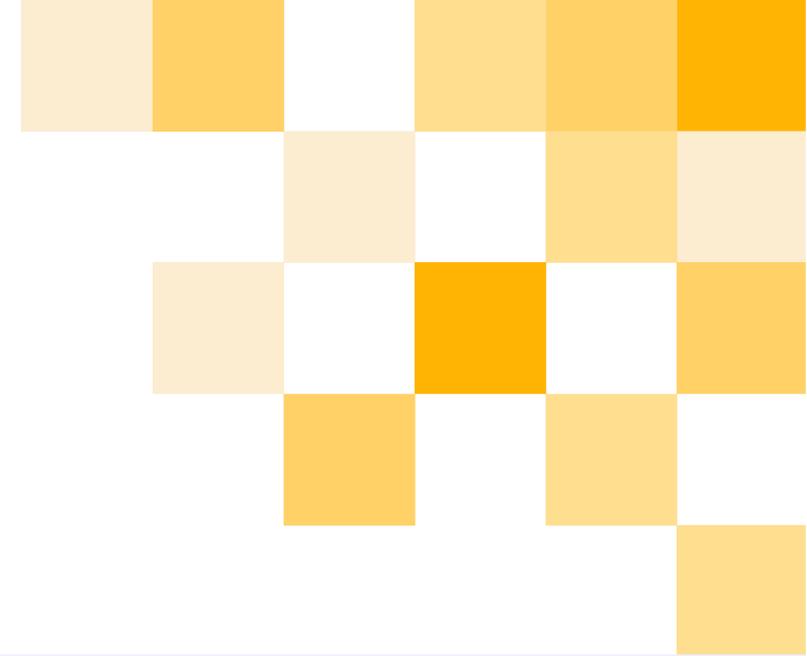




# Modelling 24/7 Carbon Free Electricity (CFE) in Asia

India – further analysis



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Our methodological approach is focused on the assessment of system-level costs and benefits of 24/7 Carbon-Free Electricity (CFE) procurement in Japan, India, Singapore, Taiwan, and Malaysia. It draws on a robust body of literature and cutting-edge modelling tools.

## TU Berlin and affiliated researchers:

- Riepin, I., & Brown, T. (2022). System-level impacts of 24/7 carbon-free electricity procurement in Europe. Zenodo. <https://doi.org/10.5281/zenodo.7180098>
- Riepin, I., & Brown, T. (2023). The value of space-time load-shifting flexibility for 24/7 carbon-free electricity procurement. Zenodo. <https://doi.org/10.5281/zenodo.8185850>

## Princeton University (ZERO Lab):

- Xu, Q., Manocha, A., Patankar, N., and Jenkins, J.D., System-level Impacts of 24/7 Carbon-free Electricity Procurement, Zero-carbon Energy Systems Research and Optimization Laboratory, Princeton University, Princeton, NJ, 16 November 2021.
- Xu, Q., & Jenkins, J. D. (2022). Electricity System and Market Impacts of Time-based Attribute Trading and 24/7 Carbon-free Electricity Procurement. Zenodo. <https://doi.org/10.5281/zenodo.7082212>

## International Energy Agency (IEA):

- *Regional insights and sectoral analyses*
- IEA (2022), *Advancing Decarbonisation through Clean Electricity Procurement*, IEA, Paris. <https://www.iea.org/reports/advancing-decarbonisation-through-clean-electricity-procurement>

Our in-house modelling leverages [PyPSA \(Python for Power System Analysis\)](https://www.pypsa.org/), an open-source framework for simulating and optimizing energy systems. This platform enables high-resolution, hourly modelling of decarbonised power systems, adapted for our country-specific analyses. We are grateful to all contributors in the open modelling community, whose tools and insights strengthen the analytical foundation for achieving global CFE goals.

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Contribution to and review of this study does not imply an endorsement by either the individual or their organisation. Any mistakes are our own.

# Executive summary



## 24/7 CFE: Looking beyond solar, wind and storage...

- Previous analysis by TransitionZero examined how carbon-free electricity round-the-clock (24/7 CFE) can be implemented in India, and the resulting impact on system costs, emissions, capacity buildout, as well as considerations for participating C&I consumers.
- However, the discussion focused on solar, wind and storage, and did not look at the potential contribution of innovative thermal technologies. What role can generators such as hydrogen-fired turbines, co-firing, or gas with CCS play in reaching 100% carbon-free electricity (CFE) around the clock?
- In this extension to our analysis, we look specifically at the cost and logistical impacts of hydrogen-fired turbines on achieving 24/7 CFE. We examine both mono-firing and co-firing with natural gas and set this against the context of the wider Indian power sector.



24/7 CFE in India

## Hydrogen turbines makes 100% CFE easier – but with several caveats

Below 100% CFE, hydrogen turbines are not cost-effective, and deployment is contingent on wider policy ambitions



With the inclusion of hydrogen turbines, reaching 100% CFE becomes dramatically easier, reducing both costs and capacity by 19% compared to only using solar, wind and battery storage.

