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

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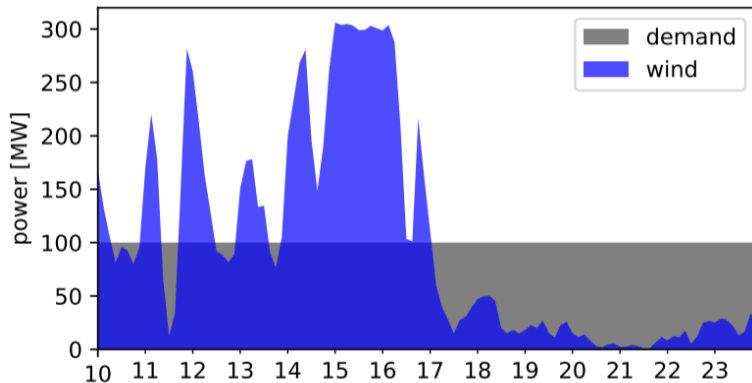
Many companies use **renewable energy sources (RES)** to match their electricity demand on an **annual basis**. More than 370 companies have pledged to reach this goal in the **RE100** group.

- 100% RES PPAs result in periods of **oversupply** and **deficit**

- Hours of deficit must be met by **rest of system**

- These hours may have **high emissions** and **high prices**

- Multi-day wind lulls **hard to bridge** with batteries

- 24/7 carbon-free energy (CFE) matches demand on **hourly basis**

Quite a few things can go wrong:

1. No **simultaneity**

2. Lack of **additionality**

3. Displaced **location**

4. Exposure to **market risk**

5. Need for **backup**

6. No **incentives** for new technology

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**.

Ideas behind 24/7 CFE procurement:

- demand is matched on an **hourly basis**

- contracted power is **additional**

- power comes from the **same bidding zone**

- power is **carbon-free** rather than renewable
  (i.e. technology neutrality)

The **24/7 Carbon-free Energy Compact**
initiative was launched in 2021.
It now includes more than
80 companies and organizations.

We want to investigate both the **means and costs of 24/7 procurement** for companies in 4 EU countries (Ireland, the Netherlands, Germany and Denmark) in 2025 & 2030. We also investigate the **system impacts** of 24/7 procurement.

We want to find out:

- How can we achieve hourly clean energy matching?

- What is the cost premium versus annual matching?

- Can long-duration storage or new dispatchable clean technologies help?

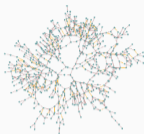- If many companies take a 24/7 approach, how does this effect the rest of the system?

A single slide about the modelling setup

PyPSA world

- PyPSA (Python for Power System Analysis) is an open source toolbox for for state-of-the-art energy system modelling.

- PyPSA development and maintenance is coordinated by the TU Berlin, **Department of Energy Systems**.

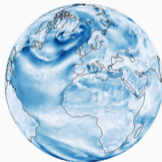- PyPSA is used worldwide by dozens of research institutes and companies. See **list of users**.

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.
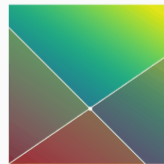
Documentation »

Linopy

Linear optimization interface for N-D labeled variables.

PyPSA

7

Study design

Scenario setup

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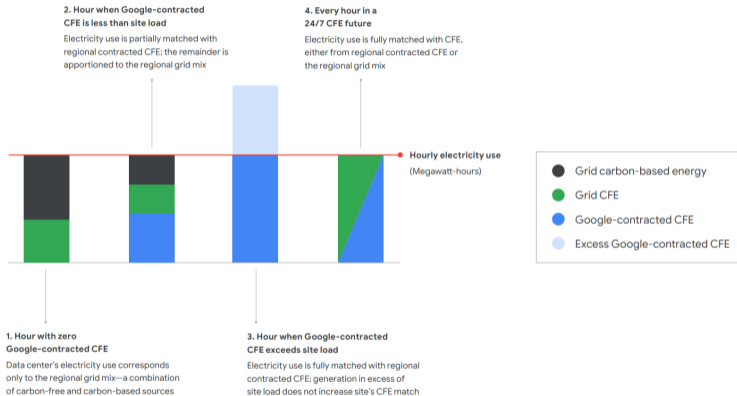
How is 24/7 carbon-free electricity (CFE) measured?

