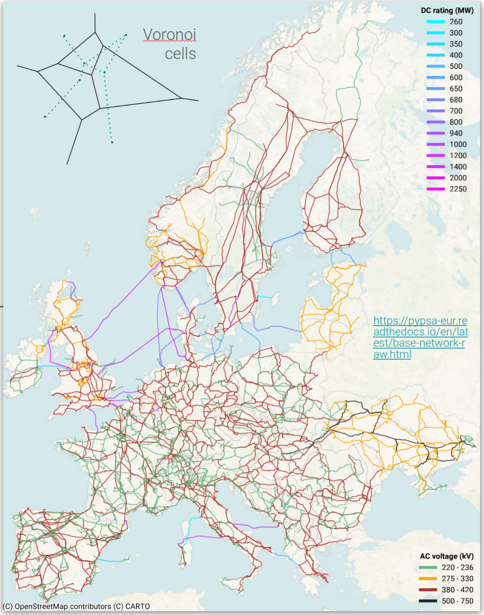
Apply **standard line types** for capacity and parameters.

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

European network with

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

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

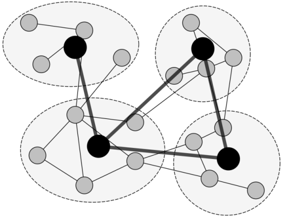


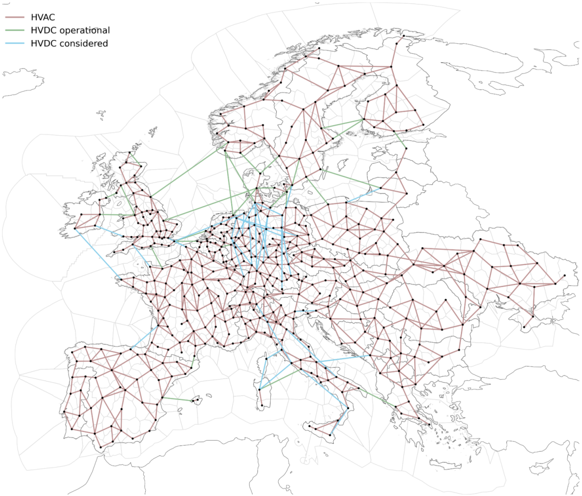
https://pypsa-eur.readthedocs.io/en/latest/base-network-raw.html

Clustering the electricity network: `cluster_network`

Transformed **to 380 kV**

Clustered to **512 regions**

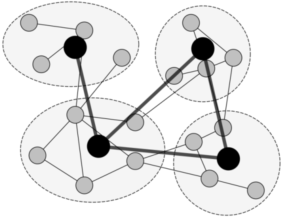


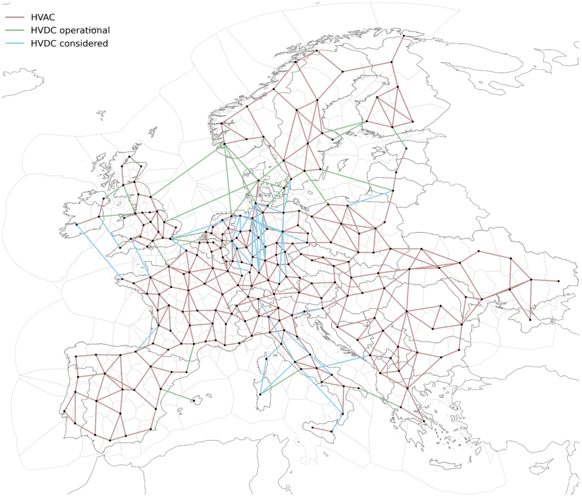


Clustering the electricity network: `cluster_network`

Transformed **to 380 kV**

Clustered to **256 regions**

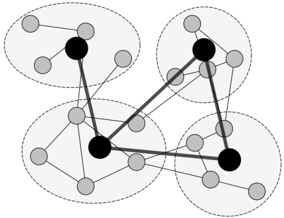




Clustering the electricity network: `cluster_network`

Transformed **to 380 kV**

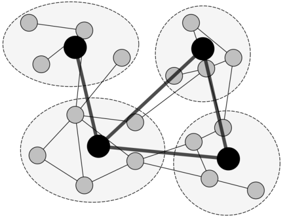
Clustered to **128 regions**



Clustering the electricity network: `cluster_network`

Transformed to 380 kV

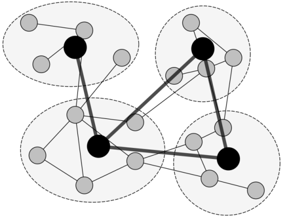
Clustered to 64 regions



Clustering the electricity network: `cluster_network`

Transformed **to 380 kV**

Clustered to **41 regions**



atlite: Convert weather data to energy systems data

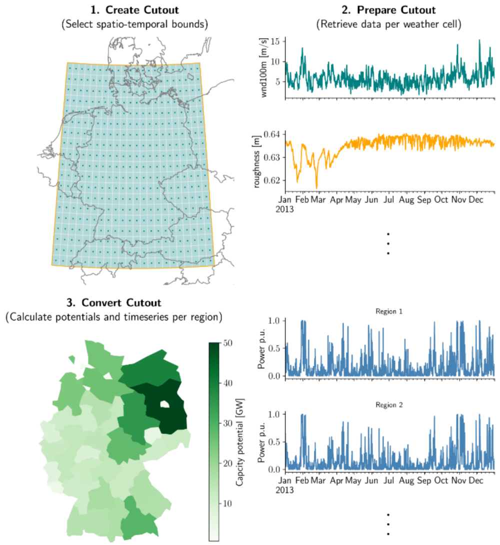
pypi v0.3.0 | conda-forge v0.3.0 | Tests passing | codecov 72% | docs passing | license MIT
REUSE compliant | JOSS 10.21105/joss.03294 | chat 52 online | stackoverflow pypsa questions 44

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`



Time series for renewables

atlite: Convert weather data to energy systems data

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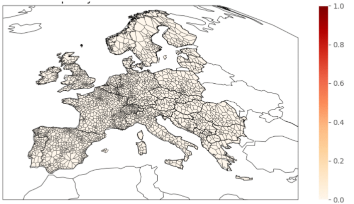
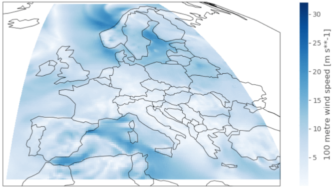
Historical meteorological weather data from ERA5 and SARAH-3
(up to 84 years, 30x30 km)

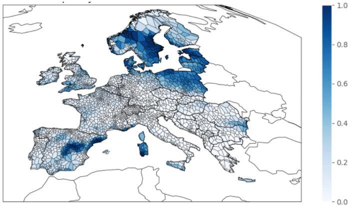
Solar panel models
- orientation
- material