The high fuel costs of green hydrogen is offset by the value of clean dispatchable power in decarbonising the most difficult hours of the year.



Below 100% CFE, there is no benefit to including hydrogen turbines compared to conventional renewable and storage technologies.

The combined factors of abundant renewable resources and the low cost of these existing technologies means that up to 99% CFE is still cheaper using only solar, wind and storage.



The feasibility of hydrogen-to-power (and other innovative thermal technologies) in India is unclear.

The National Green Hydrogen Mission sets the scene for a potentially vibrant hydrogen economy. However, it remains to be seen what proportion of this economy will go towards electricity production.

## 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 <sup>1</sup>	✗	✓	✓
H <sub>2</sub> mono- and co-firing	✗	✗	✓
Gas with CCS	✗	✗	✗

<sup>1</sup> Liquid air storage.

## 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.
- **For India we now consider the impact of technology palette 3 (innovative thermal) technologies, specifically hydrogen turbines. We test both 100% hydrogen-fired turbines (CCGT) and turbines with a 50/50 hydrogen/natural gas blend.**
- Due to a variety of cost, technical, and policy reasons, we focus on hydrogen turbines over other innovative thermal technologies, such as gas CCS, ammonia co-firing, hydrogen cell technologies, and advanced nuclear.

## Estimating the cost and technical parameters of hydrogen turbines

We use a range of research and comparisons to regular gas CCGTs to arrive at an estimated cost and operating profile

### Capital costs

We apply a **1.4x multiplier** to capital and fixed operational costs of regular gas CCGTs to estimate the cost of hydrogen-fired CCGTs.

This represents investment into novel turbine components and accessories designed specifically to handle hydrogen gases.

This multiplier is derived from a combination of academic, government, and industry research (see data and methodology).

### Fuel costs

We assume that only **green** hydrogen is used, keeping with the intent of carbon-free electricity.

Green hydrogen price estimates for 2030 in India vary greatly, ranging between 2.4 – 4.5 US\$/kg in our research. In our study we assume:

- **4.0 US\$/kg** (330 ₹/kg) as a conservative base estimate, close to the upper estimate of 4.5 US\$/kg above.
- **2.5 US\$/kg** (207 ₹/kg) as an optimistic sensitivity analysis.

### Operating characteristics

Other operating characteristics such as efficiency and lifetime are assumed to be the same as unbated gas turbines.

The surrounding infrastructure to support the wider hydrogen economy including storage, transport, etc. is assumed to already exist as part of the National Green Hydrogen Mission. Enabling costs are implicitly included in the modelled hydrogen cost in US\$/kg.

