System-level impacts of 24/7 CFE: Methodological overview

Methodology & Scope of Work

July 2025

Table of Contents

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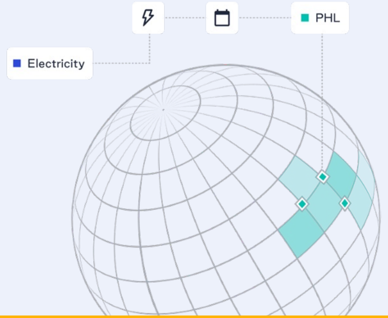

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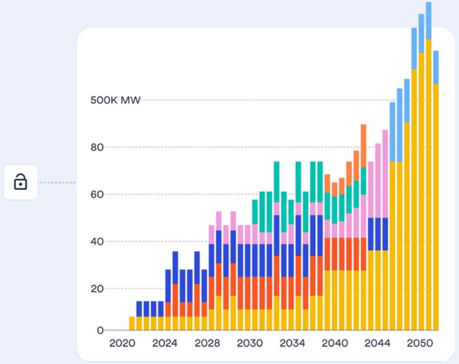

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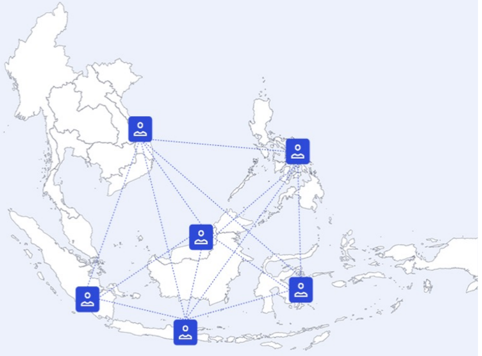

Funded by Sequoia Climate Foundation, Google.org, Bloomberg Philanthropies, Quadrature Climate Foundation

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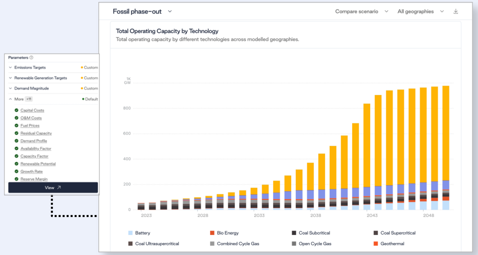
TZ-SB is free, no-code modelling platform that allows analysts working on energy transition planning to build, run, and analyse results from electricity system models – quickly, transparently, and at scale.



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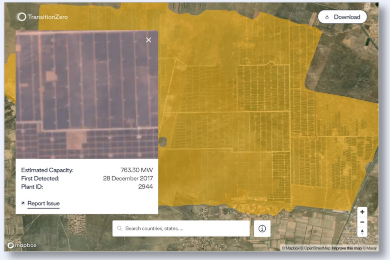
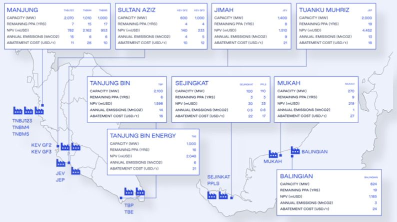
TZ-SAM is an open access dataset of solar facilities, powered by machine learning and geospatial data. Tracks 100,00 solar assets across 200 countries, with ~100 GW of capacity added each quarter.



Coal Asset Transition Tool

TZ-CAT is an open data product that supports the refinancing and replacement of coal plants in an affordable, just way. TZ-CAT is currently available for the Philippines, Indonesia, and Malaysia.



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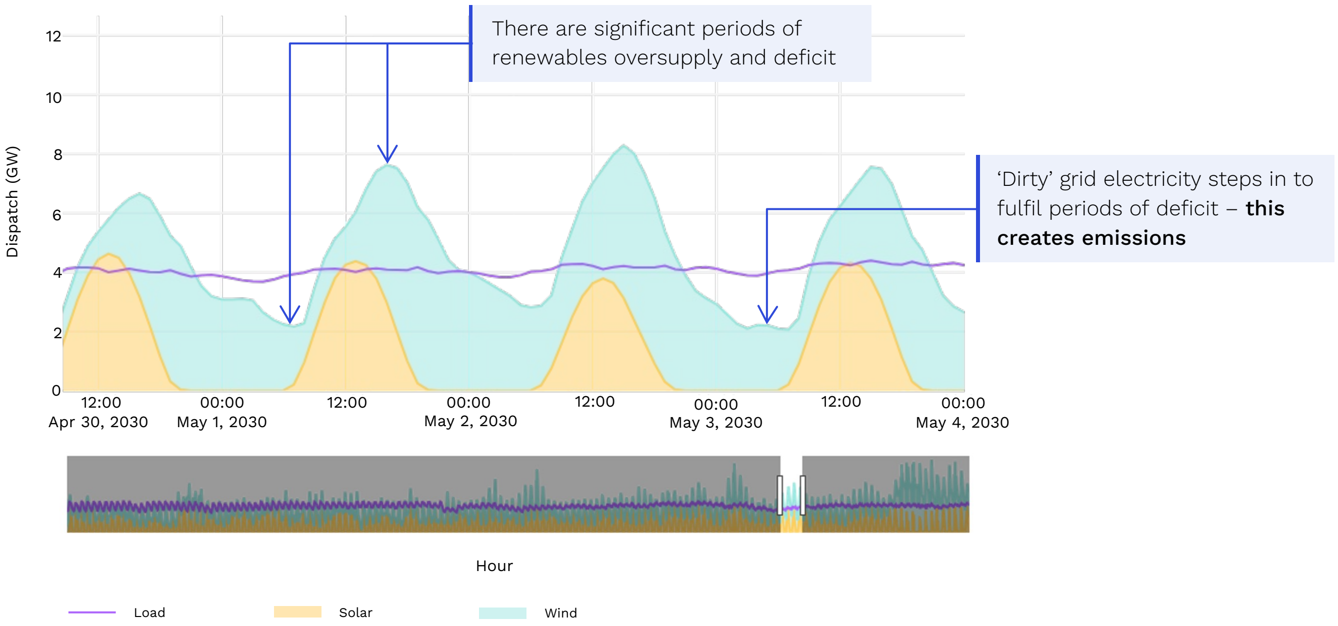
Background to 24/7 Carbon Free Electricity (CFE)