Wind and solar capacity factors



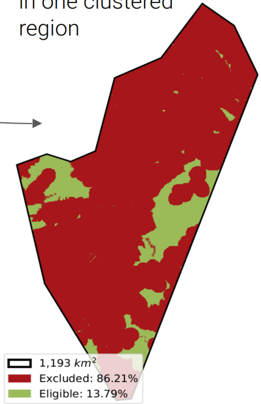


Wind turbine models
- power curve
- surface roughness



Land availability for renewables

Example:
Onshore wind
in one clustered
region



atlite: Convert weather data to energy systems data

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

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")
```

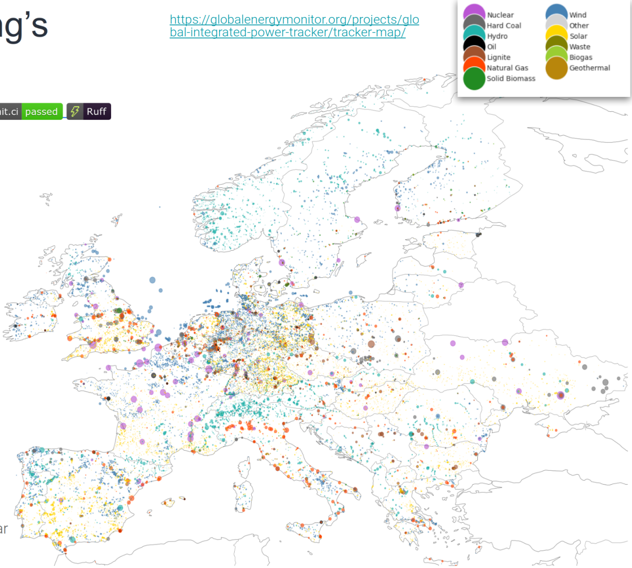
Sources

- 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

Supply, consumption and storage options by carrier

Electricity (115 regions)

Supply
- rooftop solar
- utility-scale solar
- onshore wind
- offshore wind (fixed-pole/floating, AC/DC-connected)
- nuclear
- hydro reservoirs
- pumped-hydro
- run-of-river
- import by HVDC link
- gas CHP (w/wo CC)
- biomass CHP (w/wo CC)
- gas turbine (OCGT)
- methanol turbine (OCGT)
- hydrogen turbine (OCGT)
- hydrogen fuel cell CHP
- battery discharger
- vehicle-to-grid

Withdrawal
- industry electricity
- residential electricity
- services electricity
- agriculture electricity
- air-sourced heat pump
- ground-sourced heat pump
- resistive heater
- electric vehicle charger
- battery charger
- pumped-hydro
- hydrogen pipeline (compression)
- direct air capture
- Haber-Bosch
- electric arc furnace
- direct iron reduction
- distribution grid losses
- transmission grid losses
- methanolisation
- electrolysis

Grids & Storage
- distribution grid
- transmission grid
- battery storage
- pumped-hydro storage
- electric vehicles

Hydrogen (115 regions)

Supply
- import by pipeline
- import by ship
- electrolysis
- chlor-alkali electrolysis (exogenous)
- steam methane reforming (w/wo CC)
- ammonia cracker

Withdrawal
- Fischer-Tropsch
- methanolisation
- electrobiofuels
- direct iron reduction
- Haber-Bosch
- hydrogen turbine (OCGT)
- hydrogen fuel cell CHP
- methanol-to-kerosene
- Sabatier

Grids & Storage
- new pipelines
- retrofitted pipelines
- storage in salt caverns
- storage in steel tanks

Methane (not spatially resolved)

Supply
- import by ship
- fossil gas
- biogas upgrading (w/wo CC)
- Sabatier

Withdrawal
- gas for high-T industry heat (w/wo CC)
- steam methane reforming (w/wo CC)
- gas boiler (rural/urban)
