TransitionZero

System-level impacts of 24/7 Carbon-Free Electricity (CFE)

Results for Singapore 🇸🇬

October 2025

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Additional contributors

We gratefully acknowledge the contributions of colleagues across TransitionZero — both current and former — who supported this work through communications, analysis, modelling infrastructure, and operational coordination. These include Alice Apsey, Ollie Bell, Duncan Byrne, Khandekar Mahammad Galib, Matthew Gray, Michael Guzzardi, Tim Haines, Anna Hartley, John Heal, Simone Huber, Thomas Kouroughli, Alex Luta, Aman Majid, Grace Mitchell, Irfan Mohamed, Joe O'Connor, Sabina Parvu, Abhishek Shivakumar, Stephanie Stevenson, Isabella Söldner-Rembold, Thu Vu, Dan Welsby, and Joel Yap.

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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, including:

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.* www.iea.org/reports/advancing-decarbonisation-through-clean-electricity-procurement

Our in-house modelling leverages PyPSA (Python for Power System Analysis), 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.

We thank the reviewers who provided valuable feedback and insights during the development of this work: Dr Aniq Ahsan (MOYA Analytics), Peerapat Vithayasichareon and Yinglun Teng (International Energy Agency, Bogi Hoigaard (Carbon Trust) and Dr. Victor Nian (Centre for Strategic Energy and Resources). We also extend our sincere thanks to those reviewers who chose to remain anonymous but whose insights were invaluable in shaping the final report.

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

Table of Contents

Matthew Gray
Co-founder & CEO
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Foreword

Singapore’s updated climate targets, outlined in its Second Nationally Determined Contribution submitted in February 2025, commit the country to reducing emissions to 45–50 $MtCO_2e$ by 2035. This marks a significant evolution from its earlier pledge to peak emissions before 2030 and achieve net zero by 2050. Together, these targets signal a decisive shift in how the city-state produces, consumes and procures electricity. As a highly urbanised and trade-dependent economy with limited domestic renewable resources, Singapore’s energy transition is shaped by the twin imperatives of energy security and system-level decarbonisation.

Central to this effort is the growing role of corporate clean energy procurement and the emergence of round-the-clock clean electricity — also known as 24/7 carbon-free energy (24/7 CFE). As commercial and industrial (C&I) consumers look to align with the upcoming revision of the Greenhouse Gas Protocol (GHGP) and make verifiable progress toward net zero, the key questions they face are: what is 24/7 CFE, and can it be achieved for Singapore’s power system?

24/7 CFE means matching each hour of electricity consumption with generation from carbon-free sources. This is a step beyond conventional annual matching, where companies buy renewable energy certificates without regard to when clean power is generated. For Singapore’s manufacturing, logistics, and financial sectors — whose loads are often steady and continuous — hourly matching ensures emissions reductions are real, verifiable, and grid-relevant. From a system perspective, hourly matching also aligns with core principles of power system planning: ensuring demand is met in real time and at the lowest possible system cost.

Our analysis shows that for Singapore — an Alternative Energy Disadvantaged economy — 24/7 CFE is not just a corporate climate tool. It is a complementary mechanism that reduces system fuel costs, supports battery storage deployment, and delivers clean energy outcomes without increasing overall system costs at moderate targets. Electricity imports will also play a vital role in enabling hourly decarbonisation, helping to overcome domestic resource constraints while maintaining system reliability.

We hope this analysis helps Singaporean policymakers, planners, and corporate stakeholders better understand the role that 24/7 CFE can play in accelerating clean procurement, lowering emissions, and building a more flexible and cost-effective power system — one that is not only ready for 2030, but resilient far beyond it.

About TransitionZero

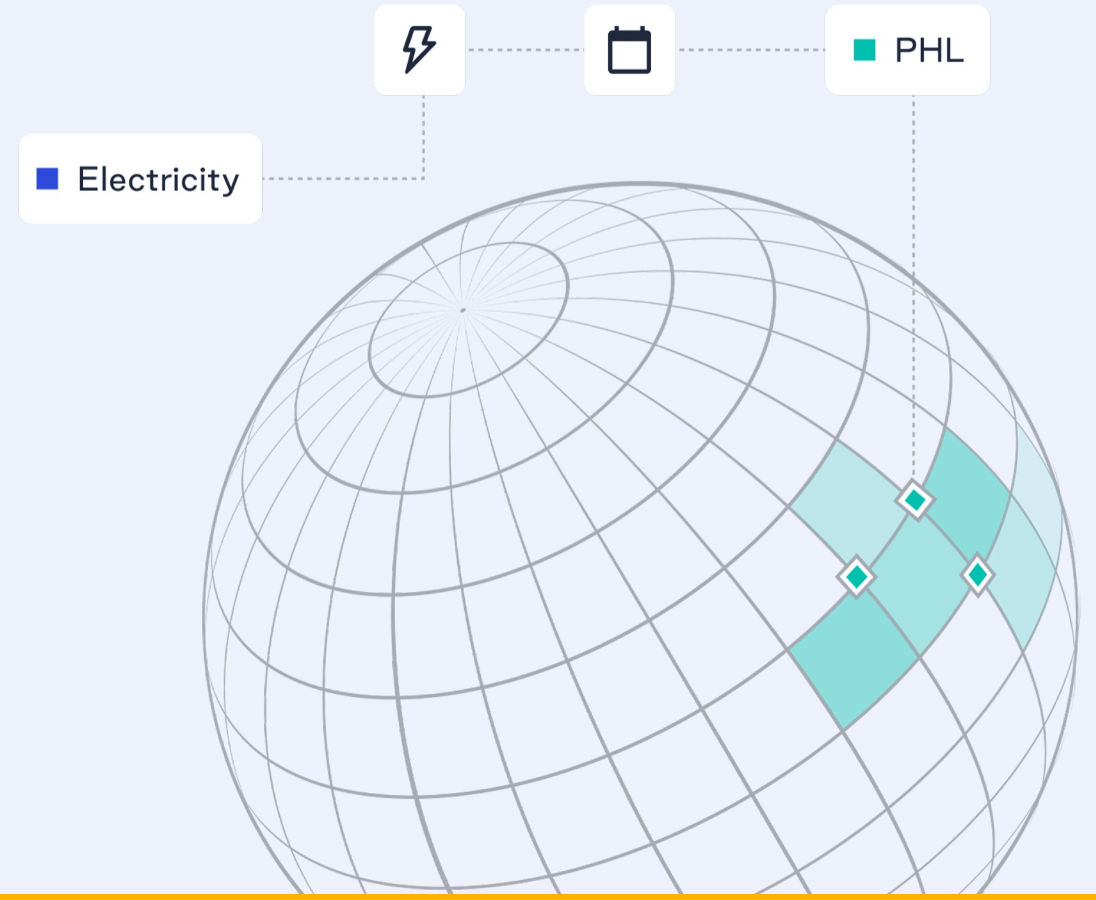
Open software, data and insights for energy transition planning