Power consumers are grappling with mismatches between the generation and consumption patterns of clean electricity

What does an annual matching regime look like?

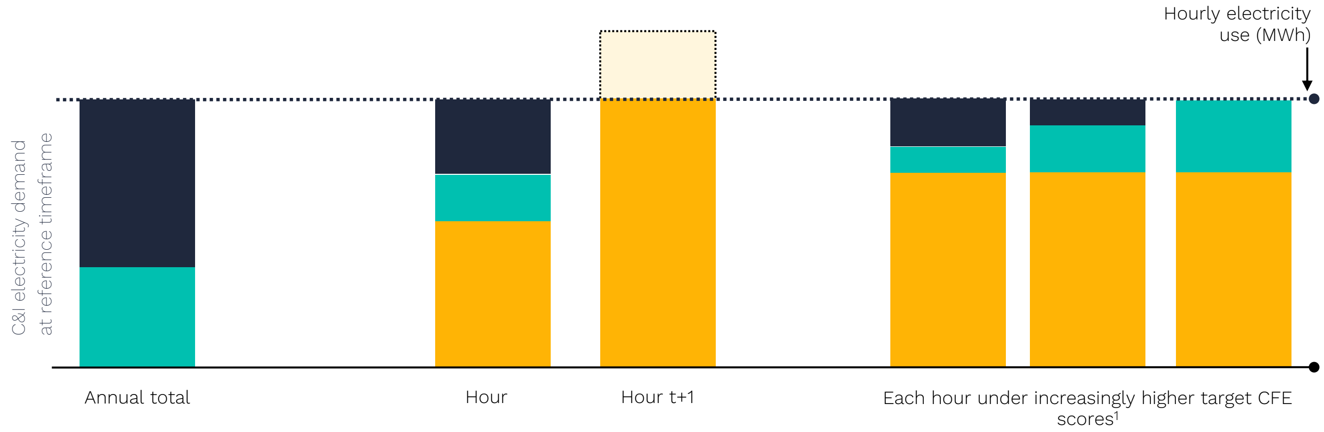


Key points

- Commercial and industrial (C&I) consumers face pressures to reduce their consumption of polluting electricity.
- Reliance on 100% annual matching through renewables PPAs results in cycles of oversupply and deficit, where only some hours truly benefit from CFE.
- When there is a deficit between procured clean energy and demand, consumers must rely on carbon-emitting system electricity.
- Matching consumption to generation hour by hour ("24/7 CFE") seeks to maximise CFE reliance round the clock.

Shifting guidance on emissions reporting

The GHG Accounting Protocol is evolving, and may require companies to report Scope 2 emissions based on hourly accounting



Situation 1:
Do nothing

C&I consumer's electricity consumption is met only by the regional grid, which is for the most part carbon-based.

Situation 2:
Annual matching (current common practice)

C&I consumer's electricity consumption is only partially matched, resulting in either a shortfall or an oversupply of CFE.

Situation 3:
24/7 CFE

Electricity use is fully matched with CFE. We can use a blended approach, in which some of the demand is matched by a PPA, while the remainder can be imported from the grid, provided it meets CFE threshold.

Key points

- A consumer's CFE score is the average of Situation 3 across all hours of the year.
- Principles that CFE should meet are to be locally sourced (from the same grid zone), time-matched (ideally hour by hour), and resulting from additional investments.
- CFE includes, by definition, a commitment to technological neutrality.

Carbon-based grid supply
CFE from grid supply
CFE PPA consumed
Excess CFE PPA (not counted towards CFE score)

[1] Note that at 100% CFE C&I consumers can rely on the grid only if the grid itself is also 100% CFE. A grid that features emitting generators can also be relied upon if the consumers seek to reach a lower CFE score.

How is Carbon Free Electricity measured?

