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.

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Introduction

Introduction

- Climate change is driving a global effort to rapidly decarbonise electricity systems across the globe. Many public and private energy buyers have joined this effort by purchasing certificates for renewable energy or by procuring renewable energy directly with Power Purchase Agreements (PPAs).
- Such **voluntary commitments accelerate the deployment of renewable capacity** above the policy requirements in the countries and jurisdictions where these companies operate, facilitating faster transformation of electricity markets.
- Additionally, many early actors in the field have paved the way for others to follow **by developing methods and establishing standard contracts** for clean energy procurement.

Introduction

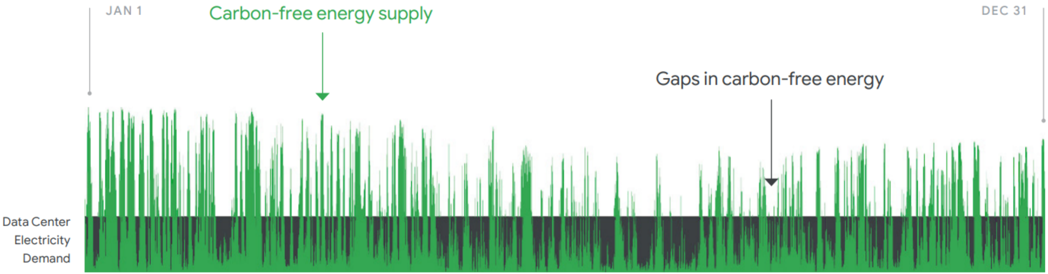
- PPAs typically are typically used for renewable energy to match generation and consumption on average over a year.
- For example, more than 370 members of the RE100 group have committed to purchasing enough renewable energy to match **100% of their electricity consumption on an annual basis**.

More than 370 companies have joined **RE100**

source: RE100

Introduction

- However, electricity buyers that commit to 100% annual matching from renewable energy sources still face times when generation from wind and solar generators is not sufficient to match the companies' electricity demand.
- Thus, although buyers match their demand on a **yearly** basis with renewable energy, on an **hourly** basis they still have hours when they have to rely on carbon-emitting technologies available on the local market, such as coal and gas-fired power plants.



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

Introduction

More generally, 100% annual matching leads to many challenges from the electricity buyers' and system perspectives:

- No **simultaneity** - variable generation of wind and solar power is not aligned with the buyers' electricity consumption profile.
- Lack of **additionality** - some buyers procure unbundled guarantees of origin from existing facilities, which does not lead to additional renewable generation.
- Displaced **location** - some buyers procure PPAs from locations far away from their consumption, where there is no way to transmit the electricity to the demand.
- Exposure to **risk** - electricity buyers are exposed to price volatility in local electricity markets, since they still have to procure electricity to cover the difference between demand and supply.
- Need for **backup** - the rest of the electricity system still has to maintain backup and flexibility options for hours with low renewable generation.

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**.

Yearly versus hourly matching

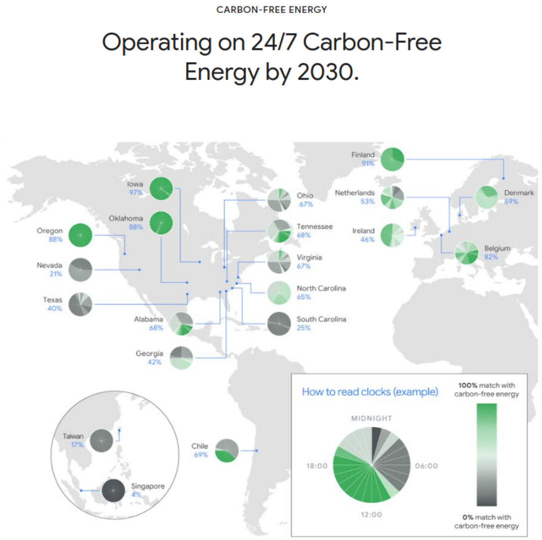
24/7 CFE procurement has potential benefits over the 100% renewable matching:

- Ensure match of electricity consumption with carbon-free resources on an **hourly basis**.
- Enable much **deeper reductions in CO_2 emissions** associated to buyer's electricity consumption.
- Ensure that contracted power is **additional** (i.e. leads to new capacity).
- Ensure that power comes from the **same bidding zone**.
- Enable technology-neutral procurement of **carbon-free** rather than renewable technologies (such as advanced clean dispatchable power generation and long-duration energy storage).

24/7 carbon-free energy

- The **24/7 Carbon-free Energy Compact** initiative was launched in 2021 by Sustainable Energy for All and the United Nations. It now includes more than 80 companies, policymakers, investors, and organizations on a mission to realize a 24/7 Carbon-Free Energy future.

- One of the front runners in the 24/7 initiative is Google Inc. In 2020 the company committed **to the goal** of operating entirely on a 24/7-CFE approach at all its data centres and campuses worldwide by 2030. Shortly after, Google published **a policy roadmap** on achieving the 24/7-CFE goal.



Google Inc.

Focus of the study

In this study, we investigate both the **means and costs of 24/7 procurement** for companies in a selection of European countries and the **system impacts** for the rest of the European electricity system.

In particular, we focus our analysis on the following quesitons:

- How can companies following 24/7 CFE procurement achieve hourly matching?
- What is the cost premium of 24/7 CFE versus 100% annual matching?
- To what extent can technologies, such as long-duration storage or advanced dispatchable clean generators, help to achieve the 24/7 CFE goal?
- To which extent can 24/7 CFE contribute to reductions in CO_2 emissions intensity of buyers' consumption?
- If many companies follow the 24/7 CFE approach, how does this affect emissions and flexibility needs in the rest of the electricity system?

Summary of key findings

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.
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.
3. Reaching 100% CFE target is possible but costly with existing renewable and storage technologies, with costs increasing rapidly above 95%.
4. 100% CFE target could have a much smaller cost premium if long duration storage or clean dispatchable technologies like advanced geothermal are available.
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.

These European study results align with **a similar study** done by Princeton University in 2021 for regions in the United States.

Methodology and study design

A quick overview

- The mathematical model for this study is build upon **PyPSA-Eur(-Sec)** – a widely-used open-source optimization model for the European energy system.
- We encode a set of new equations and routines into the PyPSA-Eur(-Sec), which allow for modelling a situation when some corporate & industrial (C&I) electricity consumers commit to a voluntary clean energy procurement.
- We compare 100% annual matching with renewable energy versus different targets for hourly CFE matching.
- We place C&I consumers committed to a clean energy procurement in a selection of European countries: Germany, Denmark, Ireland and the Netherlands. These countries differ in patterns of electricity demand, renewable potentials, national energy and climate policies, legacy fleets of generation capacities, degree of interconnectons, etc. Apart form that, we consider different C&I participation rates, a wide palette of CFE generation technologies available for 24/7 consumers, and two years (2025 and 2030). These differences help to understand and generalize the impacts of 24/7 CFE procurement.

PyPSA: an energy systems modelling toolbox

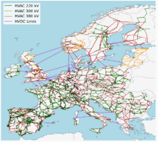
- PyPSA (Python for Power System Analysis) is an open source toolbox for for state-of-the-art energy system modelling.
- Fills gap between power flow software (e.g. PowerFactory, MATPOWER) and energy system planning software (e.g. TIMES, OSeMOSYS).
- PyPSA development and maintenance is coordinated by 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 »

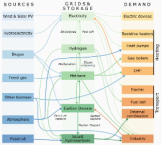
PyPSA-Eur



An open optimisation model of the European transmission system.

Documentation »

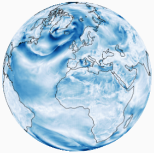
PyPSA-Eur-Sec



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

Documentation »

Atlite



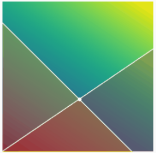
A Lightweight Python Package for Calculating Renewable Power Potentials and Time Series

Powerplantmatching

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

Documentation »

Linopy



Linear optimization interface for N-D labeled variables.