- gas CHP
- gas turbine (OCGT)

Storage hydrocarbon storage

Liquid Hydrocarbons (not spatially resolved)

Supply
- import by ship
- fossil oil refining
- Fischer-Tropsch
- electrobiofuels

Withdrawal
- kerosene for aviation
- naphtha for industry
- diesel for agriculture

Storage hydrocarbon storage

Methanol (not spatially resolved)

Supply
- import by ship
- methanolisation

Withdrawal
- methanol turbine (OCGT)
- methanol for shipping
- methanol for industry
- methanol-to-kerosene

Storage hydrocarbon storage

Ammonia (not spatially resolved)

Supply
- import by ship
- Haber-Bosch

Withdrawal
- ammonia cracker
- ammonia for fertilizer

Storage ammonia tank

Supply, consumption and storage options by carrier

Heat (115 regions)

Supply	Withdrawal
air-sourced heat pump	residential heat
ground-sourced heat pump (only rural)	services heat
resistive heater	agriculture heat
gas boiler	low-T industry heat
biomass boiler	direct air capture
solar thermal	water tank charger
water tank discharger	
biomass CHP (w/wo CC, only DH)	
gas CHP (w/wo CC, only DH)	
hydrogen fuel cell CHP (only DH)	
electrolysis (only DH)	
Haber-Bosch (only DH)	
Sabatier (only DH)	
Fischer-Tropsch (only DH)	
methanolisation (only DH)	
Storage	long-duration thermal storage (only DH)
	hot water tank

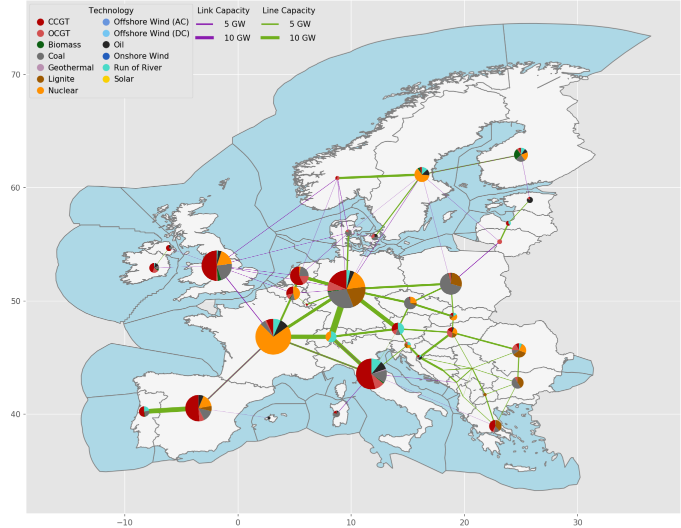
CO2 atmosphere (not spatially resolved)

Supply	Withdrawal
kerosene for aviation	solid biomass for industry (w CC)
diesel for agriculture	solid biomass CHP (w CC)
methanol for shipping	biogas upgrading (w CC)
methanol for industry	direct air capture
naphtha for industry	electrobiofuels
gas boiler	
gas CHP (w/wo CC)	
gas turbine (OCGT)	
methanol turbine (OCGT)	
process emissions (w/wo CC)	
fossil oil refining	
gas for high-T industry heat (w/wo CC)	
steam methane reforming (w/wo CC)	

CO2 commodity (not spatially resolved)

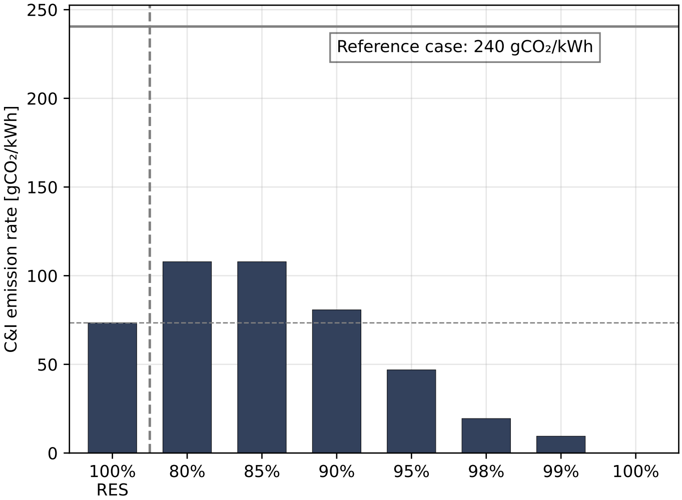
Supply	Withdrawal
direct air capture	Fischer-Tropsch
biogas upgrading (w CC)	methanolisation
gas CHP (w CC)	sequestration
biomass CHP (w CC)	Sabatier
steam methane reforming (w CC)	
process emissions (w CC)	
solid biomass for industry (w CC)	
gas for high-T industry heat (w CC)	
Storage	intermediate storage in steel tank