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

Hourly electricity use
(Megawatt-hours)

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

- ● Grid carbon-based energy
- ● Grid CFE
- ● Google-contracted CFE
- ● Excess Google-contracted CFE
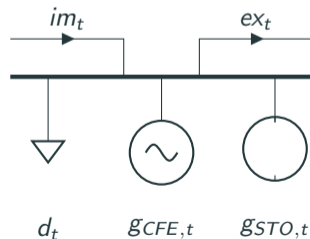
Implementation of C&I demand and supply

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.

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:

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

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.

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 ($import_t$).
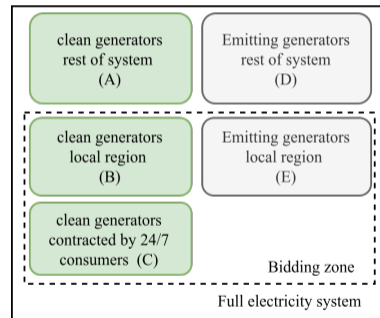
Using the notation on the right, the average cleanness of the rest of the electricity system is:

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

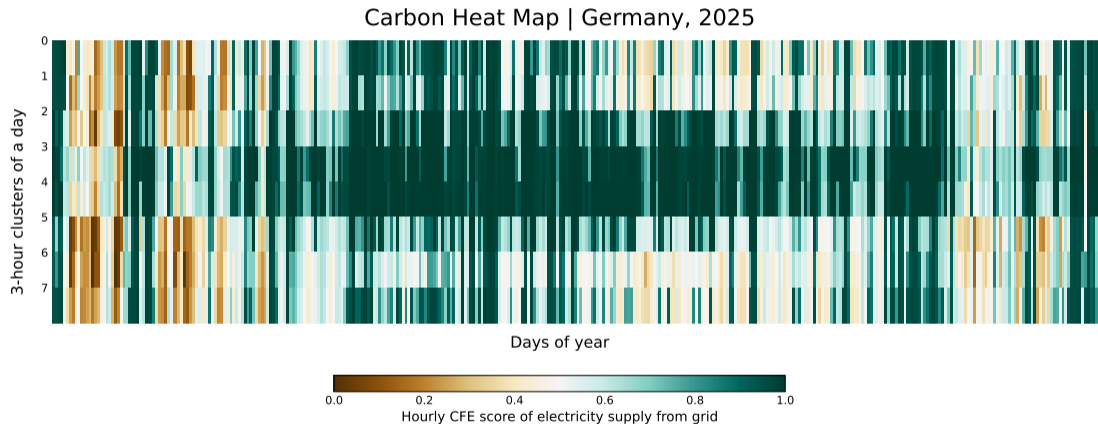The CFE factor of grid supply[a] for a given hour t is:

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

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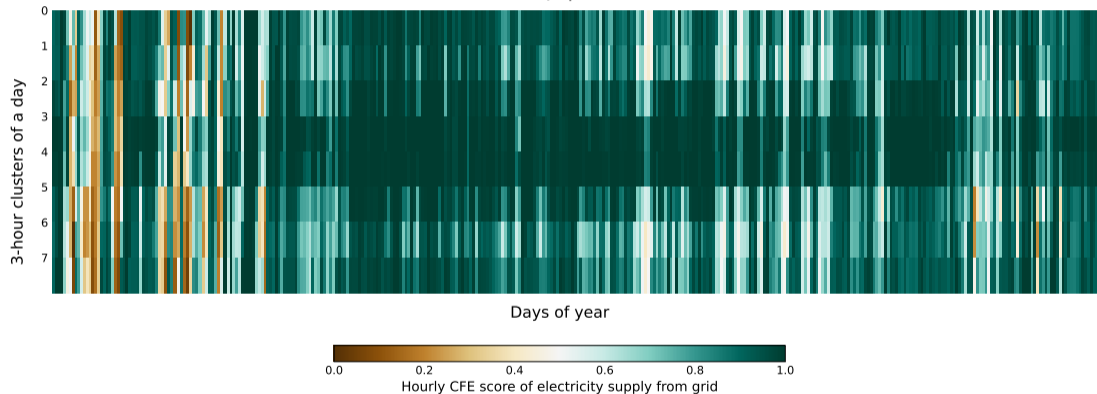

This approach is based on **Xu et al. (2021)**

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.

