Navigating to a greener Europe with 24/7 hourly clean electricity procurement

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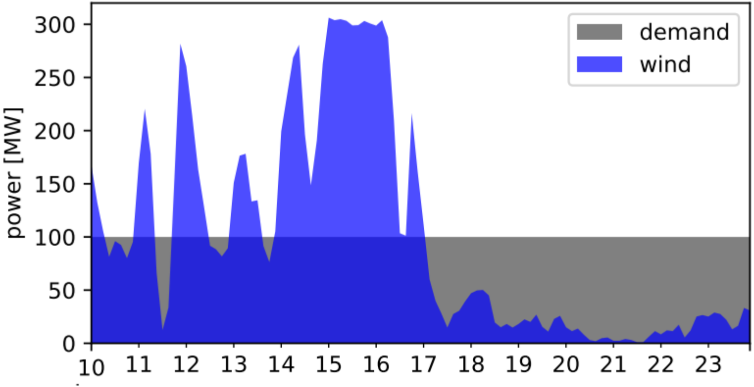
Background

100% renewable energy

Many companies use **renewable energy sources (RES)** to match their electricity demand on an **annual basis**. More than 370 companies have pledged to reach this goal in the **RE100** group.

RE100

Great, so what's the problem?



- No **simultaneity**: 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

  ..as well as

- Lack of **additionality**
- Displaced **location**
- Exposure to **market risk**
- Need for **backup**

24/7 carbon-free energy

- There is growing interest from leaders in voluntary clean electricity procurement to cover their consumption with clean energy supply on a **truly 24/7 basis**.
- Achieving 24/7 Carbon-Free Energy (CFE) means that every kilowatt-hour of electricity consumption is met with carbon-free electricity sources, **every hour of every day**.

The **24/7 Carbon-free Energy Compact**
initiative was launched in 2021.
It now includes 119 members.

UN-energy

Study 1: System-level impacts of 24/7 carbon-free electricity procurement in Europe

Study 1 (released in October 2022)

We investigate the **means and costs** of pursuing different clean electricity procurement strategies for companies in a selection of European countries. We also explore **how the 24/7 clean energy procurement affects the European electricity system**.

October 11, 2022

System-level impacts of 24/7 carbon-free electricity procurement in Europe

Riepin, Iegor; Brown, Tom

Traditional power purchase agreements for renewable energy have seen rapid growth in recent years, but they only match supply and demand on average over a longer period such as a year. There is increasing interest from leaders in voluntary clean electricity procurement to cover their consumption with clean energy supply on truly 24/7 basis. Achieving 24/7 carbon-free energy means that every kilowatt-hour of electricity consumption is met with carbon-free electricity sources, every hour of every day.

In this study, we investigate both the means and costs of pursuing different clean electricity procurement strategies for companies in a selection of European countries. We also explore how the 24/7 clean energy procurement affects the rest of the European electricity system.

The study was supported by a grant from Google Inc.

4,301 views

3,022 downloads

System-level impacts of 24/7 carbon-free electricity procurement in Europe

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24/7 carbon-free energy | electricity procurement | energy systems modelling | open-source
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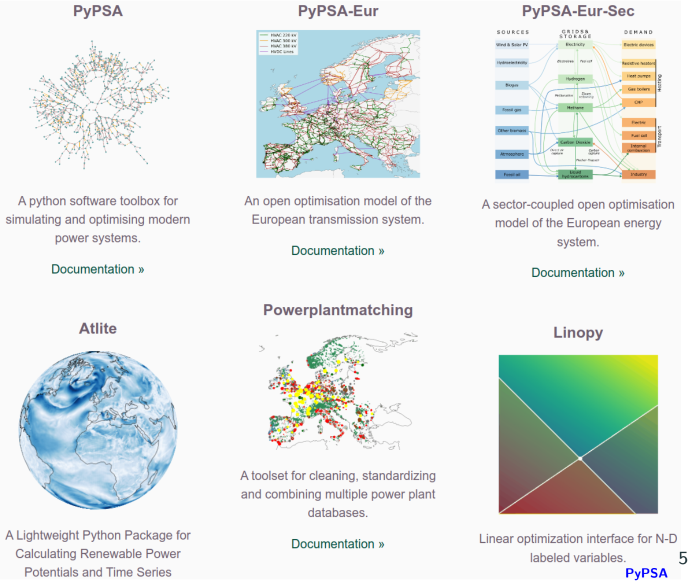
PyPSA ecosystem

- PyPSA (Python for Power System Analysis) is an open source toolbox for for state-of-the-art energy system modelling.
- Automated and configurable software pipeline from raw open data to optimised electricity system.
- PyPSA maintained by **ENSYS @ TU Berlin**.
- PyPSA is used worldwide 🌐
  Here is a **list of users**.



PyPSA

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

Documentation »

PyPSA-Eur

An open optimisation model of the European transmission system.

Documentation »

PyPSA-Eur-Sec

A sector-coupled open optimisation model of the European energy system.