We help governments and their partners plan for the transition to clean, and more reliable electricity

Visit our website

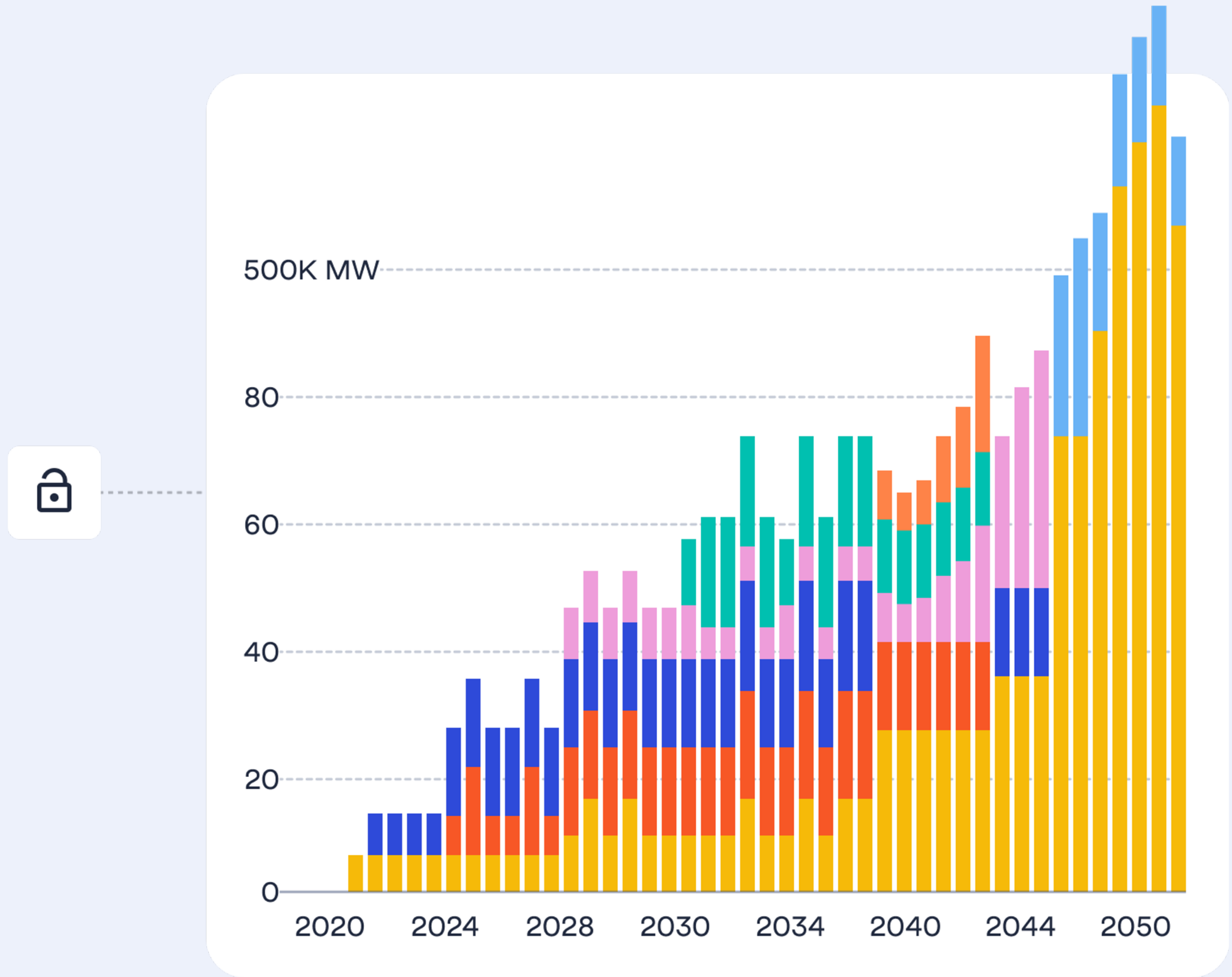
Accessible software

Our accessible system modelling software and technical training enables more efficient, effective energy transition planning.