Carbon Heat Map | Germany, 2025

Carbon Heat Map | Denmark, 2025

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

[4] Underground hydrogen storage in salt cavern

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

General assumptions

- Model is set to perform a **perfect-foresight optimization** of investment and power dispatch decisions to meet electricity demand of the 24/7 consumers, as well as the demand of other consumers in the European electricity system for 2025 or 2030.

- Electrical demand time-series is based on the **OPSD project**. We assume the same demand profile per bidding zone for 2025 and 2030, as in the representative year 2013.

- Similarly, we assume 2013 as the representative climate year for renewable in-feed.

- Renewable expansion in the regional grid where 24/7 consumers are located is based on the **national energy and climate plans**.[6]

- National policies and decommissioning plans for coal and nuclear power plants are based on the **Europe Beyond Coal**, and **world-nuclear.org** projects.

- We assume price for EU ETS allowances to be 80 €/tCO_2 and 130 €/tCO_2 for 2025 and 2030, accordingly. The price for natural gas is assumed to be 35 €/MWh.[7]

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[6] For Germany, we assume the **Easter package** to come into force as planned, i.e. RES cover 80% of gross electricity consumption by 2030.

[7] Based on the price assumptions in the **REPowerEU Plan** issued by the European Commission in May 2022
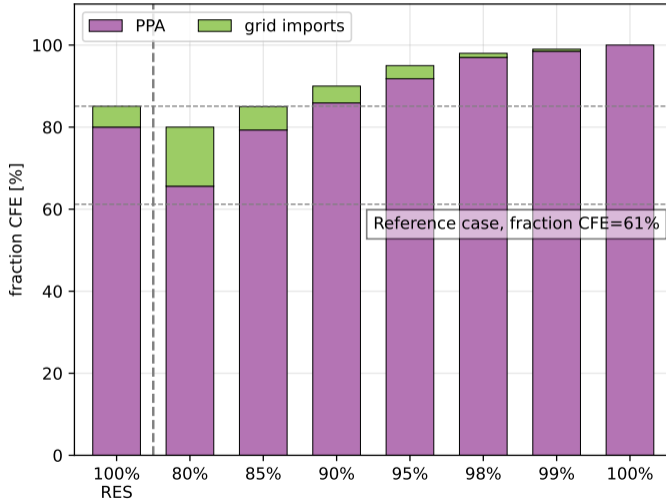
Scenario matrix

We consider a range of scenarios:

- **9 procurement strategies:** reference case with grid electricity; 100% annual RES matching; 24/7 CFE matching with scores ranging from 80% to 100%

- **4 bidding zones:** Ireland; Netherlands; Germany; Denmark West

- **3 technology palettes:** today's technologies and tomorrow's

- **2 future years:** 2025 or 2030; affects technology costs, national renewable targets, power plant fleet retirements, CO_2 and fuel prices

- **Other sensitivities:** basecase assumes 10% of C&I load participates in 24/7 and has a flat demand profile, but we also consider 25% participation and diverse load profiles
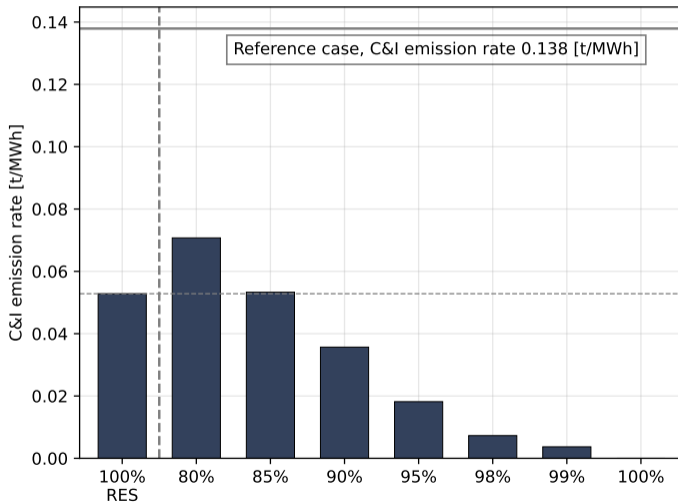
Results and takeaways

