TransitionZero

Modelling 24/7 Carbon Free Electricity (CFE) in Asia

Results for India

July 2025

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Foreword

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The COP26 announcement by Prime Minister Modi of India's goal of achieving 500 GW of non-fossil fuel capacity by 2030 was a watershed moment for the country's energy transition. India is a continent-sized country with the world's largest population and relatively low per capita income, presenting both opportunities and challenges as it transitions to an electricity grid predominantly supplied by low-cost variable renewable energy (VRE).

At the heart of this transition is India's ability to produce round-the-clock clean energy, or 24/7 carbon free energy (24/7 CFE), at cost and scale to meet the country's unrelenting economic development priorities. As energy planners and grid operators grapple with integrating more VRE, and as corporates and developers adjust their strategies in response to forthcoming Greenhouse Gas Protocol (GHGP) accounting updates, the key questions are: what is 24/7 CFE and what does it cost?

24/7 CFE means matching every hour of electricity use with electricity from carbon-free sources. It ensures clean power is actually available when it is needed, all day, every day, instead of buying annual clean energy certificates. This approach is especially important for heavy industry and cloud computing, whose electricity demand is typically flat around the clock, making it essential for their long-term decarbonisation.

This approach to procuring electricity is a central focus of the GHGP, which governs how companies account for emissions from purchased electricity, and is in the process of a multi-year revision of its standards. While hourly emissions accounting is emerging as the preferred accounting method, the GHGP does not set targets or grade performance. Moreover, from a planning perspective, 24/7 CFE aligns with robust grid planning practices. For grid operators, electricity demand must be balanced in real time while ensuring that grid expansion occurs at the lowest possible cost.

Our analysis shows 24/7 CFE planning and procurement is a 'no regrets' option for India's energy planners, grid operators, and corporates. It shows that corporates can procure high levels of hourly-matched clean electricity at no extra cost compared to annual matching. This results in carbon abatement costs being roughly three times cheaper compared to annual matching. Perhaps more importantly, these procurement strategies result in grid operators saving money through least-cost grid planning.

We hope this analysis helps India's energy planners and market participants better understand the challenges and opportunities associated with 24/7 CFE, and supports Prime Minister Modi's goal of achieving 500 GW of non-fossil fuel capacity by 2030.

TransitionZero

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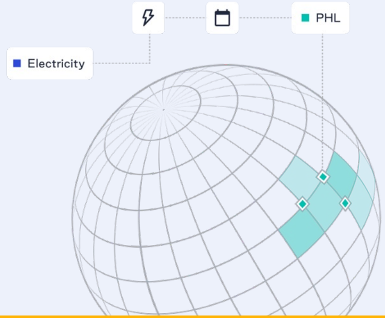

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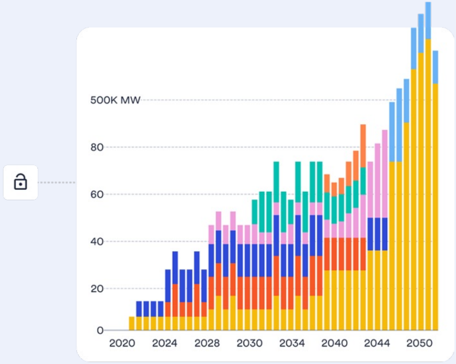

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Our analysts help decision-makers build the skills and knowledge they need to better understand energy transition risks and opportunities.

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

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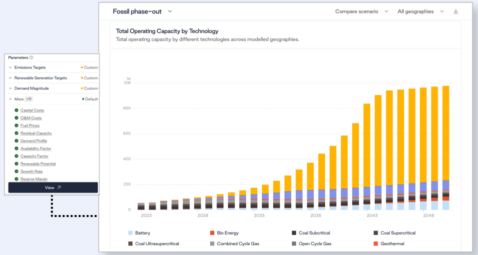
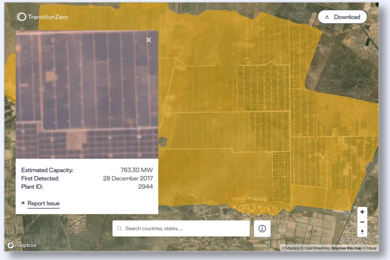
TZ-SB is free, no-code modelling platform that allows analysts working on energy transition planning to build, run, and analyse results from electricity system models – quickly, transparently, and at scale.



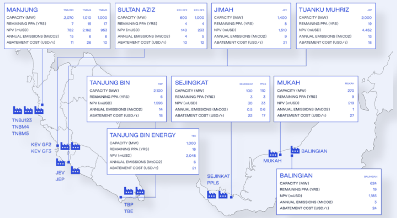
Solar Asset Mapper

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

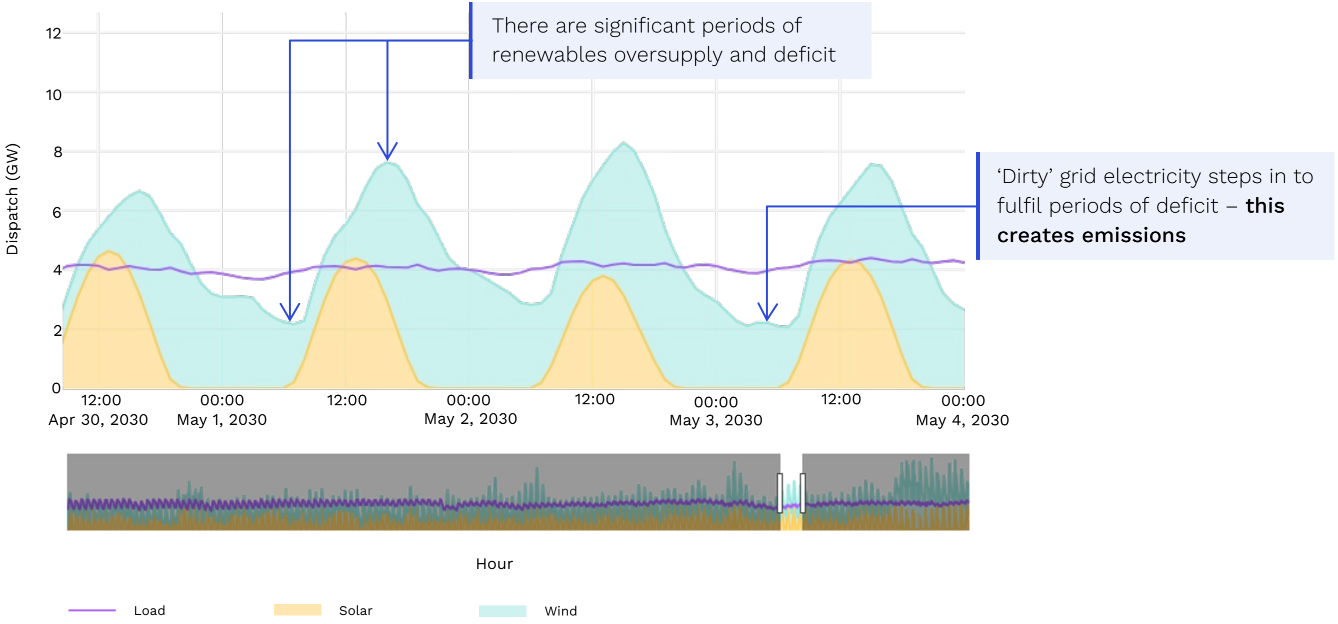
TZ-CAT is an open data product that supports the refinancing and replacement of coal plants in an affordable, just way. TZ-CAT is currently available for the Philippines, Indonesia, and Malaysia.



Background to 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?

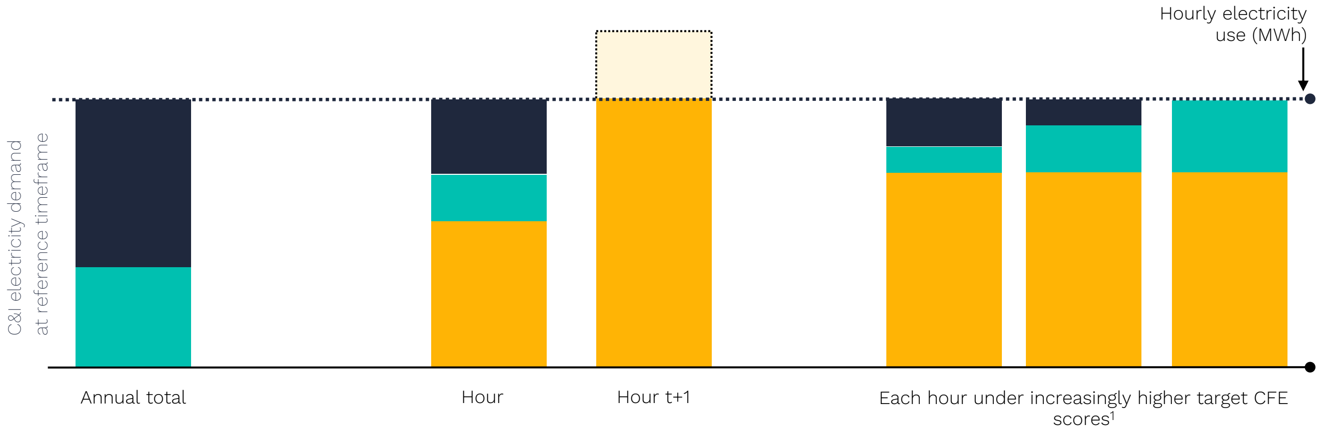


Key points

- 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. In the case of India, this considers each of the five grid zones as having distinct hourly CFE % scores.
- 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"

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 of hourly matching at the system level, i.e. the Indian power sector and the actors involved in generation, storage, transmission, and distribution?

What other implications of hourly matching are there for both the wider system and C&I consumers?

To what extent are nascent technologies (storage or innovative thermal generation) needed for higher shares of hourly matched CFE?

To what extent can different conceptions of additionality and a wider palette of CFE technologies affect system-wide costs and benefits?

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[3]
Onshore wind and solar	✓	✓	✓
Battery storage	✓	✓	✓
Long-duration energy storage[1]	✗	✓	✓
Gas with CCS	✗	✗	✓
H_2/NH_3 co-firing	✗	✗	✓

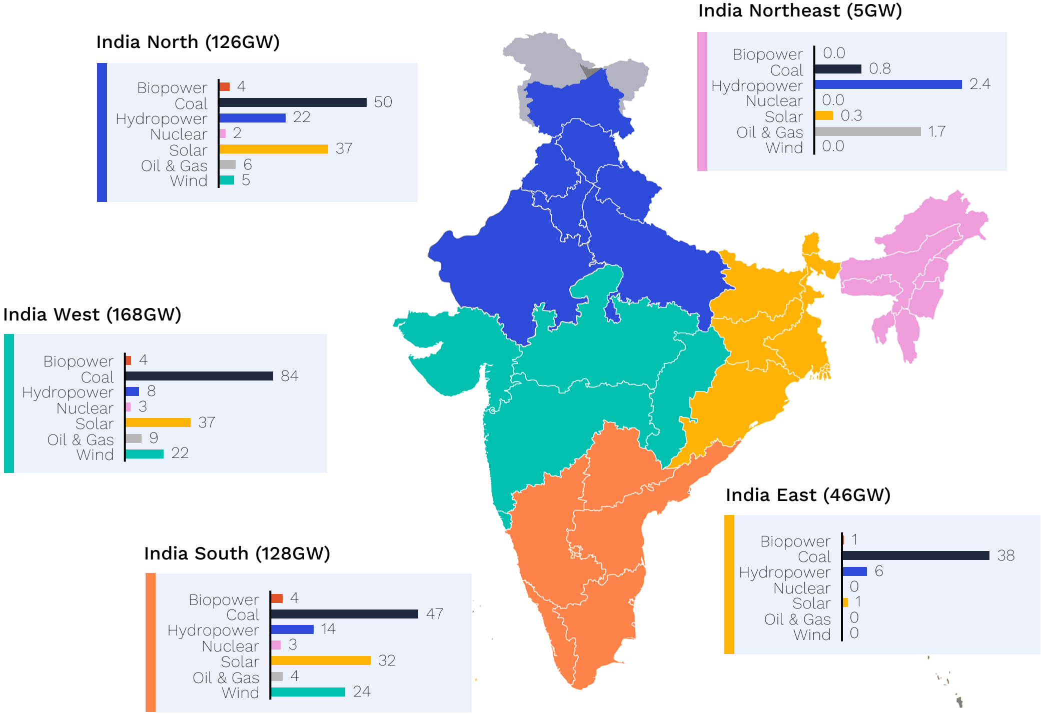
[1] Liquid air storage.
[2] For H_2/NH_3 only generation from the non-fossil share is accounted as CFE (10% and 20% respectively). For CCS we consider a 70% CO_2 capture rate, with the remaining 30% of unabated generation not accounted for as CFE.
[3] We have not considered Palette 3 for India at this stage following feedback from stakeholders.