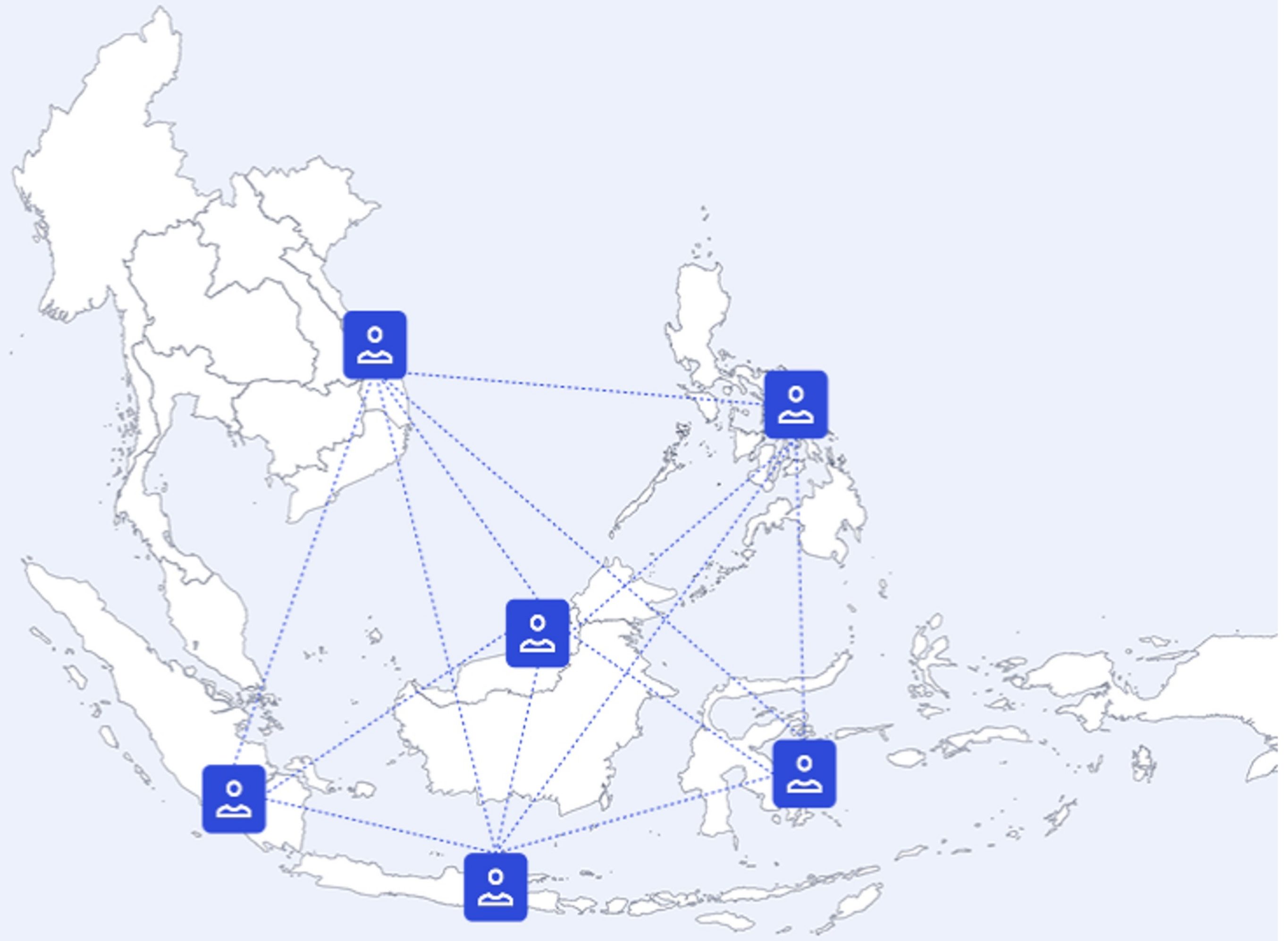
Open data

Combining AI with in-country expertise, our open datasets support high-quality system modelling.



Market analysts

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



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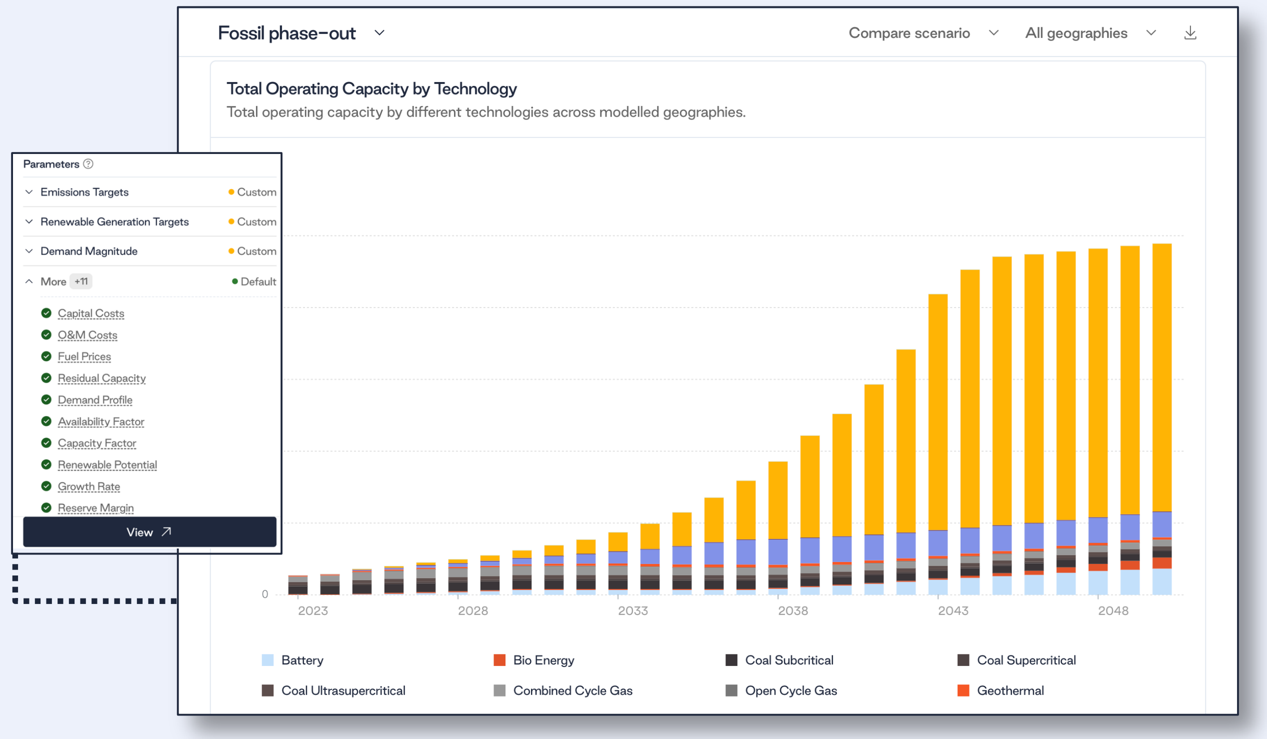
TransitionZero products

Our software and data products make energy transition planning more accessible and transparent

Explore products

Scenario Builder

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.