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

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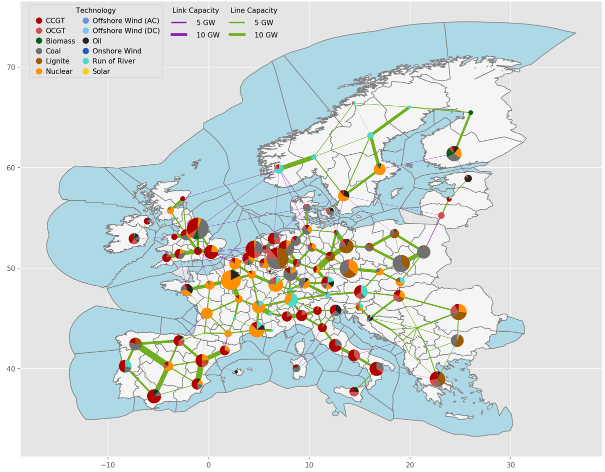
- PyPSA-Eur is an open model of the European power system at the transmission network level that covers the full ENTSO-E area.
- Only freely available and open data.
- Automated and configurable software pipeline from raw data to optimised electricity system.
- Adjustable temporal and spatial resolution.
- 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**

Modeling 24/7 CFE procurement

- We implement a set of additional constraints to the PyPSA-Eur to model a situation when a fraction of corporate and industry (C&I) demand commits to the 24/7 CFE procurement.
- The model optimises investment and operational decisions to meet projected electricity demand for the 24/7 CFE consumers, as well as the demand of other consumers in the European electricity system, while meeting all relevant engineering, reliability, and policy constraints.

The methods are based on the Google's CFE procurement framework, presented in paper

"24/7 Carbon-Free Energy: Methodologies and Metrics"

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

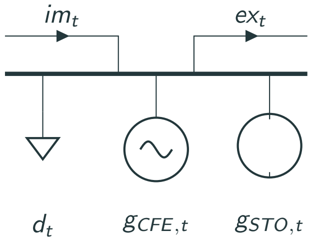
Implementation of C&I demand and supply

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

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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

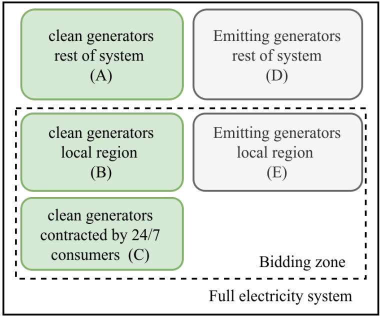
The **grid CFE factor** CFE_t in eq. (2) defines the share of carbon-free electricity in grid imports by C&I consumers following 24/7 approach. The factor depends on the generation mix in the region where C&I consumers are located, as well as on the generation mix in other regions from which electricity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

[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.

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**:

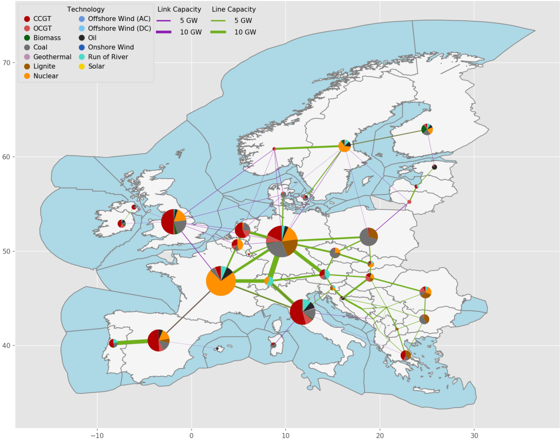
$$(C\&I)EmisRate = \frac{\sum_{t \in T} Emissions_t}{\sum_{t \in T} Load_t}$$

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):

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

Scenario setup

Scenario setup 1/3



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 one 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.[a]

[a] In reality, C&I participants can also pursue hourly matching strategies independently based on their own specific load profiles. See Qingyu & Jenkins (2022) study investigating this case.

Scenario setup 2/3

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We assume that 24/7 consumers have an access to a wide palette of carbon-free technologies[1] that are either available on the European market now or expected to be available for a commercial scale up in the near future. We formulate three scenarios grouping generators by a degree of technological maturity as of now:

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[2]	LDES
-	-	Allam cycle with CCS[3]
-	-	Advanced dispatchable generator[4]

[1] 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. Technology inclusivity is a **principle** of the 24/7 CFE methodology.

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

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

[4] 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 setup 3/3

- 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.

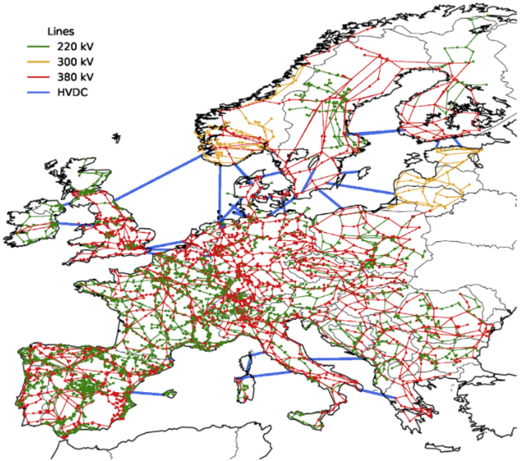
- We focus on two periods: **2025** and **2030**. The two periods differ by
  (i) Technology cost assumptions,
  (ii) National renewable expansion pathways,
  (iii) Power plant fleet (changes take place due to decommissioning based on generators' age or national policies),
  (iv) System-wide assumptions,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

- We 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.

- Finally, we conduct an analysis for different (synthetic) load profiles of C&I participants, which represent a **'baseload'** (flat), a **'datacenter'**, and an **'industry consumer'** consumption patterns.

Data sources and key assumptions

Summary of data sources: electricity grid

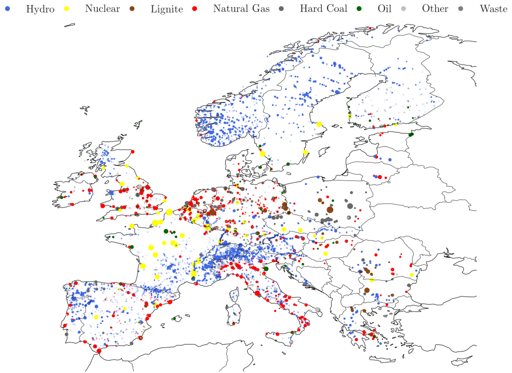


Basic validation of grid model in **Hörsch et al. (2018)**

- 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).

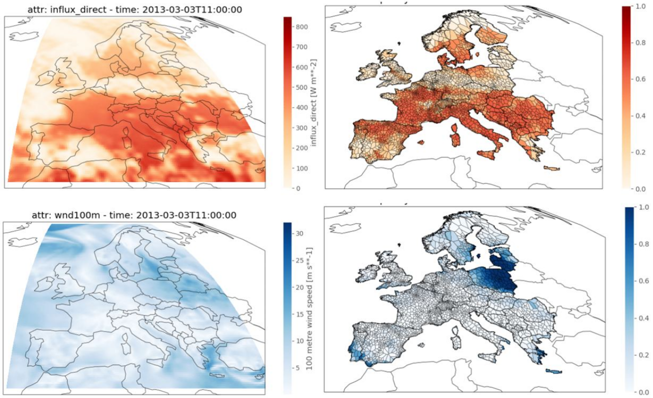
Summary of data sources: power plants and technology costs

- 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.
- 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.