A wider range of technologies 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. For India we have not yet modelled any technologies under this palette.

Overview of the Indian power sector [1]

Capacities by grid zone as of 2025 (GW)



Source: MNRE and CEA

470 GW
Total nationwide capacity

1700 TWh
Total nationwide demand

73%
Coal generation share

47%
Renewables capacity share

25GW
Solar capacity added in 2024

This map is for illustrative purposes only, and does not imply an endorsement of geographical boundaries by TransitionZero or its partners.

Overview of the Indian power sector [2]

A brief look into renewable procurement strategies

C&I consumers currently have multiple procurement options for clean electricity in the Indian electricity market. These include Power Purchase Agreements (PPAs), purchasing of Renewable Energy Certificates (RECs), installation of 'behind-the-meter' (BTM) assets, and purchasing green tariffs or power products (e.g. Green Term Ahead Market).

We focus on physical PPAs for round-the-clock matching and in our modelling. PPAs offer C&I consumers a popular and cost-effective alternative to distribution company (DISCOM) offtake. Under open-access and group-captive arrangements[1], C&I consumers can secure power directly from generators and bypass several expensive DISCOM surcharges. Regulations affecting PPAs are governed at a state level, with widely varying tariff structures and grid charges, and differing rules around open access policies such as virtual banking. These corporate PPAs are typically bilaterally negotiated, with issues like CFE under discussion.

On a central government and state-level, 'Firm and Dispatchable Renewable Energy' (FDRE) tenders are the closest current iteration of hourly matching. Early RTC tender arrangements lacked the contractual basis to truly deliver 'round-the-clock' electricity. Current FDRE tenders vary, but typically mandate a minimum availability for a peak period (e.g. 90% during a 4-hour evening peak), or a minimum demand fulfilment ratio (DFR) for set time blocks, e.g. 80-90% per month.

1. C&I consumers must own >26% of generation assets and consume >51% of its generation to qualify
2. Data from Mercom India, 'Mercom India, Q4 & Annual 2024 India Solar Open Access Market Report'

Selected moments in India's renewable procurement journey

Oct 2019 — **400MW**
The first-ever round-the-clock tender issued by SECI. Tariff set at 2.9 ₹/kWh seven months later.

June 2022 — **GEOA rules**
'Green Energy Open Access' rules is implemented by the Ministry of Power. This enables a surge of corporate PPA activity.

Nov 2023 — **FDRE**
The first 'Firm and Dispatchable Renewable Energy' tender concludes as a successor to RTC and related contracts.

2024 — **6.9GW**
Total C&I procured solar capacity through open access during the year[2].

Now — **~4-6 ₹/kWh**
Rough range of tariffs discovered for recent central government FDRE tenders.

Executive summary

Key takeaways from our CFE modelling in India

An overview of our study approach

How we modelled carbon free electricity in India in 2030

We developed a representative 2030 grid and created a dispatch model with hourly granularity to model India at the grid zone level (5 zones). We tested different clean electricity policies to see the impact of these interventions on costs, emissions and other key system metrics. **Our step-by-step process is as follows:**

01

We cycle through each grid zone and assign 5% of the total grid zone demand to C&I consumers participating in clean electricity matching. This 5% is representative of general C&I demand moving towards decarbonisation.

02

This 5% of demand is modelled as following either an annual matching or an hourly matching scheme (testing between 70-100% hourly CFE). C&I consumers procure PPAs from additional clean generators to supply this clean electricity, which are built and optimised by our model.

03

We then aggregate grid zone level results together to assess the nationwide impact of these schemes for both the C&I consumer as well as the wider system, i.e. the Indian power sector and actors involved in generation, storage, transmission, and distribution.

Hourly matching can deliver grid cost savings

Round-the-clock carbon free electricity brings net system benefits over annual matching for the Indian power sector

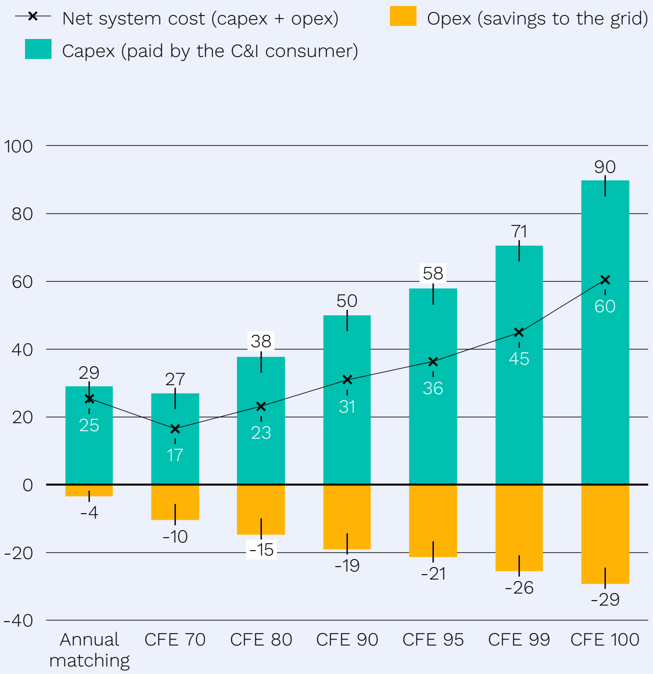
1. **70% round-the-clock (RTC) clean electricity by 2030 can be delivered at a lower cost to the grid than annual matching.** Reaching 70% carbon free electricity every hour of the year for participating C&I consumers is cheaper for the system compared to annual matching, and brings other additional benefits including lower emissions and lower curtailment of renewables.

2. **Savings to the grid increase with higher CFE targets.** Operational cost savings come through increased clean C&I exports, and reduced reliance on expensive thermal generators and associated fuel costs. The low (and steadily decreasing costs) of batteries makes it affordable and realistic to use cheap renewables to displace coal throughout the entire day. At CFE 70% opex savings are over Rs. 6 thousand crore (US$830 million) compared to annual matching.

3. **The net system cost of 70% CFE is 35% cheaper than annual matching.** At Rs. 17 thousand crore, net system costs[1] are cheaper than annual matching by Rs. 9 thousand crore (US$1 billion). 70% CFE has both lower capital costs and higher operational cost savings than annual matching. Pushing the target up to 80% CFE still sees net system savings of Rs. 2 thousand crore (US$270 million).

Benefits of hourly matching

Costs/savings to the Indian power sector in 2030 (Rs. thousand crore)



[1] System costs comprise all capital, operational, and fuel expenditure of the grid, including C&I assets.

Solar, batteries, and wind can get you to 100% CFE

Optimal combinations of renewables generation and storage is crucial to unlocking round-the-clock clean electricity

1. **Reaching 70% CFE is cheaper and more effective at emissions reduction than annual matching.** Participating C&I consumers moving to 70% CFE requires less capacity than annual matching and are 7% cheaper on average nationally, despite the higher cost per unit capacity.

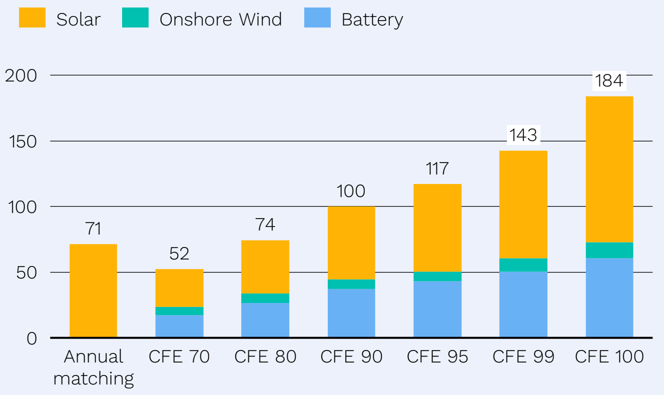
2. **Solar and batteries show the best synergy to deliver round-the-clock clean electricity.** Batteries with 4-hour duration are essential to ensure reliable supply, and charging these up with solar power is often more cost effective than using onshore wind. Each MW of generation works best with ~2 MWh of energy storage.

3. **Decarbonising the last 20% of hours requires more than a doubling of capacity and costs.** Moving from 80% to 100% means decarbonising the 'hard-to-reach' hours, which necessitates oversizing of capacity. However, as CFE score increases, the marginal cost of every extra MW decreases slightly.

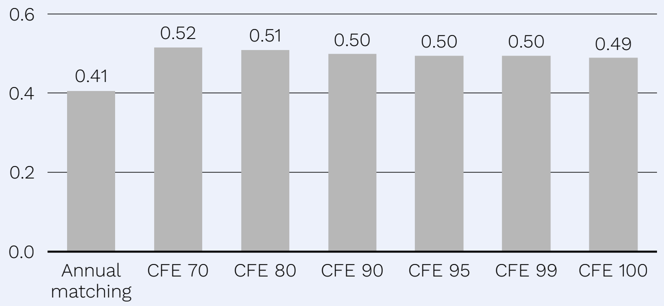
4. **Long duration energy storage (LDES) has a limited role to play.** Modelling shows that LDES only builds in small capacities at 100% CFE. The high costs of LDES, combined with the reliability of solar and wind in India, means that 4-hour duration storage from batteries is mostly sufficient.

Clean buildout required

Additional CFE capacity required in 2030 (GW)...



...and total annual cost per unit capacity to build and operate (Rs. thousand crore/MW)



Hourly matching is better at driving down emissions

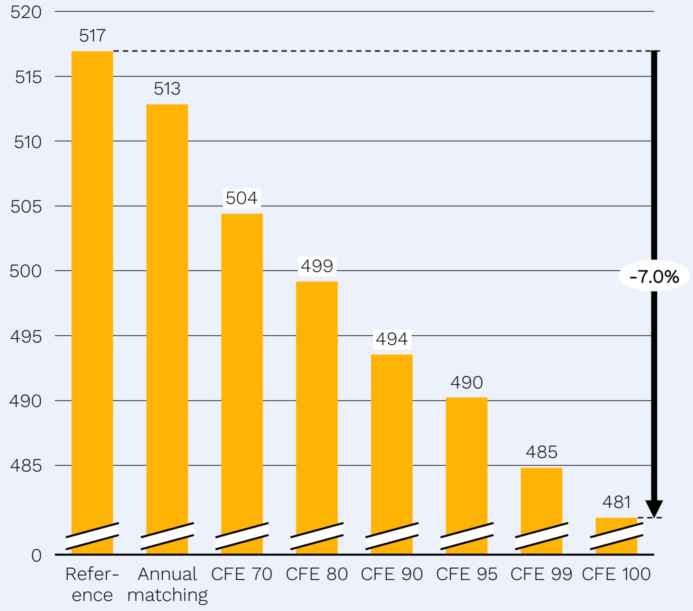
And can do so at a lower emissions abatement cost

1. **Emission reductions under hourly matching are greater than annual matching, even at 70% CFE.** At a system level, emissions can be reduced by 7% from the reference scenario when participating C&I consumers (5% of demand) move to a fully round-the-clock clean electricity supply. All levels of hourly matching tested are more effective at emissions reduction than annual matching.

2. **The carbon abatement costs are roughly three times cheaper under hourly matching compared to annual matching.** The carbon abatement cost is the cost of reducing one unit of CO_2, expressed as rupees per kilogram CO_2 avoided. Annual matching costs the C&I consumer Rs. 29 thousand crore to build and operate and reduces system emissions by 10 MtCO2, leading to an abatement cost of 29 ₹/kgCO_2. The equivalent figure for 70% CFE is roughly 9 ₹/kgCO_2, a third of the abatement cost under annual matching. Crucially, this abatement cost remains roughly the same at all levels of hourly matching, highlighting the cost effectiveness of hourly matching at reducing emissions.

Effective use of clean electricity

System-wide emissions rate under different clean electricity policies (gCO_2/kWh)



Our modelling is based on an NDC-compliant grid

The choice of this 2030 reference grid influences CFE behaviour

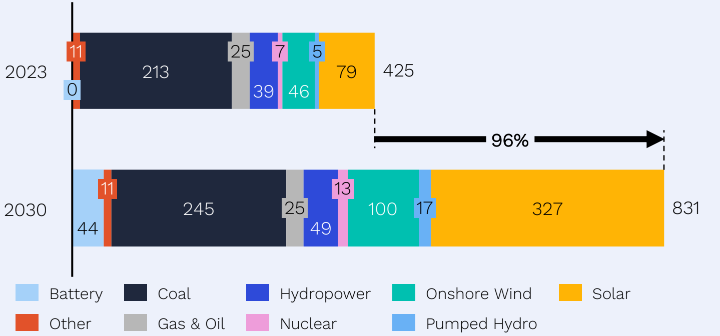
1. **Our reference grid is NDC-compliant by 2030.** We let our model build the cost-optimal 2030 power grid, ensuring certain constraints are met. These constraints include meeting the NDC targets for emissions and non-fossil fuel capacity share, reaching 500GW of non fossil fuel capacity by 2030, as well as following build and supply chain constraints. In our sensitivity analysis, we explore a subset of results under a non-NDC compliant scenario.