Total Operating Capacity by Technology

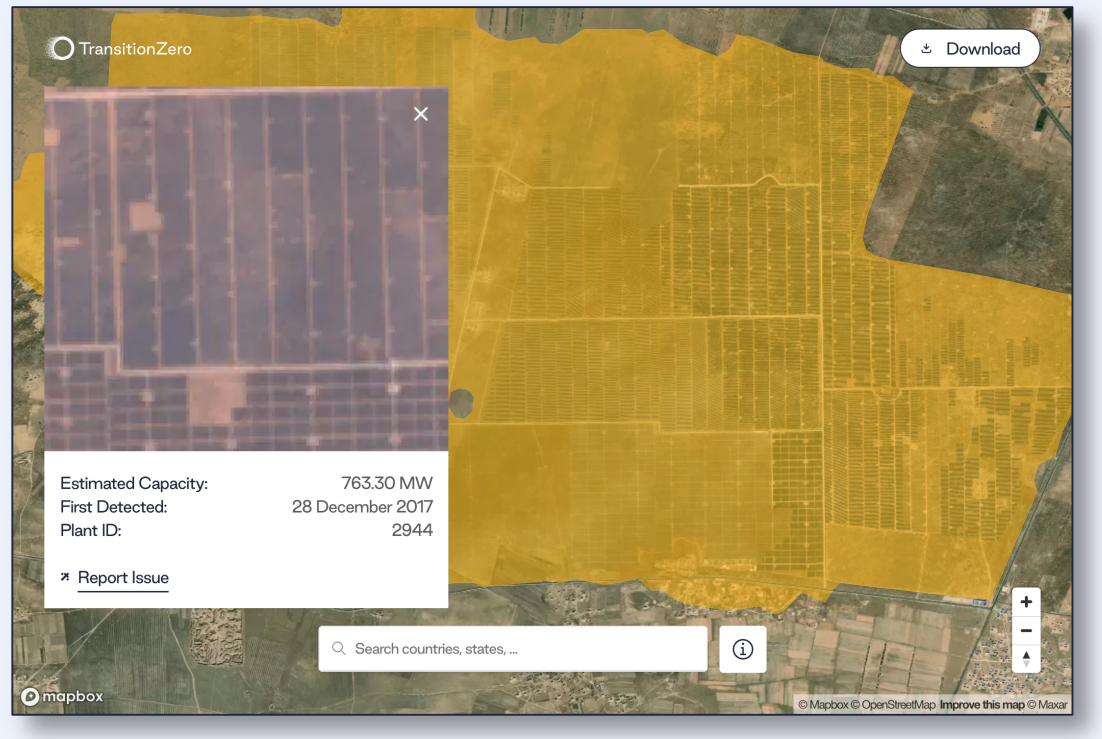
Total operating capacity by different technologies across modelled geographies.

Parameters

- Emissions Targets ● Custom
- Renewable Generation Targets ● Custom
- Demand Magnitude ● Custom
- More +11 ● Default
  - Capital Costs
  - O&M Costs
  - Fuel Prices
  - Residual Capacity
  - Demand Profile
  - Availability Factor
  - Capacity Factor
  - Renewable Potential
  - Growth Rate
  - Reserve Margin

Solar Asset Mapper

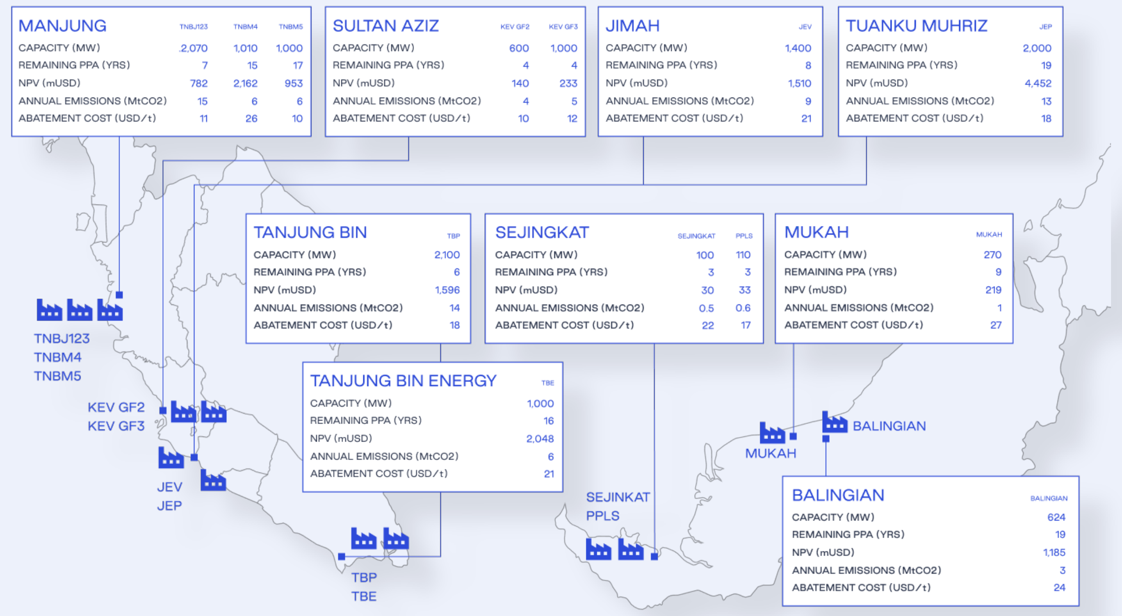
TZ-SAM is an open access, asset-level dataset of solar facilities, powered by machine learning and geospatial data. Updated quarterly, the dataset contains over 26,353 km² of solar across 200 countries.



Estimated Capacity: 763.30 MW
First Detected: 28 December 2017
Plant ID: 2944

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.



MANJUNG	TNBJ123	TNBM4	TNBM5
CAPACITY (MW)	.2,070	1,010	1,000
REMAINING PPA (YRS)	7	15	17
NPV (mUSD)	782	2,162	953
ANNUAL EMISSIONS (MtCO2)	15	6	6
ABATEMENT COST (USD/t)	11	26	10

SULTAN AZIZ	KEV GF2	KEV GF3
CAPACITY (MW)	600	1,000
REMAINING PPA (YRS)	4	4
NPV (mUSD)	140	233
ANNUAL EMISSIONS (MtCO2)	4	5
ABATEMENT COST (USD/t)	10	12

JIMAH	JEV
CAPACITY (MW)	1,400
REMAINING PPA (YRS)	8
NPV (mUSD)	1,510
ANNUAL EMISSIONS (MtCO2)	9
ABATEMENT COST (USD/t)	21

TUANKU MUHRIZ	JEP
CAPACITY (MW)	2,000
REMAINING PPA (YRS)	19
NPV (mUSD)	4,452
ANNUAL EMISSIONS (MtCO2)	13
ABATEMENT COST (USD/t)	18