Other 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**.[5]
- 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.[6]

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

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

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[7]	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[8]	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

[7] Underground hydrogen storage in salt cavern

[8] 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[9]	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[10]	2600 €/kW	14.8	3.2	0.54	30	**Navigant**, **NZA**
3	Advanced dispatchable	10000 €/kW	0	0	1	30	own assumption

[9] Underground hydrogen storage in salt cavern

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

Modelling results and analysis

Scenario space

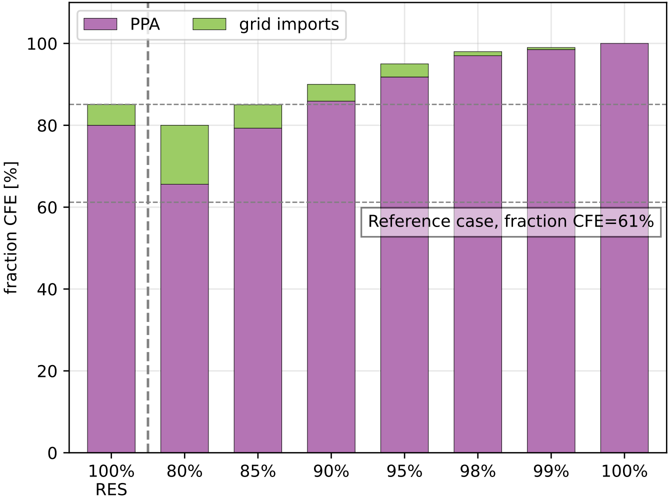
The following section presents modelling results and related analysis. For convenience, we start with a **base scenario** with the following setup:

Zone: IE — DE — DK1 — NL
Technology palette: 1 — 2 — 3
Year: 2025
Participation rate: 10% of C&I demand in a modelled zone
Demand profile: baseload (flat)

Afterwards, we explore the scenario space further by implementing one-at-a-time adjustments to the base scenario:
(i) implementing year **2030**,
(ii) implementing participation rate of **25%**,
(iii) implementing **other types of demand profiles** for C&I consumers.

For interested parties, we publish an **online annex** with a full pack of modelling results alongside this study. The annex includes modelling results for all scenario combinations.

Base scenario: Ireland – Palette 1



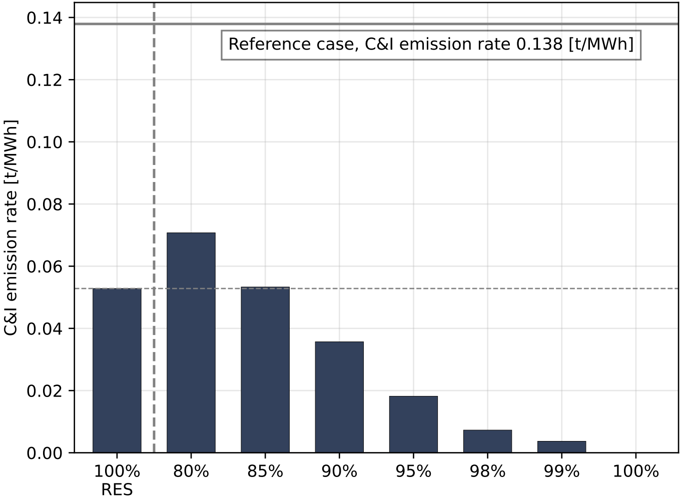
A plot on the left shows the **fraction of hourly demand met with carbon-free electricity** depending on the procurement policy that C&I consumers follow.

In the reference case, where C&I consumers do not procure any resources, relying purely on grid purchases, **only 61%** of demand is met with CFE.

100% RES – the best case for the annual renewable matching policy – results in 85% fraction. Thus, **CFE targets beyond 85%** yield higher share of hourly demand met with CFE than 100% RES procurement policy.

When CFE target approaches 100%, C&I participants **rely more on procured resources**.

Base scenario: Ireland – Palette 1



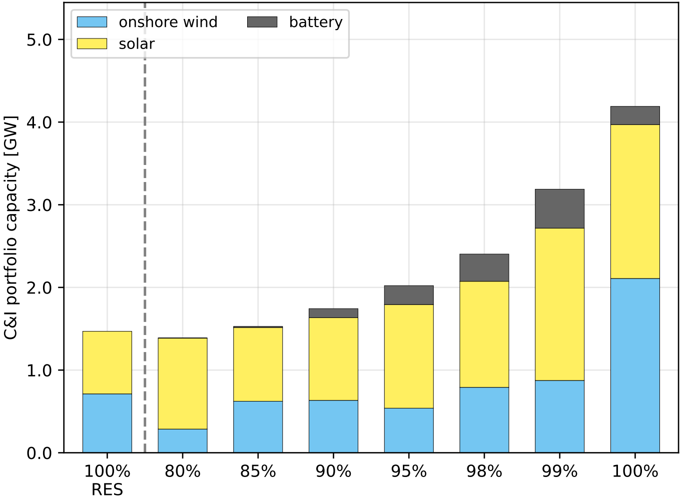
Next, we investigate how the choice of a procurement policy affects the **average emissions rate** of 24/7 participating C&I consumers.

Already in 2025, Ireland has a moderately clean electricity system: the C&I emission rate in the reference case is at 138 kg/MWh.

100% annual matching with renewable energy reduces the C&I emission rate to 53 kg/MWh.

When actively matching the carbon-free electricity and the load with 24/7 procurement, C&I participants can achieve **lower emission rates than with the 100% RES policy** with CFE targets beyond 85%. As CFE target is tightened further, average emissions **drop to zero**.

Base scenario: Ireland – Palette 1



If we now turn to the **portfolio capacity** procured by C&I consumers, we see that at this level of participation (10% of C&I load in Ireland is at 220 MW), the 100% RES policy can be me by procuring near to 1.5 GW of onshore wind and solar generators.

In this scenario, hourly matching renewable generation and the 24/7 participating load requires a **much bigger portfolio** of renewable generators than the 100% RES policy.

Also, above 85% 24/7 procurement sees **battery storage** enter the portfolio mix.

Note that for 80% CFE, 24/7 participating C&I consumers procure less capacity than for 100% RES policy, as it relies more on grid imports.

Base scenario: Ireland – Palette 1

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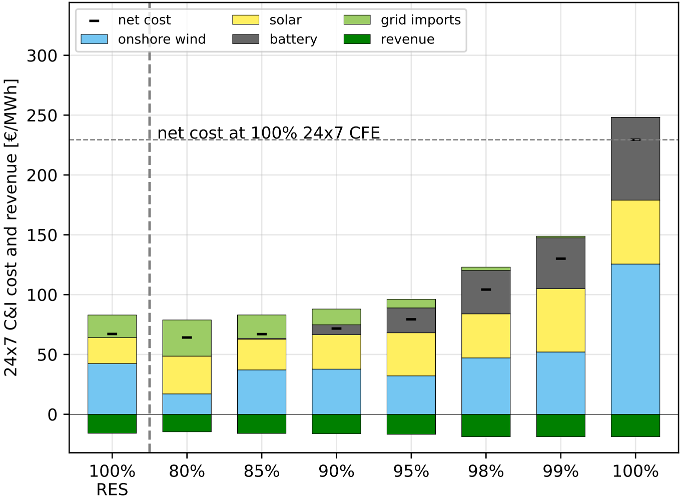
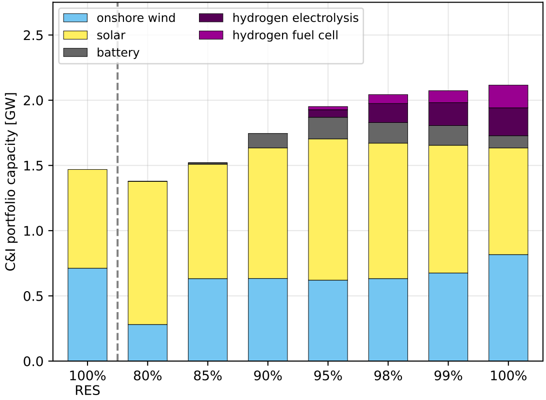


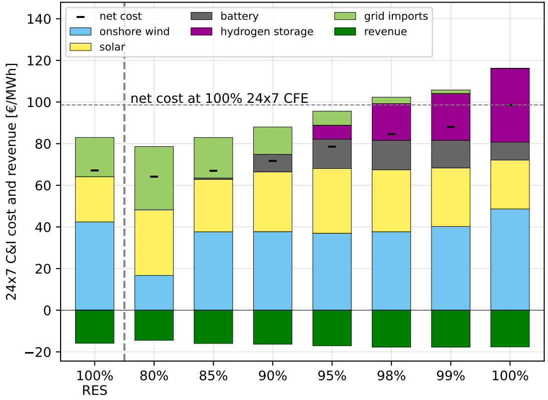
It is also interesting to look at the **breakdown of costs associated with a procurement policy** that C&I consumers choose.