2. **Reaching this reference grid requires a doubling of onshore wind and a quadrupling of solar.** Coal, hydro, and other thermal generators are generally constrained to build only what's in the current pipeline. Batteries are allowed to build (and do build) right up to recent state level targets (44GW in total).

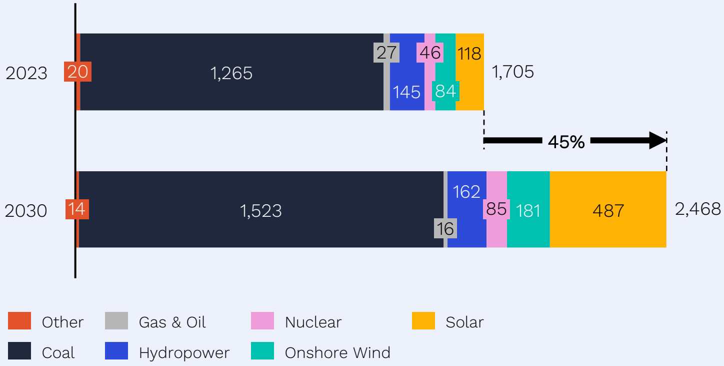
3. **The choice of the reference grid changes hourly matching strategies.** Although our projection of the 2030 grid is not the focus of this study, it will affect how CFE portfolios sell back, curtail, and import clean energy from the grid. For example, a dirtier grid will encourage selling back of cheaper renewables from the CFE node to the grid and require larger CFE portfolios, as C&I consumers must rely less on the grid to reach clean electricity targets.

Creating a 2030 reference scenario

Capacity mix for an indicative Indian power sector in 2030 (GW)



Generation* mix for an indicative Indian power sector in 2030 (TWh)



*Storage technologies not shown to avoid double counting

Methodology

How we modelled CFE in India

Key modelling design features

Key metrics

- **Year of analysis:** 2030
- **Time steps:** 8760 hours/year, i.e. hourly
- **CFE demand:** Equivalent to 5% of national electricity demand.
- **CFE demand profile:** Proportional to overall demand profile in each grid region.

Country	Grid regions	Interconnectors	
		Domestic	*International*
India	5	6	3[1]
Japan	9[2]	10	0
Malaysia	3	2	3
Singapore	1	0	1
Taiwan	1	0	0

[1] *Implicitly modelled in demand/generation due to their small flows.*
[2] *Okinawa, not being connected to the 9 Mainland price zones, is not modelled.*

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

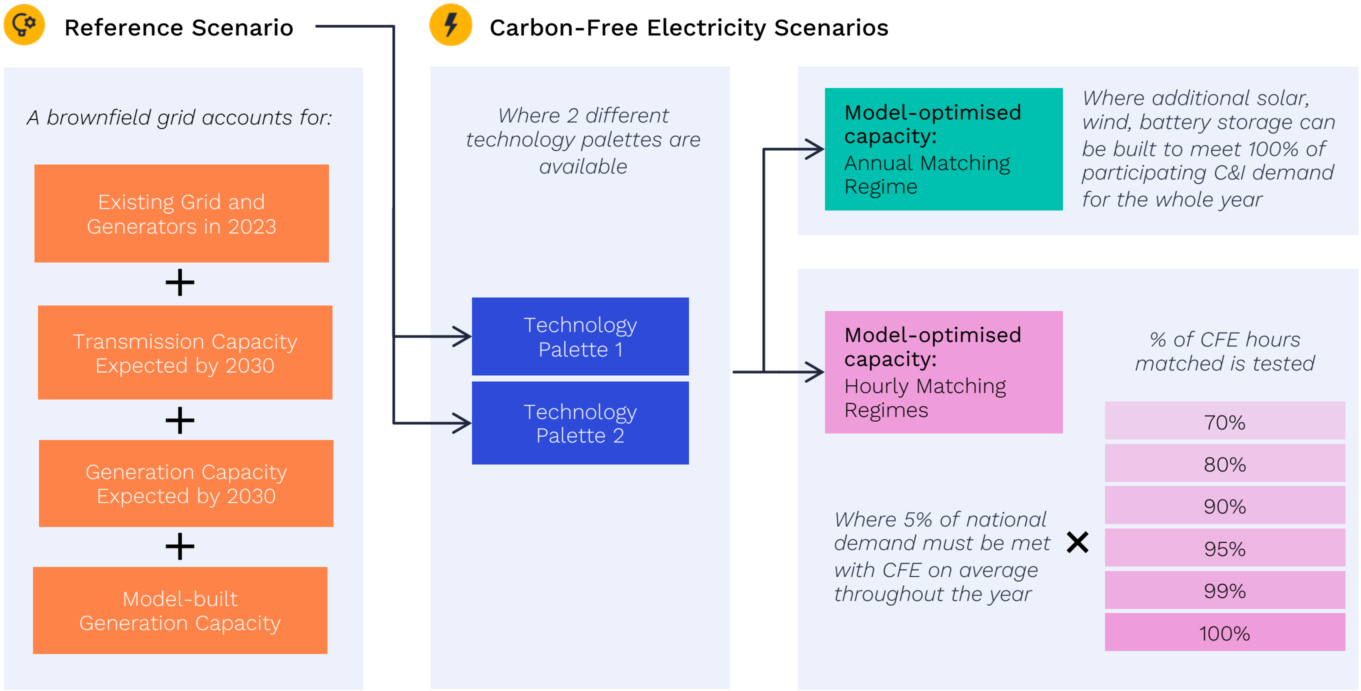
- Nodal hourly demand
- Commercial & industrial demand

National policies [2]

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

[1] VOM also covers here fuel costs and carbon penalties.
[2] National policies applied based on in-country stakeholder feedback.

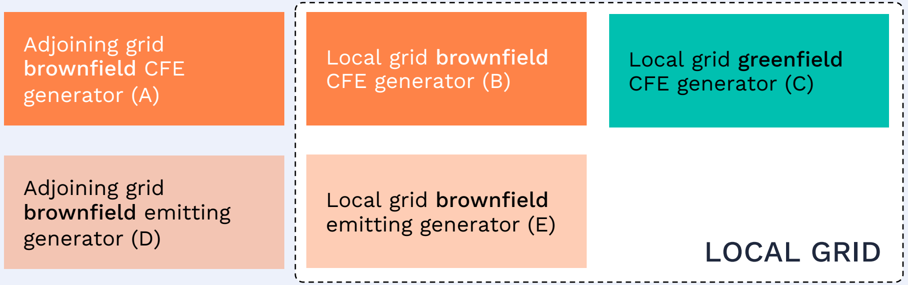
We run three scenarios to test both supply and demand for CFE in 2030



- CFE scenarios meet the equivalent of participating C&I demand 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. In Annual Matching, excess electricity is sold back to grid without limit, with no requirement to temporally match clean supply with demand.
- We then run Hourly Matching Regimes starting with a CFE share of 70% and then rising to 100% for a total of 6 runs. Under hourly matching scenarios, sell-back to the grid is limited to 20%.

Grid CFE score

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



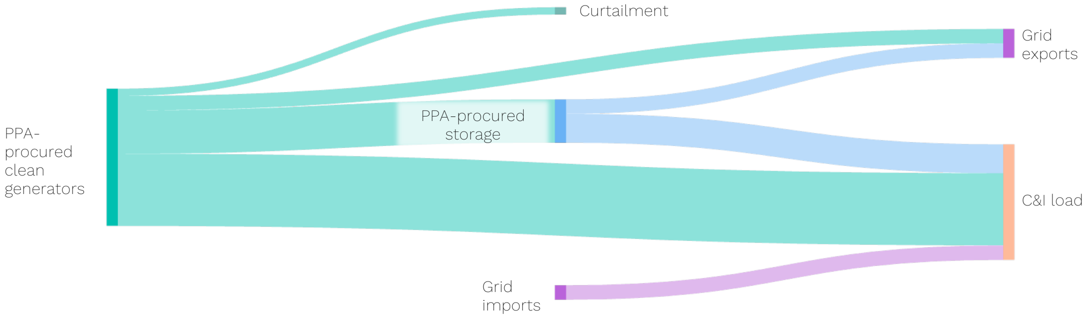
$$ImportCFE_t = \frac{A_t}{A_t + D_t}$$

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

- 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.

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



- In calculating the unit cost of electricity supplied to the C&I consumer, we can adopt a model where the PPA manager handles all of the electricity supply, including imports and exports. This means they absorb the import cost but also receive export revenue – these costs are passed on to the C&I consumer through the agreed PPA.

- The unit cost of electricity (in Rs/kWh) under this agreement would be:

$$\text{unit cost} = \frac{\text{capex} + \text{opex} + \text{grid import costs} + \text{grid export revenue}}{\text{C\&I load} + \text{grid exports} + \text{curtailment}}$$

  where the capex and opex are of the clean generators and the storage units.

- Alternatively, 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:

$$\text{unit cost} = A \times \frac{\text{capex} + \text{opex} + \text{grid export revenue}}{\text{C\&I load} - \text{grid imports} + \text{grid exports}}$$

$$+ (1 - A) \times \frac{\text{grid import costs}}{\text{grid imports}}$$

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

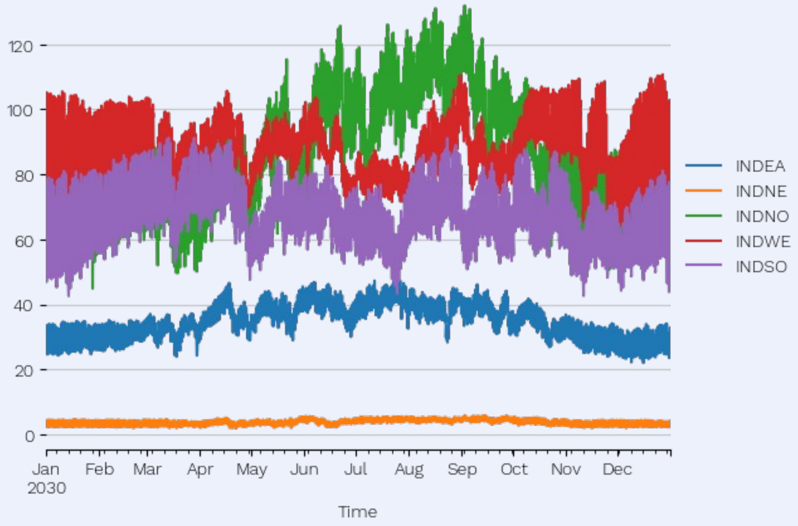
- This splits the electricity supply into the two components which come from the PPA supply and the grid respectively, which are then weighted by the proportion by which they supply the C&I load.

- For this study, we have taken the second approach.

Creating the 2030 reference scenario [1]

- **Total demand:** We follow CEA estimates from "Report on Optimal Generation Mix 2030" (April 2022).
- **Demand profiles:** Identical to today, following POSOCO reported data on 2023 hourly demand profiles by grid zone (illustrated right).
- **24/7 CFE demand:** We assume participating C&I consumers to make up 5% of total demand. This represents a general C&I consumer segment moving towards decarbonisation. We assume that the demand profile is identical to the wider grid zone.
- **Other data and assumptions:** Please see the annex for assumptions and sources around scenarios, technology costs, and operating characteristics.