The CFE score includes PPA-procured generation, and the cleanliness of the wider grid

- The CFE Score is a percentage score which measures the degree to which each hour of electricity consumption is matched with carbon-free electricity generation. We follow the methodology set out by Google[1].
- This is calculated using both carbon free electricity provided by through PPA contracts, as well as CFE coming from the overall grid mix. It is calculated as:

$$\text{CFE Score \% } (h) = \frac{\text{Contracted CFE MWh} + \text{Consumed Grid CFE MWh}}{\text{C\&I Load MWh}}$$

where:

$$\text{Contracted CFE MWh} = \text{Min (C\&I Load MWh, CFE Generation MWh)}$$

$$\text{Consumed Grid CFE MWh} = [\text{C\&I Load MWh} - \text{Contracted CFE MWh}] \times \text{Grid CFE \%}$$

- The Grid CFE % is calculated by looking at the what percentage of the generation comes from carbon free sources.
- The contracted CFE score is capped at 100%, even if there is excess CFE that is exported back to the grid.

An example calculation

Participating C&I load =	*100 MWh*
Contracted CFE generation =	*65 MWh*
Grid Imports	*100 - 65 = 35 MWh*
Grid CFE	*45%*
CFE Score =	*[65 + (35 x 0.45)] ÷ 100 = 81%*

Here, the participating C&I consumer has a load of 100 MWh which is participating in CFE/round-the-clock matching.

In this example hour, they have procured 65 MWh of clean generation through PPAs (e.g. some combination of solar and batteries) and must import the remaining 35 MWh from the grid to meet the load.

The grid at that hour has a CFE score of 45% (i.e. only 45% of generation is from CFE sources). This results in an overall CFE score for the C&I consumer of 81% in that hour.

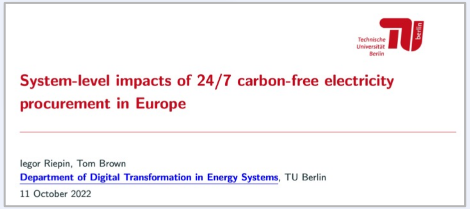
[1] Google 2021, "24/7 Carbon-Free Energy: Methodologies and Metrics"

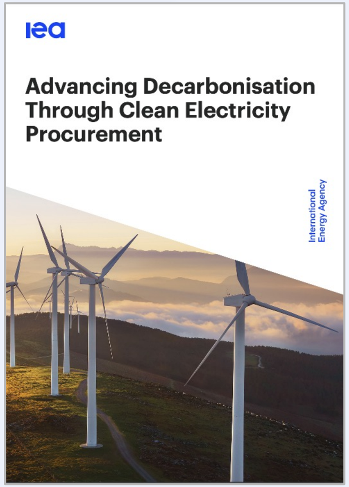
Scope of work

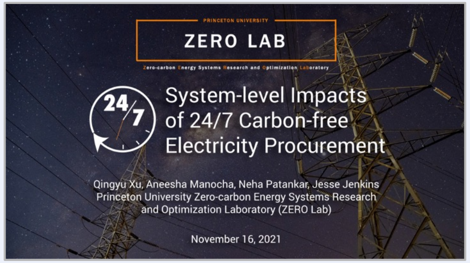
Our project

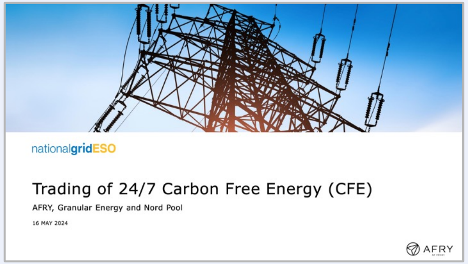
We set out to model key questions around 24/7 CFE in five geographies

- Our funder, Google, has set itself a target to achieve 24/7 CFE globally by 2030
- We are committed to assessing "…system-level costs and benefits[1] of 24/7 carbon-free electricity procurement in Japan, India, Singapore, Taiwan, and Malaysia, incorporating the costs and benefits of regional interconnectivity"
- Our work is informed by analyses such as by TU Berlin (Europe x 2) and Princeton (USA x 2), IEA (India and Indonesia), and AFRY (GB, upcoming)
- TransitionZero has applied the open-source PyPSA package to run CFE models for the 5 focus countries









[1] "Costs and benefits to be quantified by metrics covering financial costs, emissions, renewable energy deployment, and storage requirements."