TANJUNG BIN	TBP
CAPACITY (MW)	2,100
REMAINING PPA (YRS)	6
NPV (mUSD)	1,596
ANNUAL EMISSIONS (MtCO2)	14
ABATEMENT COST (USD/t)	18

SEJINGKAT	SEJINGKAT	PPLS
CAPACITY (MW)	100	110
REMAINING PPA (YRS)	3	3
NPV (mUSD)	30	33
ANNUAL EMISSIONS (MtCO2)	0.5	0.6
ABATEMENT COST (USD/t)	22	17

MUKAH	MUKAH
CAPACITY (MW)	270
REMAINING PPA (YRS)	9
NPV (mUSD)	219
ANNUAL EMISSIONS (MtCO2)	1
ABATEMENT COST (USD/t)	27

TANJUNG BIN ENERGY	TBE
CAPACITY (MW)	1,000
REMAINING PPA (YRS)	16
NPV (mUSD)	2,048
ANNUAL EMISSIONS (MtCO2)	6
ABATEMENT COST (USD/t)	21

BALINGIAN	BALINGIAN
CAPACITY (MW)	624
REMAINING PPA (YRS)	19
NPV (mUSD)	1,185
ANNUAL EMISSIONS (MtCO2)	3
ABATEMENT COST (USD/t)	24

Executive summary

From annual RECs to hourly matching

Why it matters to Singapore

- Singapore is the regional hub for leading multinational corporations at the forefront of sustainability commitments and decarbonisation efforts.
- Currently, commercial and industrial (C&I) consumers in Singapore face limited pathways to procure clean electricity, due in large part to the country's scarce domestic renewable resources, a gas-dominated generation mix, and minimal cross-border grid connectivity. As a result, reliance on renewable energy certificates (RECs) with annual matching remains the primary option to meet Scope 2 decarbonisation targets.
- The emerging view around *hourly matching* as the next benchmark in corporate emissions accounting and reporting — reflected in the ongoing revision of the GHG Protocol's Scope 2 Guidance — highlights the need to assess its implications for Singapore's power system as corporations adopt this approach.
- Facilitating C&I consumers' pursuit of hourly matching — where electricity must be generated and consumed at the same time and within the same grid system, unless storage is involved — may require structural changes to the power system, more supportive policies for corporate procurement, and closer regional cooperation. Early and proactive action in these areas would help ensure that Singapore remains well-positioned and competitive as a regional hub for industry and services, particularly as other global and regional markets pursue similar initiatives.

Key statistics on Singapore's power sector

12 GW
Total installed capacity

95%
Gas generation share

8.6 GW
Technical solar potential, mostly deployable via distributed systems

6 GW
Import target by 2035, via Indonesia, Cambodia, Vietnam; up from 200 MW today via Malaysia

Figures as of end-2024
Source Singapore Energy Market Authority (2025)

An overview of the study approach (1/2)

How we modelled carbon free electricity (CFE) scenarios for Singapore in 2030

We developed a representative model of Singapore's 2030 grid power system, treating the country as a single grid zone with two interconnectors: the existing link to Peninsular Malaysia and a planned connection to Indonesia.

Using an hourly dispatch mode, 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

In our model, 4% of Singapore's total demand is attributed to C&I consumers participating in clean electricity matching. This share is intended to represent broader trends in C&I demand moving towards decarbonisation.

02

This 4% of demand is modelled under two schemes: annual matching and hourly matching, with the latter tested at CFE levels ranging from 70 to 100%. C&I consumers meet this demand through power-purchase agreements (PPAs) with new clean generators, which the model builds and optimises.

03

Grid-zone results are then aggregated to assess the national impact of each scheme, both from the perspective of C&I consumers as well as the broader power system of Singapore, including stakeholders in government and entities involved in generation, storage and transmission.

An overview of the study approach (2/2)

We modelled 3 scenarios for 2030 — Reference, Annual matching, and Hourly matching — together with several sensitivities.

A minimum of 22 runs are done, comprised of 1 Reference + 7 Matching Regimes x 3 technology palettes.

Reference Scenario

Carbon-Free Electricity (CFE) Scenarios, where participating C&I demand is met hourly or annually by building additional capacity. This would be the equivalent of procuring additional capacity through PPAs.

A baseline case allowing new demand to be met by only new-build on the brownfield grid

Existing Grid and Generators in 2023

\+

Transmission Capacity Expected by 2030

\+

Generation Capacity Expected by 2030

\+

Model-built Generation Capacity

Where 3 different technology palettes are available for C&I to deploy and contract with

Technology Palette 1 (TP1)
Solar & Batteries

Technology Palette 2 (TP2)
TP1 + Long-duration energy storage (LDES)

Technology Palette 3 (TP3)
TP2 + Gas-Hydrogen blending + Gas-CCS

Model-optimised capacity:
Annual Matching Regime

First CFE scenario, run once for each technology palette, where CFE purchases for participating demand equals their total annual electricity consumption, without requiring that supply and demand align in real time

Model-optimised capacity:
Hourly Matching Regime

Second set of CFE scenarios, where every hour of electricity use for participating C&I demand is met with carbon-free generation in Singapore

×

Six runs per technology palette are tested, matching a percentage of hours in a year