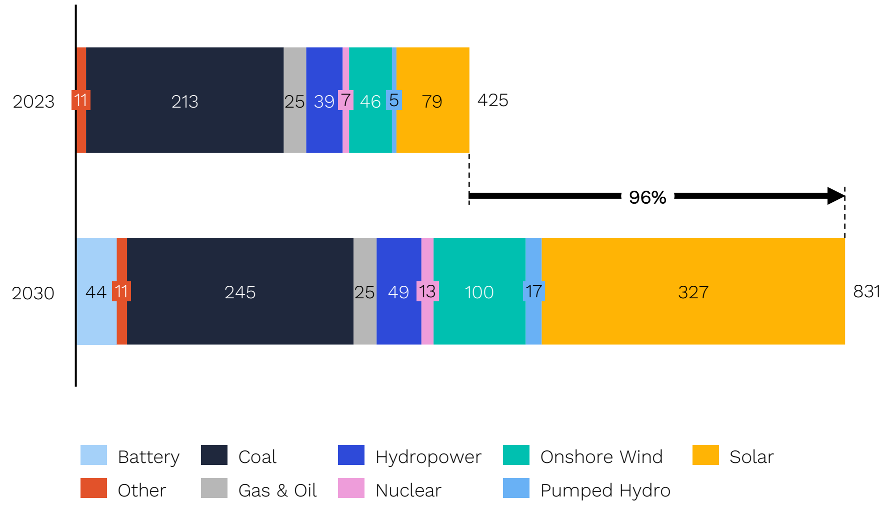
Hourly demand at a grid zone level in 2030 (GW)



Total demand in 2023	~1,700 TWh
Total demand in 2030	~2,500 TWh (+47%)

Creating the 2030 reference scenario [2]

Projected change in capacity mix between 2023 and 2030 (GW)



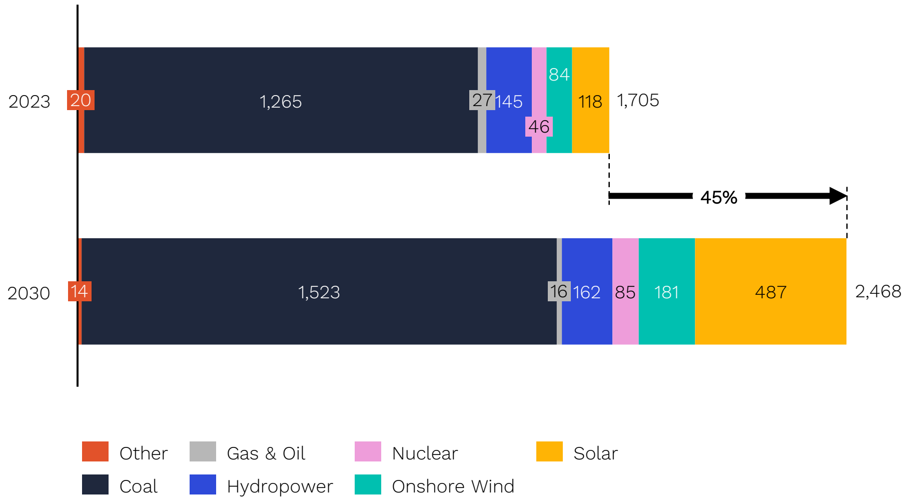
2030 capacity guidelines

- **Policy targets:** India is assumed to meet its 2030 NDC targets (emissions and non fossil fuel capacity share), and the related 500GW non-fossil fuel target.
- **Renewables:** Upper solar and onshore wind build limits are set according to historical build rates and state targets, with some flex to allow NDC and capacity policy targets to be met.
- **Coal, Nuclear & Hydro**: No closures are assumed for these technologies between 2023 and 2030. Any new build is restricted to plants which are already in the known pipeline and are expected to complete before 2030. These are left as investment options – i.e. will only be built in the model if cost optimal.
- **Pumped storage:** CEA targets and known pipeline are assumed as the upper limit for investment and allowed to build if needed[1].
- **Batteries:** State level targets are assumed as an upper limit for investment and are allowed to build if needed.
- **Inter-Regional transmission:** Capacity is allowed to build out according to CEA projections[2].

[1] "Status of Pumped Storage Development in India", CEA, March 2025.
[2] "Rolling Plan: Interstate transmission system 2028-29", CEA, July 2024.

Creating the 2030 reference scenario [3]

Projected change in generation* mix between 2023 and 2030 (TWh)



*Storage technologies not shown to avoid double counting

2030 generation guidelines

- **Operating costs:** Sourced from the CEA & DEA Indian Technology Catalogue. Where costs were not available, state-level tariff reports, Coal India Ltd price notifications, LNG spot prices, and other sources were used where necessary. Learning rates and cost reductions between 2023 and 2030 are also taken from the same catalogue. No carbon prices are assumed.
- **Technology operating characteristics:** Minimum and maximum generation levels, ramping limits, and other technical constraints are built into the model. These are sourced either from the CEA & DEA Indian Technology Catalogue, or from historical generation data sourced from the India Climate & Energy Dashboard (ICED).
- **Renewable capacity factors**: Capacity factors from a study by Chu and Hawkes (2020) are used to get state level hourly capacity factors. These are validated against outturn capacity factors from ICED. The same weather year of 2017 is assumed for consistency and comparability between scenarios.
- **Policy constraints:** NDC emissions constraints are applied (“Reduce emissions intensity of the GDP by 45% by 2030 from 2005 levels”). In practice this is not the binding constraint – the non fossil fuel capacity and capacity share constraints have a greater effect on the system mix.

Data gaps and modelling considerations

Limitations in our modelling approach

1. **Choice of 2030 reference scenario:** The reference scenario is not the primary focus of the study. However, the way additional CFE capacity affects the wider system, and its economic viability, is highly dependent on the wider system mix. As with any forecast, the evolution of India's power sector in 2030 is subject to many unknowns, including price shocks or reductions, political interventions, supply chain constraints, and weather variability.

2. **Demand in 2030:** High levels of electrification in the domestic and transport sector could increase demand projections to higher than expected by the CEA. This would affect the system capacity mix and the interactions between CFE generation and wider grid supply.

3. **Demand profile of C&I consumers:** We have assumed that C&I demand curves are identical to the wider grid. In reality, this may not be the case. However, research suggests that system level impacts "are relatively consistent even when using an approximation of a consumer's true demand profile" (Ricks and Jenkins, 2024).

4. **Single-node modelling approach:** In our study, we have applied CFE participating demand to one grid zone at a time and then aggregated the results together, ignoring potential inter-zone effects on CFE demand and behaviour. This is because of current model limitations of solving multiple adjacent grid zones at a time. A study where CFE participating demand is simultaneously applied to all grid zones may show different outcomes.

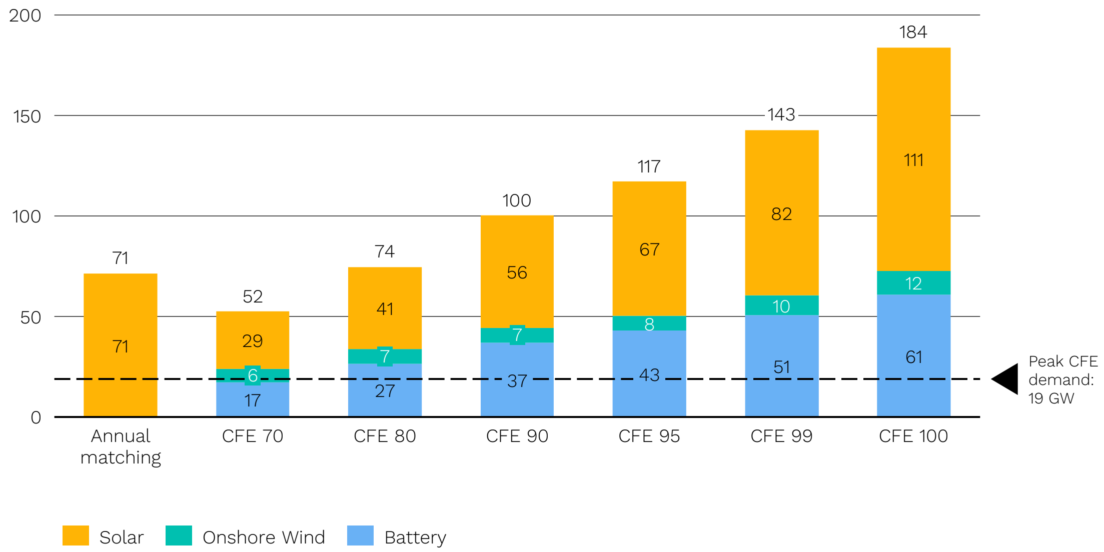
5. **CFE policy design:** Three aspects of CFE policy design have been assumed in our modelling: i) that under annual matching, C&I consumers can sell as much surplus PPA electricity back to the grid as they want (mimicking current policy design); ii) under hourly matching, this sell back constraint is limited to 20% (this prevents optimising for the grid rather than the C&I load); and iii) participating CFE demand is 5% of total electricity demand. These assumptions represent our best judgement of how to faithfully model CFE in the Indian power sector, but these assumptions can also have a large impact on the modelling results. The sell-back criteria is based on previous literature on this topic, and means that our model will build assets to primarily fulfil the CFE loads, rather than building assets for the purpose of selling back and serving the wider grid.

Modelling results

Deep-dive analysis into the national and grid-zone level findings

How much capacity does hourly matching need?

Additional capacity required when 5% of nationwide demand in India adopts clean electricity matching schemes (GW)



- Reaching 70% CFE requires less capacity than annual matching, and 80% requires only 3GW more than annual matching. However, the optimal portfolio mix is very different, with over a third of the capacity devoted to 4-hour duration batteries.
- Decarbonising the last 10% of hours for a C&I consumer requires almost a doubling of capacity and investment due to oversizing required to overcome the intermittent nature of renewables.
- The oversizing ratio required varies roughly between 3–10x the peak load of the CFE demand, depending on the hourly matching target.
- Solar power and batteries show the most synergy and make the majority of the cost-optimal CFE portfolio. Batteries are essential to guarantee clean electricity around the clock – and charging up these batteries is often cheaper and easier done with solar rather than onshore wind. However, onshore wind still has a role to play in the optimum cost mix as its intermittency can complement solar generation.
- The optimum ratio of generation capacity to storage is around 1 MW of generation for every 2 MWh/0.5 MW of storage (assuming 4-hour duration batteries). This varies by grid zone and CFE score.

Grid zone level capacity build-out

Demand levels, renewables potentials, and grid cleanliness all affect optimal CFE portfolios

In grid zones with plentiful clean electricity, achieving 80% or even 90% CFE is possible with minimal extra capacity compared to annual matching. For example, in India Northeast, the high hydropower capacity means that reaching 70% and 80% CFE for 5% of demand in that grid zone requires little additional build, even less so than annual matching. A similar picture can be seen in India South with its good onshore wind potential. In contrast, areas with poor onshore wind power potential give rise to a CFE portfolio exclusively made of solar and batteries, such as in INDEA and INDNO (up until 99% CFE).

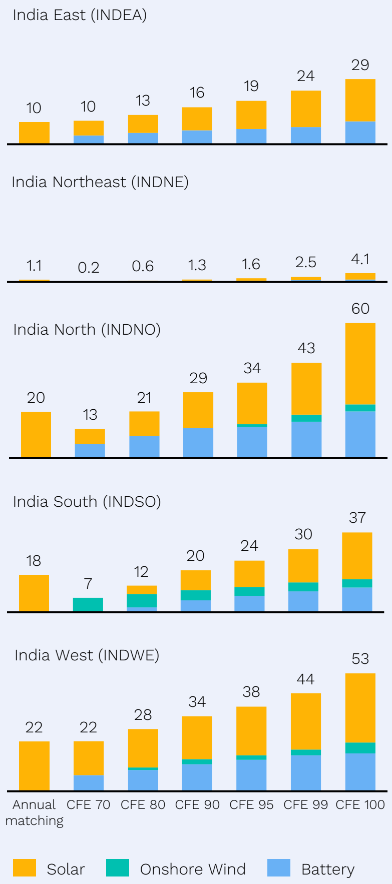
Solar is generally preferred in the optimal mix due to its higher value per unit cost in suppling clean electricity. Testing during modelling showed that if costs shifted 10-20% in favour of onshore wind, CFE capacity mixes shift more heavily to onshore wind. The capacity mix would similarly change if onshore wind capacity factors improve significantly from the current national average. This is already happening given current technology learning curves, higher hub heights, improved turbines, and access to better siting. However, this must be balanced against potential saturation and cannibalisation of renewable generators, as well as the exhaustion of good plant locations, especially given the volume of build being considered in this study.

These capacity levels are meant to be indicative of a potential solution to meet CFE demands, rather than a projection of future capacity build out. In our CFE100 scenario, a total of 110GW of solar and 61GW of battery build is needed. This represents an extra 35% and 139% respective additional build on top of our 2030 reference scenario. This is challenging, but this total capacity build out is proportional to the percentage of national demand shifting towards CFE, and what level of clean hourly matching is pursued. Cost implications and emissions savings will also be proportional.

Total annual and operational costs (explored later) for different CFE target scores follow the same trends as the capacities shown here. Very roughly, for every 1 GW of CFE portfolio, C&I consumers can expect to pay Rs. 0.5 thousand crore.