Key questions

Stakeholders need to better understand the implications of this shift

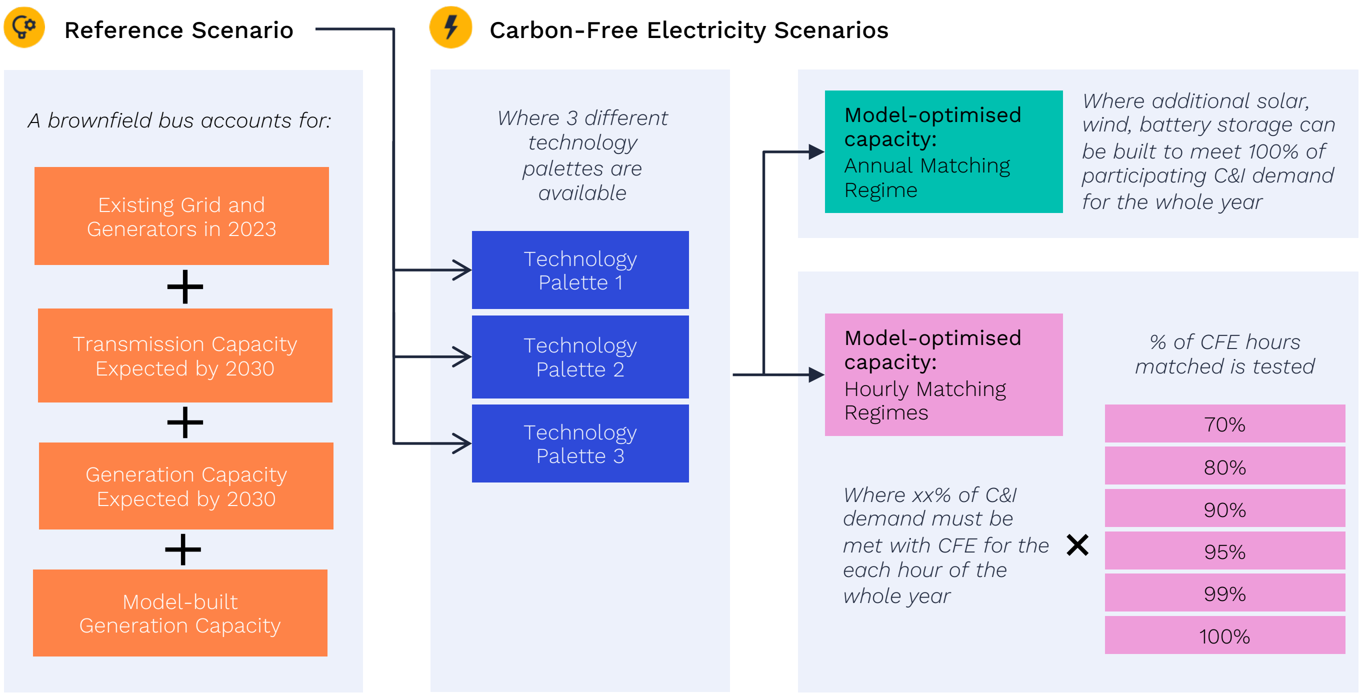
What are the implications in markets with high levels of fossil generation when a significant share of C&I consumers shift from annual to hourly matching?

What are the costs and benefits at the system level associated with hourly matching?

What other implications of hourly matching at 100% CFE score are there for the wider system?

To what extent can a wider palette of CFE technologies affect system-wide costs and benefits? What role can nascent technologies (storage or innovative thermal generation) play?

We run three sets of scenarios to test both supply and demand for CFE in 2030



Notes

- CFE scenarios meet the participating C&I demand either on an annual or an hourly basis by building additional capacity (equivalent to procuring additional capacity through PPAs).
- Before modelling any CFE scenarios, we run a Reference scenario, allowing new-build on the brownfield bus only.
- For each technology palette the first CFE scenario is the Annual Matching Regime, which we run only once.
- We then run Hourly Matching Regimes starting with a CFE share of 70% and then rising to 100% for a total of 6 runs (see infographic on left).
- The total number of runs is 22, made up of 1 Reference Scenario and 7 matching regime runs each for each technology palette.

Technology palettes

We explore how additionality and technological choice affect system costs and benefits arising from greenfield investments

Technology	Palette 1	Palette 2	Palette 3
Onshore wind and solar	✓	✓	✓
Battery storage	✓	✓	✓
Long-duration energy storage[1]	✗	✓	✓
Gas with carbon-capture and storage (CCS)	✗	✗	✓
Hydrogen (H_2)/ Ammonia (NH_3) co-firing	✗	✗	✓

[1] Liquid air storage is applied for Japan, India and Taiwan, while redox flow and pumped hydro are made available for Singapore and Malaysia.
[2] For H_2/NH_3 only generation from the non-fossil share is accounted as CFE(10% and 20% respectively). For CCS we consider a 70% CO_2 capture rate, with the remaining 30% of unabated generation not accounted for as CFE.

Wider technical scope should lower system costs

- The "brownfield" capacity mix in our Reference Scenario will include CFE sources of low additionality (pre-existing nuclear, hydro, renewables plants, as well as pumped and battery storage) and CFE plants likely to be built under business as usual conditions – all of which will contribute to the CFE score of the local grid.
- In our annual and hourly matching scenarios, C&I consumers can procure additional generating capacity in the "greenfield" through PPAs with technologies restricted to these palettes.
- Palette 3 also considers the non-conventional parts of innovative thermal plants[2] as additional.

Methodology

Key modelling design features

Relevant parameters of the 24/7 CFE model

- **Year of analysis:** 2030.
- **Time steps:** 8760 hours/year, i.e. hourly.
- **Modelling framework:** PyPSA open-source linear optimisation of dispatch in copper-plated zones without intra-zone power flows.
- **CFE demand:** country-specific subset of demand from emerging sectors.
- **CFE demand profile:** Proportional to overall demand profile in each grid region.

Modelled nodes by country

Country	Grid regions	Interconnectors	
		Domestic	*International*
India	5	10	3 [2]
Japan	9 [1]	9	-
Malaysia	3	2	3
Singapore	1	-	2
Taiwan	1	-	-

[1] Okinawa, not being connected to the 9 Mainland price zones, is not modelled.
[2] Modelled as generators due to their low demand/supply levels.