- 70%
- 80%
- 90%
- 95%
- 99%
- 100%

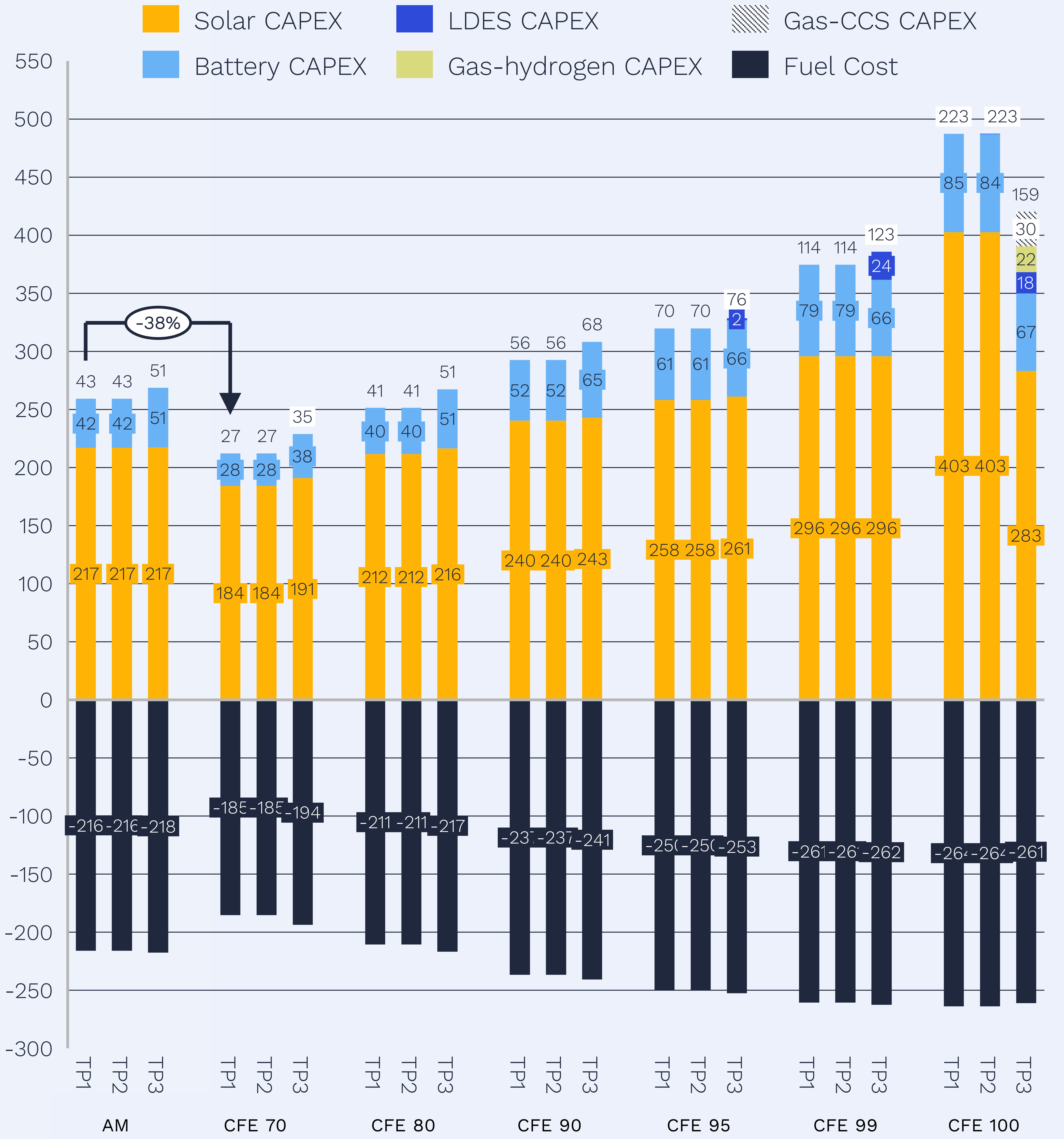
Hourly matching can deliver grid cost savings

Round-the-clock carbon free electricity can deliver grid savings from avoided fuel, starting at US$185 million per year

1. **70% round-the-clock clean electricity by 2030 has a net system cost that is US$16 million less than annual matching.** Achieving 70% carbon free electricity (CFE) every hour of the year for participating C&I consumers — equivalent to 4% of national demand — cost the system net 38% less than annual matching, while still delivering reductions in emissions and savings on fuel. System costs include all capital, operational and fuel expenditure of the grid, including C&I assets.
2. **Hourly matching offers benefits at each stage of matching, with more room for growth and increased avoided emissions and savings over time.** At 80% CFE, procurement and benefits closely align with those of full annual matching. Higher CFE scores shift procurement needs to C&I consumers while providing increased benefits to the wider Singapore grid.
3. **Savings to the grid rise with higher CFE targets, as excess renewable generation from C&I consumers can cut fuel costs.** Operational cost savings from avoided fuel generation are achieved through the sell-back of surplus clean power from C&I consumers to the grid, displacing thermal generation in the merit order. Conventional generators save between US$185 million under 70% CFE up to US$261 million in 100% CFE. This can lower overall system costs by as much as 26% under 100% CFE. On the other hand, fuel cost savings from annual matching are capped at US$218 million.
4. **Solar and 4-hour batteries are the foundation of CFE.** The low and steadily falling costs of solar and battery storage make it increasingly feasible to use renewables to displace some high-cost LNG. Each MW of solar working optimally with 2 kWh of storage can firm output and ensure reliability.
5. **Gains from alternative technologies like long-duration energy storage (LDES), Gas Carbon Capture and Storage (CCS) and Blended thermal technologies are limited.** Due to their projected costs in 2030, such technologies are only optimal for the last 1-5% of CFE. CCS and gas-hydrogen blending could reduce net system costs for 100% CFE by 28% compared with solar-plus-storage only. However, these offer less fuel savings and additional risks from emissions leakage.

Benefits of hourly matching

Costs/savings to the Singapore power sector in 2030 (million US$)