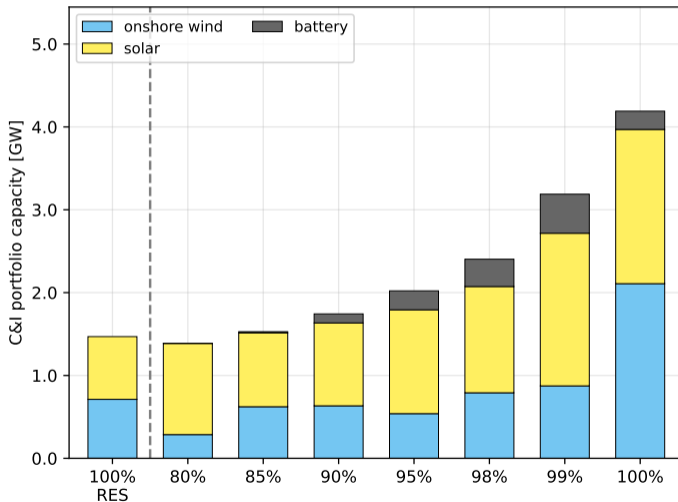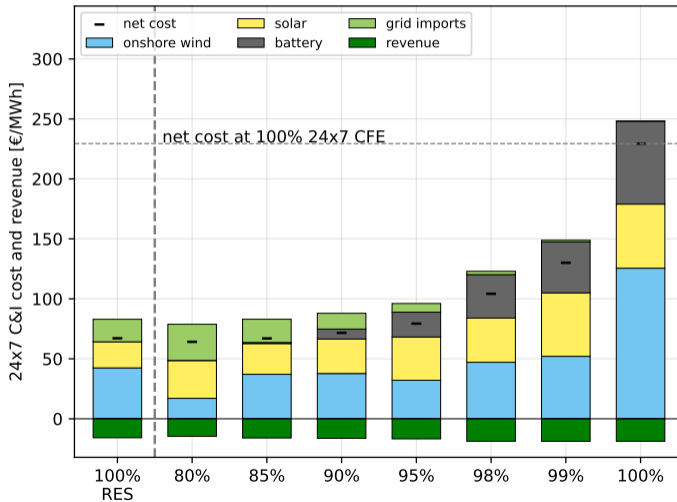# 2025 – Ireland – Palette 1: Fraction of hourly demand met by CFE

- **61%** of grid electricity is hourly CFE in Ireland in 2025

- 100% RES annual matching reaches 85% if you include grid CFE to cover demand (green)

- CFE above 85% requires dedicated CFE targets

- High CFE scores **rely more on directly contracted resources** (purple)

Reference case, C&I emission rate 0.138 [t/MWh]

- Procurement affects **average emissions rate** of used electricity

- Reference system is moderately clean at 138 kgCO$_2$/MWh

- 100% annual RES reduces rate to 53 kgCO$_2$/MWh

- As CFE target tightens, emissions **drop to zero**

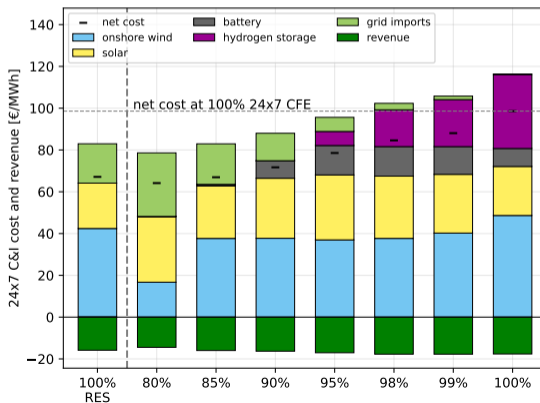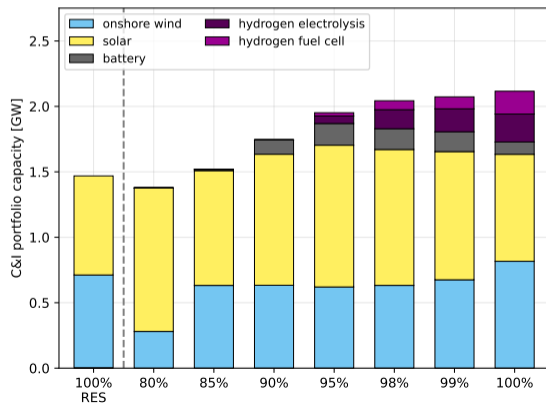# 2025 – Ireland – Palette 1: Portfolio of capacity