Note that revenues from selling the excess electricity to the regional grid (dark green) at market prices can be treated as "negative costs" and subtracted from the net procurement cost.

A CFE target of 90-95% can be achieved at a small cost premium to 100% annual renewable matching with solar, wind and batteries. However, what stands out in the plot is the rapid increase of procurement costs for high CFE targets. For example, 98% CFE target has cost premium of only 55% over 100% annual renewable matching; while **the last 2% of hourly CFE matching more than doubles the cost**.

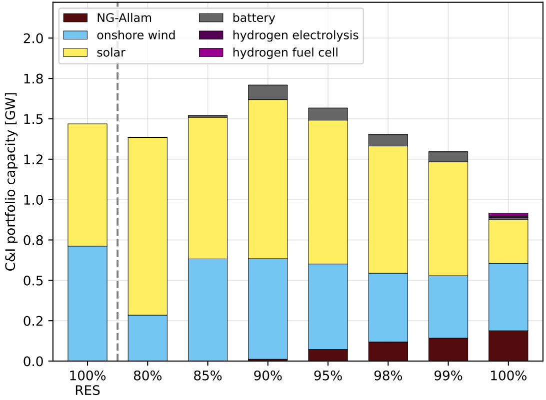
Base scenario: Ireland – Palette 2

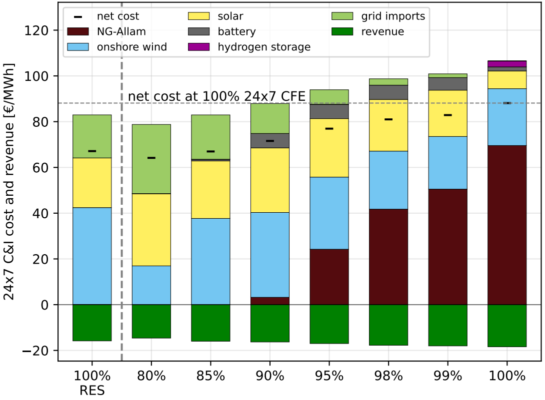




If we look at the results for the technological **Palette 2** – when C&I consumers have an access to the long-duration energy storage (LDES) – we see a different picture. The portfolio of renewable capacity C&I consumers for the 100% CFE target is not much larger than for 100% RES (see the left panel). The LDES system helps to align the load with the generation of procured variable renewable resources. In the right panel, we can see that a LDES system (here 2.5 €/kWh hydrogen storage in caverns) can **significantly limit the procurement cost increase** at high CFE targets. In this scenario, 100% CFE costs only 50% more than a 100% RES policy.

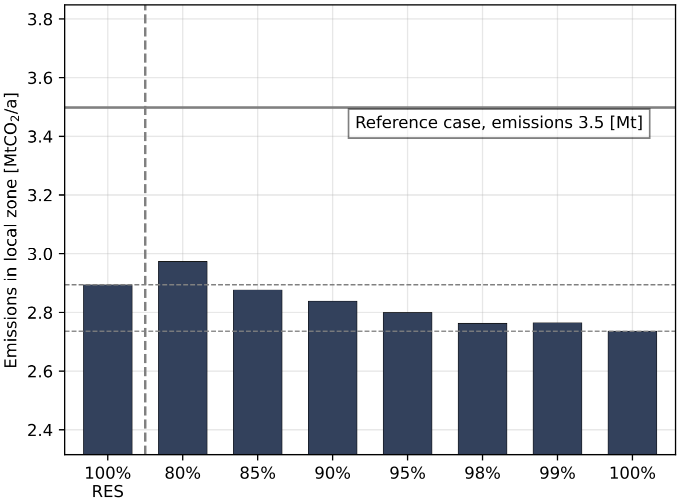
Base scenario: Ireland – Palette 3





Finally, the results for technological **Palette 3** scenario show that 24/7 procurement can create a market for and benefit from the advanced technologies such as NG Allam Cycle generator with carbon capture and sequestration or advanced geothermal systems. In the case of Ireland, NG Allam Cycle generator is added to the procured portfolio. The clean dispatchable technology **further limits the hourly CFE cost premium** above annual renewable matching. Inclusion of clean firm generation also reduces storage requirements.

Base scenario: Ireland – Palette 3



In the next step, we explore how the 24/7 procurement affects the rest of the electricity system. The plot on the left shows **CO_2 emissions in the local region** of 24/7 participating consumers – Ireland.

Without any procurement, the model estimates Irish power sector carbon emissions to be at the level of 3.5 $MtCO_2$ (for comparison, **seai.ie** reports this value to be at 8.4 $MtCO_2$ in 2020, with a strong decreasing trend).

100% annual renewable matching can deliver greater system-level CO_2 emissions reductions than lower CFE scores. 100% RES reduces emissions in Ireland by ca. 0.6 $MtCO_2$ per year (at 10% participation rate).

However, beyond 85% CFE targets, 24/7 hourly matching achieves **greater emissions reductions** than 100% RES.

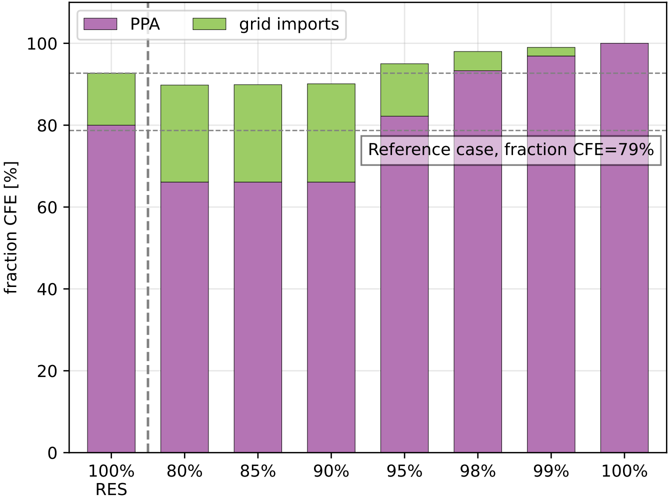
Base scenario: other regions

Results for other regions in Europe where C&I load commits to voluntary CFE procurement show **similar trends.**

However, each region has a **unique set of characteristics** that depend on local resources, renewable potentials, national energy and climate policies, degree of interconnections, etc.

Despite regional differences, the dynamics of 24/7 CFE procurement, observed in the example of Ireland, repeat in other regions.

Base scenario: Germany – Palette 1



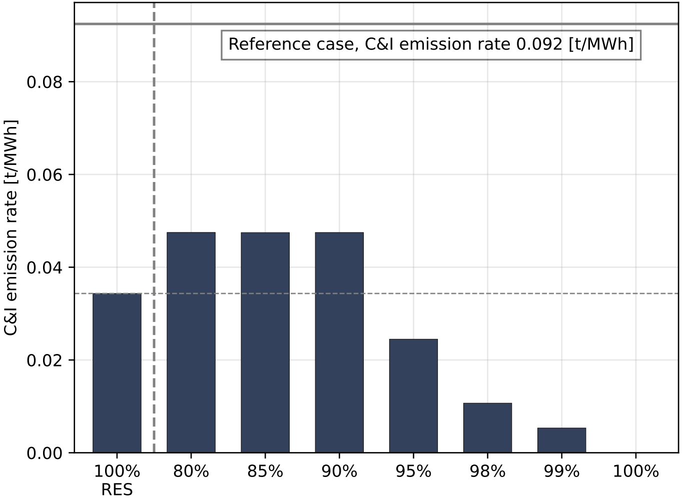
In comparison to the case of Ireland, the German grid is cleaner in 2025, in particular due to good interconnections with e.g., France and Denmark. Thus, without procuring any resources, C&I consumers reach a 79% share of demand met with CFE.