# Detailed results

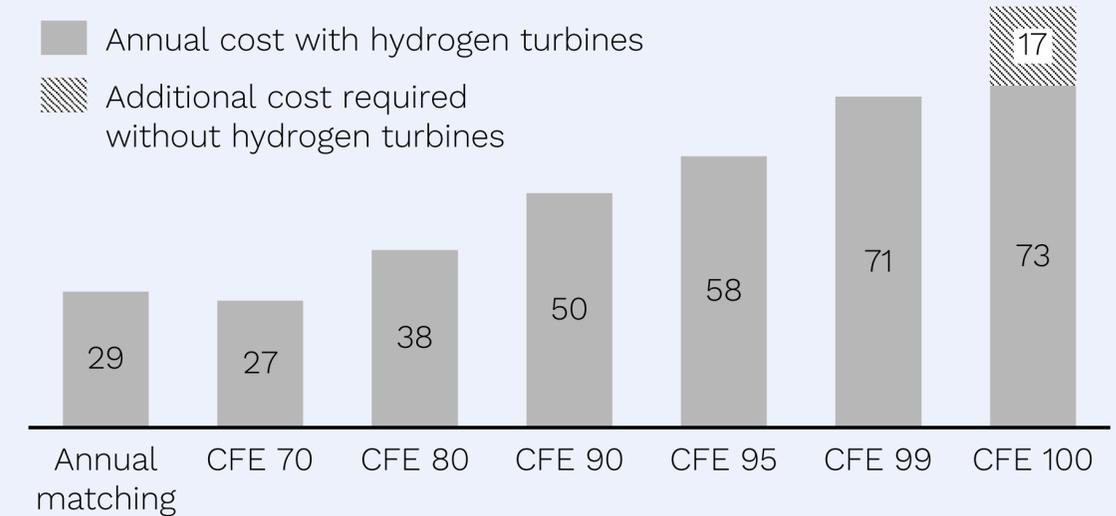


## Hydrogen turbines reduce C&I costs at CFE 100

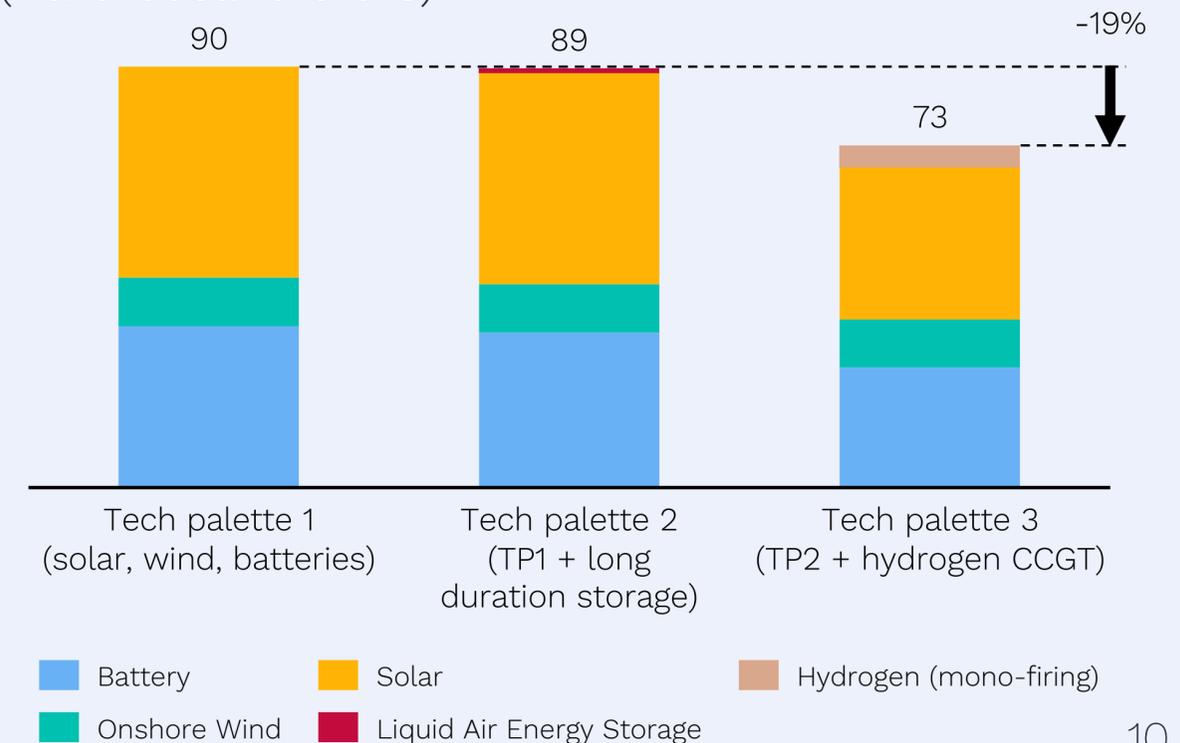
Although expensive, the dispatchable nature of hydrogen is valuable when aiming for 100% CFE

- Introducing hydrogen turbines to the mix allows a 19% annual cost reduction at 100% CFE compared to technology palette 1.** The high operational costs of hydrogen fired turbines is offset by its dispatchable nature. This means that C&I consumers can save costs by reducing the overbuilding of renewables and storage required. Nationwide, this leads to over ₹17 thousand crore (US\$2 billion) of savings for participating C&I consumers (equal to 5% of nationwide demand), when compared to using solar, wind and batteries alone.
- However, hydrogen turbines are only cost effective at 100% CFE.** At lower CFE targets, it is still cheaper to invest heavily in renewables and storage. Only the last 1% of hours benefit and see cost reductions by introducing clean dispatchable generation.
- Mono-firing hydrogen turbines are more cost-effective than co-firing hydrogen turbines, when considering matching constraints.** In our model, we tested a 50/50 hydrogen-methane blend, which should reduce fuel costs by blending in cheaper methane gas. However, this means that the total capacity of the turbine must double in order to provide the same amount of ‘carbon-free electricity’. From a cost perspective, the higher operational costs, but lower equivalent capital costs, of mono-firing hydrogen turbines are preferred. This opens the question to future research looking at whether CCGTs or peaking-style OCGTs are better suited for CFE.

Annual capital and operational costs to C&I consumers in 2030, with and without hydrogen turbines (Rs. thousand crore)



Annual capital and operational costs by technology at CFE 100 across technology palettes (Rs. thousand crore)