- 100% RES for 10% of C&I demand is met with 1.5 GW of **onshore wind and solar**

- Above 85% CFE **batteries enter the mix**

- With only wind, solar and batteries, a **large portfolio** is needed to bridge dark wind lulls (*Dunkelflauten*)

- 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

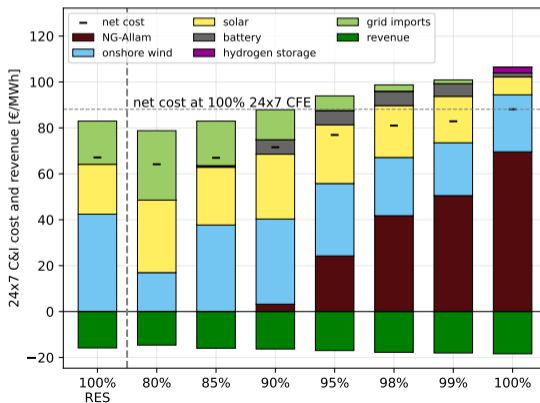- But the last 2% of hourly CFE matching more than **doubles the cost**
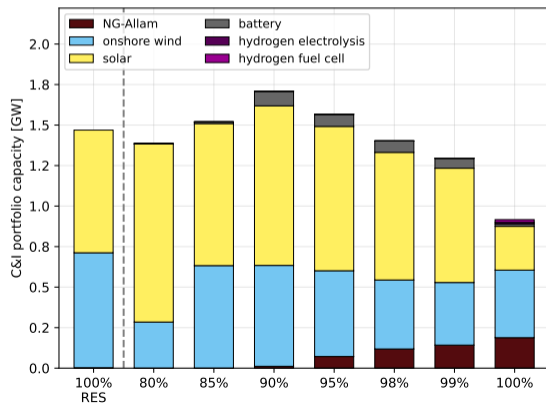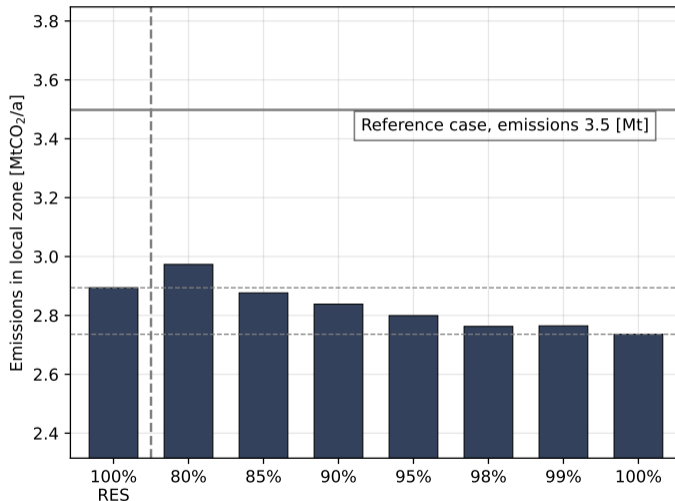
Adding **long-duration energy storage (LDES)** to the mix (represented here by hydrogen storage in salt caverns at 2.5 €/kWh) **reduces the portfolio size** for 100% CFE and **limits the cost premium to 50%** over annual RES matching.

2025 – Ireland – Palette 3: Including dispatchable generators

If **dispatchable technologies** are included, such as a natural gas Allam cycle generator with CCS, advanced geothermal or nuclear, this **further limits the hourly CFE cost premium** above annual renewable matching, as well as reducing storage and capacity needs.