Documentation »

Atlite

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

Powerplantmatching

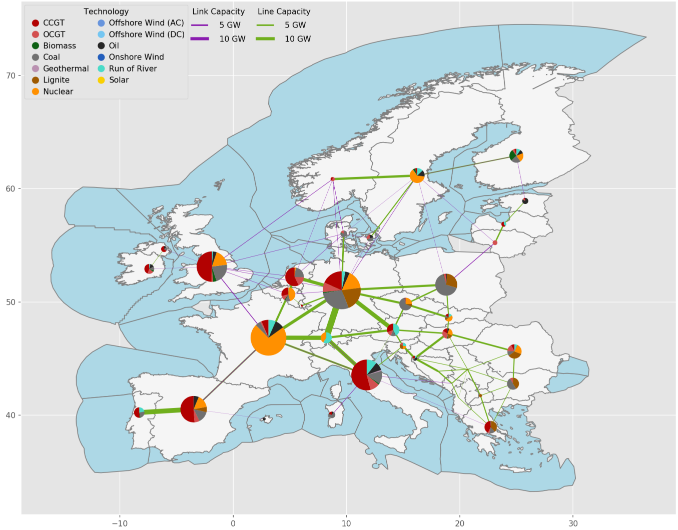
A toolset for cleaning, standardizing and combining multiple power plant databases.

Documentation »

Linopy

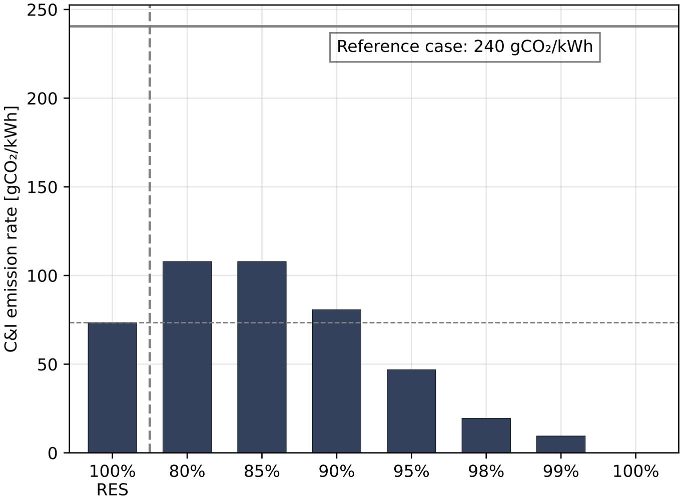
Linear optimization interface for N-D labeled variables.

Study design



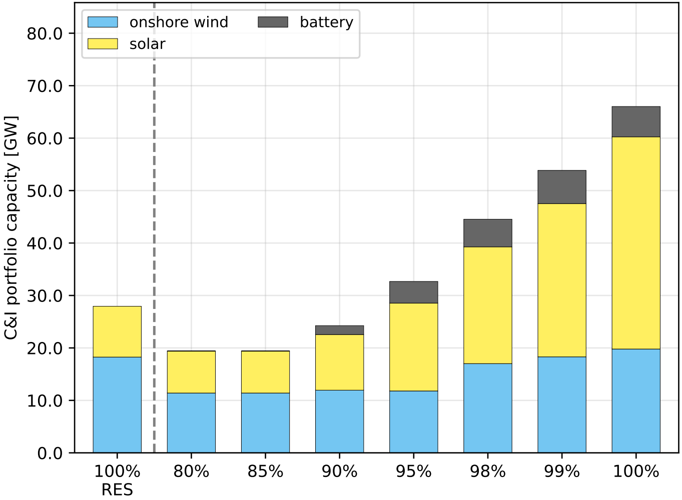
- We model the European power system with **capacity expansion** for the years **2025** & **2030**.
- Implemented in European model PyPSA-Eur-Sec of our open-source framework **PyPSA**.
- Consumers following 24/7 approach can be located in one of the **four zones**: Ireland, Denmark (zone DK1), Germany and the Netherlands.
- We implement a set of constraints to model a situation when a **fraction of corporate and industry (C&I) demand** in a selected zone commits to the 24/7 CFE procurement (i.e. C&I have an aggregated demand profile).

2025 – Germany: Average emissions rate of participating consumers



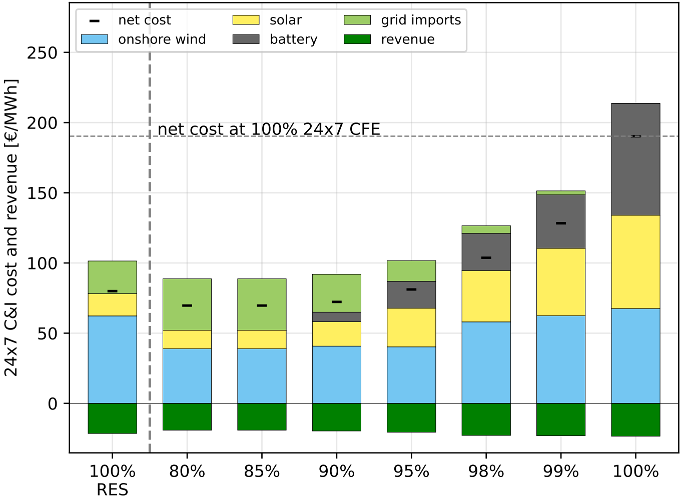
- Voluntary clean energy procurement goals affect **average emissions rate** of used electricity
- German system is moderately clean in 2025 at 240 gCO_2/kWh
- 100% annual matching with RES reduces rate to 73 gCO_2/kWh
- As hourly matching target tightens, emissions **drop to zero**

2025 – Germany: Portfolio capacity procured by participating consumers



- 100% annual matching for 10% of C&I demand in Germany (ca. 3.8 GW) is met with 28 GW of **onshore wind and solar** mix
- Above 85% CFE target **batteries enter the mix**
- With only wind, solar and batteries, a **large portfolio** is needed to bridge dark wind lulls (*Dunkelflauten*)

