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

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- The content of this study, including any errors or omissions, are the responsibility of the authors alone.

Introduction

100% renewable energy

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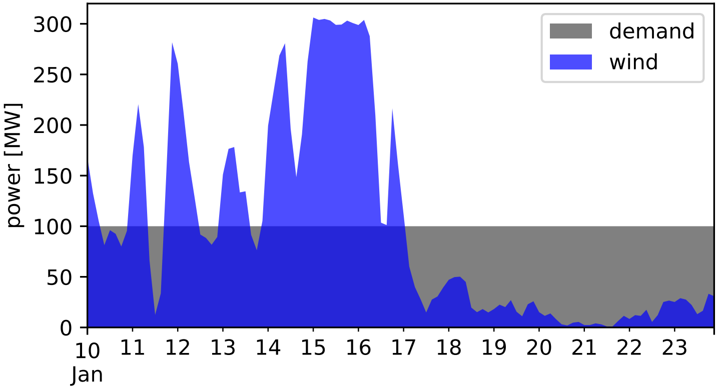
Many companies use **renewable energy sources (RES)** to match their electricity demand on an **annual basis**. More than 370 companies have pledged to reach this goal in the RE100 group.

Source: RE100

100% RES annual matching does not match hourly demand



- 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**

Questions addressed in this study

We compare 100% annual renewable matching to **24/7 carbon-free procurement** in 4 EU countries (Ireland, the Netherlands, Germany and Denmark) in 2025 & 2030.

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**?

Methodology and study design

Scenario setup

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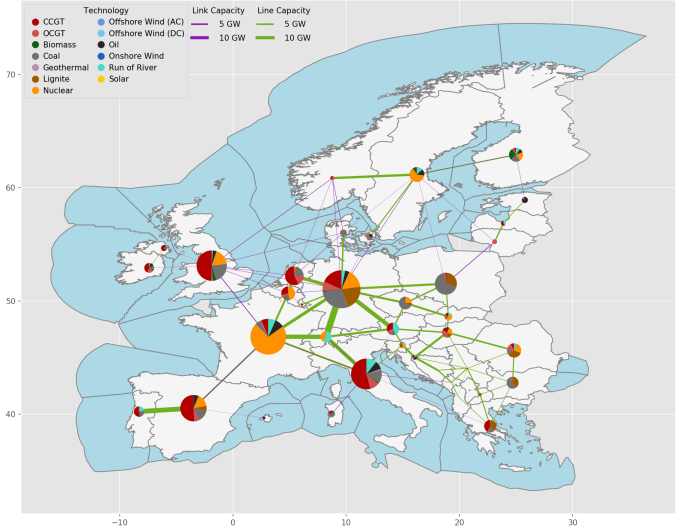


- We model the European power system clustered to **37 zones** with capacity expansion for the years **2025** & **2030**.
- Implemented in European model **PyPSA-Eur-Sec** of our widely-used open-source framework **PyPSA**.
- Consumers following 24/7 approach can be located in one of the **four zones**: Ireland, Denmark (zone DK1), Germany and the Netherlands.
- We aggregate consumers using 24/7 matching to a single demand profile.[a]

[a] In reality, C&I participants can also pursue hourly matching strategies independently based on their own specific load profiles and trade hourly certificates (T-EACs).

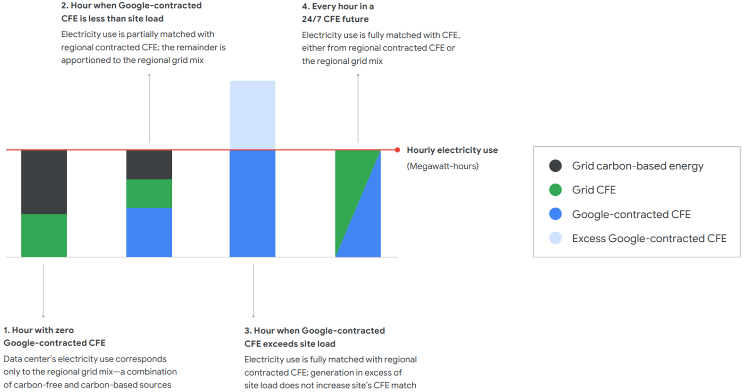
How is 24/7 carbon-free electricity (CFE) measured?