Ireland – Palette 3 – 2025 – 10% – baseload

- **CO_2 emissions in the local bidding zone** are also reduced by CFE procurement

- If 10% of C&I follows 24/7, total emission are reduced by a further 0.2 $MtCO_2$ 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
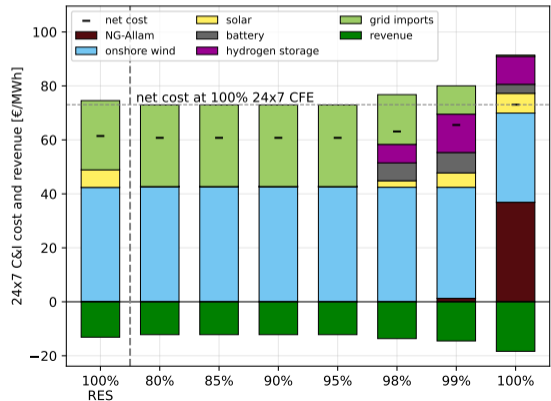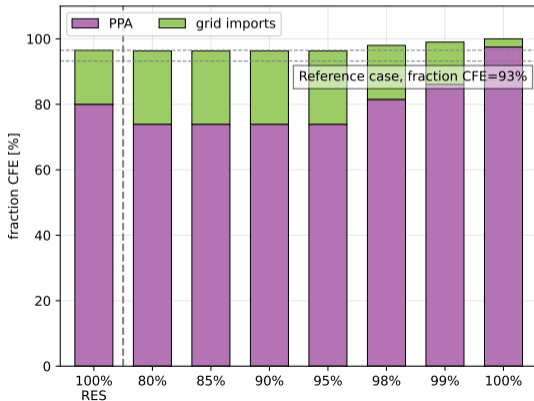
What changes if we look at 24/7 procurement in other EU countries and in 2030 not 2025?

- Broadly the results are **similar** in the other case studies.

- **Different countries**: each country has a **unique set of characteristics** that depend on local resources, renewable potentials, existing power plants, national policies, interconenction; this affects technology mix.

- Moving from 2025 to **2030**: technology costs sink, particularly the cost of storage and advanced dispatchable generators; also the background grid becomes cleaner with retirements and NECP additions. Effect: **lower cost for 100% CFE** in 2030.

- Changing cause of reduction of **system emissions**: in fossil-heavy systems, the volume effect dominates emission reductions; while in cleaner systems, the timing of procurement dominates emissions reductions.

Thanks to its NECP aimed at **110% renewable electricity** in 2030, the Danish example shows what happens in a **very clean system**. The grid already reaches 93% CFE, and the grid can be used for lower targets. Dispatchable technologies only needed for 100% CFE.

Denmark – Palette 3 – 2030 – 10% – baseload

28

24/7 CFE doesn't just reduce system emissions, it also **reduces system flexibility needs**. Graphs show generation capacity differences with reference case. In Ireland (left) we see less battery capacity and in Germany (right) less open cycle (OC) gas turbine capacity.

2030 scenario: summary of costs for 24/7 participating consumers

Net procurement costs of achieving 98% and 100% CFE targets (and % increase compared to the 100% annual renewable matching) for the 2030 scenario (2020 €/MWh):

Similarly to the 2025 scenario, 100% CFE could have a **much smaller cost premium** if LDES or clean dispatchable technologies are available.

NB: This calculation assumes that the costs of 24/7 procurement are internalized by participants; i.e., C&I participants are responsible for paying 100% of the incremental system costs resulting from 24/7 procurement.

Zone	Palette	100% RES	98% CFE	100% CFE
IE	Palette 1	72.5	79.5(+10%)	192.4(+165%)
IE	Palette 2	72.5	74.8(+3%)	85.8(+18%)
IE	Palette 3	72.5	74.8(+3%)	80.4(+11%)
DE	Palette 1	86.8	85.7(-1%)	156.7(+80%)
DE	Palette 2	86.8	85.6(-1%)	102.3(+18%)
DE	Palette 3	86.8	83.0(-4%)	89.2(+3%)
DK1	Palette 1	61.4	63.5(+3%)	121.9(+98%)
DK1	Palette 2	61.4	63.1(+3%)	74.8(+22%)
DK1	Palette 3	61.4	63.1(+3%)	73.1(+19%)
NL	Palette 1	67.4	75.1(+11%)	134.8(+100%)
NL	Palette 2	67.4	71.3(+6%)	79.5(+18%)
NL	Palette 3	67.4	71.1(+5%)	77.0(+14%)

Conclusions and project outlook

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**.