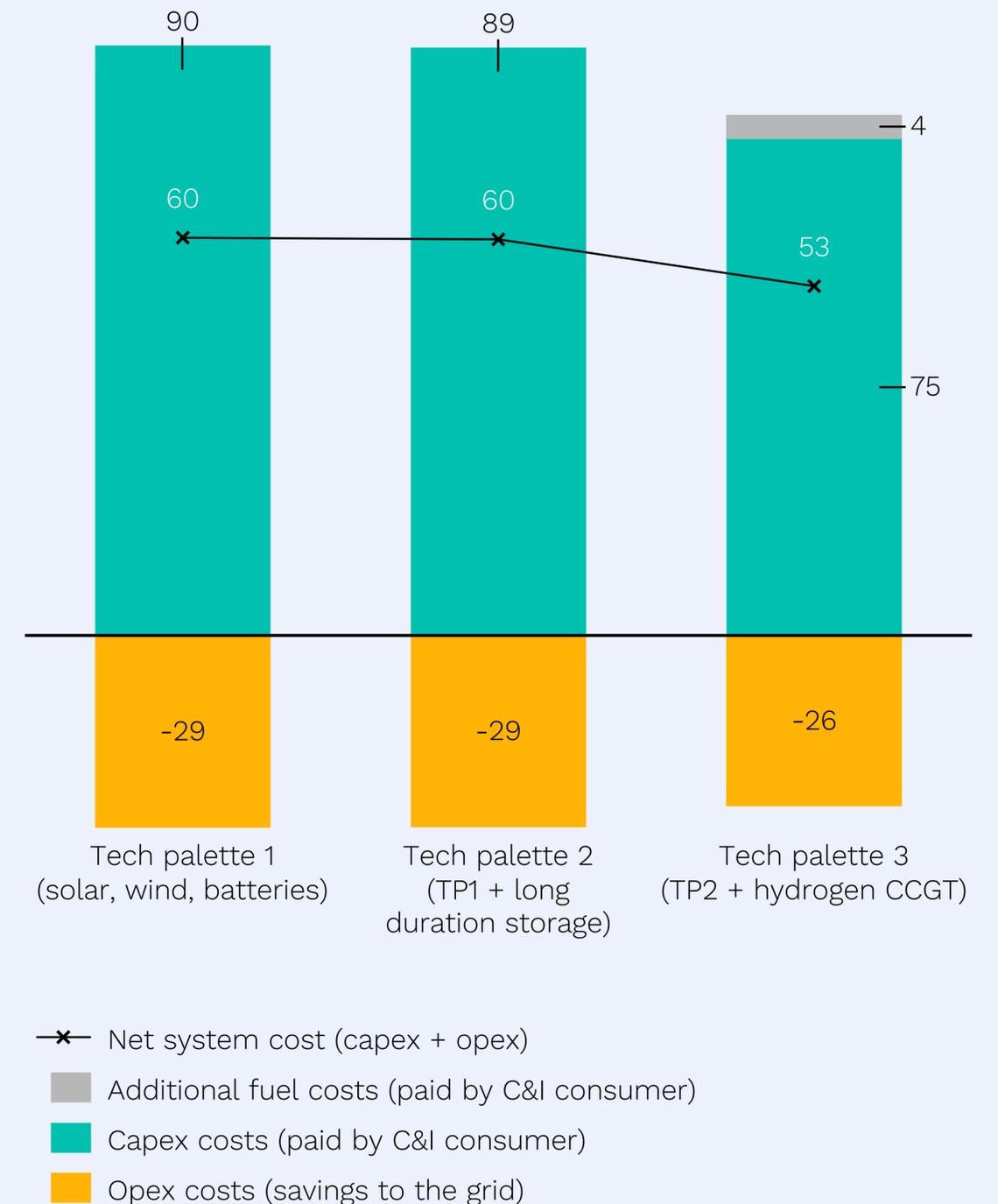
## Cost savings pass through to the wider system

Operational cost savings are reduced under TP3 compared to other tech palettes, but net system savings are still seen through capex reductions

- 1. Sell-back, and operational cost savings on the main grid are slightly reduced.** Fewer renewables are contracted and built by C&I consumers - therefore there is less excess renewable generation sold back to the grid and displacing fossil fuels. Clean generation from hydrogen-fired turbines is used exclusively for C&I consumers, as it's not cost-effective in the main grid where there is no clean energy matching requirement.
- 2. However, lower capital costs mean net system costs are still smaller compared to other technology palettes at CFE100.** The capital cost savings more than offset the reduction in operational cost savings. Technology palette 3 can save ₹7 thousand crore to the wider grid (US\$ 0.9 billion) in comparison to technology palette 1, a 12% reduction in system costs. Note that C&I consumers now also pay an additional fuel cost from the hydrogen turbines, as opposed to mostly capital costs in tech palettes 1 and 2.
- 3. Modelling shows hydrogen turbines operate at a capacity factor of 9%.** This indicates that the best way to operate these turbines is not as a baseload generator. Instead, they are better used to fill those hours in the year where there is low solar/wind generation for extended periods of time. The capacity factor (and total capacity built) may therefore be very sensitive to the assumed weather behaviour. Further analysis is needed to reconcile operating regimes that are beneficial for the system, but also for the asset owner/investor.<sup>1</sup>

## System cost reduces between palettes

Comparative impact on total annual system costs between technology palettes at CFE 100 (Rs. thousand crore)