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:



Source: Google 2021, 24/7 CFE: Methodologies and Metrics

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]

[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.

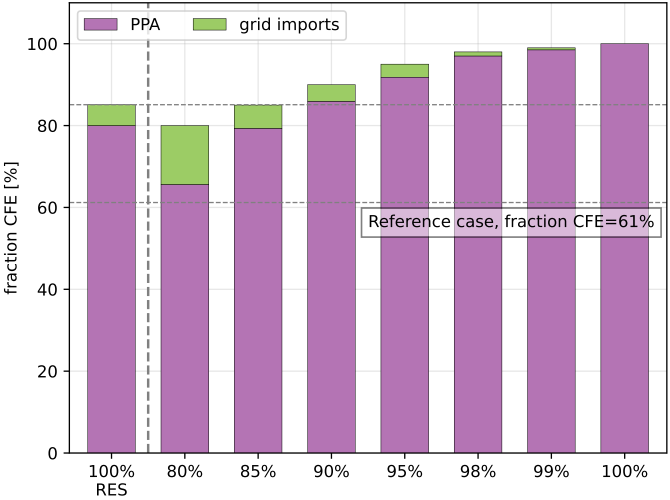
Scenario matrix

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

Modelling results and analysis

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)

Source: Ireland – Palette 1 – 2025 – 10% – baseload

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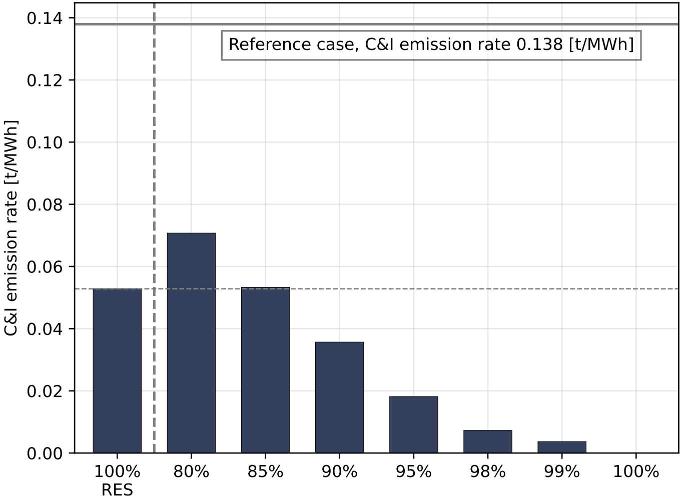
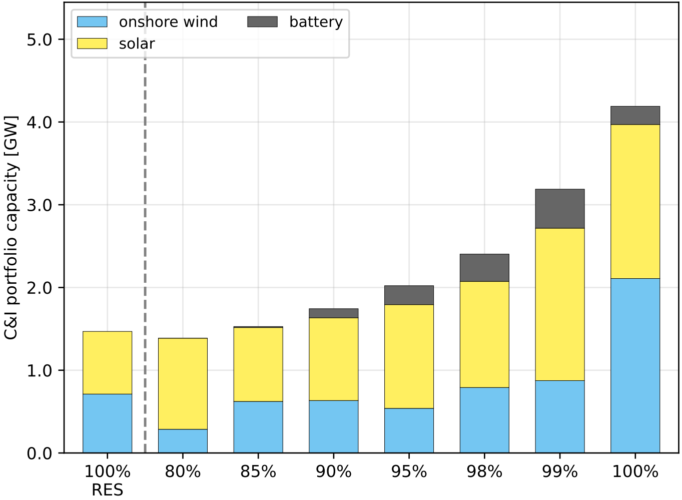


- Procurement affects **average emissions rate** of used electricity
- Reference system is moderately clean at 138 $kgCO_2/MWh$
- 100% annual RES reduces rate to 53 $kgCO_2/MWh$
- As CFE target tightens, emissions **drop to zero**