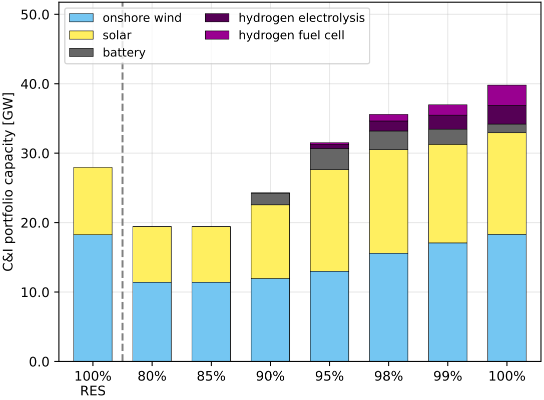
2025 – Germany: Cost breakdown

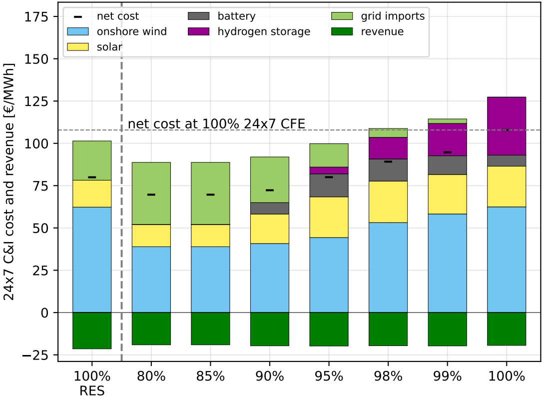


- The **cost breakdown** shows the average costs of meeting demand with the policy, including grid electricity consumption costs netted by revenue selling to the grid
- There is only a **small cost premium** going to 95-98% CFE matching
- But the last 2% of hourly CFE matching more than **doubles the cost**

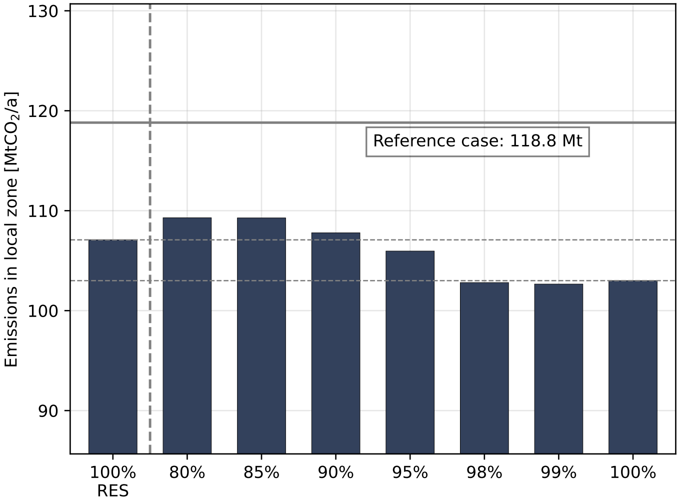
2025 – Germany: Including long-duration storage (LDES)

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** and **limits the cost premium** for 24/7 CFE.





2025 – Germany: System emissions are also reduced



- CO$_2$ emissions in local grids are also reduced by CFE procurement
- If 10% of C&I consumers follows 24/7 goal, Germany's electricity sector emissions are reduced by **14 MtCO$_2$ per year**
- Two effects are responsible: **volume effect** of more CFE with high targets; **profile effect** of the timing of feed-in at highly-emitting times

(A teaser of) Study 2: On the space-time load-shifting flexibility from data centers

Study 2 (to be released in June 2023)

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

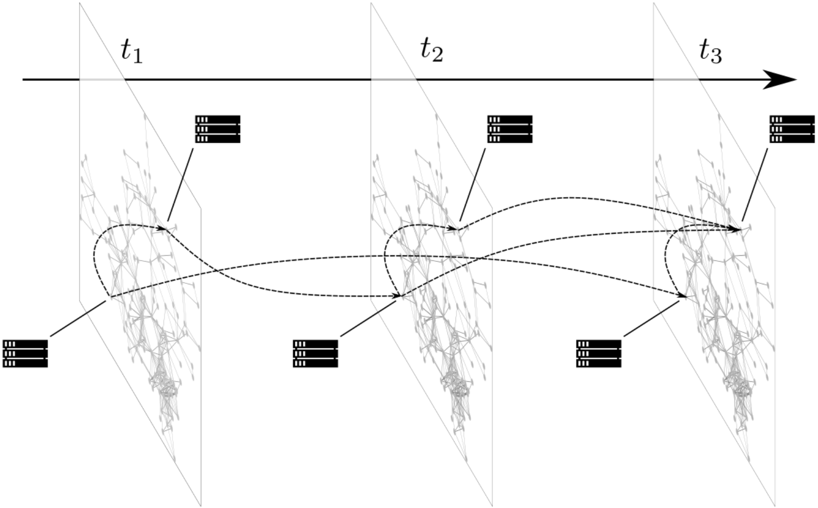
Addressing the challenge of climate change demands a transformation in how the world produces and uses energy. Google has been carbon neutral since 2007, and 2019 marks the third year in a row that we've matched our energy usage with 100 percent renewable energy purchases. Now, we're working toward 24x7 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

In Study 2, we focus on the **load-shifting flexibility** provided by data centers:

- shifting loads across **time** (via job scheduling);
- shifting loads across **space** (via service migration).