Common inputs

Our models utilise the full suite of inputs required for power systems modelling

Technology

- Capacities
- Maximum build-constraints
- Renewable profiles
- Efficiencies
- Emissions factors

Financial

- Cost of capital
- CAPEX
- OPEX (FOM/VOM[1])

Demand

- Nodal hourly demand
- Commercial & industrial demand

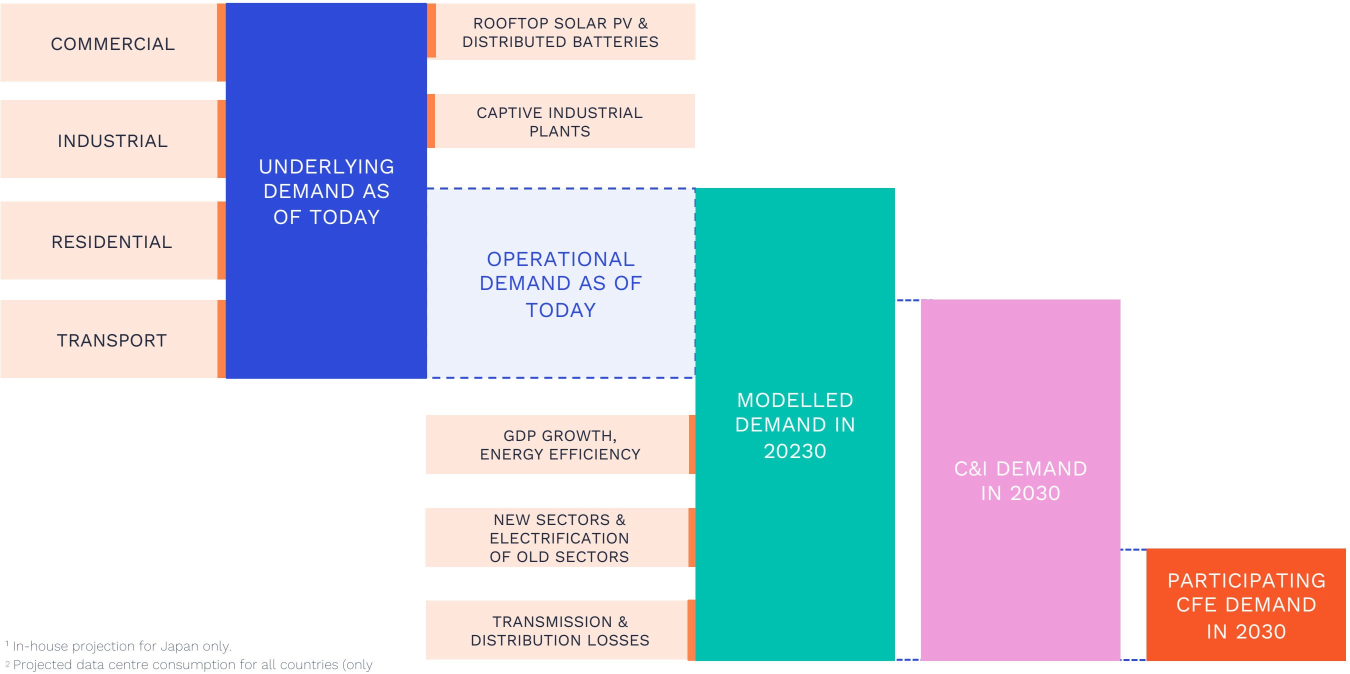
National policies [2]

- Planned expansions
- Capacity mix targets
- Decarbonisation targets
- Transmission plans

[1] VOM also covers here fuel costs and carbon penalties.
[2] We will apply a delay of up to 5 years on policies that do not seem realistic, in consultation with our Working Group partners.

Demand in 2030

Our model considers both demand for both conventional electricity and CFE



[1] In-house projection for Japan only.
[2] Projected data centre consumption for all countries (only 25% of projected total for Malaysia and Singapore).