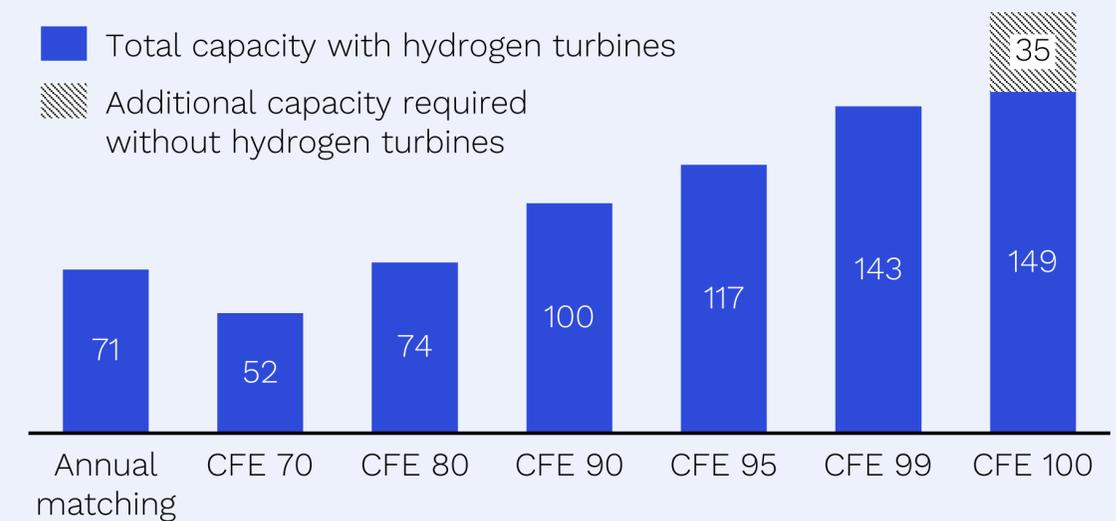


## Total capacity required at CFE 100 is also reduced

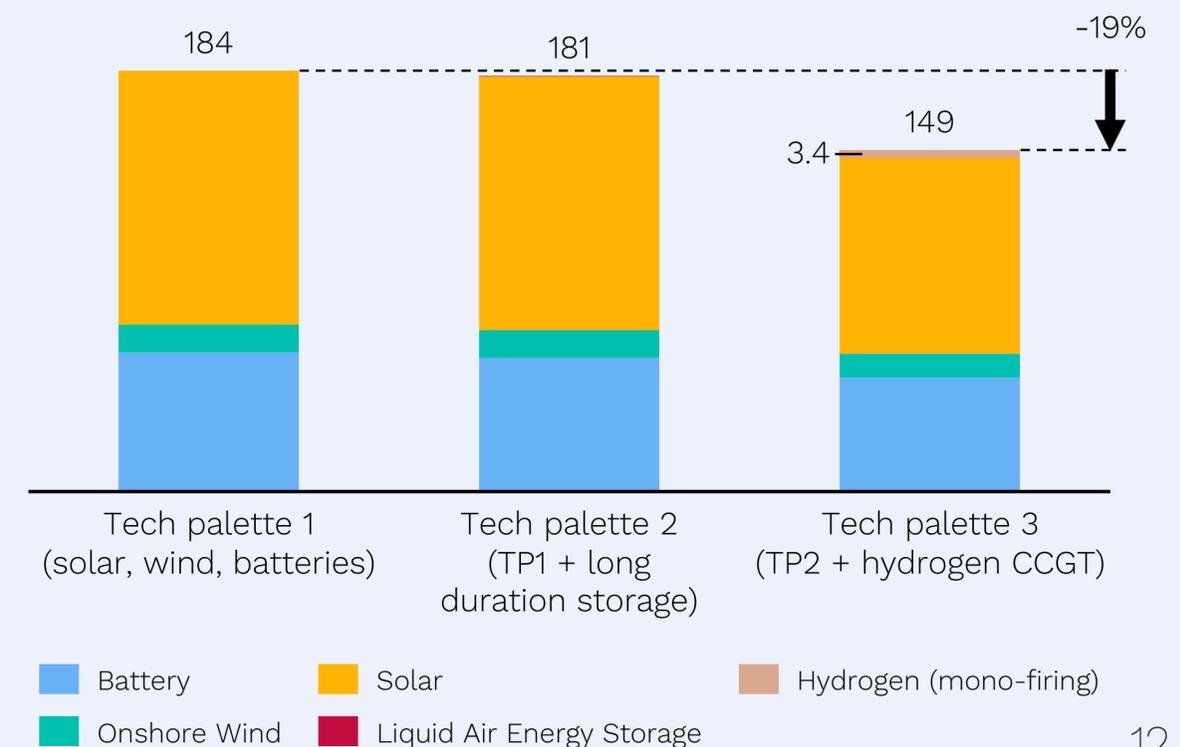
Building hydrogen turbines dramatically reduces the solar and battery build required for C&I consumers to meet 100% CFE

- 3.4GW of hydrogen-fired CCGTs can displace 35GW of solar and batteries.** Without clean dispatchable generation, reaching true 24/7 carbon-free electricity is only achievable through overbuilding solar, wind and batteries to about 10x peak demand. With hydrogen CCGTs, this overbuilding ratio drops to about 8x peak demand, a 19% reduction in total capacity required. This means that hydrogen turbines displaces roughly 10 times its own capacity in renewables and storage.
- By including hydrogen turbines, the jump from CFE90 to CFE100 now only requires 50% more buildout.** Under technology palette 1, decarbonising the last 10% of hours for a C&I consumer came at a steep cost and a doubling of contracted generating capacity. Here, hydrogen fired turbines show the potential of innovative thermal technologies in decarbonising the 1% most carbon-intensive hours.
- Hydrogen turbines remove the need for long duration storage.** At 100% CFE, long duration storage is fully replaced by hydrogen turbines. The modelling suggests that it is more cost effective to invest in clean dispatchable technologies rather than long duration storage to overcome the intermittency of renewables. However, this analysis is extremely sensitive to future cost reductions of these uncertain technologies and the wider hydrogen economy.