	long-term geological sequestration

On the means, costs, and system-level impacts of 24/7 carbon-free energy procurement



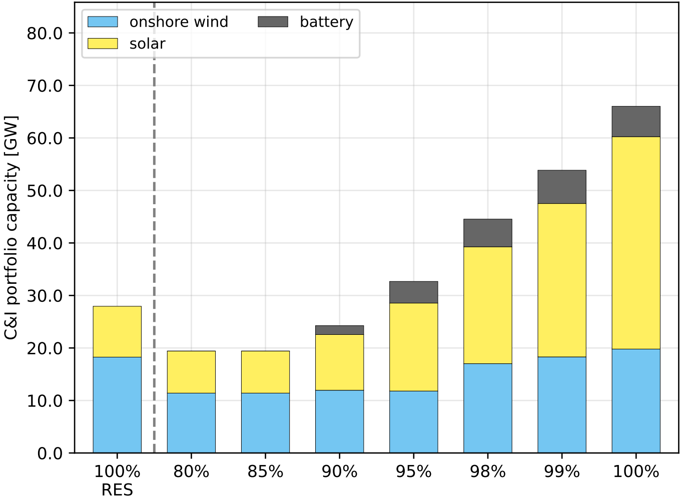
- We model the European power system with **capacity expansion** for the years **2025** & **2030**
- Consumers following 24/7 approach can be located in one of the **four zones**: Ireland, Denmark (zone DK1), Germany and the Netherlands
- A set of constraints to model a situation when a **fraction of corporate and industry (C&I) demand** in a selected zone commits to 24/7 CFE (i.e. C&I have an aggregated demand profile)
- Study: **doi.org/10.5281/zenodo.7180098**
- Paper: **doi.org/10.1016/j.esr.2024.101488**

Average emissions of procured electricity



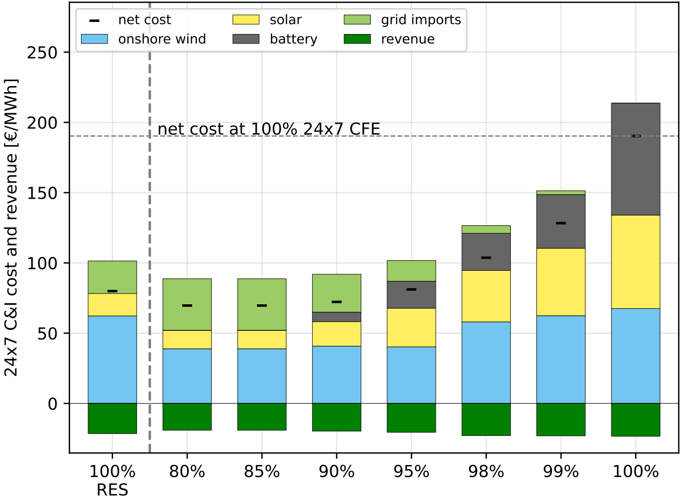
- Procurement affects **average emissions rate** of used electricity
- Reference system has average emissions rate at 240 $kgCO_2/MWh$
- 100% annual RES reduces rate to 73 $kgCO_2/MWh$
- As CFE target tightens, emissions **drop to zero**

Portfolio of procured capacity



- 100% RES for 10% of C&I demand (3.8 GW load) is met with 28 GW of **onshore wind and solar**
- Above 90% CFE **batteries enter the mix**
- With only wind, solar and batteries, a **large portfolio** is needed to bridge dark wind lulls (*Dunkelflauten*)

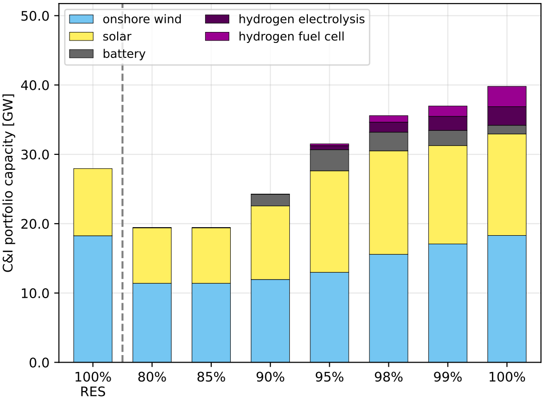
24/7 CFE cost breakdown

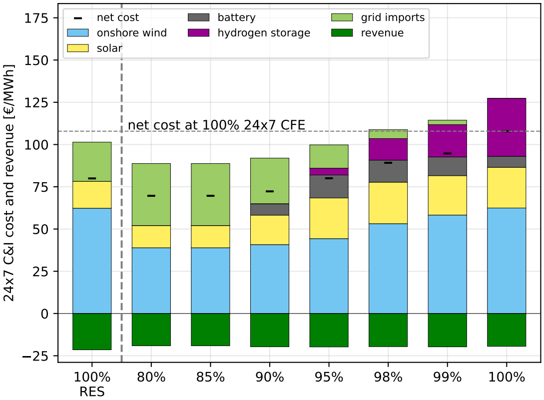


- The **cost breakdown** shows the average costs of meeting demand with the policy, including grid electricity consumption costs netted by revenue selling to the grid
- There is only a **small cost premium** going to 90-95% CFE matching
- But the last 2% of hourly CFE matching more than **doubles the cost**

Including long-duration storage (LDES)

Adding **long-duration energy storage (LDES)** to the mix (represented here by hydrogen storage in salt caverns at 2.5 €/kWh) **reduces the portfolio size** for 100% CFE and **limits the cost premium to 50%** over annual RES matching.





Germany – Palette 2 – 2025 – 10% – baseload

On demand flexibility & 24/7 CFE matching

ICT companies work demand flexibility concepts and technical solutions

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DATA CENTERS AND INFRASTRUCTURE