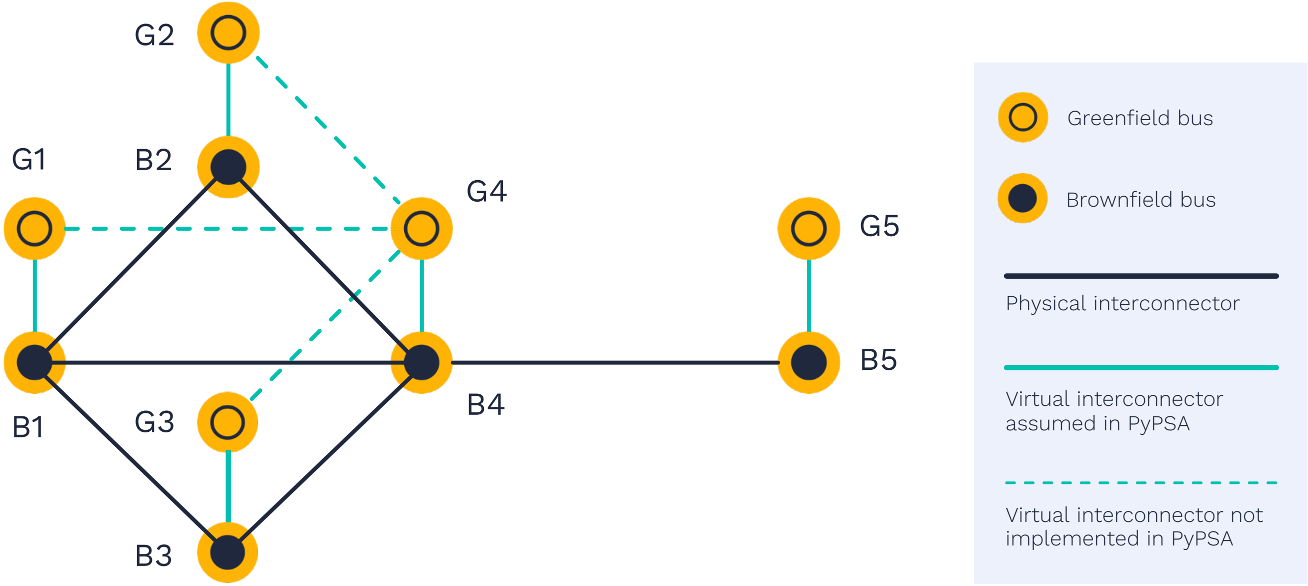
Notes

- Our demands for 2030 account for several sources of change from the present – either explicitly through in-house modelling[1] or by incorporating projections made by local authorities
- In our Reference Scenario the model only seeks to meet demand for conventional electricity
- In our CFE scenarios we expect that a certain share of C&I consumers switch to consuming only CFE, thereby triggering PPA developers to build new capacities
- The reference point for CFE demand matches projections for the growth of demand in the AI sector[2] in 2030
- Actual CFE demand in each model run depends on the CFE% targeted in each Hourly Matching Regime

Market	CFE volume [TWh]	CFE % [relative to 2030 demand]
India	122 TWh	5%
Japan	29 TWh	3%
Malaysia	14 TWh	5%
Singapore	3.5 TWh	4%
Taiwan	16 TWh	5%

Connections among buses

We break down complex markets featuring multiple zones connected through interconnectors into multiple linked buses

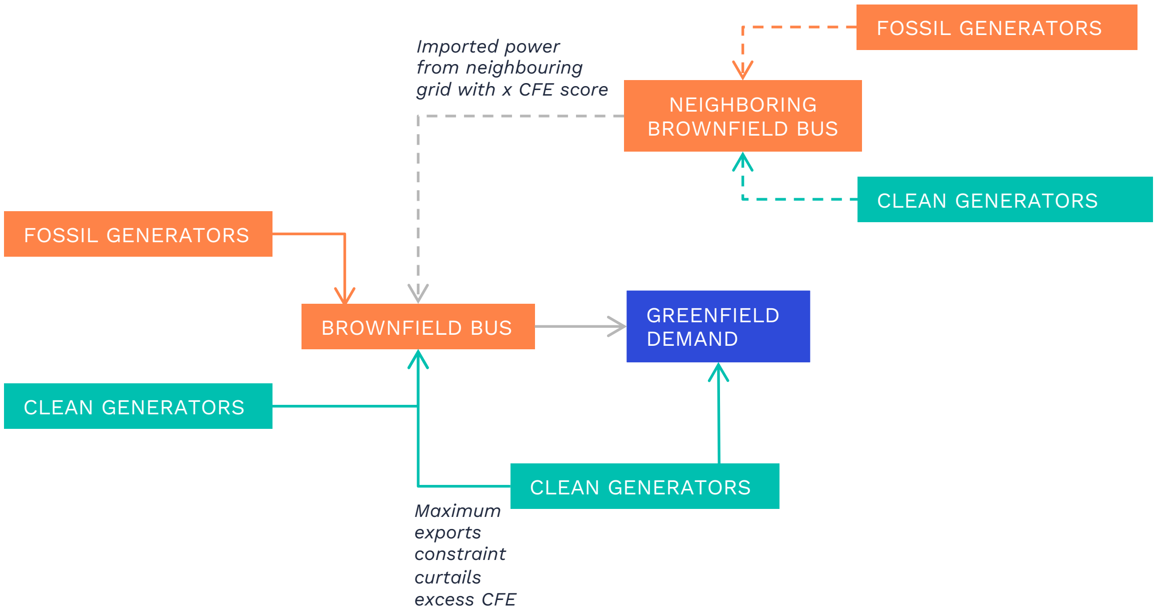


Notes

- In PyPSA we implement brownfield buses connected through links in a topology that reflects real-world grid zones and the interconnectors between them
- The brownfield buses contain the same generators and loads as in the real world
- To each brownfield bus we attach a single virtual greenfield bus to house generators financed through the CFE PPAs by interested C&I consumers located in the original grid zone
- In this project greenfield generators can only supply C&I consumers on the brownfield bus they are directly connected to, i.e. there are no linkages to other greenfield or brownfield buses

Procurement across links between buses

Our model allows for bi-directional trade between the greenfield and brownfield buses