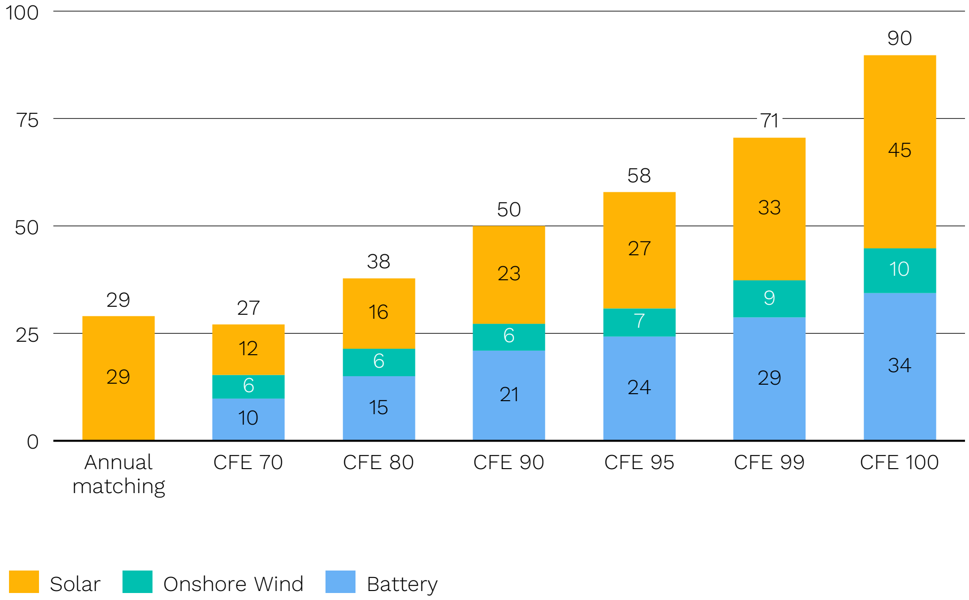
Portfolios differ by grid

CFE capacity required by Indian grid zone (GW)



Total costs increase with higher CFE levels.... [1]

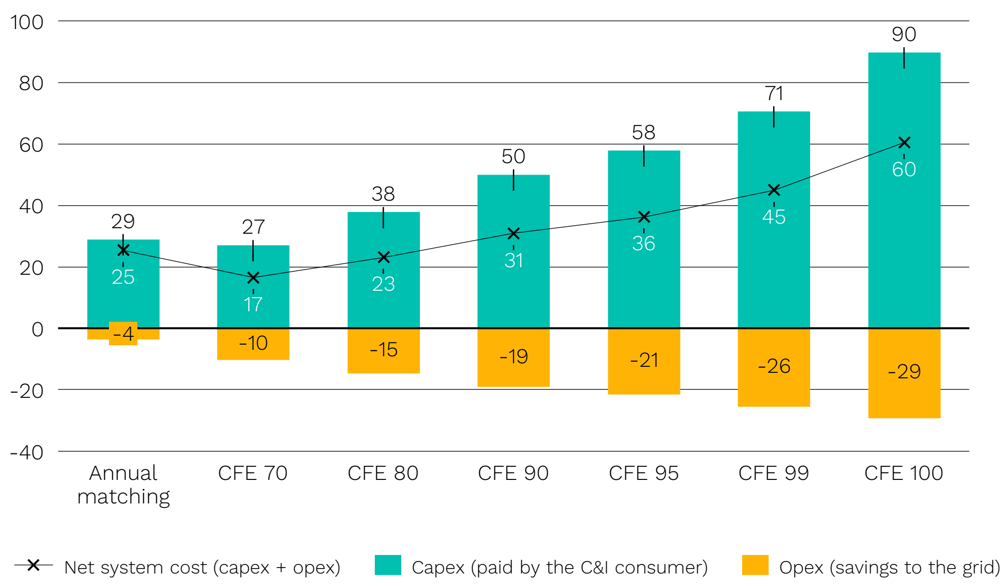
Annual capital and operational costs for participating Indian C&I consumers (Rs. thousand crore)



- CFE 70% can be delivered at a lower cost than annual matching - effective use of renewables and storage means that more clean electricity can be usefully delivered per unit capacity.
- Participating C&I consumers face higher capital and operational costs under hourly matching arrangements from 80% CFE target scores and higher – however this comes with the benefits of being shielded from volatile grid supply shocks and high C&I electricity tariffs. Additionally, options to sell back excess electricity present extra revenue streams.
- These costs do not include wheeling/transmission charges, open access, or other surcharges payable to the DISCOM where applicable. They also do not include additional Renewable Energy Certificates (RECs) where required to attribute all procured generation as ‘clean’.
- These costs face regulatory uncertainty –tariffs, open access rules and other policies set at a state level and under regular review, C&I consumers face uncertainty on the additional costs required and the true cost of PPAs to enable 24/7 CFE. These factors are examined further in our unit cost analysis, examining the costs faced from the point of view of the C&I consumers.
- The annual capital and operational costs presented here are purely from the point of view of the C&I consumer, and do not represent the whole picture. We need to look at the whole system to understand the implications of CFE.

...but higher CFE levels bring grid savings [2]

Costs/savings to the Indian power system under clean electricity matching schemes (Rs. thousand crore)



- Hourly matching with 80% clean electricity can be met at a lower net cost to the system compared to annual matching. This can save the system roughly Rs. 2 thousand crore, representing 9% savings.
- A target of 70% CFE has both lower capital costs, and higher operational cost savings, compared to annual matching, and can save the system roughly Rs. 9 thousand crore, 35% compared to annual matching.
- Hourly matching and the constraint of granular accounting means that the renewables are used more effectively and are truly additional to the rest of the system. C&I consumers are incentivising renewables and storage build that truly complements and contributes to the wider grid.
- Under annual matching, there are high levels of export of excess electricity to the grid. However, this electricity is of low value to the wider system primarily due to its timing. We explore this further in our analysis of curtailment and energy balance.
- All levels of hourly matching leads to increased operational cost savings to the grid. Whilst the additional capital costs are likely going to be absorbed by C&I consumers, the operational cost savings can be passed directly to the grid operator and the consumer. These cost savings are largely from saved fuel costs due to reduced usage of expensive thermal generators and better usage of renewables.

Curtailment and energy balance

Hourly matching makes effective use of procured PPA supply, with minimal sell-back

Annual matching makes poor use of the procured clean PPA supply and must sell back excess electricity to the grid. This sell-back is likely to occur at times of existing renewables saturation and possible cannibalisation, reducing the value of this electricity to the grid and causing curtailment in other sectors of the power system. In contrast, excess electricity at higher hourly matching levels can be sold back at valuable times for the grid, i.e. displacing expensive peaking plants and thermal generators.

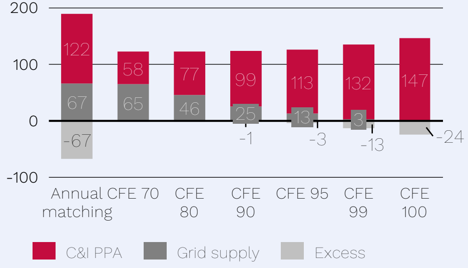
Hourly matching and the use of batteries means that minimal surplus electricity is created. Therefore, most of the additional clean generation can be used to directly serve the C&I load. Depending on the PPA arrangement, this can be advantageous in constrained grid situations where upgrading the distribution and transmission network would otherwise be necessary to evacuate this surplus generation.

Curtailment of the procured PPA generators can be kept at relatively low levels until CFE scores of 99%. After this point, curtailment levels of solar and onshore wind reach roughly 10% and above, with solar reaching 26% by 100% CFE. Here, the PPA generators start coming up against our imposed 20% sell-back constraint, where no more than 20% of the total electricity generated by the procured PPA supply can be sold back to the grid. Relaxing this constraint could reduce curtailment but this would come with additional balancing and management costs to the system operator.

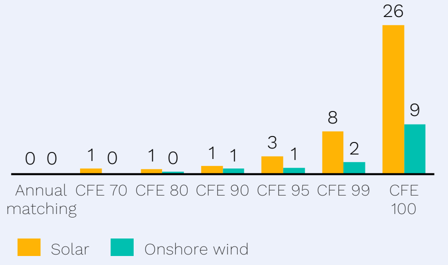
On a system-wide level however, curtailment of all solar and onshore wind generators drops in hourly matching schemes compared to annual matching. This demonstrates the value of battery storage in the CFE portfolio, allowing the wider system renewables and the C&I PPA renewables to complement each other.

The choice of exporting or importing to and from the wider grid depends on the capacity and generation mix of the wider grid. For example, a dirtier grid will reduce grid imports, as the CFE score of the grid will not be high enough to meet the C&I CFE targets. A more expensive grid may see PPA managers prioritising export revenue over clean C&I supply, leading to a different levels of PPA build.

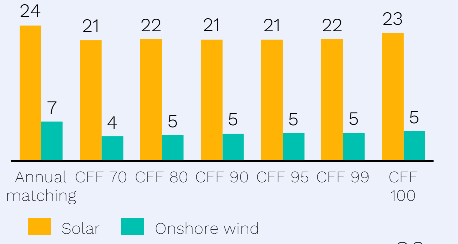
Energy balance for the CFE loads (TWh)



Curtailment of PPA generators for CFE load (%)

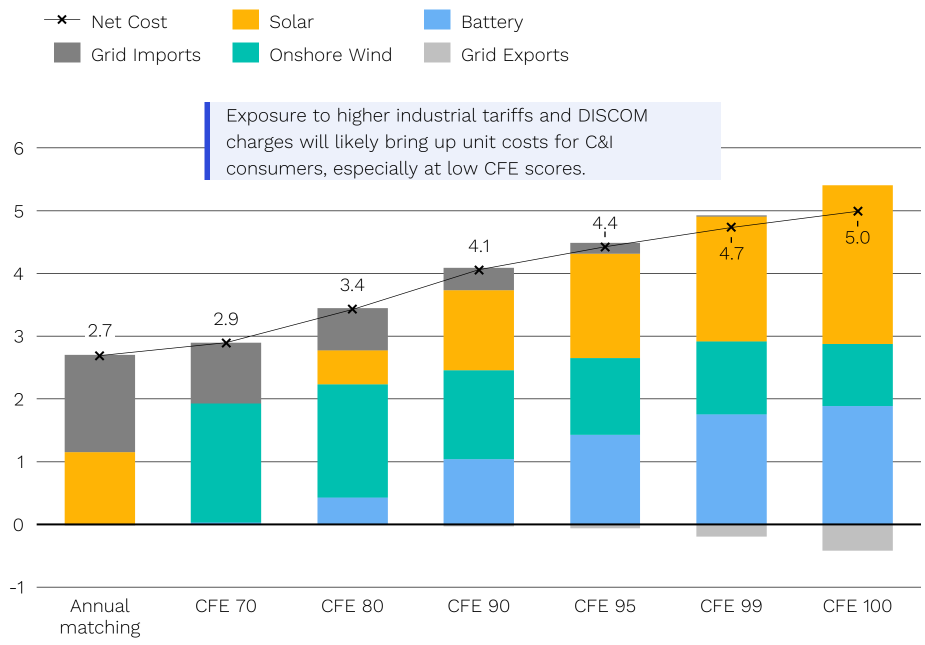


Curtailment of nationwide generators (%)