The cleaner grid results in a higher fraction (ca. 92% CFE) achieved with the 100% annual renewable matching policy.

Similar to the Irish results, C&I participants rely more on procured resources with tighter CFE targets.

Note that for lower CFE targets, constraint (2) is not binding, what makes the same cost-optimal shares of procured portfolio and grid imports repeat until the CFE target becomes tight enough.

Base scenario: Germany – Palette 1



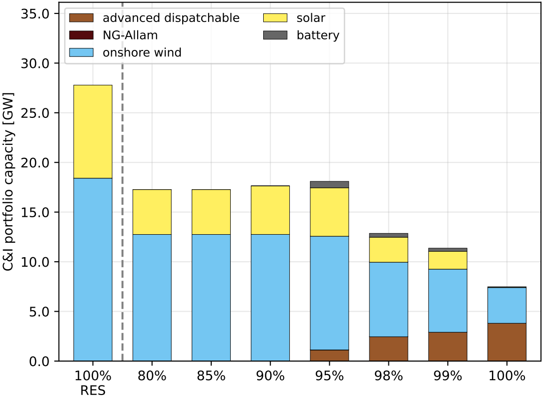
As can be expected, the cleaner grid in the German case results in a lower value of the average emissions rate of 24/7 participating C&I consumers than in the case of Ireland. The value is at 92 kg/MWh in the reference case.

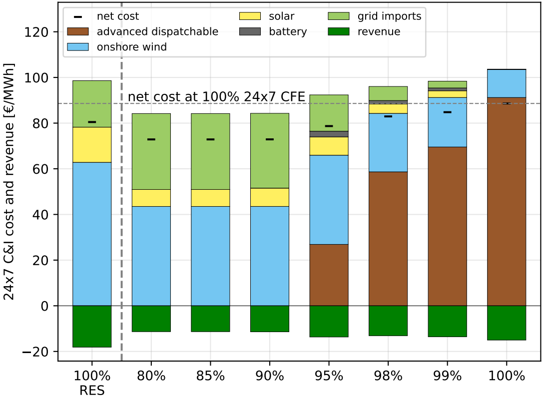
As in Ireland, **two key observations** can be made:

(i) the voluntary commitment to 100% annual matching with renewable energy greatly reduces the C&I emission rate, to 34 kg/MWh in this case, and

(ii) with 24/7 CFE procurement, C&I participants achieve much lower emissions rates than 100% annual matching with higher CFE targets. Emissions rates fall to zero at 100% CFE score.

Base scenario: Germany – Palette 3





What stands out in the results for Germany is the cost-optimal portfolio procured by C&I consumers. The plots on top show the porfolio capacity and the procurement costs for one selected technology scenario – **Palette 3**. In this case, the 24/7 CFE requires **considerably less renewable capacity** in the portfolio compared to 100% RES. The reason for this is two-fold. To achieve lower CFE targets, C&I consumers can complement portfolio with larger volume of imports from the fairly clean grid. To achieve higher CFE targets, an **advanced dispatchable generator** is added to the C&I portfolio that greatly reduces the need for renewable energy to match load on an hourly basis.

Base scenario: Germany – Palette 3

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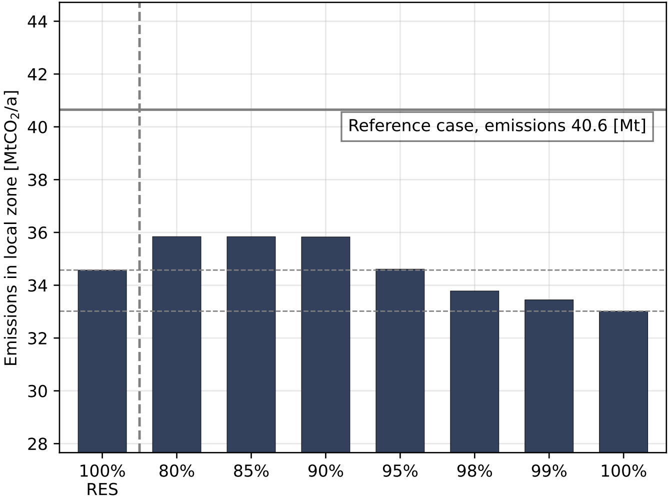


Another result that stands out in the case of Germany is the impact of the 24/7 procurement on the system-level CO_2 emissions.

Without any CFE procurement stategy, the German power sector carbon emissions are at the level of 40.6 $MtCO_2$ in 2025.

With just 10% participation rate, ca. **3.8 GW** of C&I load follows voluntary procurement. With this participation, the 100% RES can reduce system-level CO_2 emissions by **6 $MtCO_2$** per year. With the 24/7 hourly matching, C&I consumers achieve greater impact on emissions, up to **8 $MtCO_2$** per year with CFE 100% target.

NB this impact can be achieved with just a **10% cost premium** on top of the 100% annual renewable matching (see C&I cost analysis above).

Base 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 base scenario (2020 €/MWh):

High CFE targets could have a **much smaller cost premium** if long duration storage or clean dispatchable technologies like advanced geothermal 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.

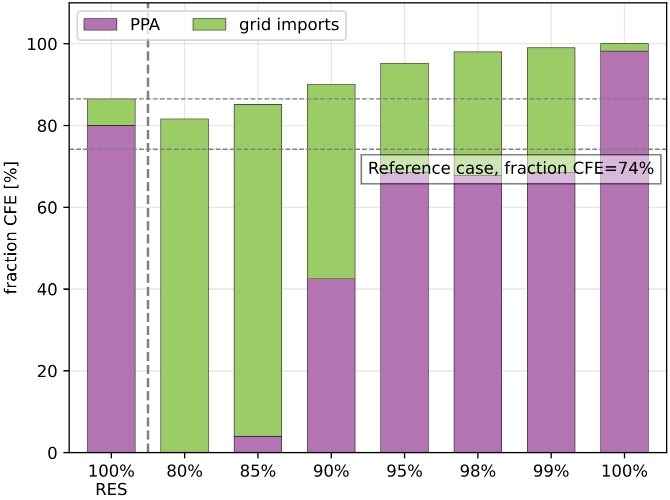
Zone	Palette	100% RES	98% CFE	100% CFE
IE	Palette 1	67.1	104.2(+55%)	229.4(+242%)
IE	Palette 2	67.1	84.6(+26%)	98.6(+47%)
IE	Palette 3	67.1	81.0(+21%)	88.1(+31%)
DE	Palette 1	80.5	98.3(+22%)	193.5(+141%)
DE	Palette 2	80.5	92.2(+15%)	113.5(+41%)
DE	Palette 3	80.5	82.9(+3%)	88.6(+10%)
DK1	Palette 1	56.0	70.3(+26%)	153.7(+175%)
DK1	Palette 2	56.0	65.2(+16%)	84.7(+51%)
DK1	Palette 3	56.0	62.7(+12%)	77.1(+38%)
NL	Palette 1	63.7	91.1(+43%)	172.1(+170%)
NL	Palette 2	63.7	78.6(+23%)	92.2(+45%)
NL	Palette 3	63.7	73.5(+15%)	82.5(+29%)

So far, we have been exploring 24/7 CFE procurement within the European electricity system in **2025**.

However, what happens if we look 5 years more ahead – in **2030**?

From the modelling perspective, **many system parameters change** with a step to 2030. In particular, the technology costs decline due to economics of scale and incremental innovation, national energy- and climate policies become more tight, some legacy power plants leave the market. An overarching feature of the energy transition is a **cleaner state of the electricity grids**.