Notes

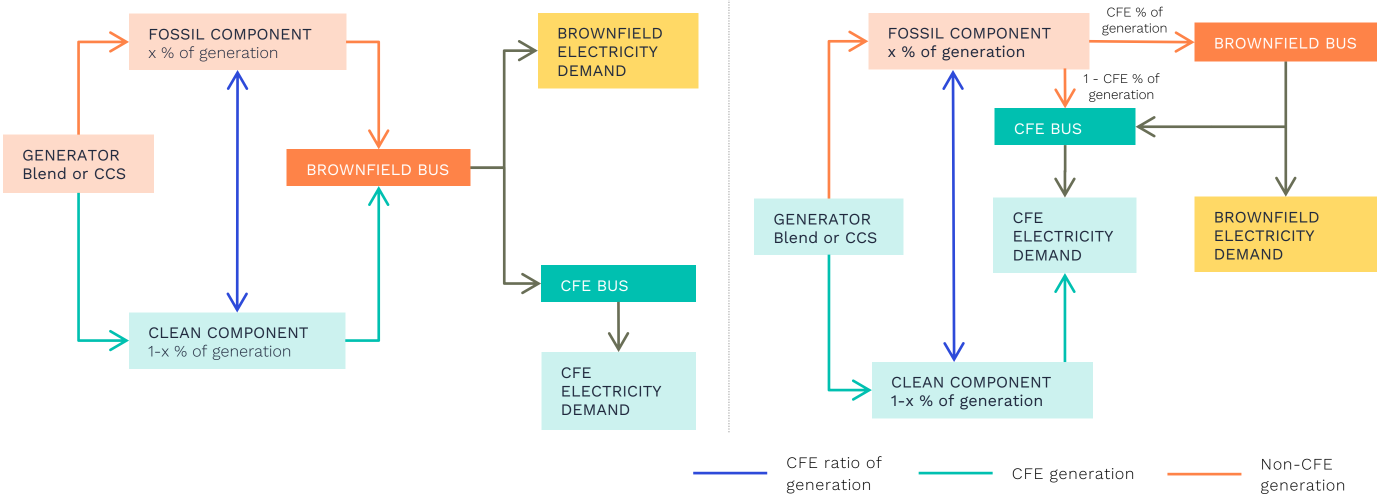
- C&I consumers can use brownfield procurement to top up insufficient PPA generation.
- If their local grid is interconnected with another grid, then the CFE score of their brownfield procurement will be affected by the CFE score of the net imports from that other grid.
- For certain countries, we allow exports **of excess generation back to the grid**, reflecting a conservative assumption based on grid technical constraints in handling additional exogenous generation at both hourly and annual scales. This maximum sell-back is set at 20% for hourly CFE in India, and 15% in Malaysia and Singapore.

CFE scoring for TP3's innovative thermal plants

We ensure that only an appropriate share of generation from low-carbon generators can be used to meet CFE demand

Built on the brownfield

Built on the greenfield



[1] Expressed as the CFE share of the hourly matching regime.
[2] For the 100% CFE hourly matching regime the model will allow only CFE consumption on the CFE bus, but for lower matching regimes some emitting generation is permitted.
[3] As a share of energy, derived from policy objectives of the Japanese authorities. Technologies available for TP3 differs per country.

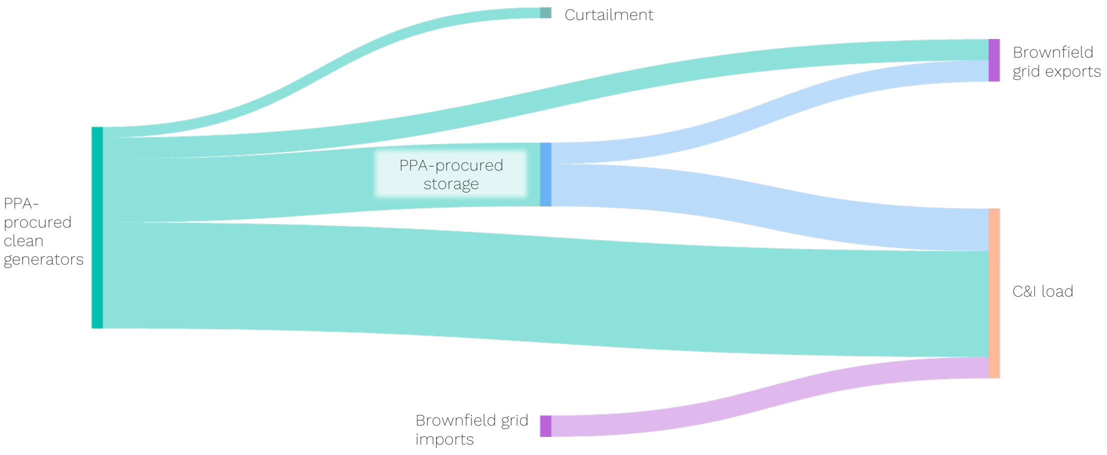
Notes

- Whereas loads on the brownfield bus consume any kind of electricity, consumers on the CFE bus want to meet a minimum share of their consumption from CFE[1].
- The generation from plants that blend fossil and non-fossil fuels and CCS plants with imperfect capture rates cannot be said to be 100% CFE.
- For each such plant we implement a CFE generation ratio that is fixed at all time steps.
- For plants on the brownfield bus (present in the Reference Scenario) their generation mingles with all other pre-existing plants' generation, affecting the CFE % of the brownfield, and this total generation may then flow into the CFE bus depending on the target matching regime.[2]
- For plants on the greenfield bus (present in technology palette 3) the non-CFE share of their generation flows immediately to the brownfield bus, from where it may return to the CFE bus depending as in above point on the target matching regime.