Modelling shows a unit cost premium for CFE

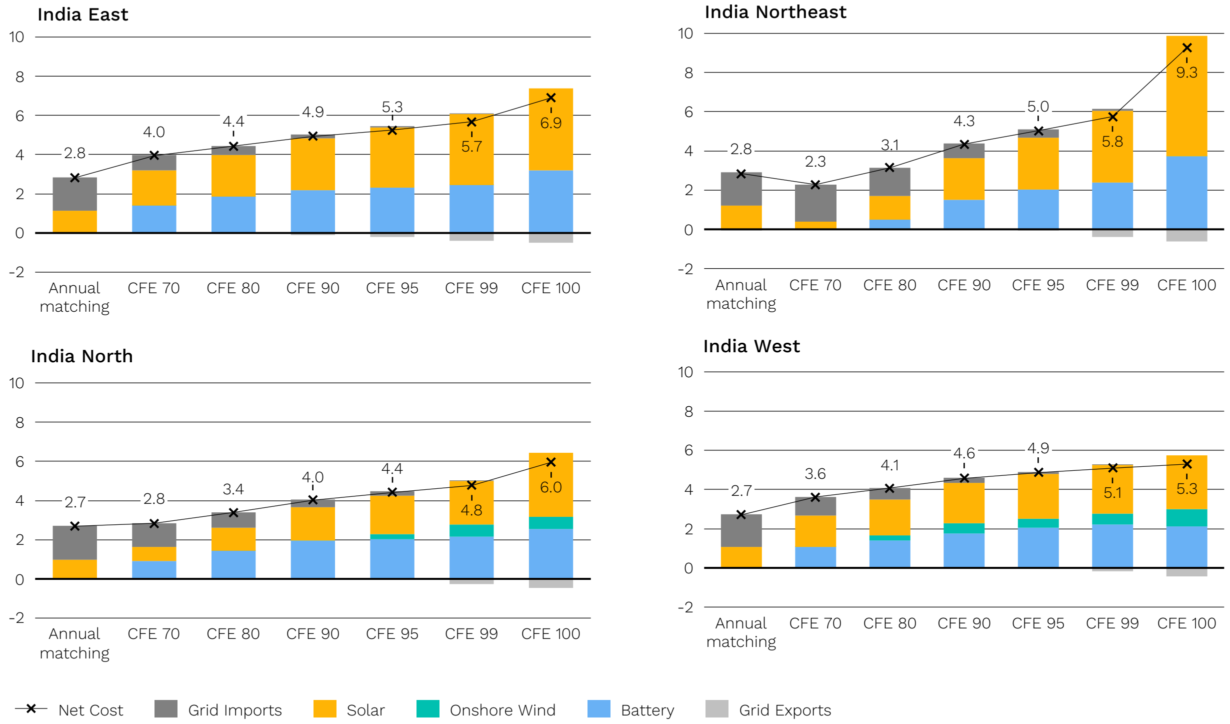
Modelled unit cost of electricity faced by C&I consumers in India South under different clean electricity matching regimes (₹/kWh)



- C&I consumers will likely pay more for hourly matching when looking at the cost of the entire load. Although the total annual electricity supplied is the same in all scenarios, moving from annual to higher levels of annual matching means moving from cheap solar (which only delivers during daylight hours) to more expensive wind and battery combinations which can spread clean electricity delivery throughout the day, and reduced use of grid electricity.
- Costs/revenues of import and export depend on the wider grid. In our cost model, the PPA manager can sell excess revenue to the grid and pass on the savings to the C&I consumer through a lower PPA tariff. C&I consumers must also pay to import electricity from the grid at times of PPA deficit (provided that the grid CFE score is higher than the target CFE score). These modelled import costs and export revenue therefore depend on the cleanliness and price of the wider grid.
- Exporting surplus under annual matching is not cost-optimal. We see high export volume, but low export revenue – likely because exports are occurring at times of low value as discussed. At higher CFE scenarios, battery storage gives consumers the flexibility to balance between supplying CFE to their loads, maximising export revenue (and value to the system), and minimising import costs.
- However, our model of marginal costs and pricing may not represent reality. This calculation of unit costs assumes that grid imports and exports are priced at the modelled marginal price of the wider grid. This does not account for the range of state level policies governing industrial tariffs, open access agreements, virtual banking, and more.
- Industrial tariffs for C&I consumers can be around 6-9 ₹/kWh, which is higher than all the costs displayed here. As is the case now, these CFE PPAs will likely give C&I consumers long-term price certainty and reduced exposure to volatile grid tariffs, especially at higher CFE target scores.

CFE unit costs vary significantly across grid zones

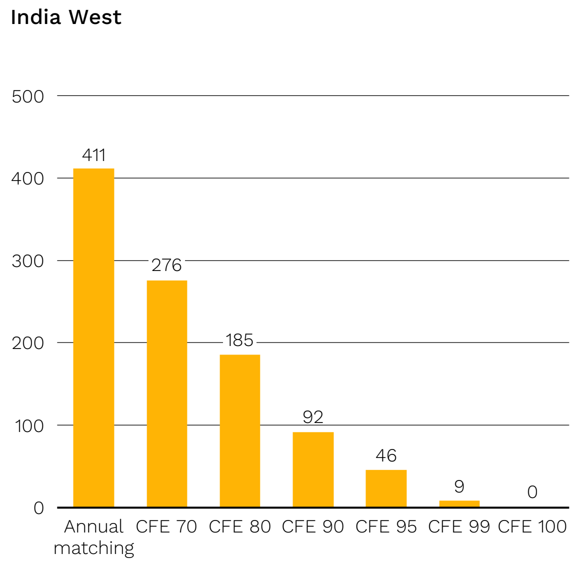
Modelled unit cost of electricity faced by C&I consumers in other Indian grid zones under different clean electricity matching regimes (₹/kWh)

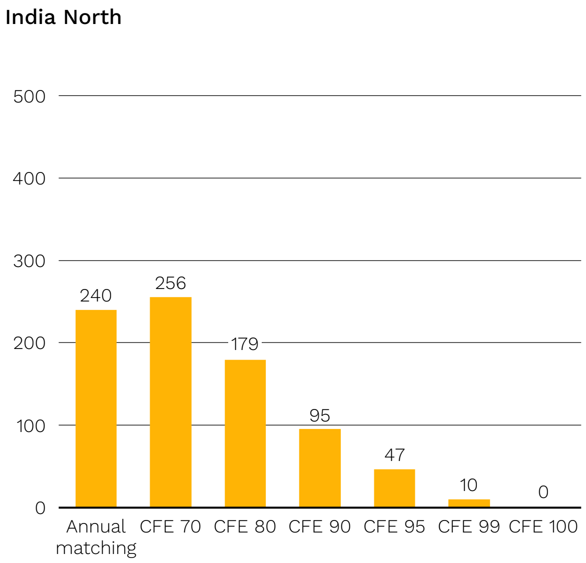


- Unit costs can vary quite significantly between grid zones, mainly due to two factors: i) the underlying generation mix of the regional grid; and ii) the renewables potential of the regional grid zone.
- In general, these unit electricity costs reflect the capacity buildout required.
- For example, in India Northeast our modelling found that low levels of CFE were achievable with minimal extra build due to existing hydropower assets, and this is reflected in the unit costs. However, due to the poor onshore and solar wind potential of the area, reaching 100% comes at a much higher cost than even 99% CFE.
- In contrast, other grid zones such as India West show a much smoother trajectory of unit cost increases.
- These costs again may not reflect true electricity costs that will be faced by C&I consumers, due to the range of tariffs and surcharges.

Impact on C&I consumer emissions

Emissions rate of C&I consumers participating in clean electricity schemes in India West and India North (gCO_2/kWh)

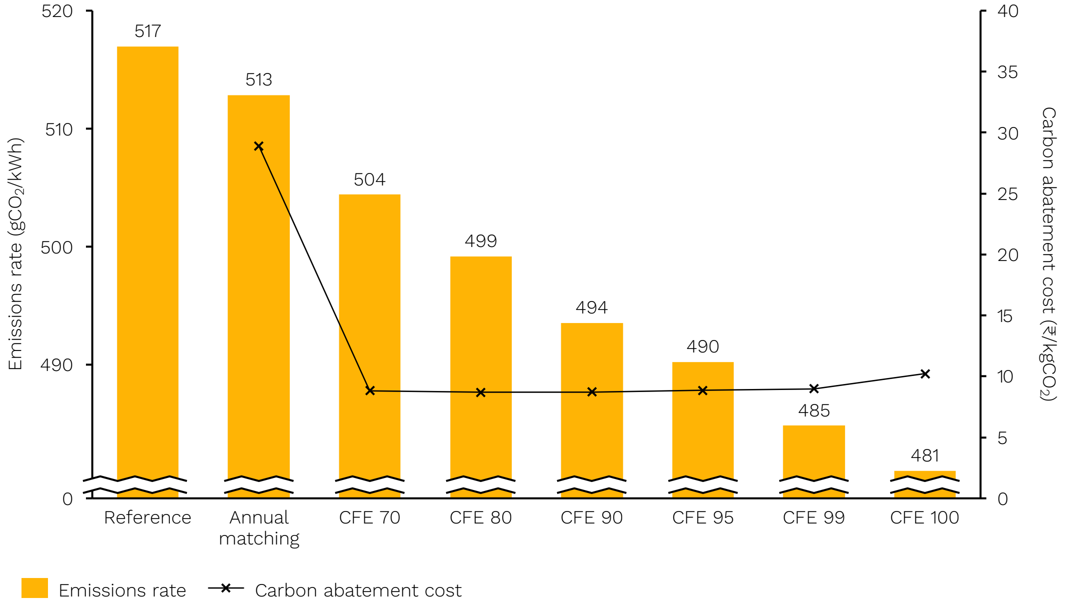




- In most cases, C&I consumer emission rates for hourly matching are lower than annual matching once 80% CFE or above is reached.
- However, this is not always the case. Emissions rate reductions between annual and hourly matching are variable and depends on the grid zone and capacity mix.
- This difference arises from the CFE scoring methodology, which only considers 100% clean electricity to be CFE, and does not differentiate between electricity supplies with an emissions rate greater than zero.
- This could lead to a situation where a C&I consumer ‘A’ has a CFE score of 80% but imports the remaining 20% from coal-fired plants, and C&I consumer ‘B’ has a CFE score of 70% but imports the remaining 30% from a mix of renewables and coal. Consumer ‘B’ may have a lower overall emissions rate but still have a lower CFE score.

Impact on system-wide emissions

Emissions rate of the Indian power system under different clean electricity schemes (gCO_2/kWh), compared to carbon abatement costs for each clean electricity policy (₹/$kgCO_2$)

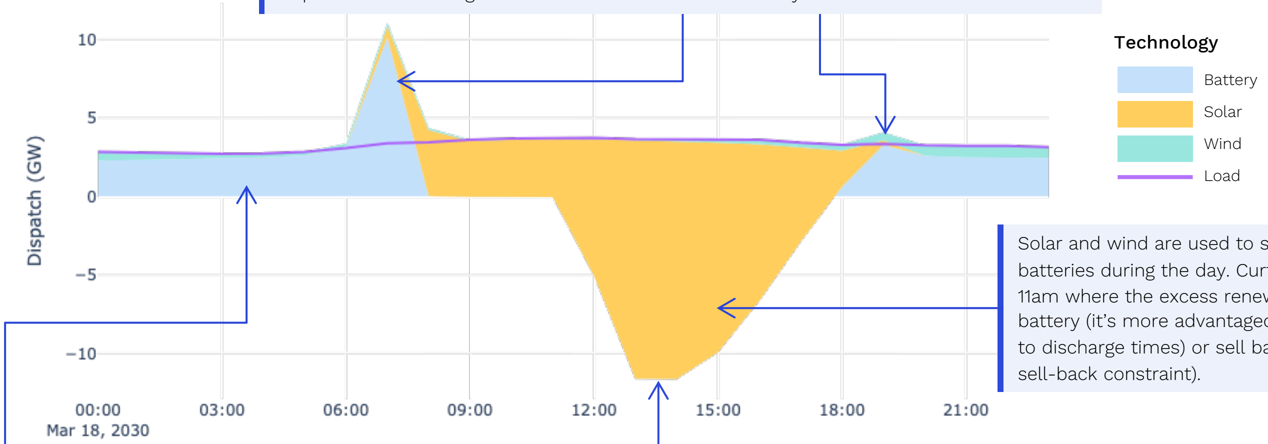


- At a system-wide perspective, hourly matching schemes are much more effective at reducing emissions, even at a score of 70% CFE.
- Annual matching provides very low emissions reductions despite matching 100% of demand with clean generation on paper. Hourly matching means the renewables are used more efficiently and there is real decarbonisation, rather than decarbonisation from a purely accounting point of view.
- A 5% shift of demand as modelled in this study to 100% CFE shows system-wide emissions reduction of 7%. This outsized impact can be attributed to sell-back during times of excess and the well-timed deployment of renewables and battery storage.
- The carbon abatement costs are roughly three times cheaper under hourly matching compared to annual matching. RTC clean electricity supply reduces emissions at a cost of roughly 9-10 ₹/kgCO2, whereas the equivalent cost for annual matching is about 29 ₹/kgCO2. This can be attributed to the 'efficient' use of renewable generation in displacing thermal generation.
- This partly arises from a mismatch in the 'CFE' metric versus emissions intensity. A change of 5% in the CFE may not always mean the same percentage change in emissions.
- These carbon abatement costs also remain relatively static for all levels of CFE tested. Every additional ₹10 invested into hourly matching directly translates into another kilogram of CO2 avoided, with minimal drop-off at higher CFE levels.

A closer look at the delivery of clean power to the C&I consumer [1]

Hourly dispatch behaviour of the CFE PPA generators under 100% CFE conditions, for an indicative day (GW)

Periods of excess solar, onshore and battery storage are sold back to the grid at times of most value - i.e. during early morning and late evening hours, when they can displace expensive fossil fuel generators. This sell-back is limited by the 20% sell-back constraint.