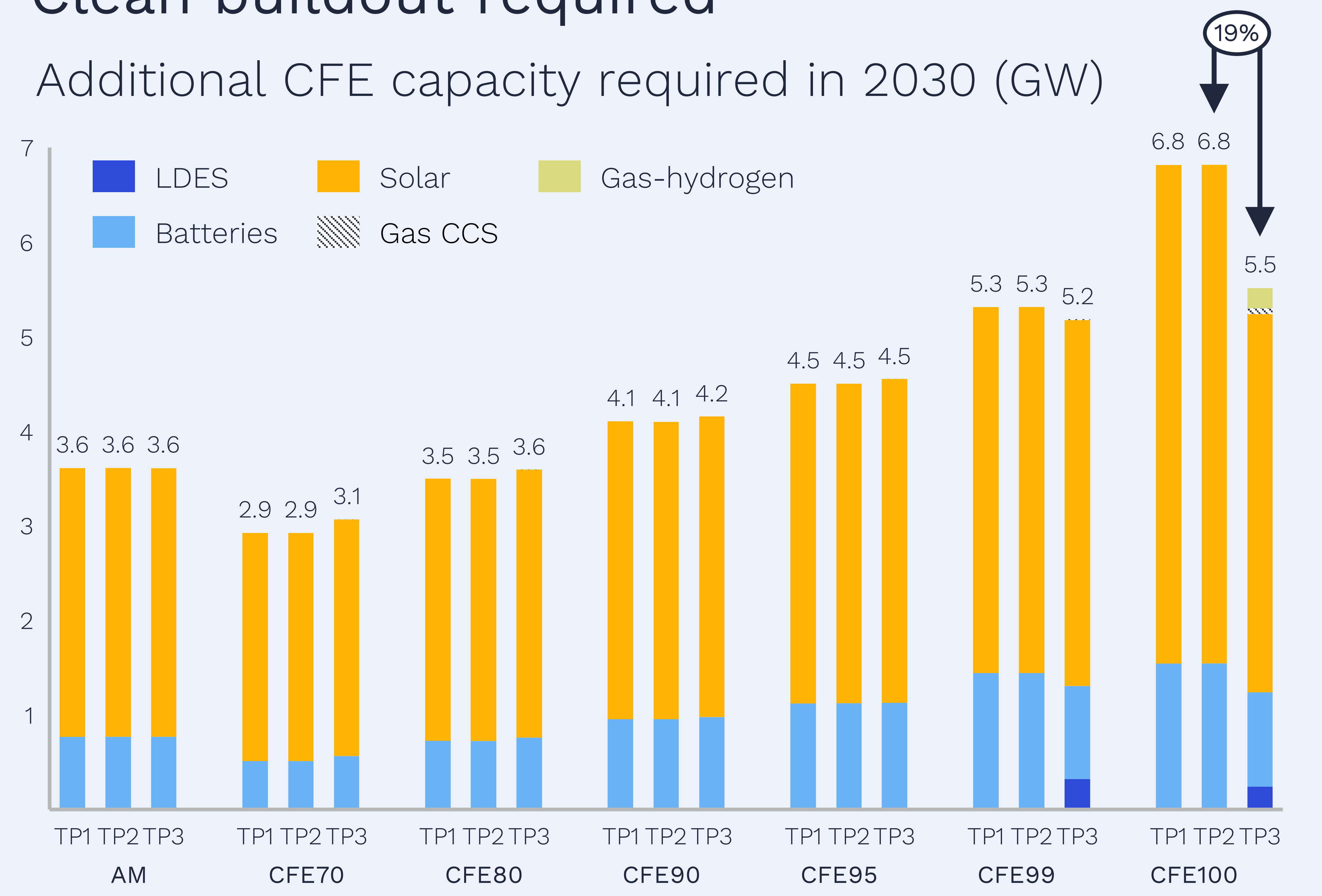
Solar and batteries can get Singapore to 100% CFE

Optimal combinations of domestic generation, storage and regional renewable imports can unlock round-the-clock clean electricity

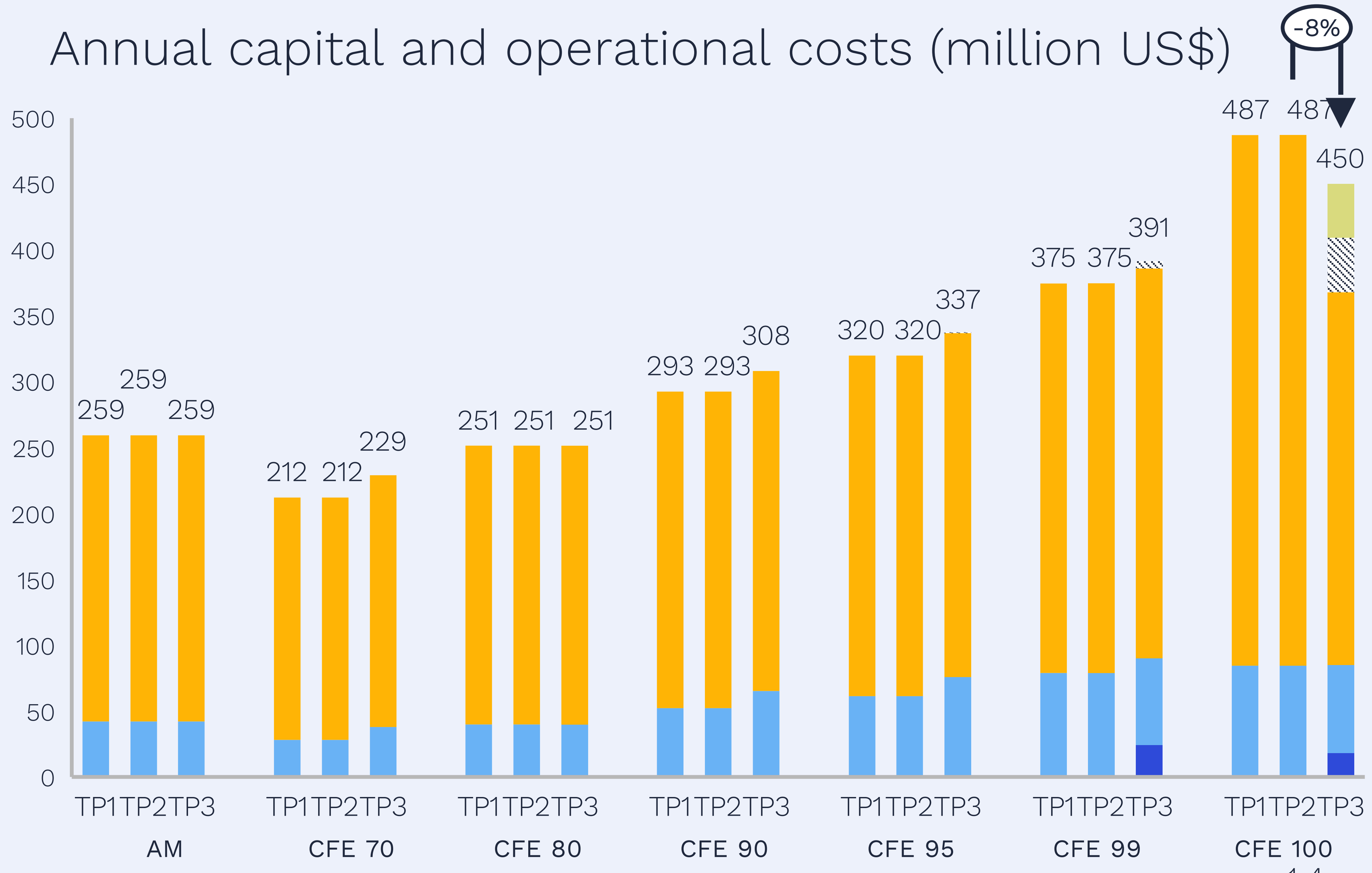
1. **Achieving 70% CFE requires 700 MW more capacity than annual matching and cost US$47 million less in capital expenditure**. 70% CFE would entail building approximately 2.4 GW of solar and 0.5 GW of batteries, or 433 MW less solar and 200 MW less battery than an annual matching scenario. This is 19% cheaper for C&I consumers compared to annual matching while still bringing lower emissions and lower fuel requirements to the overall system.
2. **CAPEX rises exponentially under the highest CFE scores.** Moving from 80% to 100% matching doubles both the capacity and investment required, as decarbonising 'hard-to-reach' hours necessitates oversizing solar and storage capacity, particularly in the last 1% of CFE.
3. **Lithium-ion batteries will be essential for C&I consumers.** Even at 100% CFE, the long-duration energy storage (LDES) vanadium redox flow batteries add minimal system value due to their high cost and modest 10–hour duration. Longer-duration storage (e.g. weeklong storage from liquid air batteries) could materially change results if available and cost-effective, but results indicate the existing battery technologies with 4-hour storage durations are sufficient to enable higher hourly CFE matching. LDES is only used for intra-day shifting for C&I consumers at very high CFE scores.
4. **If made available, Gas Carbon Capture and Storage (CCS) and Blended thermal technologies are only optimal at 99% CFE and beyond.** While Gas CCS and hydrogen/ammonia blending are not a realistic options for C&I procurement by 2030, given its current technical limitations that make it cost-prohibitive in the near-term, it is included in our modelling as a sensitivity to illustrate the relative benefits of such technology. Even then, both technologies only appear at 100% CFE, in very small capacities, displacing around 1.6 GW of solar. This highlights only a marginal benefit compared to other commercially available options, one that comes with high additional capital and fuel costs related to storage and fuel.