2030 scenario: Ireland – Palette 3

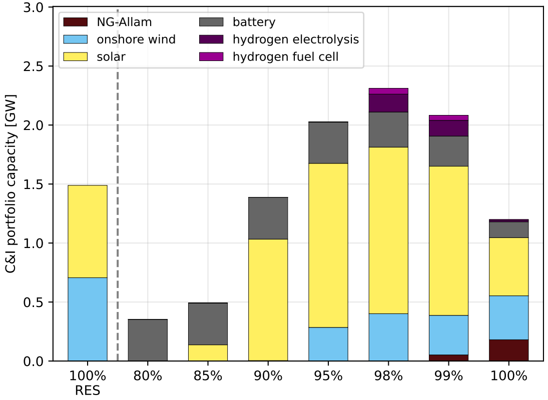


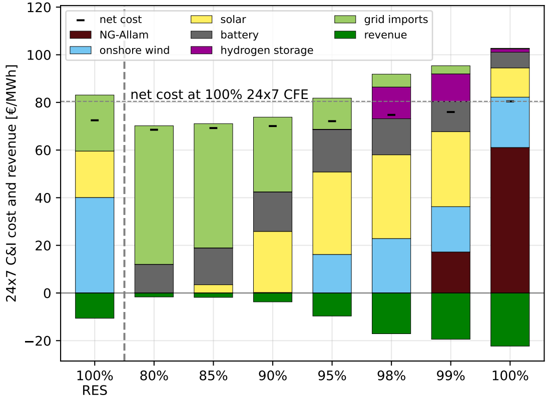
The plot on the left shows **the fraction of hourly demand met with CFE** for different procurement policies for C&I load in Ireland – now for 2030. The first observation is that in the reference case, 74% of demand is met with CFE, which is 13% more than in 2025. Furthermore, there are **two findings** on the hourly 24/7 matching:

First, lower CFE targets (such as 80%) can be met without any procurement of renewable generators by C&I consumers. Instead, the target is reached by a combination of grid imports and battery storage (see next slide).

Second, grid imports can still play a role in reaching 100% CFE, as LDES and advanced dispatchable technologies offer flexibility in matching renewable generation with C&I load on hourly basis, while grid imports are possible during the hours when regional grid is clean.

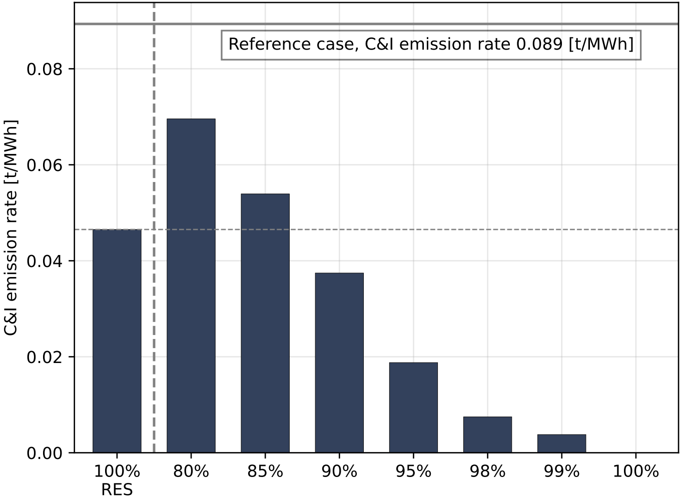
2030 scenario: Ireland – Palette 3





Here we look at the **portfolio capacity** and the **C&I cost breakdown** for Ireland-2030 scenario with the technology **Palette 3**. The 24/7 procurement has a very **diverse portfolio of technologies depending on the CFE target** – from battery storage (combined with grid imports only) in 80% CFE – to a mix of NG Allam Cycle, solar, onshore wind, battery storage and LDES for the tighter CFE targets. NB: despite a much cleaner grid in 2030, a similar 1.5 GW mix of wind and solar is contracted to meet the 220 MW of C&I load for the 100% RES policy as in 2025.

2030 scenario: Ireland – Palette 3

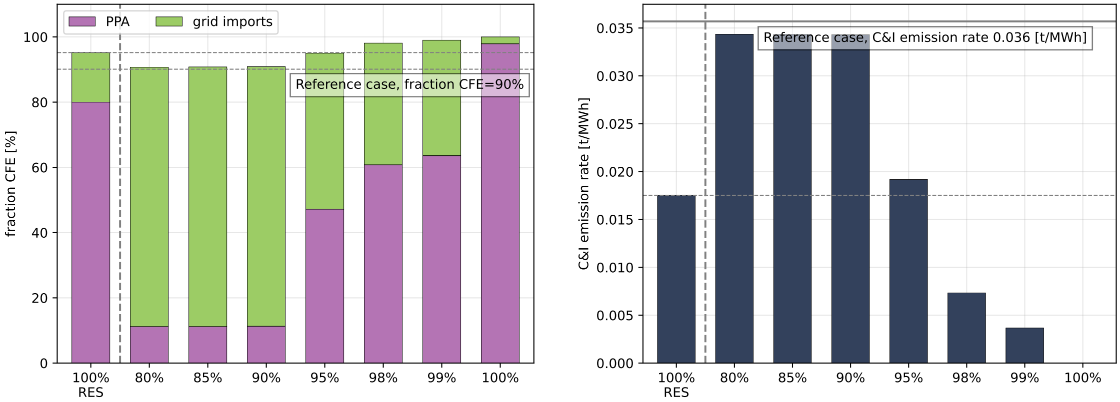


The **average emissions rate** of 24/7 participating C&I consumers is intuitively lower with a cleaner regional network – the reference case value is reduced from 138 kg/MWh in 2025 to 89 kg/MWh in 2030.

Nevertheless, the dynamics of 24/7 CFE vs 100% RES procurement remains the same also in 2030: an hourly 24/7 matching allows for net-zero emissions associated with the C&I buyers' consumption, with a lower emission rate already above ca. 85% CFE (in this scenario).

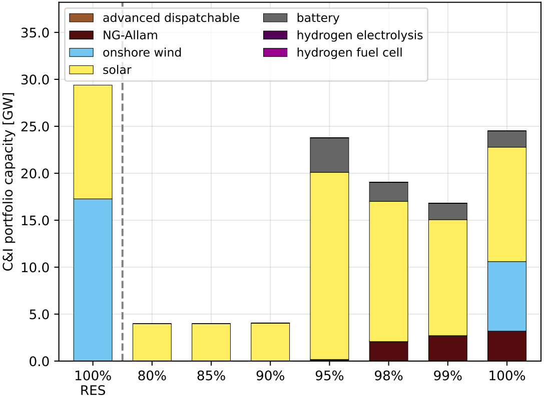
Another interesting result is that a CFE target of 90% yields **lower C&I emission rate** than 100% RES policy, although it **costs less** (by ca. 2.5 €/MWh, see the C&I cost plot above).

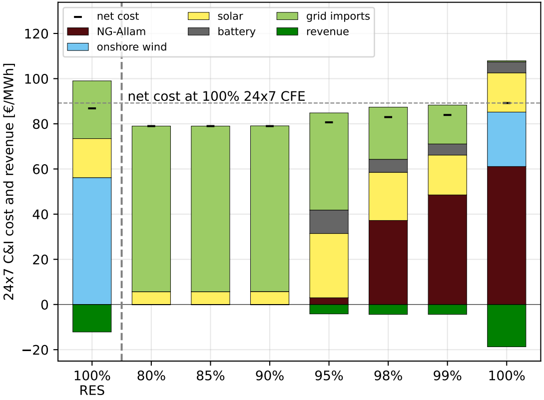
2030 scenario: Germany – Palette 3



Similar effects can be observed if C&I participants are located in other countries. The figure above shows the **fraction of hourly demand met with CFE** (left panel) and the **average emission rate** of 24/7 participating consumers (right panel) for the case of Germany & technology **Palette 3**. As in the Ireland 2030, lower CFE targets can now be met with a very large share of grid imports, while C&I participants continue to mostly rely on procured resources once CFE targets become more tight. Similar dynamics can also be seen on the C&I emission rate plot.