Our data centers now work harder when the sun shines and wind blows

Apr 22, 2020 · 3 min read

Ana Radovanovic
Technical Lead for Carbon-Intelligent Computing

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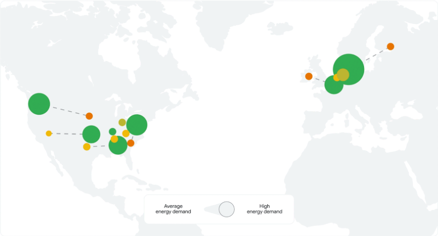
Addressing the challenge of climate change demands a transformation in how the world produces and uses energy. Google has been carbon neutral since 2007, and 2019 marks the third year in a row that we've matched our energy usage with 100 percent renewable energy purchases. Now, we're working toward 24x7 carbon-free energy everywhere we have data centers, which deliver our products to billions of people around the world. To achieve 24x7 carbon-free energy, our data centers need to work more closely with carbon-free energy sources like solar and wind.

SUSTAINABILITY

We now do more computing where there's cleaner energy

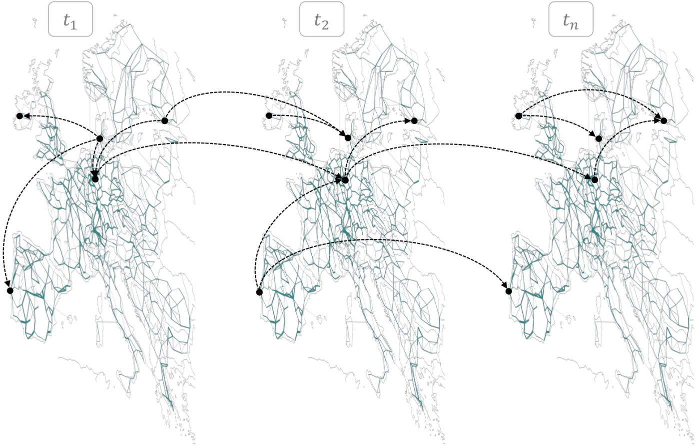
May 18, 2021 · 2 min read

Ross Koningstein
Co-founder, Carbon-Intelligent Computing



Sources:
blog.google/data-centers-work-harder-sun-shines-wind-blows
blog.google/carbon-aware-computing-location

Open study, research papers, code, and other resources

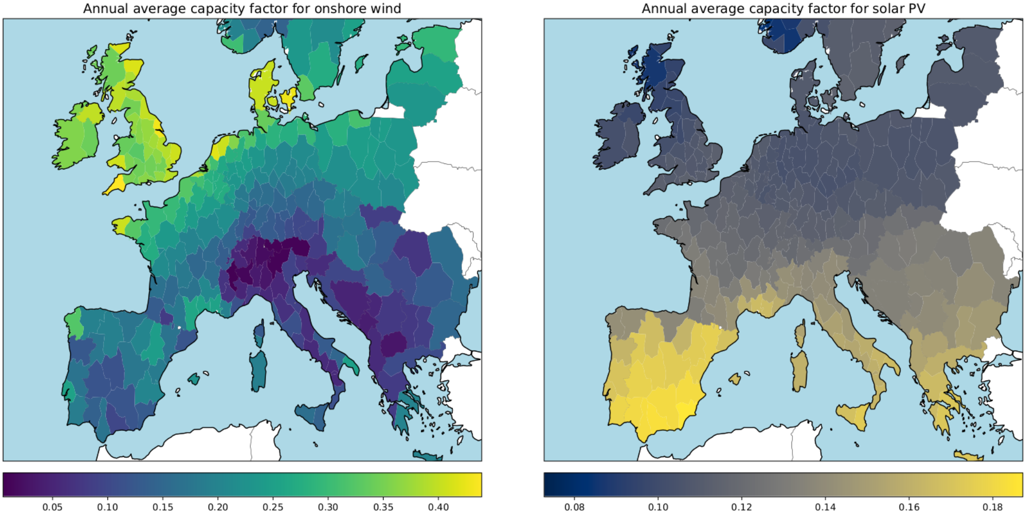


- Key focuses:
  - – How can demand flexibility reduce the required **resources** and **costs** of 24/7 CFE matching?
  - – What are the **signals** for optimal utilisation of demand flexibility?
  - – What are the trade-offs and synergies from co-optimisation of **spatial** and **temporal** load shifting?
- Open-access study:

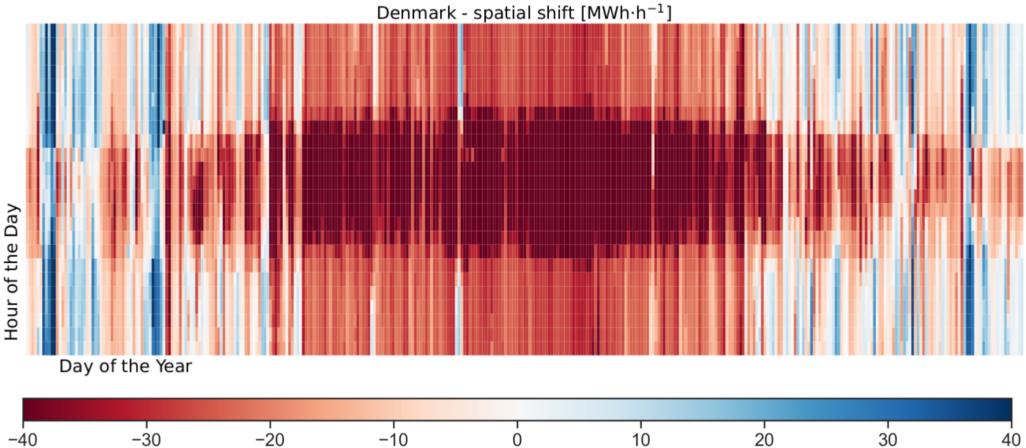
  🔓 study: zenodo.org/records/8185850
  🔓 code: github.com/PyPSA/247-cfe
- Follow-up research paper: "Spatio-temporal load shifting for truly clean computing"

  🔓 paper: doi.org/10.1016/j.adapen.2024.100202
  🔓 code: ../space-time-optimization

Quality of local renewable resouces

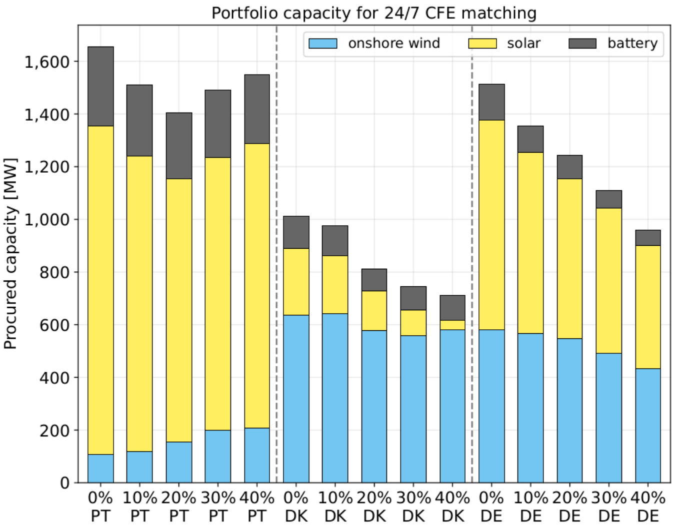


Time-series of optimized spatial load shifts (locations: PT-DK-DE)



Negative values mapped to red color represent decrease of a load
Positive values mapped to blue color represent increase of a load

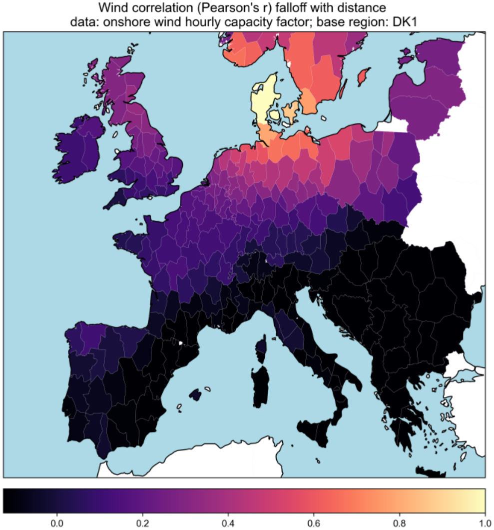