Project outlook

This project will continue analysing the impact of 24/7 procurement in Europe until March 2024. We will deepen the analysis by examining the following:

- The impacts of **temporal demand-side management** at datacenters;

- The impact of **spatial demand-shifting between datacenters** at different locations, so that compute jobs can move where the clean energy is available;

- The impacts of **parametric uncertainties** and corresponding assumptions when constructing the model of the European energy system. These include:
  - (i) Scenarios for carbon price developments in the EU ETS;
  - (ii) Scenarios for inter-connector capacities based on the TYNDP or free optimization;
  - (iii) Scenarios for expansion of electric vehicles, heat pumps, industry electrification;
  - (iv) Prices for primary energy carriers;
  - (v) Weather year realizations.

- In addition, the modelling will use a **higher-resolution grid** model, so that transmission network impacts can be estimated.

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

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 this study:
https://zenodo.org/record/7181236
A fixed link to the complete study:
ttps://doi.org/10.5281/zenodo.7180098

For questions and inquiries, please contact
Dr. Iegor Riepin, iegor.riepin@tu-berlin.de
Prof. Tom Brown, t.brown@tu-berlin.de

backup

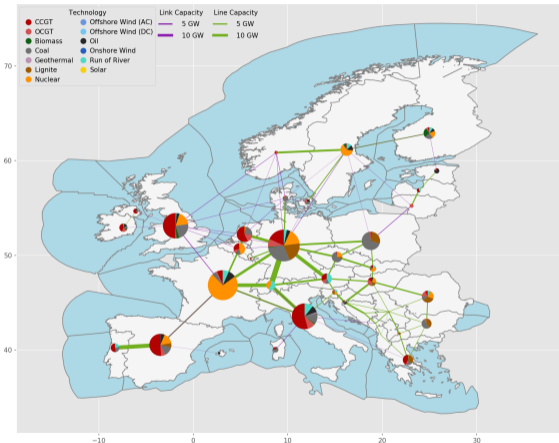# PyPSA-Eur(-Sec): open models of the European energy system

- 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

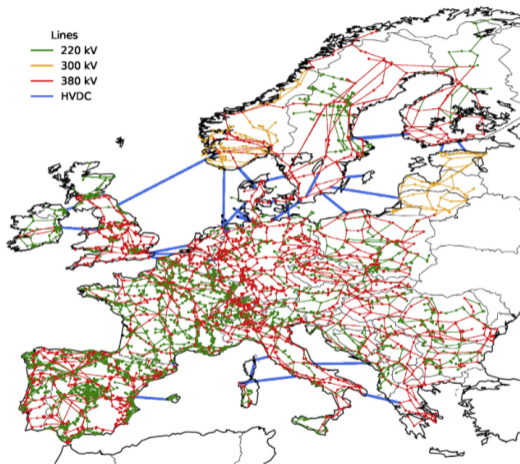PyPSA-Eur(-Sec) suite of models are available on **GitHub**

PyPSA-Eur network clustered to 37 zones

- In each scenario, we model the full European power system clustered to **37 zones**.

- Each zone represents an individual country. Some countries that straddle different synchronous areas are split to individual bidding zones, such as DK1 (West) and DK2 (East).

- Consumers following 24/7 approach can be located in either of the **four zones**: Ireland, Denmark (zone DK1), Germany and the Netherlands.

- We assume that all consumers committed to 24/7 matching, form an alliance and sign contracts with CFE generators so that their aggregated consumption can be matched on an hour-by-hour basis with clean generation to achieve a given CFE matching score.

35

- We model various procurement policies and targets. The scenarios include:
  (i) **24/7 CFE matching** with seven different CFE scores in a range from 80% to 100%,
  (ii) **100% annual renewable matching** – the best case scenario for the annual matching policy,
  (iii) **A reference case** when 24/7 consumers cover their load purely with grid purchases without any policy regarding the origin of electricity.

- We conduct an analysis for different rates of participation. The two scenarios assume that **10%** and **25%** of commercial and industrial load in a given zone participate in 24/7 CFE matching.