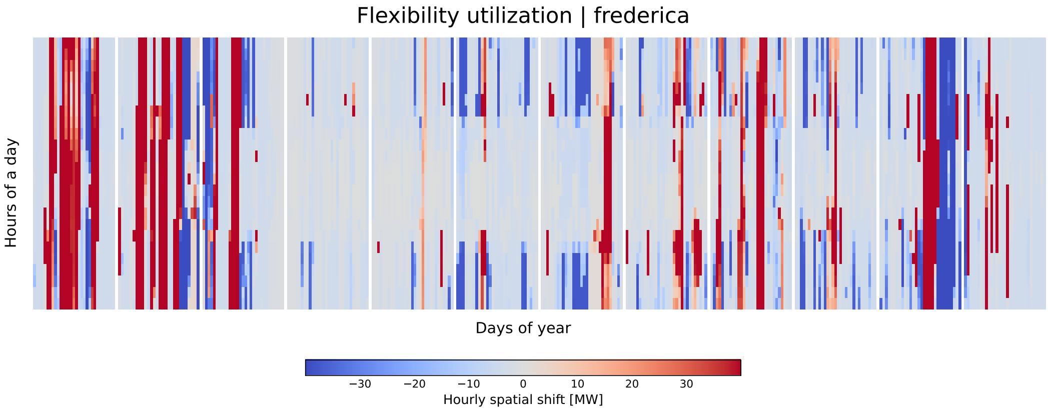
data-centers-work-harder-sun-shines-wind-blows

Illustration of space-time load shifting using virtual links



Zhang & Zavala (2022)

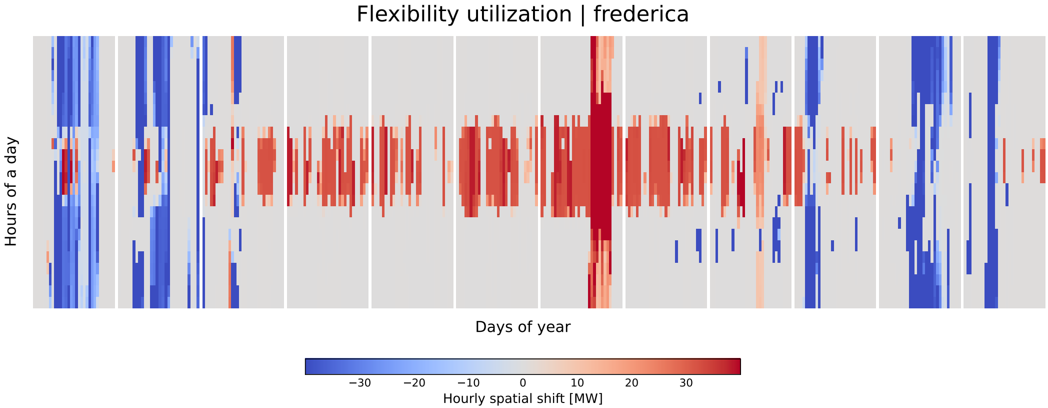
Spatial flexibility utilization for DK1–IE data center pair



Negative value (blue) indicates that load is shifted from the data center located in IE to the one in DK1.

There are notable load shifts also in another direction (red) driven by weather conditions in local zones.

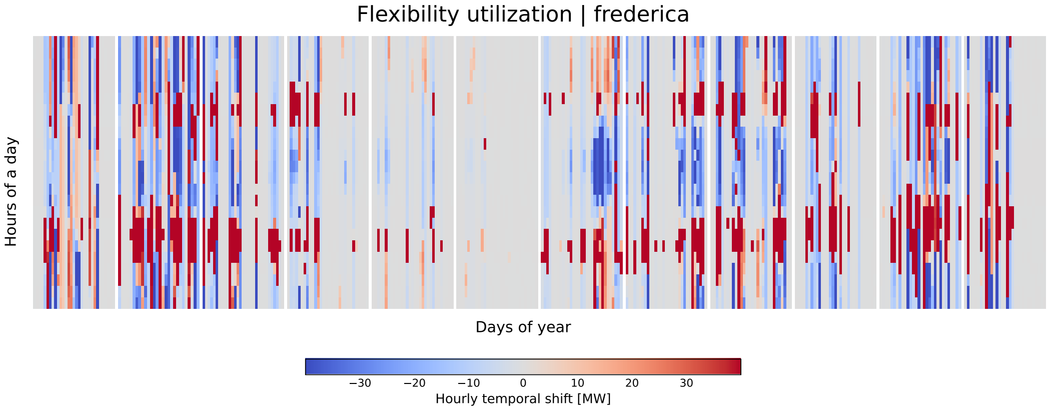
Spatial flexibility utilization for DK1–DE data center pair



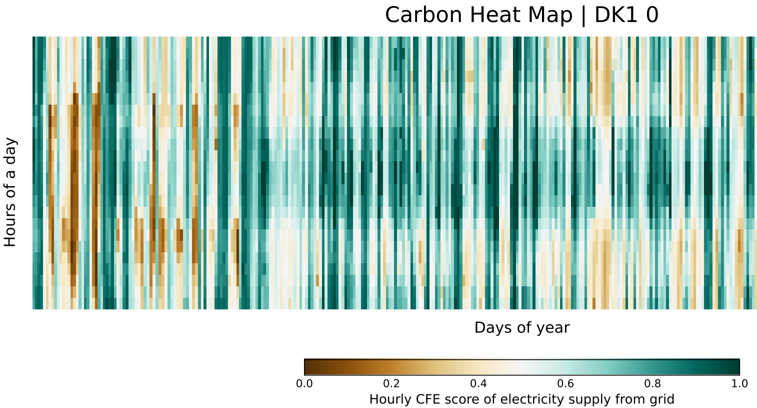
Load shifts have a clear daily pattern.

Temporal flexibility utilization for DK1 data center (isolated)

Note the **bimodal distribution** of temporal flexibility utilization. This is driven by the **Duck Curve** of grid CFE.