Asset class	CFE share[3]
Coal-ammonia co-firing	20%
Gas-hydrogen co-firing	10-30%
CCS	70%
Coal-biomass co-firing	15%

Energy flows and costs for the C&I load

Sankey diagram showing indicative energy flows between clean generators, storage units, the grid, and the C&I load



Relevant formulas

- In calculating the unit cost of electricity supplied to the C&I consumer, the C&I consumer could handle the grid imports themselves, and the PPA manager handles the PPA supply and export revenue from excess supply. This would lead to the following unit cost calculation:

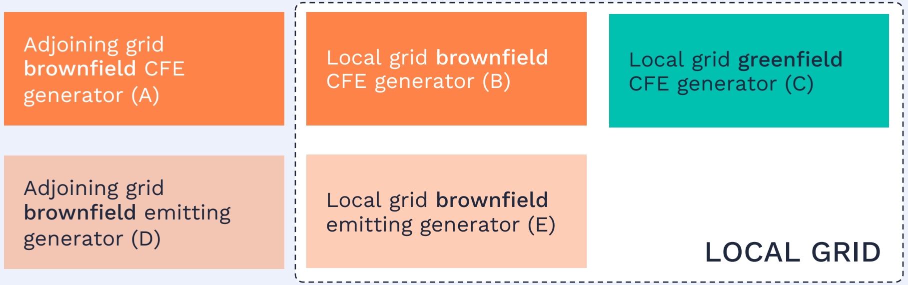
$$\text{Unit cost} = A \times \frac{\text{capex + opex + grid export revenue}}{\text{C\&I load} - \text{grid imports} + \text{grid exports}} + (1-A) \times \frac{\text{grid import costs}}{\text{grid imports}}$$

$$\text{Where } A = \frac{\text{C\&I load - imports}}{\text{C\&I load}}$$

- This splits the electricity supply into the two components which come from the PPA supply and the grid respectively, which are then weighted by the proportion by which they supply the C&I load.

Grid CFE score

We iterate to avoid the CFE build-out in adjoining grid zones from creating a nonconvex modelling problem



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

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

- To determine whether C&I consumers can use the brownfield grid to meet their target CFE score we calculate a “grid CFE score”, showing what ratio of all brownfield generation comes from CFE sources
- When C&I consumers use brownfield procurement to top up insufficient PPA generation, if their local grid is interconnected with another grid, then the CFE score of their brownfield procurement will be affected by the CFE score of the net imports from that other grid
- However, because all grids are building out CFE capacity to meet matching regime requirements, this creates a nonconvex modelling problem
- We avoid this problem by treating the grid CFE score as a parameter that is iteratively updated, with convergence expected after 2 iterations

Limitations of the study

We have taken several decisions to simplify the scope of our study

Considerations	Decision
Multi-period investment optimisation	Not included: We only model one step from the calibrated base year of 2023 to the target year of 2030
Trading of Energy Attribute Certificates	Not included
Demand shifting (in time and space)	Not included
Impact of asset age on additionality	We are not exploring the RE100 guidance to treat all renewable assets younger than 15 years as additional
CFE status of discharges from storage assets on brownfield buses	Not included

Annex

Glossary (1/2)

Term	Definition
Brownfield generators	Total CFE and non-CFE capacity mix forming the basis of our Reference Scenario, required by 2030 to meet overall electricity demand, resulting from a mixture of present capacity and new-build to account for variations in demand, retirements of current plants, and restart of idled plants.
Brownfield procurement	CFE procured by C&I consumers from brownfield generators from the same grid zone when contracted same-zone greenfield generators are insufficient to cover CFE demand.
C&I	Commercial and Industry.
CFE	Carbon-free electricity, including renewables, nuclear power, and the emission-free part of innovative thermal plants.
Consumer CFE score	Hourly share of CFE from a consumers' total electricity consumption, resulting from both greenfield and brownfield procurement.
Grid CFE score	Hourly share of CFE within all brownfield generation from a single grid zone.
Greenfield demand	Synonymous with 'Participating CFE demand'.

Glossary (2/2)

Term	Definition
Grid zones	Part of a country's grid characterised by a common price, grid operator or administrative region. For instance, India has five regional grid zones, i.e. India North, India South, India East, India West, and India North-East. See methodology section and individual country reports for breakdown.
Imports	Flows across interconnectors from adjoining grid zones to satisfy demand for electricity generally or CFE specifically.
Innovative thermal	Thermal plants that are either equipped carbon capture (capacity adjusted for leakage) or are co-firing fuels deemed to emit no CO2 at the point of combustion (hydrogen, ammonia, biomass).
Interconnector	Transmission-level power cables connecting two countries or two grid zones within a country.
Matching regime	Modelling constraint forcing C&I consumers to reach a specified CFE score, matched either against total annual consumption or across each hour of the year.
Palette	Scenario-specific combination of technologies deemed eligible for CFE status.
Participating CFE demand	Percentage of national demand that is participating in CFE hourly matching.
Sell-back constraint	Maximum volume of electricity that can be exported and sold from the Greenfield to the Brownfield, expressed as a share of total annual CFE load (%).