Additional CFE capacity required nationwide in 2030, with and without hydrogen turbines (GW)



Additional CFE capacity by technology at CFE100 across technology palettes (GW)



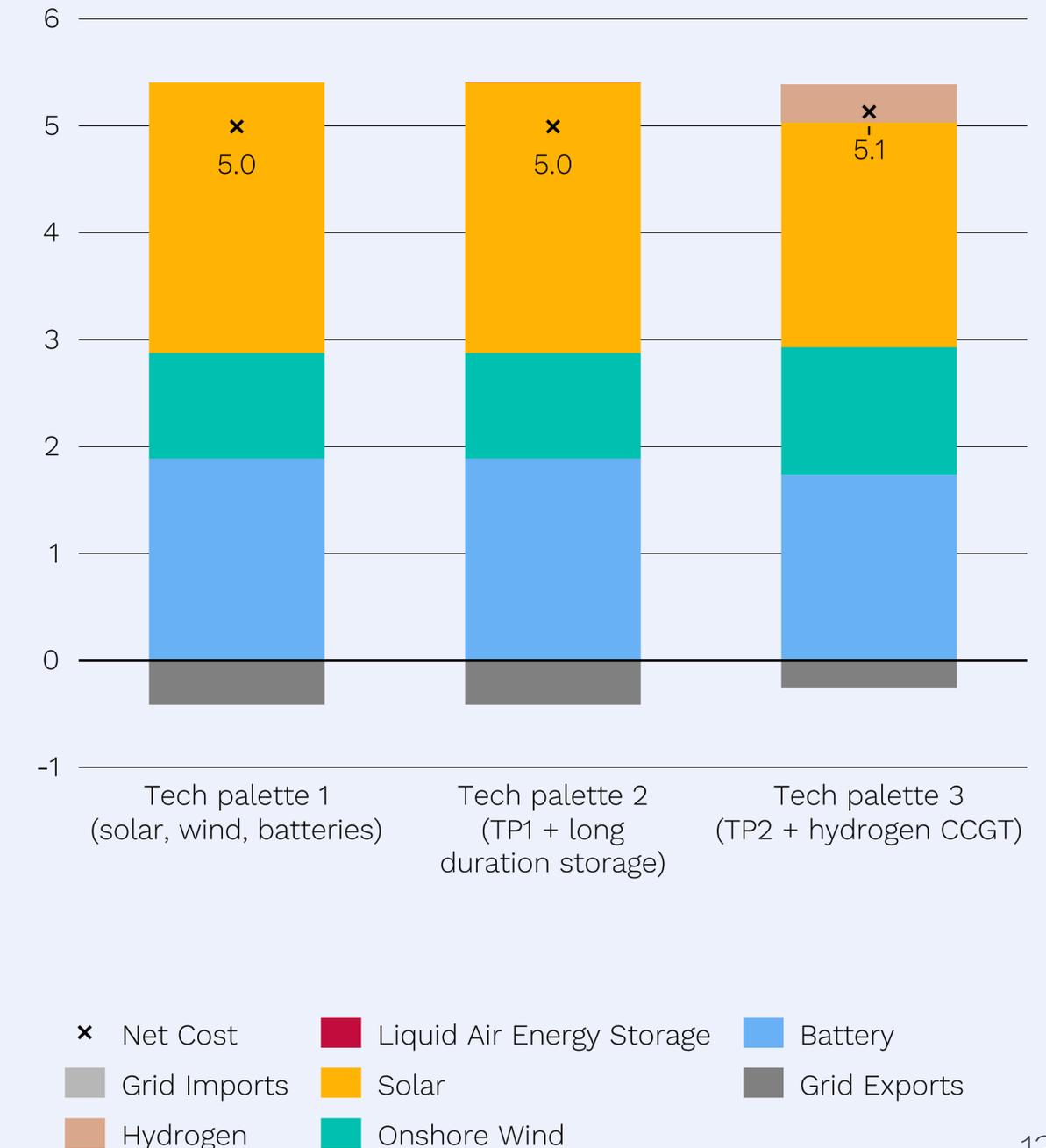
## Unit costs increase slightly with hydrogen turbines

There are reduced opportunities to sell back and gain export revenue

- 1. Total capital and operational costs per kWh are lower under technology palette 3.**  
We have shown that total costs are reduced at CFE100 under technology palette 3, and this is also true on a unit cost basis. When considering the value of their dispatchable power, hydrogen turbines are more valuable in meeting CFE matching regimes.
- 2. However, export revenue also decreases, leading to an overall increase in unit cost.**  
The hydrogen generation displaces generation from solar and wind, including excess generation from these technologies. Typically, excess renewable generation (that cannot be stored or otherwise used) could be sold back to the grid by the PPA manager or the C&I consumer. Reduced excess renewables generation means reduced revenue, leading to a higher unit cost. It is not economical to sell electricity generated from hydrogen, given its high marginal cost.
- 3. This trend holds true across grid regions.** Here we look specifically at the India South grid region, but the general trend is common across other grid regions. It is important to note that regulatory policies will vary between states, which will affect sell-back tariffs and resulting export revenue for C&I consumers.