Source: Ireland – Palette 1 – 2025 – 10% – baseload

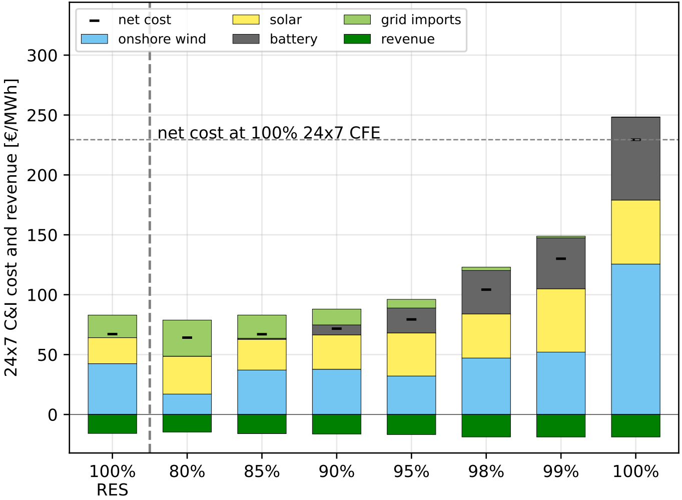
2025 – Ireland – Palette 1: Portfolio of capacity



- 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*)

Source: Ireland – Palette 1 – 2025 – 10% – baseload

2025 – Ireland – Palette 1: Cost breakdown

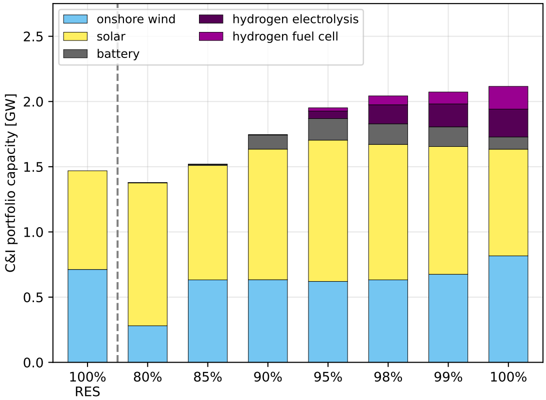


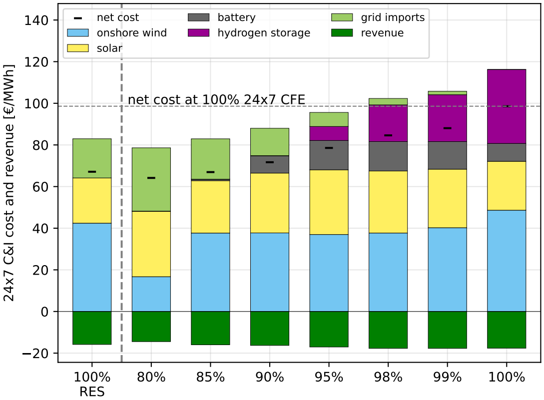
- The **cost breakdown** shows the average costs of meeting demand with the policy, including grid electricity consumption costs netted by revenue selling to the grid
- There is only a **small cost premium** going to 90-95% CFE matching
- But the last 2% of hourly CFE matching more than **doubles the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

Source: Ireland – Palette 1 – 2025 – 10% – baseload

2025 – Ireland – Palette 2: 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.





Source: Ireland – Palette 2 – 2025 – 10% – baseload

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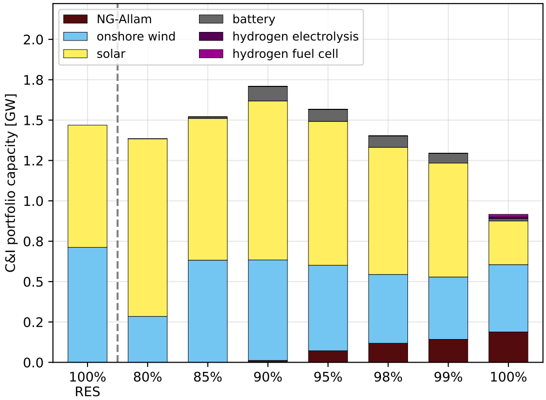
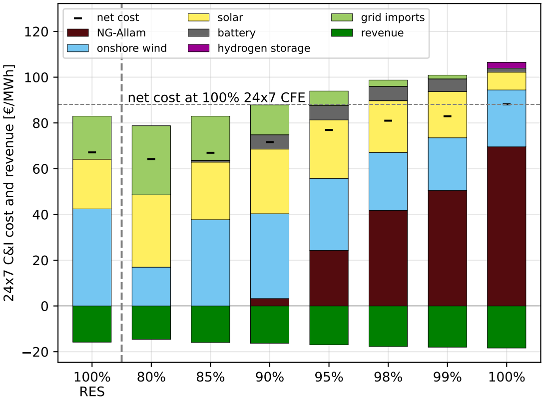
If **dispatchable technologies** are included, such as a natural gas Allam cycle generator with CCS, advanced geothermal or nuclear, this **further limits the hourly CFE cost premium** above annual renewable matching, as well as reducing storage and capacity needs.