Procurement as a function of load flexibility (locations: PT-DK-DE)

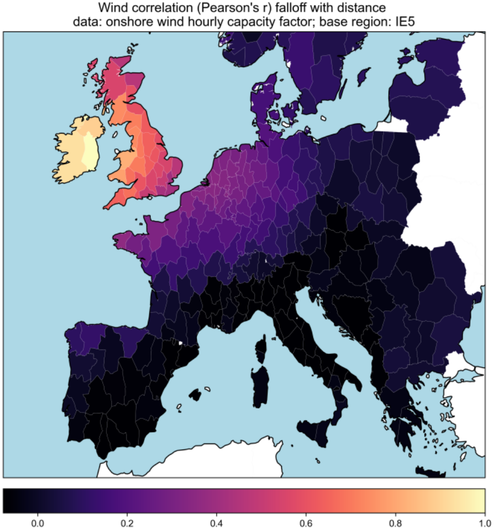


- Optimal procurement strategies to match 100 MW load with 24/7 CFE displayed per datacenter location and share of flexible loads {0% .. 40%}
- The required portfolio capacity is **significantly reduced** when load shifting becomes possible
- Demand flexibility facilitates the **efficiency and affordability** of 24/7 CFE matching

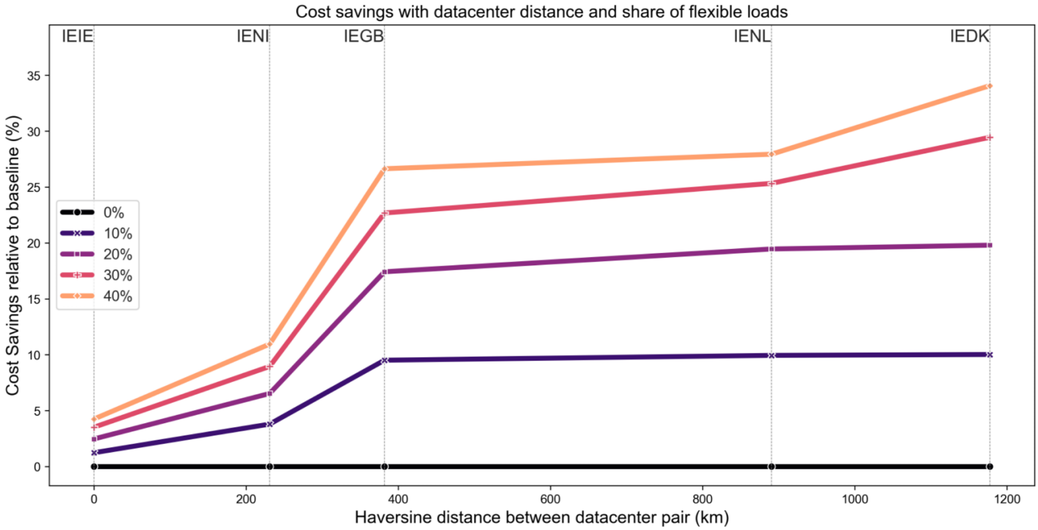
Scenario: 24/7 CFE with 100% score,
commercially available technologies,
2025 DEA technology cost assumptions
co-optimised spatial & temporal load shifts

Low correlation of wind power generation over long distances

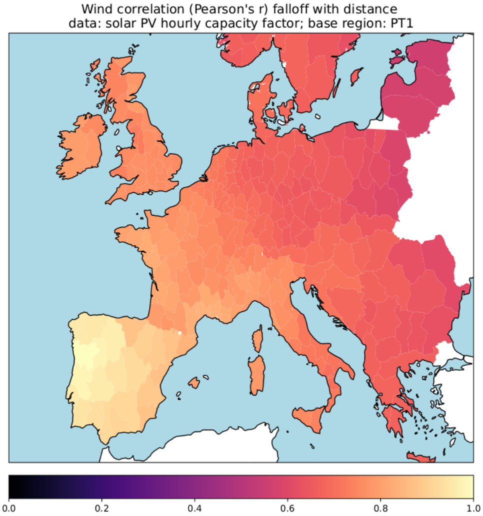


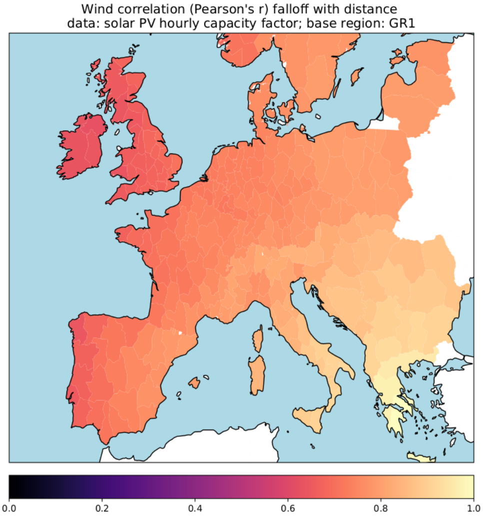


Cost savings as a function of distance between datacenter pair

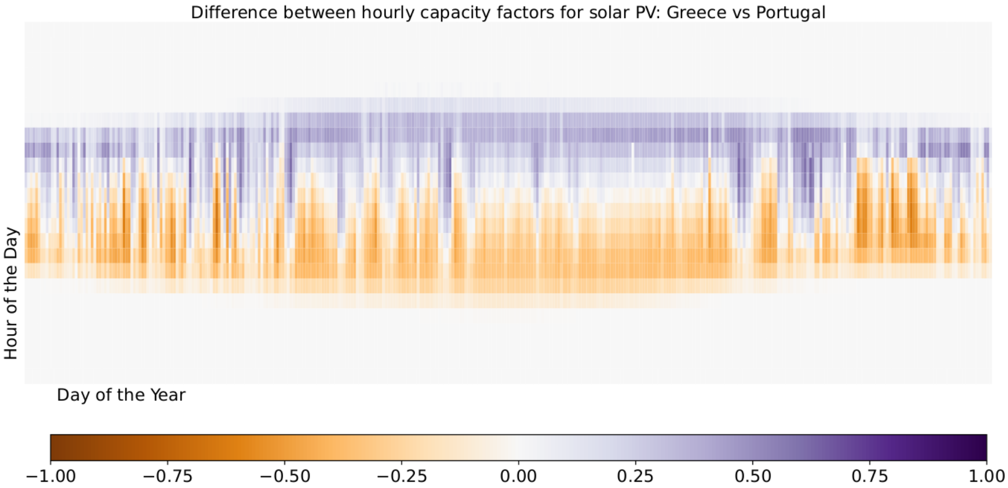


Time lag in solar radiation peaks due to Earth's rotation (1/2)

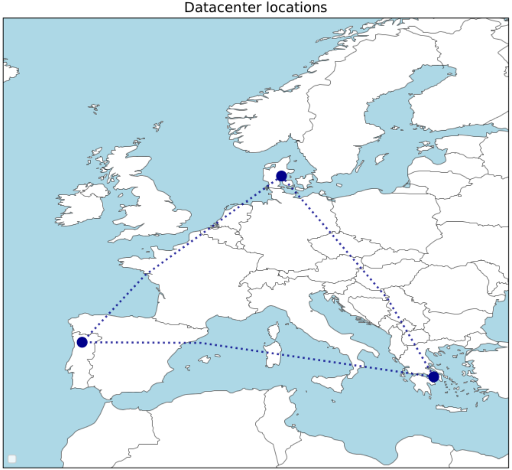


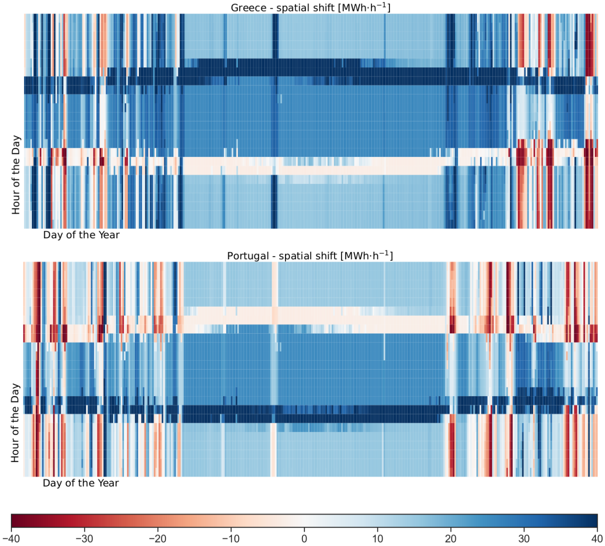


Time lag in solar radiation peaks due to Earth's rotation (2/2)



Time-series of optimized spatial load shifts (locations: DK-PT-GR)





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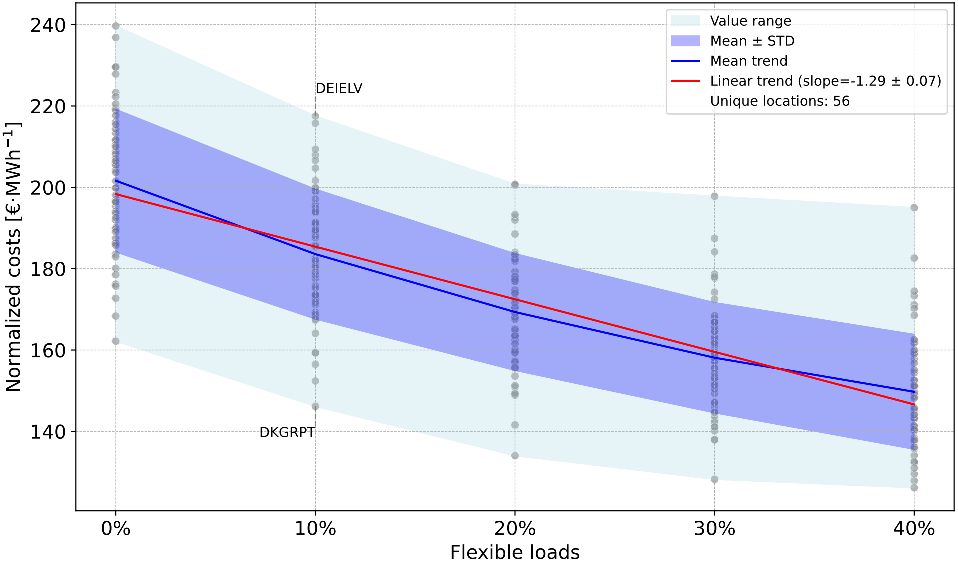
Results can be generalized beyond specific load locations



Also in the study on DSM for 24/7 CFE

- Scenarios for **co-optimised** and **isolated** utilisation of space-time load-shifting;
- Scenarios for 24/7 CFE with **98% and 100%** matching targets;
- Scenarios with different **24/7 technology options** (e.g., Long Duration Energy Storage);
- 24/7 CFE **cost breakdowns** and **procurement strategies** for individual locations;
- **Synergies** and **trade-offs** between spatial and temporal load shifting;
- Analysis of **net load migration** across locations;
- Simulated **energy balances** for selected datacenters.

On the role of 24/7 CFE in accelerating advanced clean energy technologies

Research questions

- Key focuses:
  - What role can 24/7 CFE play in accelerating advanced clean electricity technologies?
  - How can 24/7 CFE procurement facilitate **technology learning**?
  - What are the associated **system decarbonization** effects?