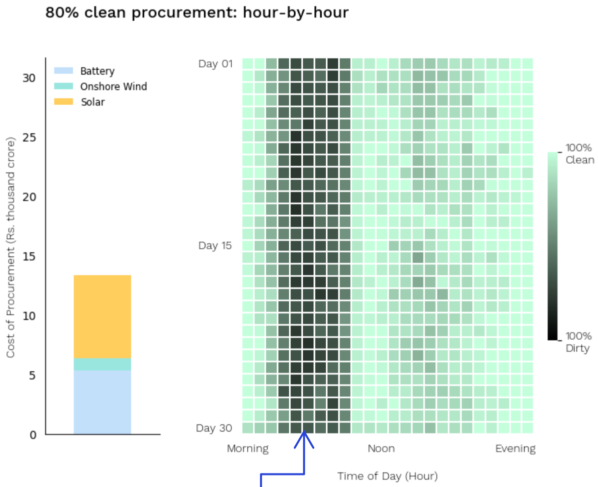
Solar and wind are used to serve the load and charge up batteries during the day. Curtailment occurs during 8am – 11am where the excess renewables cannot charge up the battery (it's more advantageous to charge up later, closer to discharge times) or sell back to the grid (due to the sell-back constraint).

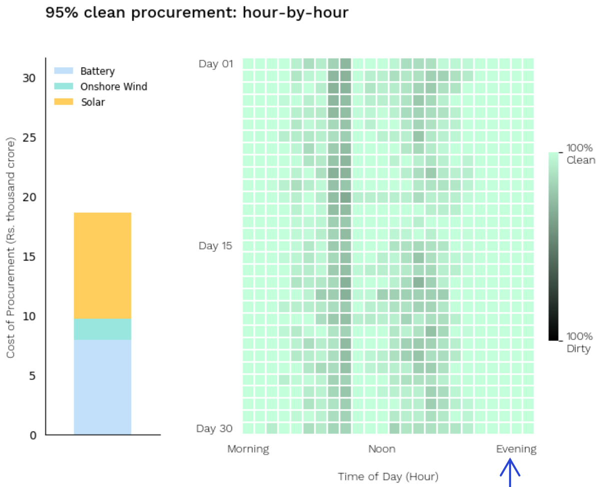
Morning and evening hours are serviced by battery discharge and some onshore wind. Lithium-ion batteries are modelled with 4-hour duration, so overbuilding is needed to ensure supply throughout the evening and the morning.

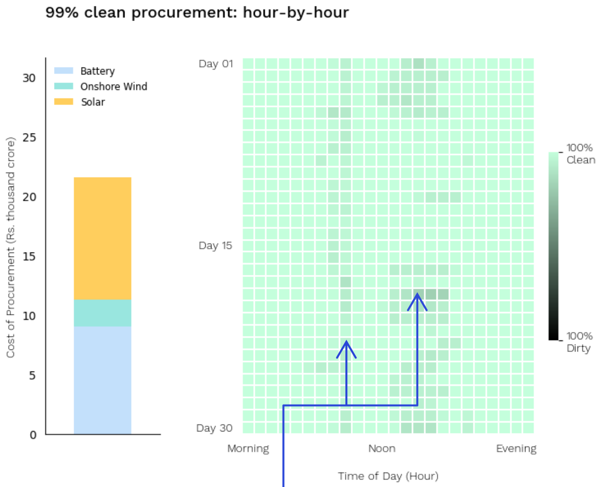
Curtailment occurs here when battery storage units have been fully charged.

A closer look at the delivery of clean power to the C&I consumer [2]

CFE score hour-by-hour for an average month, for India West, under different CFE levels (%), alongside annual procurement cost (Rs. thousand crore)







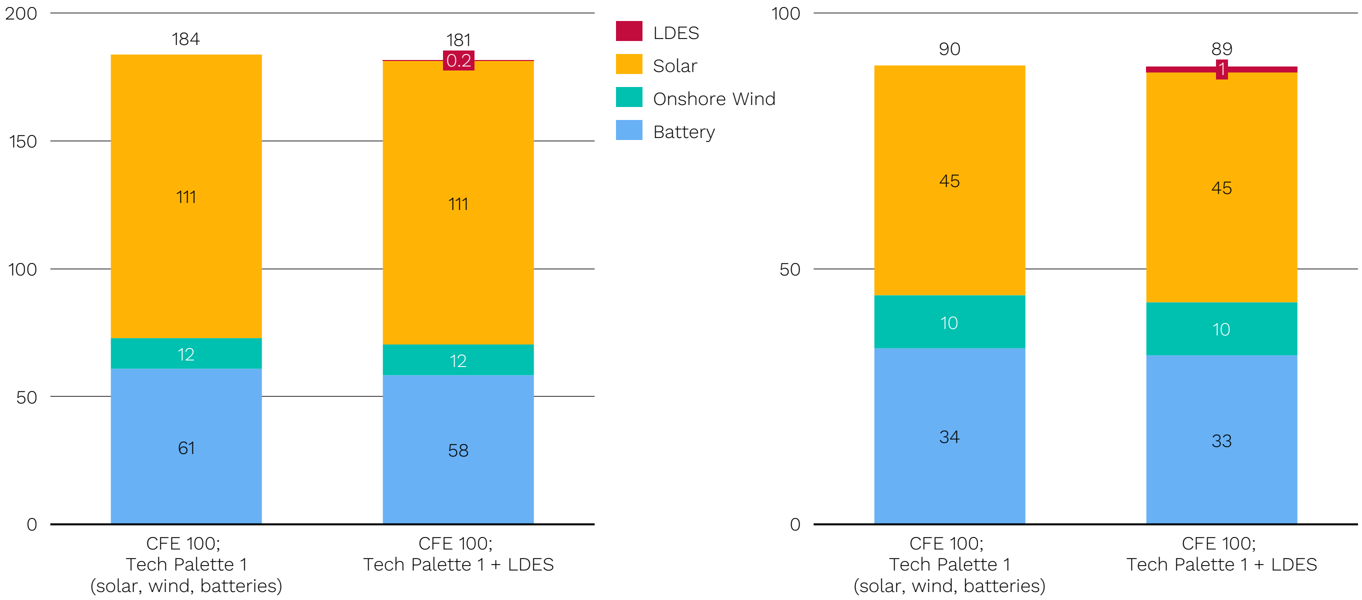
Early morning hours are difficult to decarbonise – there is no solar, and batteries have likely already discharged overnight This picture changes where there is more onshore wind in the mix, such as in INDSO, which decarbonises more evenly throughout the day.

The evening hours are easy to decarbonise – demand is lower compared to peak hours, and batteries are freshly charged from excess solar and onshore wind generation during the day.

From a systems cost perspective, these daytime hours represent the least attractive to fully decarbonise. Instead of switching from expensive coal to cheap renewables, you would be displacing existing cheap renewable generation.

Long duration energy storage is not commercially viable by 2030

Additional capacity required (left, GW) and total costs (right, Rs. thousand crore) when participating C&I consumers in India adopt 100% CFE under different technology palettes



- Long duration energy storage (LDES) only builds at 100% CFE, building 200MW in total across India East and Northeast.
- This 200MW of LDES can displace roughly 2.5GW of regular battery storage, but it does not displace generating technologies. Introducing LDES into the mix reduces annual costs by less than 1%.
- In this study, we have modelled Liquid Air Energy Storage as the specific LDES technology, with a storage capability of 7 days and an overnight capital cost of roughly 6 million USD/MW (50 crore ₹/MW), over ten times the modelled cost of battery storage.
- LDES costs must come down significantly before they can play a large part in CFE portfolios by 2030. However, there are numerous candidates for LDES carriers, including redox flow, hydrogen electrolysers with storage, or compressed air. Hydrogen specifically could see cost reductions under India's National Hydrogen Mission.

Conclusions

Incorporating CFE 24/7 into India's energy transition

Carbon free electricity can bring benefits to both the system and C&I consumers

Supporting policy and clear price signals are needed to further incentivise CFE procurement

01

Targeting 70% CFE for C&I consumers provides multiple benefits for the power sector in 2030.

In many cases, 70% CFE can be achieved at a lower cost to both the C&I consumer and the wider power system, in addition to reducing emissions more effectively compared to annual matching.

For C&I consumers, these CFE PPAs generate long-term price certainty whilst meeting corporate sustainability goals. For the wider power sector, CFE increases the value of homegrown renewables and reduces potentially expensive fuel imports.

02

When C&I consumers participate in CFE, this brings net system benefits over annual matching for both costs and emissions.

As India's grid gets greener and renewables penetration increases, further renewables integration strategies must evolve to provide reliable and clean energy, avoid curtailment and cannibalisation, and continue to provide value to the grid.

Policies that support granular accounting and 24/7 procurement will enable further cost savings to the grid and drive down emissions at a lower abatement cost.

03

Solar and batteries are the backbone of a successful CFE portfolio, with CFE encouraging diverse build-outs compared to annual matching.

Cheap solar power and increasingly lower battery costs means that 100% CFE is technically feasible for a portion of India's demand, albeit with high levels of overbuild and naturally higher costs.

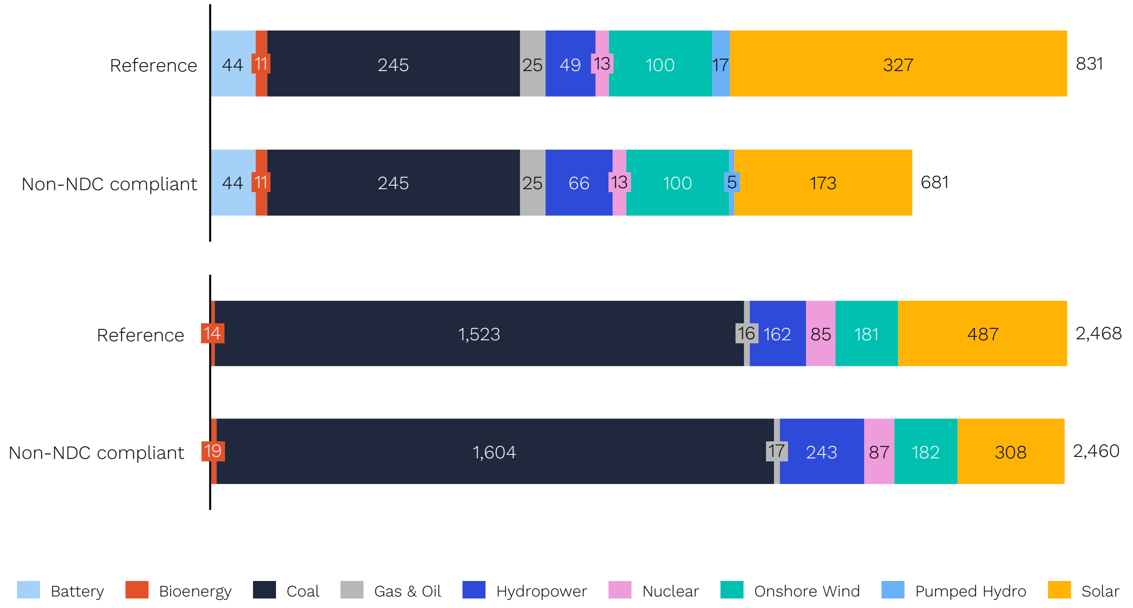
Falling battery prices and other storage vectors could bring 100% CFE closer to economic feasibility. However, our modelling indicates LDES must mature as a technology before this is possible.

Sensitivity analysis

What happens with alternative assumptions?