- We focus on two periods: **2025** and **2030**. The two periods differ by
  (i) Technology cost assumptions,
  (ii) National renewable expansion pathways,
  (iii) Power plant fleet (changes take place due to decommissioning based on generators' age or national policies),
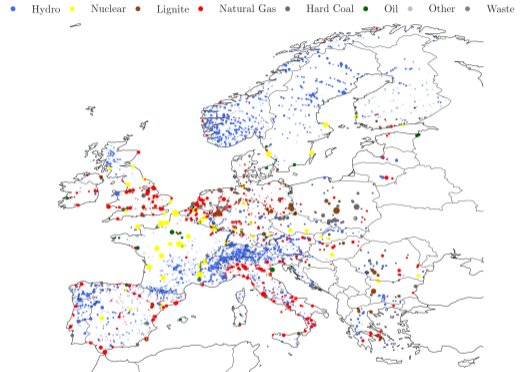 (iv) System-wide assumptions, such as price for EU ETS allowances.

- We assume that 24/7 consumers have an access to a wide palette of carbon-free technologies that are either available on the European market now or expected to be available for a commercial scale up in the near future.

- We deliberately encode prospective technologies into the analysis. The **technology inclusivity** is an **important principle** of the 24/7 CFE methodology. Thus, we consider carbon-free power generation technologies that we believe can play important roles in facilitating CFE matching on hourly basis, while enabling deeper decarbonization of electricity systems at the same time.

- We formulate three scenarios grouping generators by a degree of technological maturity as of now:
  Palette 1: onshore wind, utility-scale solar, battery storage
  Palette 2: all above + long-duration energy storage (hydrogen storage system)
  Palette 3: all above + Allam Cycle natural gas generator with carbon capture and sequestration + advanced clean dispatchable generator (e.g., advanced geothermal system or advanced nuclear technology)

Summary of data sources: electricity grid

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

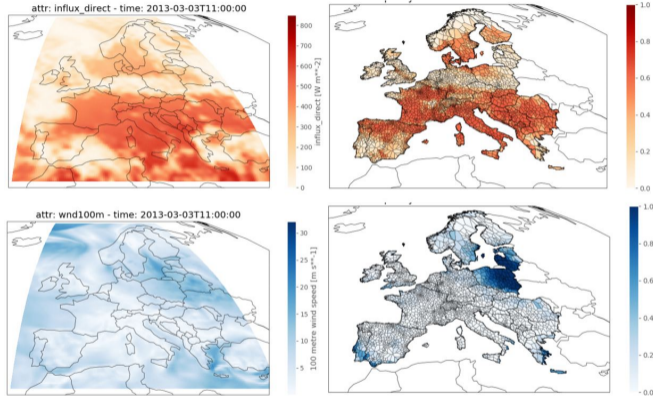- Grid data contains AC lines at and above 220 kV voltage level, all high voltage DC lines, and substations for the full **ENTSO-E area**.

- 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).

- 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**

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.

- Geographic potentials for renewable energy are based on the **GLAES** framework. 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.

Technologies available for 24/7 consumers - 2030

Palette	Technology	CAPEX (overnight cost)	FOM (%/year)	VOM (€/MWh)	Eff. (per unit)	lifetime (years)	Original reference (**technology data**)
1,2,3	solar	492 €/kW	2.0	0.01	-	40	**DEA**
1,2,3	onshore wind	1035 €/kW	1.2	1.35	-	30	**DEA**
1,2,3	battery storage	142 €/kWh	-	-	-	25.0	**DEA**
1,2,3	battery inverter	160 €/kW	0.3	-	0.96	10.0	**DEA**
2,3	hydrogen storage[8]	2.0 €/kWh	0	0	-	100	**DEA**
2,3	electrolysis	450 €/kW	2.0	-	0.68	30.0	**DEA**
2,3	fuel cell	1100 €/kW	5.0	-	0.5	10.0	**DEA**
3	NG Allam cycle[9]	2600 €/kW	14.8	3.2	0.54	30	**Navigant**, **NZA**
3	Advanced dispatchable[10]	10000 €/kW	0	0	1	30	own estimates

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[8]Underground hydrogen storage in salt cavern

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

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

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.

2025 - Germany - Palette 3: Prefers advanced dispatchable

To achieve higher CFE scores in Germany with Palette 3, the model uses high-fixed-cost advanced dispatchable generators (e.g. advanced geothermal or nuclear) rather than the high-variable-cost Allam cycle generator chosen in Ireland.

Germany – Palette 3 – 2025 – 10% – baseload