- Deliverables:

  🔓 Commentary article in Joule: **https://doi.org/10.1016/j.joule.2024.101808**
  🔓 Code: **https://github.com/PyPSA/247-cfe**
  🔓 Op-ed @ Latitude Media:
  ../how-24-7-carbon-free-energy-can-catalyze-clean-energy-innovation/
  🔓 Our results depicted in Forbes:
  ../businesses-and-investors-must-confront-new-federal-climate-edicts/
  🔓 More on our media coverage: **https://irieo.github.io/247cfe.github.io/**

“Virtuous circle” kickstarted by first 24/7 CFE commitments

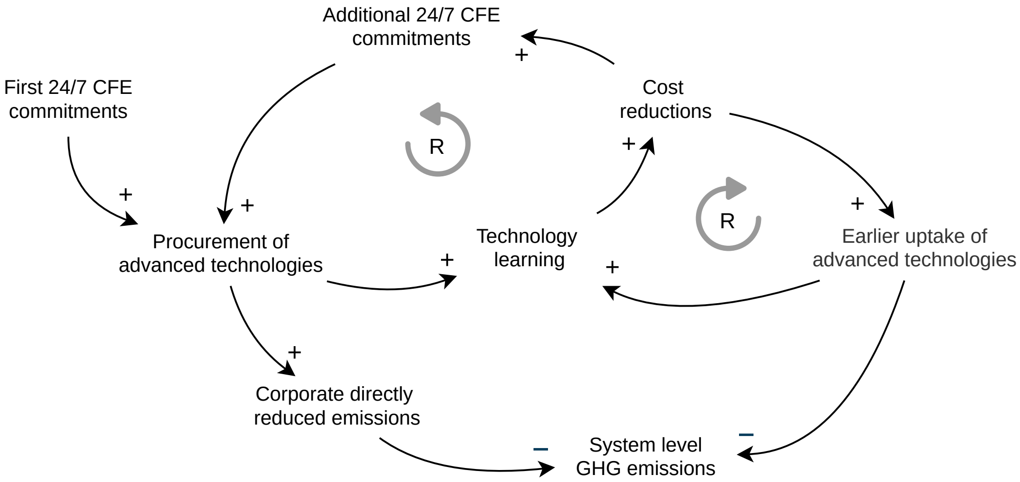
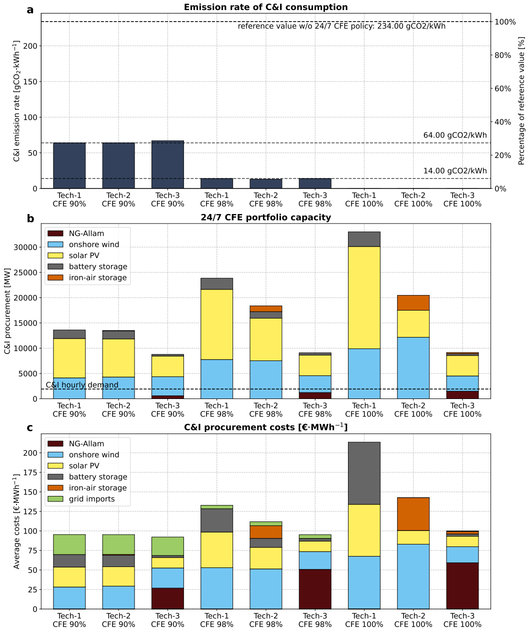


Illustration: Riepin et al (2025)

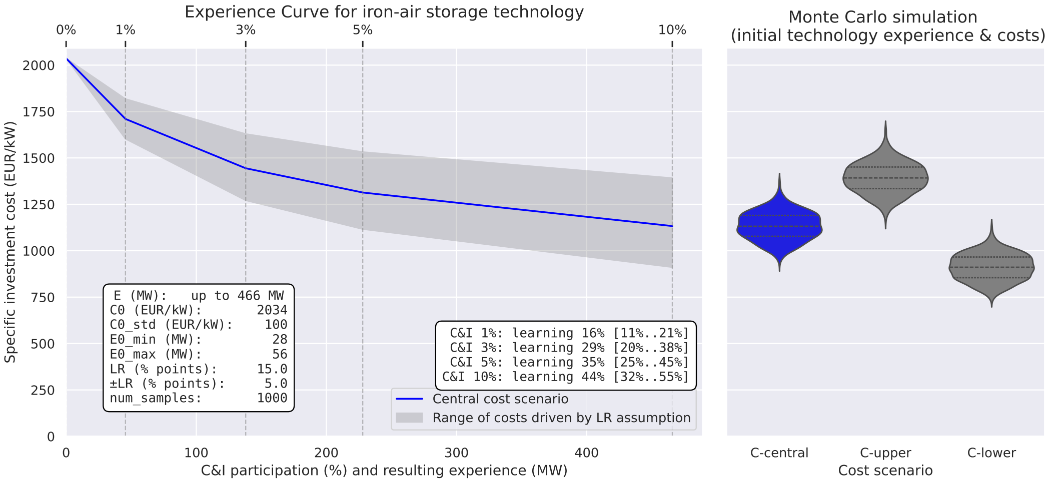


- With only wind, solar and batteries, a **large portfolio** is needed to bridge dark wind lulls (*Dunkelflauten*)
- This makes the last 2% of hourly CFE matching to come with a **high cost premium**
- Adding **LDES** to the mix (here: iron-air battery) or **clean firm generation** technology (here: NG-Allam plant) **reduces the portfolio size** and **limits the cost premium**
- Procurement affects **average emissions rate** of used electricity. Background grid (here: Germany 2025) has 234 gCO_2/kWh. As CFE target tightens, emissions of 24/7 CFE participants **drop to zero**

Scenario: Germany 2025
5% of C&I demand (1900 MW) follow 24/7 CFE
24/7 CFE with 90%, 98% 100% score
p1 commercially available technologies
p2 above plus LDES
p3 above plus clean firm generator

Illustration: Riepin et al (2025)

Impact of 24/7 CFE procurement on technology learning



Scenario: 24/7 CFE with 100% score
[0%..10%] of C&I demand follow 24/7 CFE
Learning model & Monte Carlo parametrisation are on figure
Illustration: **Riepin et al (2025)**

Impact of technology learning on background energy system

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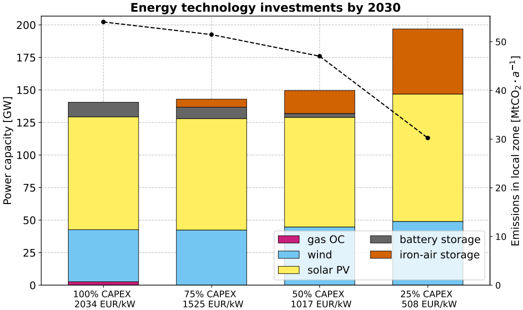

- Iron-air battery storage breaks even into technology investment mix with 25% CAPEX reduction (basis level: \$2300/kW)
- **System-level emissions drop**: iron-air storage substitutes fossil-based peakers, and allows for efficient use of renewable excess energy
- For this effect, announced capacity of iron-air battery **has to be doubled twice**[1] with $LR \approx 0.15$