Hourly CFE score of supply from grid – Denmark 2025



Navigating to a greener Europe with 24/7 hourly clean electricity procurement

The research on this project is done in open-source:

https://github.com/PyPSA/247-cfe

A fixed link to the input data and code for Study 1:

https://zenodo.org/record/7181236

A fixed link to the Study 1 report:

ttps://doi.org/10.5281/zenodo.7180098

For questions and inquiries, please contact
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Prof. Tom Brown, t.brown@tu-berlin.de

backup

Spatial load shifting problem

Problem definition

1) Nodal energy balance

$$\sum_{r\in CFE} g_{r,t,n} + \sum_{s\in STO} (\bar{g}_{s,t,n} - \underline{g}_{s,t,n}) - ex_{t,n} + im_{t,n} = \bar{d}_{t,n} + \sum_{v\in V_n^{rec}} \delta_{t,v} - \sum_{v\in V_n^{snd}} \delta_{t,v} : n\in N_{Datacenter}, t\in T$$

2) Flexibility constraints

$$\underbrace{\overbrace{\underline{d}^{inflex}_{t,n} \le \underbrace{\bar{d}_{t,n} + \sum_{v\in V_n^{rec}} \delta_{t,v} - \sum_{v\in V_n^{snd}} \delta_{t,v}}_{A}}^{C} \le \bar{d}^{max}_{t,n}}_{B} \quad : n\in N_{datacenter}, t\in T$$

A: Requested Load at datacenter n, given that some loads can be shifted to other locations ($\tilde{d}_{t,n}$)

B: capacity constraint of Datacenter n

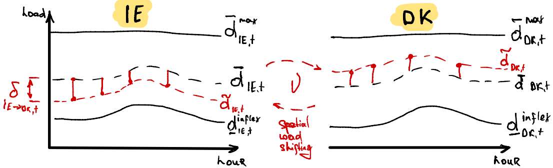
C: inflexible tasks (and assoc. Loads) cannot be shifted

3) Carbon-awareness in a form of a procurement goal

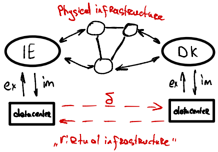
$$\sum_{r,t} g_{r,t,n} + \sum_{s,t} (\bar{g}_{s,t,n} - \underline{g}_{s,t,n}) - \sum_t ex_{t,n} + \sum_t \underbrace{CFE_{t,n} \cdot im_{t,n}} \ge \underbrace{X_n} \cdot \sum_t \left(\bar{d}_{t,n} + \sum_{v\in V_n^{rec}} \delta_{t,v} - \sum_{v\in V_n^{snd}}\right) : n\in N_{Datacenter}$$

Grid CFE factor → hourly carbon intensity

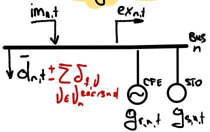
CFE score of a Datacenter



System view



Nodal energy Balance



$\bar{d}_{n,t}$ – nominal load

$\delta_{t,v} \in R_+$ – amount of load that is shifted over v

$v\in V$ – set of pathways (aka virtual links) between datacenters

$V_n^{snd} := \{v\in V \mid snd(v) = n\} \subseteq V$

$V_n^{rec} := \{v\in V \mid rec(v) = n\} \subseteq V$

Temporal load shifting problem

Problem definition

1) Nodal energy balance

$$\sum_{r\in CFE} g_{r,t} + \sum_{s\in STO}(\bar{g}_{s,t} - \underline{g}_{s,t}) - ex_t + im_t = \bar{d}_t + \sum_{s'\in DSM}(\bar{g}_{s',t} - \underline{g}_{s',t}) \quad : \{N_{datacenter}\}, t\in T$$

2) Flexibility constraints

$$\overbrace{\underline{d}_t^{inflex} \le \underbrace{\underbrace{\bar{d}_t + \sum_{s'\in DSM}(\bar{g}_{s',t} - \underline{g}_{s',t})}_{A} \le \bar{d}_{t,n}^{max}}_{B}}^{C} \quad : \{N_{datacenter}\}, t\in T$$

A: Requested Load at datacenter n, given that some loads can be shifted to later times $(\tilde{d}_t)$
B: capacity constraint of Datacenter n
C: inflexible tasks (and assoc. Loads) cannot be shifted

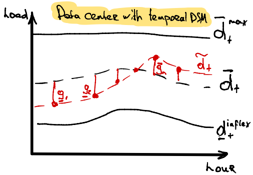
3) Carbon-awareness in a form of a procurement goal

$$\sum_{r,t} g_{r,t} + \sum_{s,t}(\bar{g}_{s,t} - \underline{g}_{s,t}) - \sum_t ex_t + \sum_t \underbrace{CFE_t}_{\text{Grid CFE factor} \to \text{hourly carbon intensity}} \cdot im_t \ge \underbrace{x}_{\text{CFE score of a Datacenter}} \cdot \sum_t\left(\bar{d}_t + \sum_{s'\in DSM}(\bar{g}_{s',t} - \underline{g}_{s',t})\right) : \{N_{datacenter}\}$$

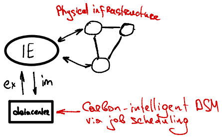
4) The 'daily usage conservation rule' that limits the daily shift of flexible workloads:

→ Radovanovic et al. form: $\sum_h \delta(c,h) = 0 \quad \forall c$

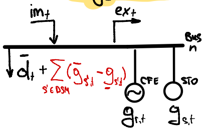
→ that is equivalent to: $\sum_{t \mid t\in days}(\bar{g}_{s',t} - \underline{g}_{s',t}) \quad \forall\{s'\}$
a storage problem with $\eta = 1$