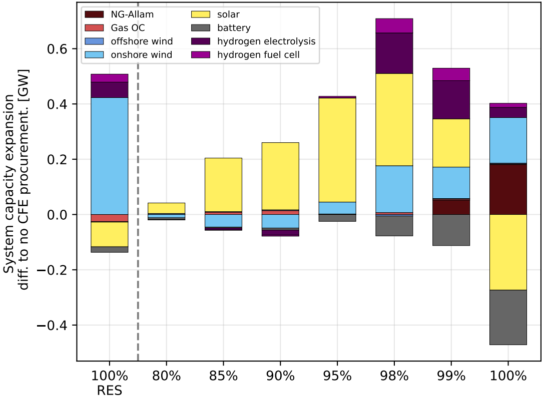
2030 scenario: Germany – Palette 3

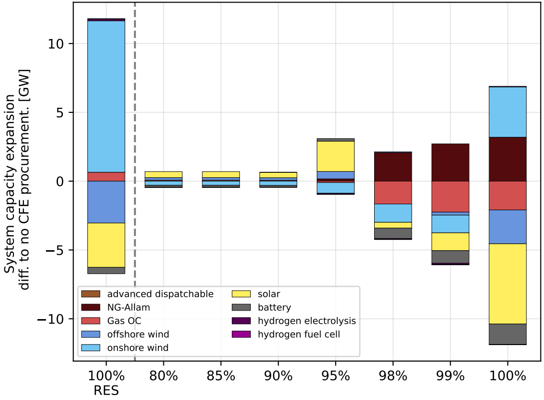




If we now look at the **portfolio capacity** and the **C&I cost breakdown** for Germany-2030-**Palette 3** scenario, the single most striking observation is that a cost-optimal portfolio mix procured by the C&I participants for CFE 100% target comes at **almost no cost premium** to 100% annual renewable matching (the difference is ca. 2.3 €/MWh). At the same time, C&I participants achieve a **zero emission rate** associated to their electricity consumption (see above).

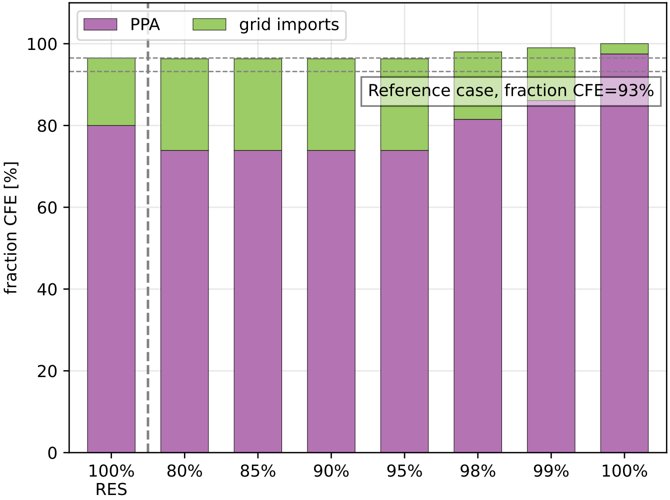
2030 scenario: Ireland & Germany – Palette 3





Another important question is how 24/7 procurement affects the capacity mix in the rest of the system. The plots present the **difference in the generation capacity expansion of the whole European electricity system (including C&I resources) with and without 24/7 procurement** for the cases where C&I load is located in Ireland (left panel) and in Germany (right panel) in 2030. A 24/7 portfolio benefits the system by **reducing flexibility needs** – the system requires less battery storage and peaker capacity in the form of Gas Open Cycle (OC) technology. The substitution of Gas OC capacity with C&I resources **facilitates decarbonization** of the entire system.

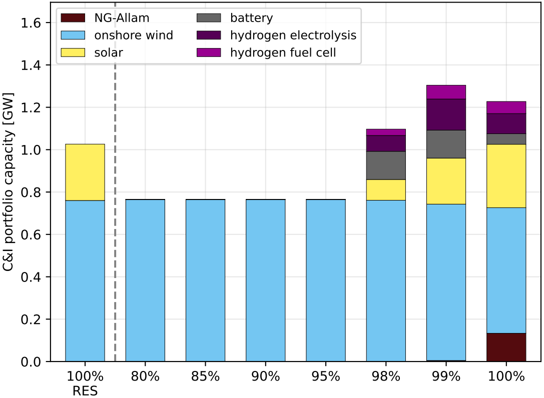
2030 scenario: Denmark (an extremely clean grid case)

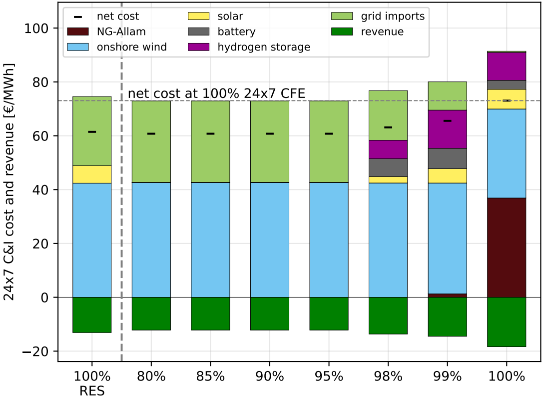


The case of Denmark in 2030 is special. This is driven by the Danish **national energy and climate policy** aimed at **110% of renewable electricity** in the national consumption mix by 2030.

This can be illustrated well with the **fraction of hourly demand met with CFE**, where the reference value reaches as much as **93%**, and 100% annual renewable matching – **96.5%**. Thus, only the **CFE targets above 97%** can deliver a higher fraction of demand met with CFE than 100% RES.

2030 scenario: Denmark – Palette 3





The **portfolio capacity** analysis for the DK-2030 scenario, reveals two findings driven by the excellent potentials for onshore wind in Denmark. **First**, the cost-optimal 24/7 procurement for lower CFE targets still contains resources contracted by C&I consumers, despite the fact that the grid is extremely clean. Thus, the additional capacity procured by C&I participants can benefit (from the cost-minimization perspective) the rest of the system. **Second**, NG Allam Cycle generators are added to the portfolio **only for the CFE 100% target**. The targets ≤100% are cost-optimally met by a combination of existing technologies, LDES and grid imports.

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: Counterintuitively, 100% RES cost levels are slightly above the 2025 scenario. This is driven by lower revenues from the excess electricity sales to the regional grid due to the (short-term) merit order effect of renewable energies.

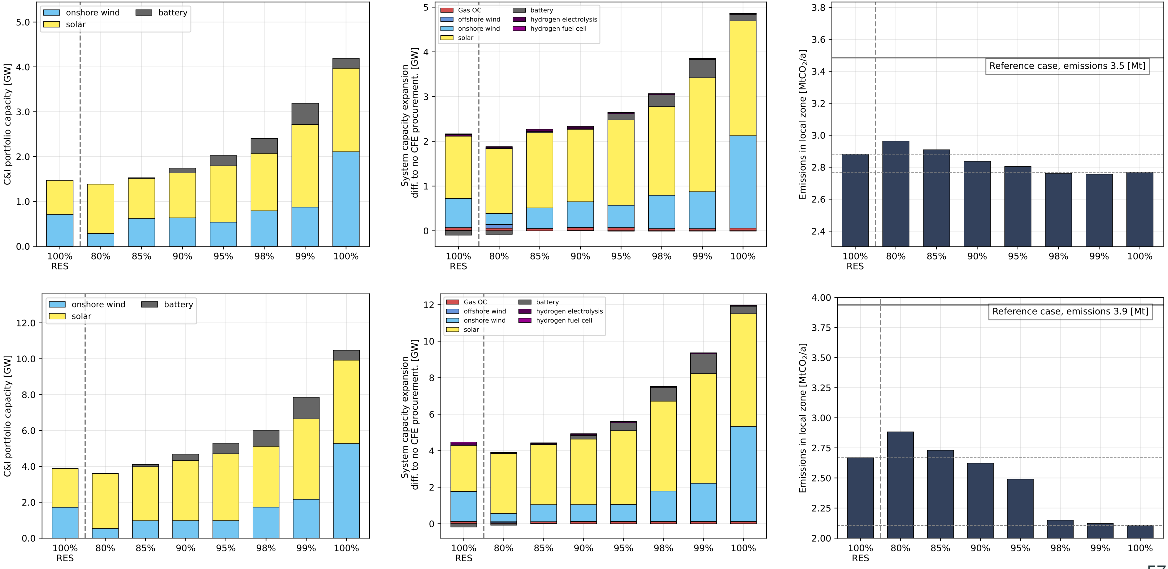
Zone	Palette	100% RES	98% CFE	100% CFE
IE	Palette 1	72.5	79.5(+10%)	192.4(+165%)
IE	Palette 2	72.5	74.8(+3%)	85.8(+18%)
IE	Palette 3	72.5	74.8(+3%)	80.4(+11%)
DE	Palette 1	86.8	85.7(-1%)	156.7(+80%)
DE	Palette 2	86.8	85.6(-1%)	102.3(+18%)
DE	Palette 3	86.8	83.0(-4%)	89.2(+3%)
DK1	Palette 1	61.4	63.5(+3%)	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%)

Finally, we explore two more sensitivity scenarios.
In particular, we are interested in the following questions:

(i) How do the findings change with higher participation rates of C&I consumers? For this analysis, we assume that **25%** of C&I consumers in a selected region joins voluntary clean energy procurement.
Finding: Higher participation rates result in a similar mix of procured resources (for a given zone, year and palette of technologies) and associated costs for C&I participants, while facilitating a much greater impact on the rest of the system.