Source: Ireland – Palette 3 – 2025 – 10% – baseload

2025 – Ireland – Palette 3: System emissions are also reduced

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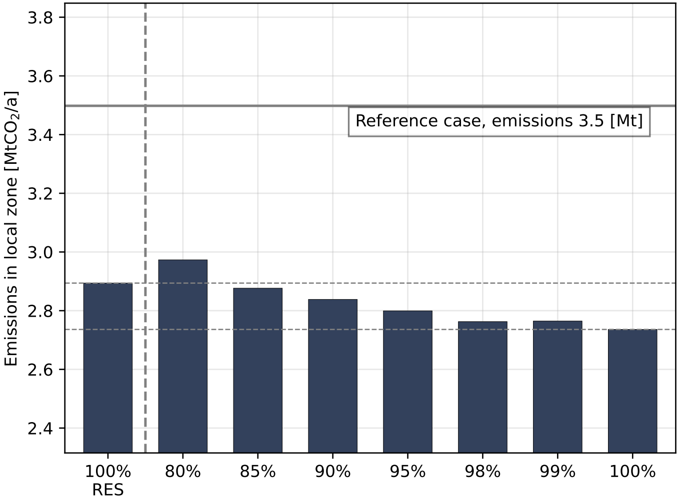

- **CO_2 emissions in the local bidding zone** are also reduced by CFE procurement
- If 10% of C&I follows 24/7, total emission are reduced by a further 0.2 $MtCO_2$ compared to 100% RES
- Two effects are responsible: **volume effect** of more CFE with high targets; **profile effect** of the timing of feed-in at highly-emitting times

Source: Ireland – Palette 3 – 2025 – 10% – baseload

Broadening the scope: other countries, from 2025 to 2030

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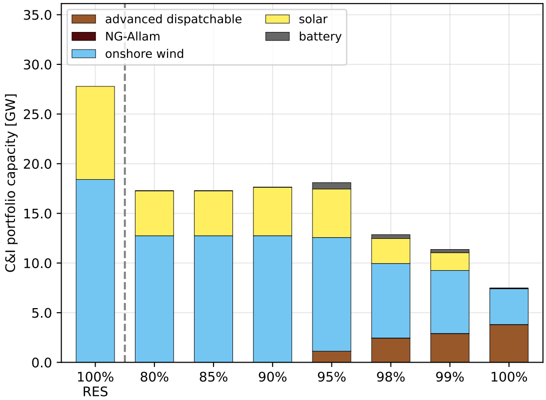
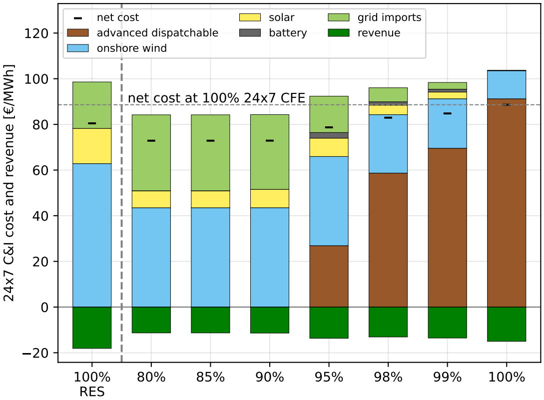
What changes if we look at 24/7 procurement in other EU countries and in 2030 not 2025?

- 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.

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.