## Hydrogen slightly impacts unit costs

Comparative unit cost between technology palettes; CFE100 for participating C&I consumers in India South (₹/kWh)



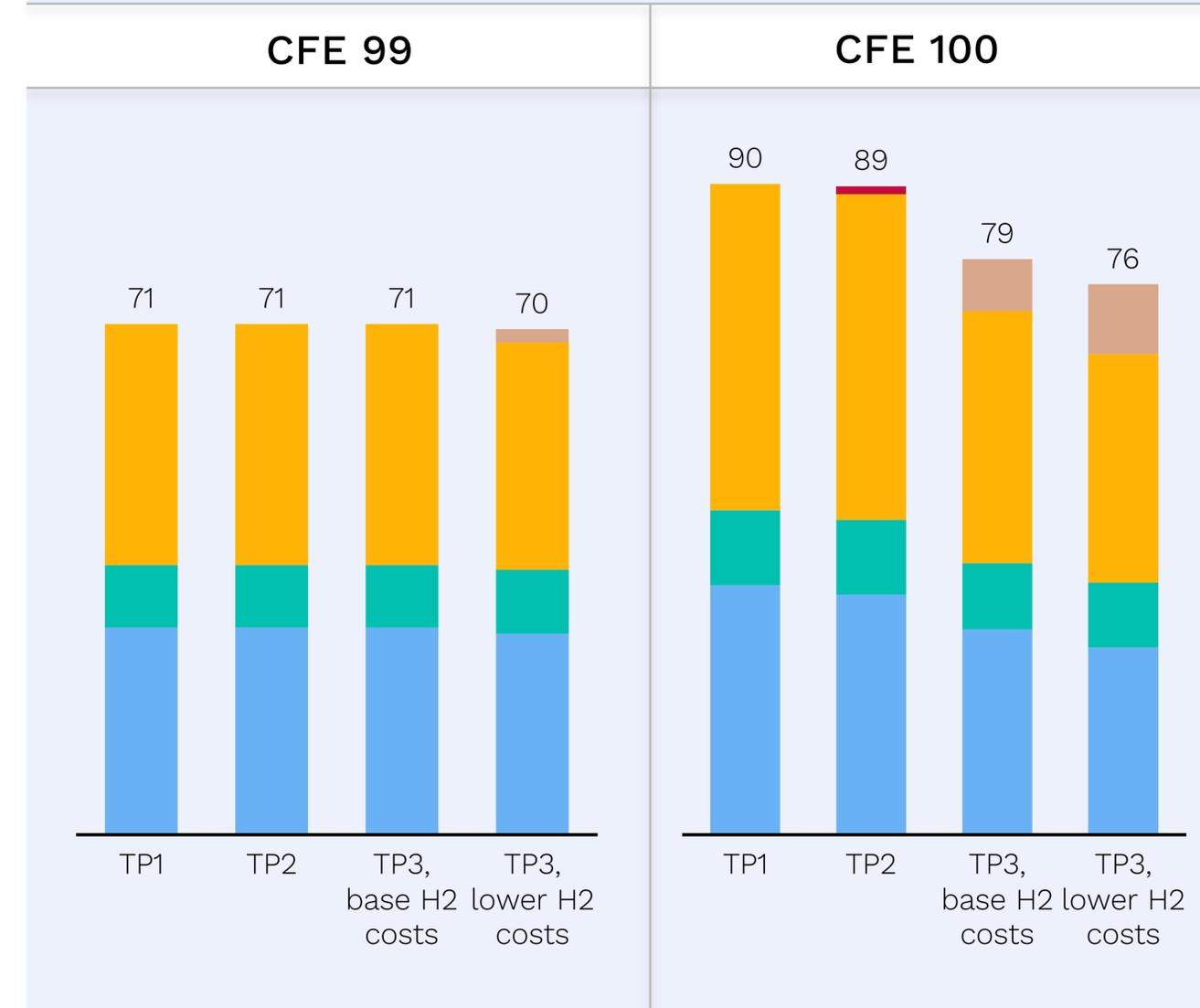
## What happens when hydrogen is cheaper?