  [1] 56.5 MW / 5.65 GWh is planned by 2025
- ca. **EUR 0.35B investment** required to bring iron-air technology for economical break-even (an estimate based on LR, initial experience & costs, background system assumptions)

Scenario: Germany 2030
Varying CAPEX of iron-air battery
no C&I demand

Illustration: Riepin et al (2025)

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Learn more about our 24/7 CFE research: https://irieo.github.io/247cfe.github.io/

Code: This project—each study, paper and slide deck—is done in a spirit of open and reproducible research

Hourly matching research on EU electrolytic hydrogen regulation:
Temporal regulation of renewable supply for electrolytic hydrogen
by Elisabeth Zeyen et al, 2024, Environ. Res. Lett. 19, 024034

PyPSA ecosystem: https://pypsa.org/

Annex

How is 24/7 carbon-free electricity (CFE) measured?

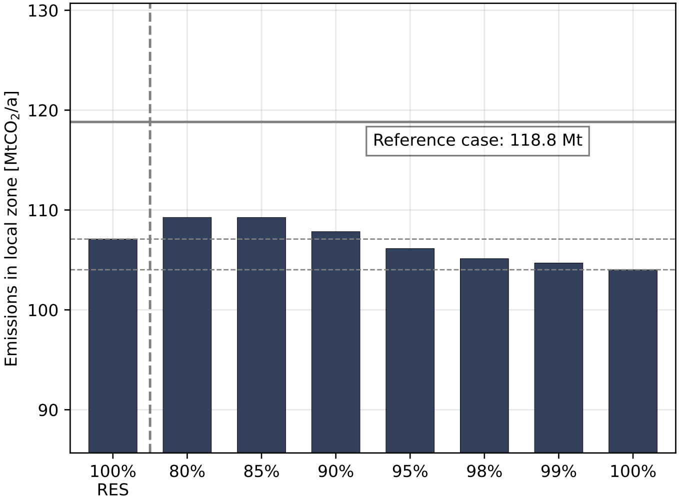
Electricity in an hour is counted as **carbon-free (CFE)** if:

- Directly contracted carbon-free assets are generating (generation above company demand is ignored)
- Energy consumed from the grid is carbon-free (counted according to mix in local bidding zone and any imports)

CFE fraction in each hour is averaged to **CFE score** for year.

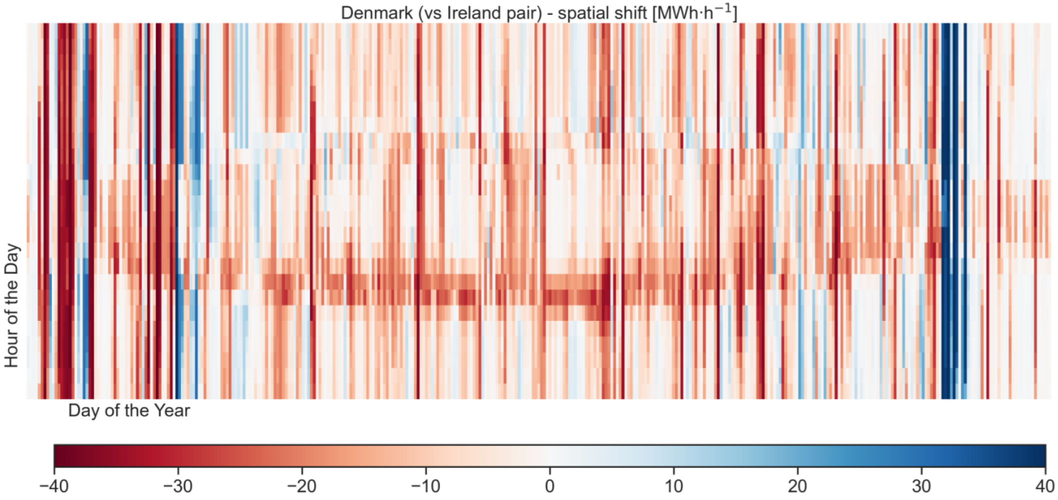
Google 2021, 24/7 CFE: Methodologies and Metrics

System emissions are also reduced (power sector values for Germany)



- **CO_2 emissions in the local bidding zone** are also reduced by CFE procurement
- If 10% of C&I follows 24/7, total system emission are reduced further compared to 100% RES
- Two effects are responsible: **volume effect** of more CFE with high targets; **profile effect** of the timing of feed-in at highly-emitting times

Time-series of optimized spatial load shifts (locations: DK-IE)



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Barriers to advanced clean technology commercialization

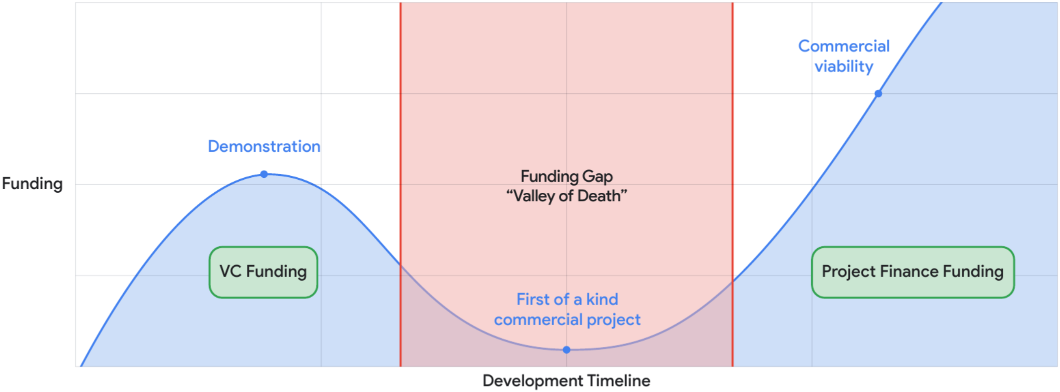

Illustration: **Google (2023)**
see also **Prime Coalition (2022) study**

Another perspective

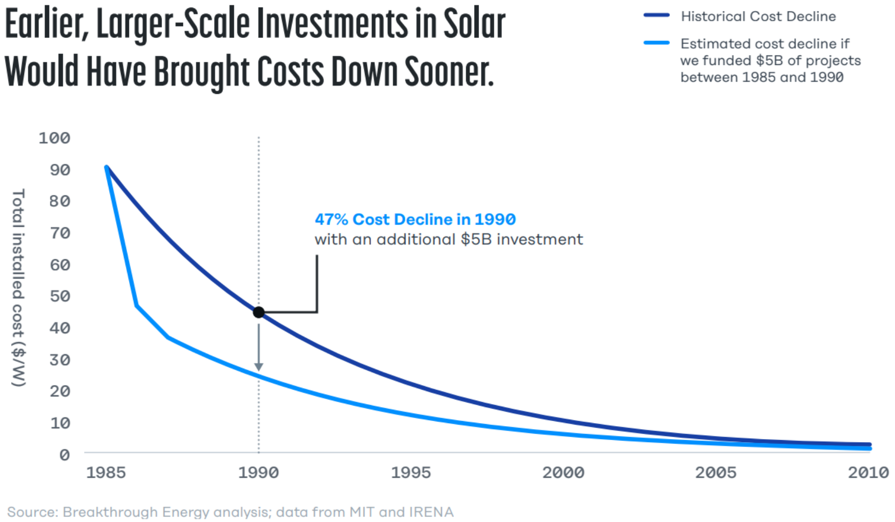

Illustration: B. Gates (2021),
see also: https://www.howsolargotcheap.com/