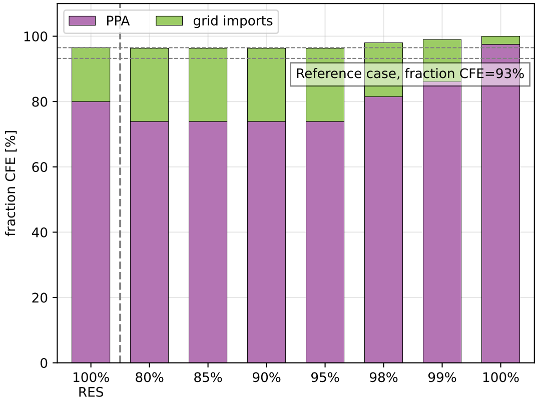


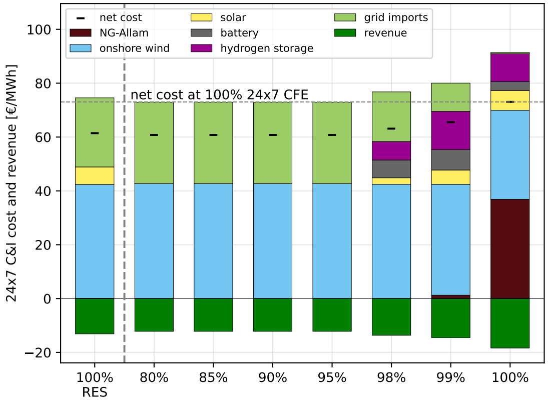


Source: Germany – Palette 3 – 2025 – 10% – baseload

2030 – Denmark – Palette 3: System is already very clean

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.

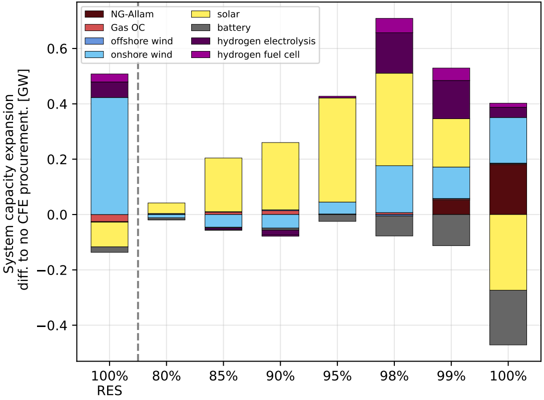


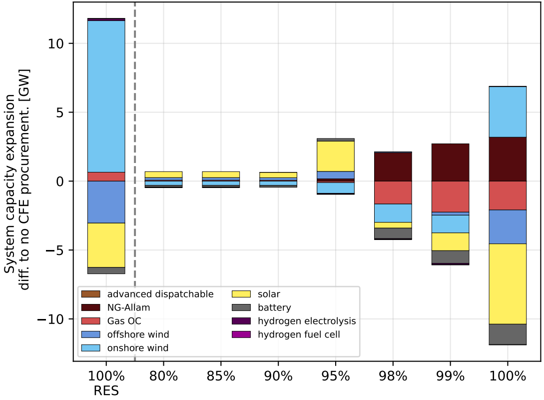


Source: Denmark – Palette 3 – 2030 – 10% – baseload

2030 – IE & DE – Palette 3: 24/7 reduces system flexibility needs

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.





Source: Ireland/Germany – Palette 3 – 2030 – 10% – baseload

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

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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

Conclusions

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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.

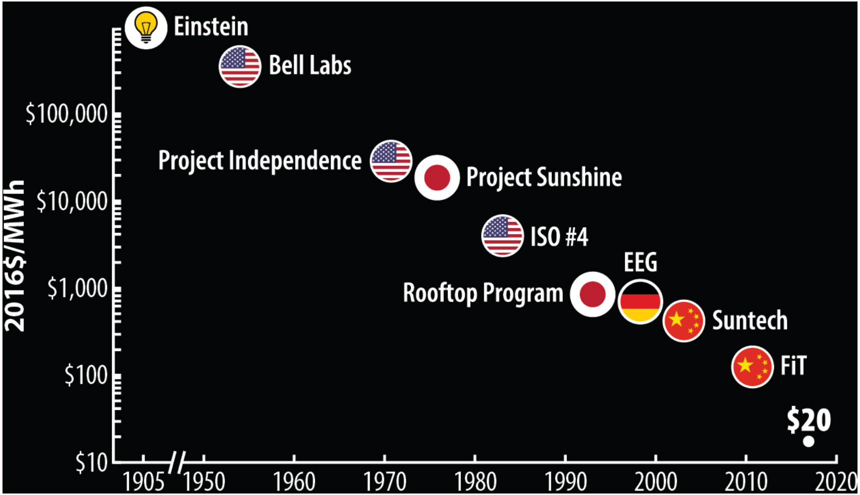
Conclusion 3: Reaching 100% CFE target is possible but costly with existing renewable and storage technologies, with **costs increasing rapidly above 95%**.