We reduce the green hydrogen price from 4 USD/kg to 2.5 USD/kg

- 1. Hydrogen turbines become viable at 99% CFE.** Lower hydrogen costs of 2.5 US\$/kg (207 ₹/kg) means that hydrogen turbines become cost efficient not just at 100% CFE, but also at 99% CFE. Total annual costs at 99% CFE can be reduced by 1.3% compared to our base scenario where hydrogen costs 4 US\$/kg. At 100% CFE, this cost reduction is 4.3% compared to our base hydrogen costs.
- 2. However, this assumes a very optimistic cost for hydrogen.** A hydrogen cost of 2.5 US\$/kg (207 ₹/kg) is on the lower end of current research estimates, and puts the marginal cost of hydrogen-fired turbines only 50% higher than natural gas fired turbines. This represents a very optimistic cost reduction pathway – and yet we still only see its effects at 99% CFE and higher. Capital cost reductions are likely also needed to incentivise further use of hydrogen in CFE matching regimes.
- 3. Conventional renewable and storage technologies are still dominant.** Current cost trajectories for solar and batteries means that on an economic basis, it is difficult for innovative thermal technologies to compete without additional support. For the majority of C&I consumers looking to start hourly matching, they should turn to solar, wind, and battery storage as reliable, cheap, and well understood technologies. The current market and tender landscape can serve these customers well. Only consumers looking to fully decarbonise should start to seriously consider these innovative thermal technologies.

## (Small) effects now seen at 99% CFE

Total annual costs for participating C&I consumers, under CFE99 and CFE100, between technology palettes (Rs. thousand crore)



## Context within the wider economy and power sector

The National Green Hydrogen Mission (NGHM) could be a key enabler of hydrogen turbines for CFE, but the outlook is uncertain

- 1. The NGHM aims to incentivise both the supply and demand of green hydrogen.**  
The NGHM provides a useful background to consider the feasibility of innovative thermal generators, specifically, hydrogen-fired turbines. The NHGM aims to support both domestic supply industries, and position India as a key exporter of green hydrogen.
- 2. C&I consumers would use only 2% of the NGHM’s planned annual green hydrogen production.** Our modelling shows that at 100% CFE, participating C&I consumers (5% of national demand), would consume around 120 thousand tons of hydrogen a year – equivalent to 2% of the planned annual production estimated by the NGHM.
- 3. However, the role of hydrogen-to-power in the NGHM is unclear.** 99% of current grey hydrogen demand in India is for petroleum refining and ammonia manufacturing for fertilisers. It is likely that future domestic supply will be for these same sectors, with projects announced for industry and manufacturing (steel, cement, aluminium), and transport (hydrogen fuel cells). Hydrogen-to-power projects remain in the minority.
- 4. Only one hydrogen-fired plant has been announced so far under the NHGM.** NTPC and GE Gas Power signed a memorandum of understanding (in 2022) to demonstrate the feasibility of co-firing a hydrogen/natural gas blend at NTPC’s Kawas power plant (645 MW), starting with a 5% hydrogen share. GE states that its current E-class turbines can burn a 100% hydrogen blend, pending modification of turbine accessories.

## Overview of the NGHM by 2030



**5 million metric tons**

Annual planned production of green hydrogen under the NHGM



**₹8 lakh crore**

Planned investment into the NGHM



**125 GW**

Additional renewable capacity to support hydrogen production under the NGHM



**2%**

Our modelled CFE consumption of green hydrogen as a percentage of NHGM’s anticipated supply

## Hydrogen turbine data inputs overview

Technology	Value <sup>a</sup>	Derivation	Sources
Overnight capital cost (cr. ₹/MW)	5.45	1.4x multiplier (multiple sources) applied to unabated gas CCGT	1, 2, 3, 4
Annual fixed costs (cr. ₹/MW/year)	0.45	1.4x multiplier (multiple sources) applied to unabated gas CCGT	1, 2, 3, 4
Fuel cost (US\$/kg)	4.0/2.5 <sup>b</sup>	Desk research from multiple sources	5, 6, 7, 8
Marginal cost, mono-firing (₹/kWh)	16.8/10.5 <sup>b</sup>	Desk research from multiple sources	5, 6, 7, 8
Marginal cost, co-firing (₹/kWh)	11.9	Desk research from multiple sources, Asia LNG spot price	5, 6, 7, 8
Weighted average cost of capital (%)	10	Cross-cutting assumption	
Efficiency (%)	56	Assumed identical to unabated gas CCGT	1
Lifetime (years)	25	Assumed identical to unabated gas CCGT	1
Emissions factor (tCO <sub>2</sub> /MWh)	0	Zero-emission hydrogen fuel when mono-firing	

<sup>a</sup> All prices in 2022₹ (INR)

<sup>b</sup> Sensitivity of 2.5 USD/kg also tested

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## Attribution

To cite this document and the larger body of CFE work from TransitionZero, use the following:

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The modelling in this report is based on TransitionZero's country-level 24/7 CFE framework, built using the [PyPSA \(Python for Power System Analysis\) platform](#). The model and methodology will be released under the AGPL-3.0 open-source license in September 2025. This license requires that any public use or adaptation of the model be shared under the same terms. Documentation and data files can be downloaded at: [transitionzero.org/cfe](https://transitionzero.org/cfe).