(ii) To what extent do consumption profiles of C&I participants drive the results? Here we model **two synthetic hourly demand profiles** representing 'datacenter' and 'industry consumer' and benchmark the two with the reference baseload (flat) profile.
Finding: The shape of consumption profiles of C&I participants affect the cost-optimal technology mix in a procured portfolio; however, the impacts on the procurement cost, emissionality of the portfolio, as well as the system impacts of 24/7 procurement are negligible.

The impact of higher participation rates (selected IE – P1 – 2025)



Results for participation rates of 10% (top row) and 25% (bottom row)

The impact of higher participation rates (selected DE – P2 – 2030)

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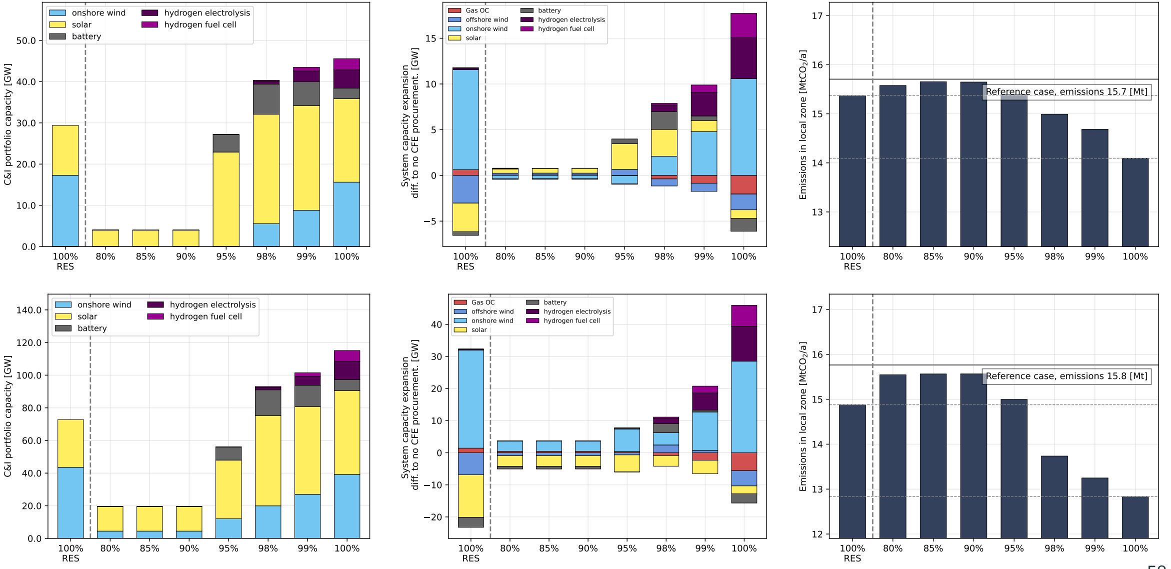
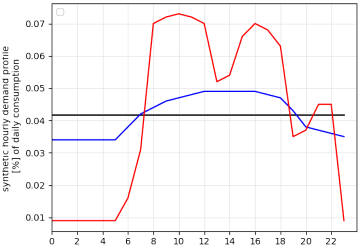
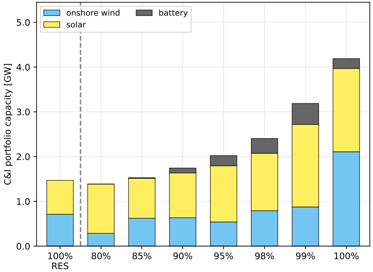


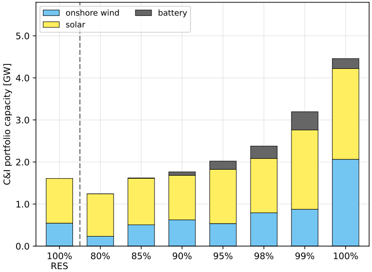
Results for participation rates of 10% (top row) and 25% (bottom row)

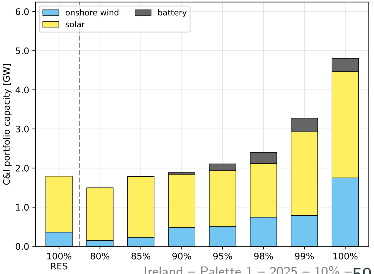
The impact of C&I consumption profiles (selected IE – P1 – 2025)



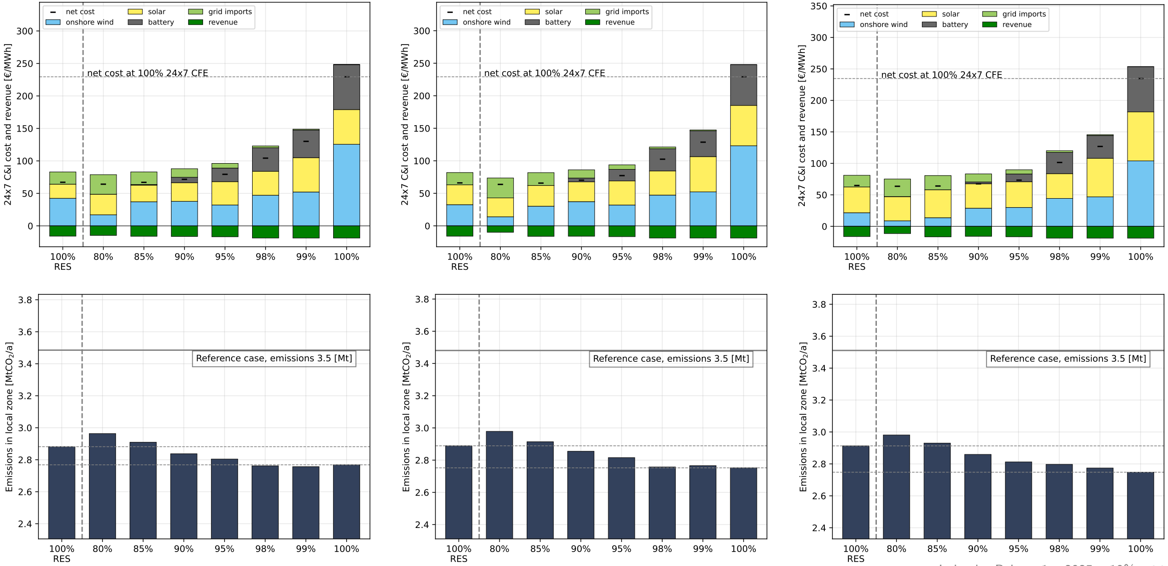
The plots below depict **portfolio capacity** procured by C&I consumers with different load profiles:
(i) 'baseload (flat)' – black line – portfolio on the lower left panel,
(ii) 'datacenter' – blue line – portfolio on the lower middle panel,
(iii) 'industry' – red line – portfolio on the lower right panel.







The impact of C&I consumption profiles (selected IE–P1–2025)



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**.

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

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