What happens if India does not meet its NDC targets? [1]

India's 2030 capacity mix (top, GW) and generation* mix (bottom, TWh) when NDC targets are not met

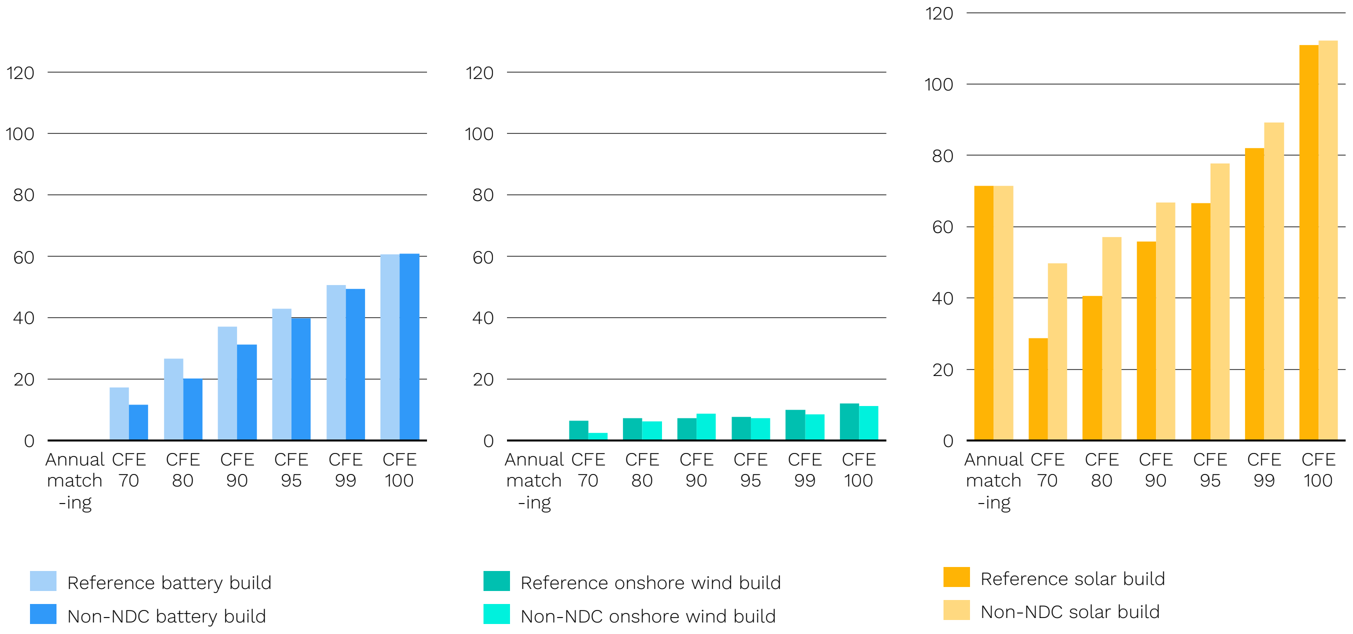


*Storage technologies not shown to avoid double counting. The small differences in generation between scenarios are due to storage losses.

- Under this non-NDC scenario, we don't constrain the model to meet the following targets:
  1. Reducing emissions intensity of the GDP by 40% from 2005 levels
  2. 50% cumulative capacity share from non fossil fuels
  3. 500 GW non fossil fuel capacity (non-NDC target)
- The resulting capacity share shows less buildout of solar and pumped hydro, and more buildout of hydropower. Other plant capacities do not change much because of supply chain constraints.
- The generation share shifts towards coal and hydropower, as generation from solar decreases, alongside pumped hydro usage.

What happens if India does not meet its NDC targets? [2]

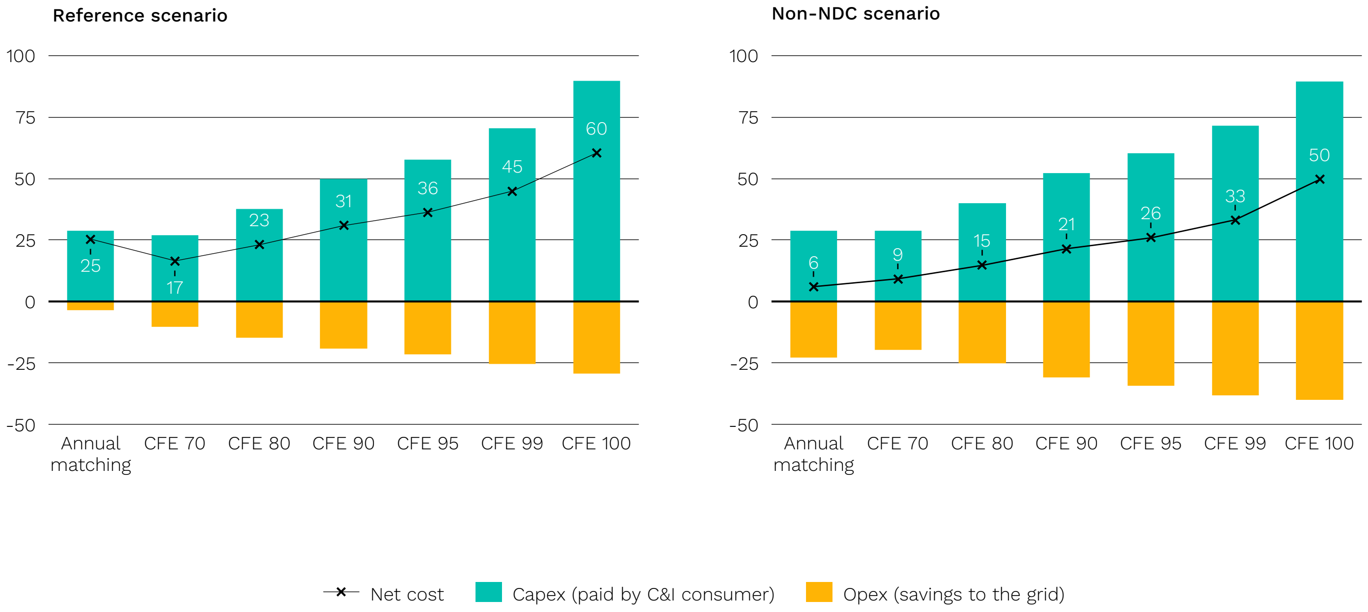
Buildout of CFE capacity nationwide for each technology under the reference scenario and the non-NDC scenario, for different clean electricity matching schemes (GW)



- Generally, not much change is seen in the capacities required for hourly matching.
- At lower CFE levels, more solar and less battery builds. This is likely because the background system is less clean (i.e. has less generation from renewables). Therefore, C&I consumers must build procure more clean generation themselves to achieve the same CFE score.
- This difference reduces as the model approaches CFE 100, when the C&I loads are least reliant on the wider grid.
- The resulting procurement costs remain very similar between these two scenarios, differing by 7% at most in at CFE70, where the non-NDC scenario is more expensive.

What happens if India does not meet its NDC targets? [3]

System cost and benefits of annual and hourly matching schemes under different scenarios (Rs. thousand crore)



- Exploring the system costs impacts shows two contrasting but related findings.
- On one hand, all annual and hourly matching regimes shows greater system benefits in our non-NDC scenario, i.e. they have lower net costs. Lower levels of solar penetration in the wider grid means C&I procured PPA displaces more thermal generation and creates more operational cost savings.
- On the other hand, this also means that annual matching has lower net system costs than 70% CFE – the renewables added to the system are already valuable, even when not paired with battery storage. However, from 80% CFE onwards, savings to the grid operator still exceed annual matching.
- This suggests that from a systems impact perspective, a minimum level of grid greening and renewables penetration must be reached before all of the benefits of hourly matching over annual matching become apparent.

TransitionZero

Annex

Further information, data and assumptions

Assumptions (1/3) – plant information

Assumption	Source
Thermal and hydro plant capacities	Central Electricity Authority - plant level data, aggregated up to grid zone
Renewable plant capacities	Central Electricity Authority and Global Energy Monitor - plant level data, aggregated up to grid zone
Renewable capacity factors	Chu and Hawkes (2020), matched with plant data from Global Energy Monitor to get grid zone level estimates
Non-renewable capacity factors	India Climate & Energy Dashboard
Technology capital costs	CEA and DEA, Indian technology catalogue (2022)
Technology information	CEA and DEA, Indian technology catalogue (2022)
Fuel and variable costs	A combination of: Coal India Limited price notifications, LNG spot prices, IEA reporting, and state level tariff publications
Weighted Average Cost of Capital (WACC)	Assumed to be 10% for all technologies

Assumptions (2/3) - 2030 build options

Assumption	Source
Renewables build constraints	Adhering to historical build limits but allowing some extra flex to meet 2030 NDC and 500GW targets.
Battery build constraints	State level BESS targets are considered as model investment options.
Coal, nuclear and hydro build constraints	Only plants in the known pipeline for completion by 2030, are considered as model investment options. Data from CEA.
Pumped hydro build constraints	Only plants in the known pipeline for completion by 2030, are considered as model investment options. Data from CEA.
Other technology build constraints	No change in capacities of other technologies is assumed.
Demand levels in 2030	Total demand levels as per CEA forecast - ”Report on Optimal Generation Mix 2030”. Demand curves identical to today.
Transmission network build	As per Central Transmission Utility of India Ltd - “Rolling Plan: Interstate transmission system 2028-29”.

Assumptions (3/3) - government targets

Assumption	Source
Emissions targets (NDC)	Reduce GDP emissions intensity by 45% by 2030 compared to 2005 levels
Non-fossil fuel capacity share (NDC)	50% cumulative electric power installed capacity from non-fossil fuels by 2030
Non-fossil fuel absolute capacity	500GW of non-fossil fuel capacity by 2030

Glossary (1/3)

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, the emission-free part of innovative thermal plants, and electricity discharging from storage technologies [after being charged up from generation from the previous categories]
Consumer CFE score	Hourly share of CFE from a consumers' total electricity consumption, resulting from both greenfield and brownfield procurement
DISCOM	Distribution Company

Glossary (2/3)

Term	Definition
Grid CFE score	Hourly share of CFE within all brownfield generation from a single grid zone
Grid zones	The five regional grid zones in India, i.e. India North, India South, India East, India West, and India North-East.
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 CO_2 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

Glossary (3/3)

Term	Definition
Palette	Scenario-specific combination of technologies deemed eligible for CFE status

Data inputs overview

Technology	Overnight capital cost (cr. ₹/MW)	Annual fixed costs (cr. ₹/MW)	Marginal cost (₹/kWh)	Weighted average cost of capital (%)	Annual capacity factor (%)	Efficiency (%)	Lifetime (years)	Emissions factor (tCO_2/MWh)	Sources	Notes
Biomass - bagasse	5.61	0.11	0.10	10	14	35	20	0	a	1
Biomass - other	5.61	0.11	2.45	10	18	35	20	0	a, b	
Coal - subcritical	10.25	0.29	2.59	10	67	36	25	0.316	a, c	2, 5
Coal - supercritical	9.25	0.22	2.33	10	76	40	25	0.316	a, c	2, 5
Coal - ultrasupercritical	9.36	0.22	2.22	10	79	42	25	0.316	a, c	2, 5
Gas turbine - open cycle	5.61	0.20	6.92	10	<1	38	25	0.2	a, d	
Gas turbine - closed cycle	3.90	0.32	10.20	10	7	56	25	0.2	a, d	
Solar - utility scale	3.24	0.03	0.10	10	16	100	28	0	a	3, 6
Onshore wind	6.99	0.07	0.10	10	20	100	30	0	a	3, 6
Nuclear - PHWR	13.00	0.48	0.82	10	75	33	30	0	a	2
Nuclear - LWR	21.11	0.29	0.82	10	75	38	30	0	a	2
Hydro - reservoir	9.26	1.01	0.10	10	39	100	40	0	a	2, 3
Hydro - run of river	11.94	0.49	0.10	10	40	100	40	0	a	2, 3
Pumped hydro	4.28	0.11	0.00	10	n/a	95	40	0	a	
BESS - Li-ion	4.34	0.06	0.00	10	n/a	95	25	0	a	4
Liquid Air Energy Storage	47.16	0.00	0.00	10	n/a	57	25	0	e	

Sources

a. CEA and DEA, Indian technology catalogue (2022).
b. State level tariff analysis used to determine marginal costs.
c. IEA, Projected Costs of Generating Electricity, (2020).
d. Analysis of LNG spot prices used to determine marginal costs.
e. She, Xiaohui, et al. "Liquid air energy storage–A critical review." Renewable and Sustainable Energy Reviews 208 (2025): 114986.

Notes

All prices are converted to 2022 real prices, for assets commissioning/operating in 2030.

1. Bagasse plants are assumed captive and therefore have near-zero marginal cost to ensure dispatch.
2. Initial lifetimes shown, but these plants typically undergo lifetime extensions.
3. Near-zero marginal costs assumed for renewable technologies.
4. This lifetime is likely too high and will be revised down to 20 years. The expected impact on annualised battery costs is 6%.
5. Emissions factors assume 5% biomass co-firing as per government policy.
6. These show national average capacity factors. Capacity factors of individual sites can reach much higher values.

Demand inputs overview

Node	Total annual demand (TWh)	Peak demand (GW)	Participating C&I demand (%)
India East	303	47	5
India Northeast	32	6	5
India North	760	132	5
India South	588	91	5
India West	765	111	5

Sources

a. CEA, Report on Optimal Generation Mix 2030 (2023).
b. CTU, Rolling Plan: Interstate transmission system 2028-29 (2024).
c. State-wise hourly demand met data from POSOCO, obtained via ICED Climate and Energy Dashboard.

Decision record

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