Data center with temporal DSM

System view



Nodal energy balance



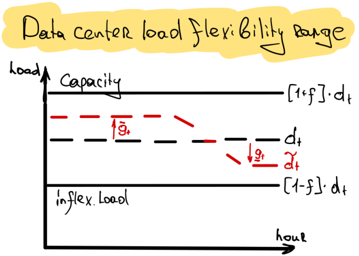
$\bar{d}_t$ – nominal load

$s'\in DSM$ – demand-side management system allowing job (and associated) Load scheduling
→ is a singleton per Location

$\bar{g}_{s',t} / \underline{g}_{s',t}$ – Loads rescheduled to time t / from time t to later point

$\bar{g} / \underline{g} \in R_+$

Data center parametrization



$$[1-f]\cdot d_t \le d_t + (\bar{g}_t - \underline{g}_t) \quad : n \in N_{datacenter}$$
$$[1+f]\cdot d_t \ge d_t + (\bar{g}_t - \underline{g}_t) \quad t \in T$$

- **Multiple data centers** (consumers following 24/7 approach) can be located in any bidding zone of the ENTSO-E area
- Data centers a have a nominal load of **100 MW** (baseload profile)
- Requested load $\widetilde{d}_t$ at any data center can deviate from the nominal load d_t. Requested load is constrained by the **data center capacity** (an upper limit) and the **inflexible loads** (a lower limit)
- Data centers can **shift loads across space** (service migration)
- Data centers can **shift loads across time** (via job scheduling)
- Adjusted scenario palette and new metrics to focus on flexibility & 24/7 CFE procurement

Take-aways from Study 1

Conclusion 1: 24/7 carbon-free energy (CFE) procurement leads to **lower emissions for both the buyer and the system**, as well as reducing the needs for flexibility in the rest of the system.

Conclusion 2: Reaching CFE for 90-95% of the time can be done with only a **small cost premium** compared to annually matching 100% renewable energy. 90-95% CFE can be met by supplementing wind and solar with battery storage.

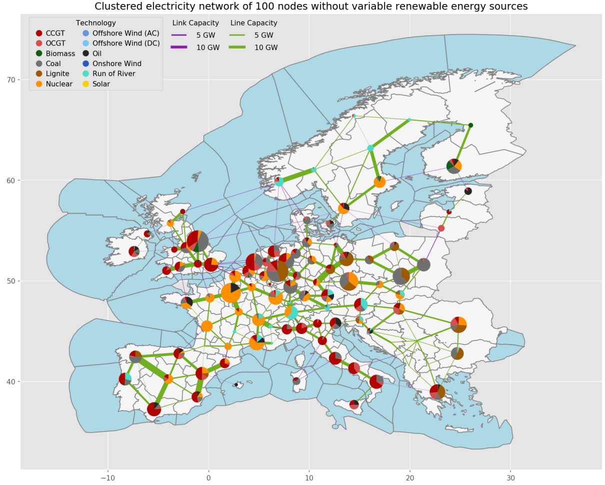
Conclusion 3: Reaching 100% CFE target is possible but costly with existing renewable and storage technologies, with **costs increasing rapidly above 95%**.

Conclusion 4: 100% CFE target could have a **much smaller cost premium** if long duration storage or clean dispatchable technologies like advanced geothermal are available.

Conclusion 5: 24/7 CFE procurement would create an early market for the advanced technologies, stimulating innovation and learning from which the **whole electricity system would benefit**.

PyPSA-Eur: open model of the European energy system

- PyPSA-Eur is an open model of the European power system at the transmission network level that covers the full ENTSO-E area.
- Only freely available and open data.
- Automated and configurable software pipeline from raw data to optimised electricity system.
- Adjustable temporal and spatial resolution.
- See **documentation** and **feature summary** for more details.
- PyPSA-Eur-**Sec** version of the model adds building heating, transport and industry sectors, as well as gas networks.


Clustered electricity network of 100 nodes without variable renewable energy sources

PyPSA-Eur(-Sec) suite of models are available on **GitHub**

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

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

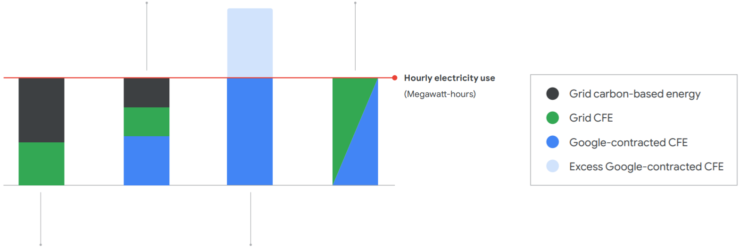
- Directly contracted carbon-free assets are generating (generation above company demand is ignored)
- Energy consumed from the grid is carbon-free (counted according to mix in local bidding zone and any imports)

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

In any given hour, a data center's energy profile takes one of the following forms:

2. Hour when Google-contracted CFE is less than site load
Electricity use is partially matched with regional contracted CFE; the remainder is apportioned to the regional grid mix

4. Every hour in a 24/7 CFE future
Electricity use is fully matched with CFE, either from regional contracted CFE or the regional grid mix



1. Hour with zero Google-contracted CFE
Data center's electricity use corresponds only to the regional grid mix—a combination of carbon-free and carbon-based sources

3. Hour when Google-contracted CFE exceeds site load
Electricity use is fully matched with regional contracted CFE; generation in excess of site load does not increase site's CFE match

Google 2021, 24/7 CFE: Methodologies and Metrics

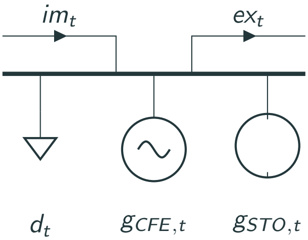
Implementation of C&I demand and supply

The model optimizes a portfolio of carbon-free generation and storage technologies procured by the participating C&I consumers. The portfolio assets have to be located in the same market zone.