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**.

Early markets spur deployment spur lower costs

Solar scaled up and reduced in cost thanks to deployment driven by a **demand pull**.



Source: How Solar Became Cheap, Nemet, 2019

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.

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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 pack of modelling results for this study:

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

For questions and inquiries related to this study, please contact

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Implementation of C&I demand and supply

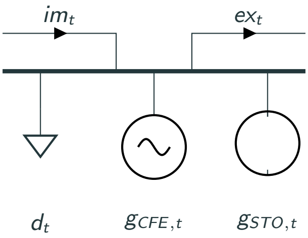
The model optimizes a portfolio of carbon-free generation and storage technologies procured by the participating C&I consumers. The portfolio assets have to be located in the same market zone.

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 ($import_t$).

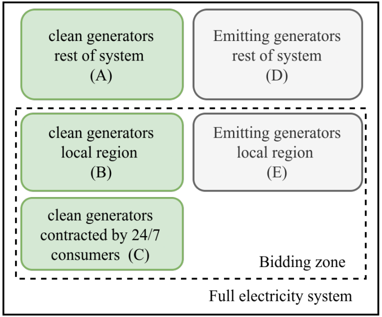
Using the notation on the right, the average cleanness of the rest of the electricity system is:

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

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

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

[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.

CO_2 emissions rate of the regional grid and 24/7 portfolio, 1/2

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CO_2 emissions associated with the dispatch of emitting power plants in the European electricity system are part of the model solution. We can use this information to calculate (i) the *emissionality* of generation that serves participating 24/7 demand, and (ii) the *avoided emissions*, i.e., the difference in regional CO_2 emissions with and without 24/7 procurement. Similarly to the logic of computing the grid CFE factor, we need to consider imported emissions also in this calculation.

First, let $X(D)_t$ be hourly emissions $[tCO_2]$ in the rest of the electricity system. The average emissions rate of the rest of the system is calculated as:

$$SystemEmisRate = \frac{X(D)_t}{A_t + D_t}$$

Second, let $Y(E)_t$ be hourly emissions in the regional grid where 24/7 consumers are located. The emissions rate of grid supply is then:

$$GridSupplyEmisRate = \frac{Y(E)_t + SystemEmisRate * import_t}{B_t + E_t + import_t}$$

CO_2 emissions rate of the regional grid and 24/7 portfolio, 2/2

Third, we calculate CO_2 emissions associated with the electricity consumption of 24/7 participating consumers on an hourly basis:

$$Emissions_t = GridSupply_t * GridSupplyEmisRate_t$$

Now, we have the necessary components to calculate two metrics of interest for our analysis. A first metric is the **average emissions rate of 24/7 consumers**:

$$(C\&I)EmisRate = \frac{\sum_{t \in T} Emissions_t}{\sum_{t \in T} Load_t}$$

A second metric is the **avoided emissions** by 24/7 procurement. The calculation is based on the difference between the total CO_2 emissions in the regional grid where 24/7 consumers are located with and without 24/7 procurement (*'247-cfe'* and *'reference'* labels, accordingly):

$$AvoidedEmissions = \sum_{t \in T} Y(E)_t^{reference} - \sum_{t \in T} Y(E)_t^{247-cfe}$$

Other assumptions

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- 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**.[4]
- 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.[5]

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

Technologies available for 24/7 consumers - 2025

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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[6]	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[7]	2760 €/kW	14.8	3.2	0.54	30.0	Navigant, NZA
3	Advanced dispatchable	10000 €/kW	0	0	1.00	30.0	own assumption

[6] Underground hydrogen storage in salt cavern

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

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	10000 €/kW	0	0	1	30	own assumption

[8] Underground hydrogen storage in salt cavern

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