The hourly demand of C&I consumers d_t for hour t can be met by a combination of the following:

- dispatch $g_{r,t}$ of procured CFE generators $r \in CFE$
- dispatch $\bar{g}_{s,t}$ of procured storage technologies $s \in STO$ (requires charge $\underline{g}_{s,t}$)
- imports from the grid im_t.

$$\sum_{r \in CFE} g_{r,t} + \sum_{s \in STO} \left(\bar{g}_{s,t} - \underline{g}_{s,t} \right) - ex_t + im_t = d_t \qquad \forall t$$



NB: the excess from the local supply ex_t can either be sold to the grid at market prices or curtailed.

Implementation of 100% annual matching

The **100% annual matching** is modelled with a constraint (1), which requires C&I consumers to purchase enough renewable electricity from the local bidding zone to match all of their electricity consumption on an annual basis.

More formally, the sum of all dispatch $g_{r,t}$ for RES generators $r \in RES$ over the year $t \in T$ is equal to the annual demand d_t of C&I consumers:

$$\sum_{r \in RES, t \in T} g_{r,t} = \sum_{t \in T} d_t \tag{1}$$

Implementation of 24/7 CFE matching

The **24/7 CFE matching** is modelled with a constraint (2), which matches demand of C&I consumers with carbon-free resources on an hourly basis.

More formally, the constraint states that sum over generators from procured CFE resources $r \in CFE$, discharge and charge from storage technologies $s \in STO$, as well as import from the grid im_t multiplied by the grid's CFE factor CFE_t must be higher or equal than a certain CFE target x multiplied with the total load:

$$\sum_{r \in CFE, t \in T} g_{r,t} + \sum_{s \in STO, t \in T} \left(\bar{g}_{s,t} - \underline{g}_{s,t} \right) - \sum_{t \in T} ex_t + \sum_{t \in T} CFE_t \cdot im_t \geq x \cdot \sum_{t \in T} d_t \tag{2}$$

The **CFE Score** x [%] measures the degree to which hourly electricity consumption is matched with carbon-free electricity generation within the regional grid.

Note that the grid CFE factor CFE_t is affected by capacity procured by C&I consumers. This introduces a nonconvex term to the optimization problem. The nonconvexity can be avoided by treating the grid CFE factor as a parameter that is iteratively updated (starting with $CFE_t = 0 \ \forall t$). Similarly to the **Xu et al. (2021)** study, we find that one forward pass (i.e. 2 iterations) yields very good convergence.

Implementation of 24/7 CFE matching

The excess generation ex_t from the procured resources represents clean electricity sold to the rest of the grid. The **excess is not counted toward the CFE score** – and thus it is subtracted on the left-hand side of the eq. (2).

CFE generation above the demand can be stored and shifted to another hour where procured resources generate less than the C&I demand, sold to the regional grid as excess ex_t at **market prices**, or curtailed. The total amount of excess generation is constrained to a certain level on an annual basis. In this study, the limit is set to 20% of annual 24/7 participating customer's demand:

$$\sum_{t \in T} ex_t \leq ExLimit \cdot \sum_{t \in T} d_t \tag{3}$$

The constraint (3) gives the C&I consumers the flexibility to sell electricity to the regional grid, while avoiding the situation that sales to the grid become significantly larger than supply to the C&I's own demand.

The **market prices** are derived from the dual variable of each zone's energy balance constraint. An infinitely small relaxation of the constraint, i.e., one unit of load less to be met, returns the marginal costs of providing that unit, which can be used as the electricity price indicator in a competitive market.

CFE factor of the regional grid

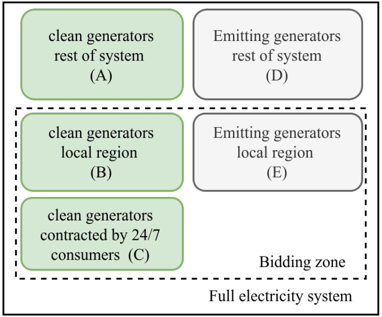
The **grid CFE factor** CFE_t in eq. (2) defines the share of carbon-free electricity in grid imports by C&I consumers following 24/7 approach. The factor depends on the generation mix in the region where C&I consumers are located, as well as on the generation mix in other regions from which electricity is imported to the local region ($import_t$).

Using the notation on the right, the average cleanness of the rest of the electricity system is:

$$ImportCFE_t = \frac{A_t}{A_t + D_t}$$

The CFE factor of grid supply[a] for a given hour t is:

$$CFE_t = \frac{B_t + ImportCFE_t * import_t}{B_t + E_t + import_t}$$



This approach is based on **Xu et al. (2021)**

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[a] Note that generators contracted by 24/7 consumers (C) are excluded from the grid supply.

CFE_t can be seen as the percentage of clean electricity in each MWh of imported electricity from the grid to supply participating 24/7 loads in a given hour.

Technology palettes span different commercial maturities

We consider carbon-free technologies available today and that could scale up soon. We formulate **three palettes** grouping generators by a degree of technological maturity:

Palette 1	**Palette 2**	**Palette 3**
onshore wind	onshore wind	onshore wind
utility scale solar	utility scale solar	utility scale solar
battery storage	battery storage	battery storage
-	LDES[1]	LDES
-	-	Allam cycle with CCS[2]
-	-	Advanced dispatchable generator[3]

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[1] Long-duration energy storage (LDES).

[2] Allam cycle is a natural gas power plant with up to 100% of carbon capture and sequestration.

[3] A stand-in for clean dispatchable technologies, such as advanced geothermal (closed-loop) or nuclear systems. See e.g., **Eavor** developing a promising solution for clean baseload & dispatchable power with a potential for a commercial scale up in Europe.

Technologies available for 24/7 consumers - 2025

Palette	Technology	CAPEX (overnight cost)	FOM (%/year)	VOM (€/MWh)	Eff. (per unit)	lifetime (years)	Original reference (**technology data**)
1,2,3	solar	612 €/kW	1.7	0.01	-	37.5	**DEA**
1,2,3	onshore wind	1077 €/kW	1.2	1.42	-	28.5	**DEA**
1,2,3	battery storage	187 €/kWh	-	-	-	22.5	**DEA**
1,2,3	battery inverter	215 €/kW	0.3	-	0.96	10.0	**DEA**
2,3	hydrogen storage[4]	2.5 €/kWh	0	0	-	100.0	**DEA**
2,3	electrolysis	550 €/kW	2.0	-	0.67	27.5	**DEA**
2,3	fuel cell	1200 €/kW	5.0	-	0.50	10.0	**DEA**
3	NG Allam cycle[5]	2760 €/kW	14.8	3.2	0.54	30.0	**Navigant**, **NZA**
3	Advanced dispatchable	10000 €/kW	0	0	1.00	30.0	own estimates

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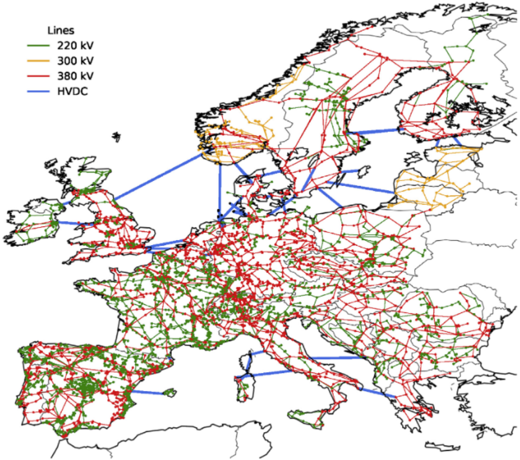
[4] Underground hydrogen storage in salt cavern

[5] Costs also include estimate of 40 €/ton for CO_2 transport & sequestration.

Summary of data sources: electricity grid



Basic validation of grid model in **Hörsch et al. (2018)**

- Grid data contains AC lines at and above 220 kV voltage level, all high voltage DC lines, and substations for the full **ENTSO-E area**.
- Grid data is collected by **GridKit extraction** of ENTSO-E interactive map
- Spatial resolution is **adjustable**, what allows spatial and topological analysis at different levels (e.g. by transforming the transmission grid to a 380 kV only equivalent network).

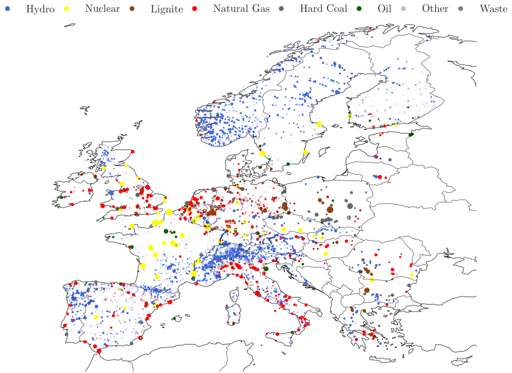
Summary of data sources: power plants and technology costs

- Existing generation fleet data is collected by cleaning, standardizing and merging multiple power plant databases.

- The process is transparent and open-sourced via the **powerplantmatching** package. The package provides all the important information about power plants in a ready-to-use format for the European power system.

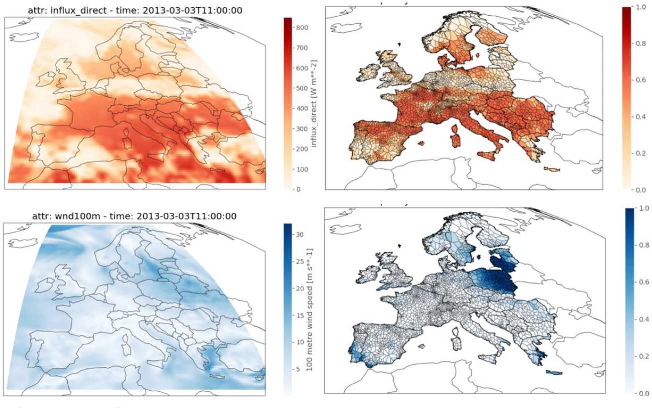
- Assumptions on energy system technologies (such as capital and operational costs, efficiencies, lifetimes, etc.) are gathered from variety of open sources. The process is also open-sourced via the **technology-data** project.

- Both tools are maintained by TU Berlin team.



A showcase example of **powerplantmatching**

Summary of data sources: renewable potentials and time series



Converting weather data to energy system data with **atlite**

- Renewable power potentials and generation profiles are processed by the open-source **atlite** package, which converts terabytes of weather data (like wind speeds, solar influx) into the data for energy systems modelling.
- We gather and process datasets for land cover (CORINE2018), natural protection areas (NATURA2000), bathymetry (GEBCO2018) and **other** to conduct own geospatial land availability analysis.
- The **atlite** project is also maintained by TU Berlin team.