Clean buildout required

Additional CFE capacity required in 2030 (GW)



Annual capital and operational costs (million US$)



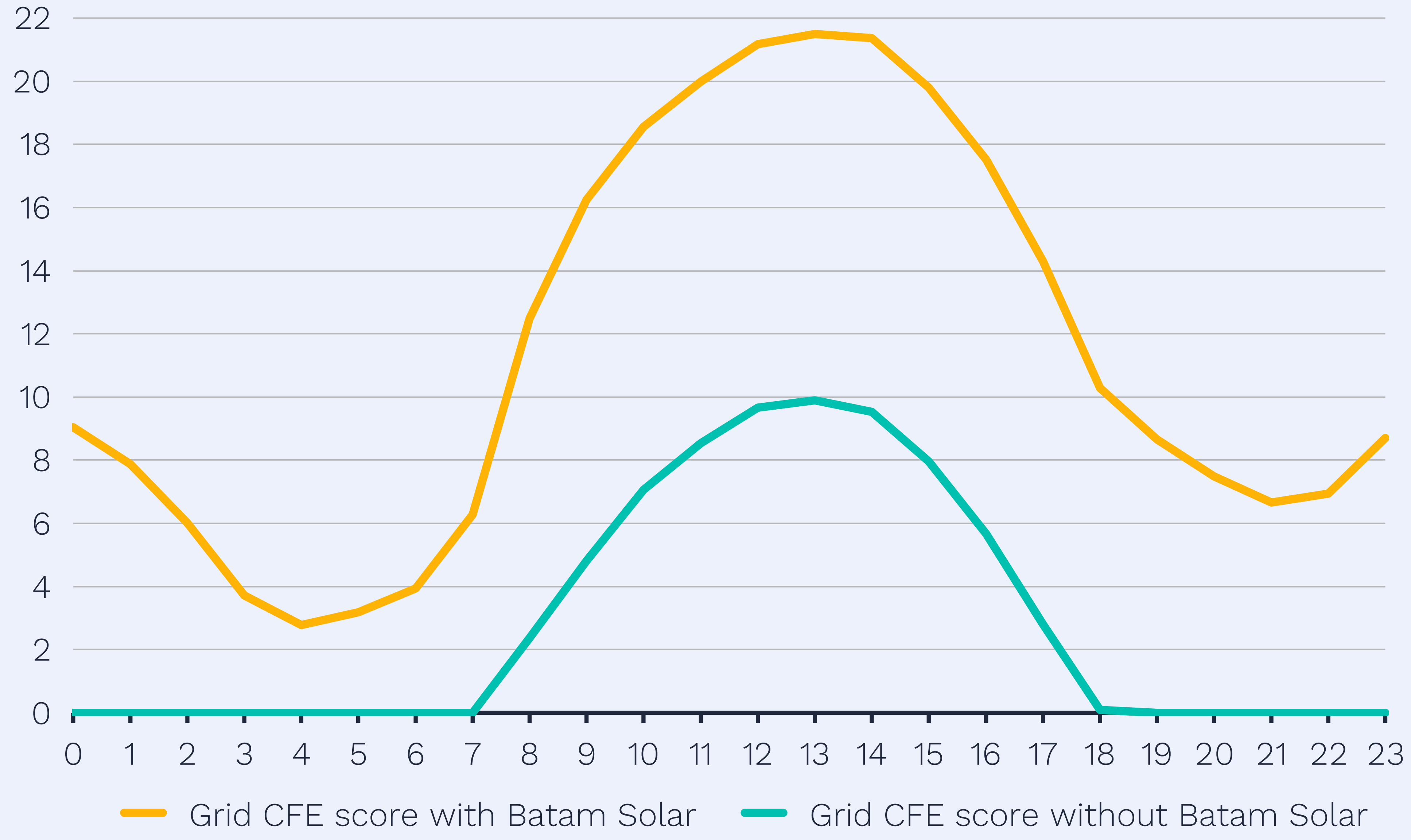
Imports raise Singapore's base CFE score

Regional interconnection for clean energy further unlocks round-the-clock power

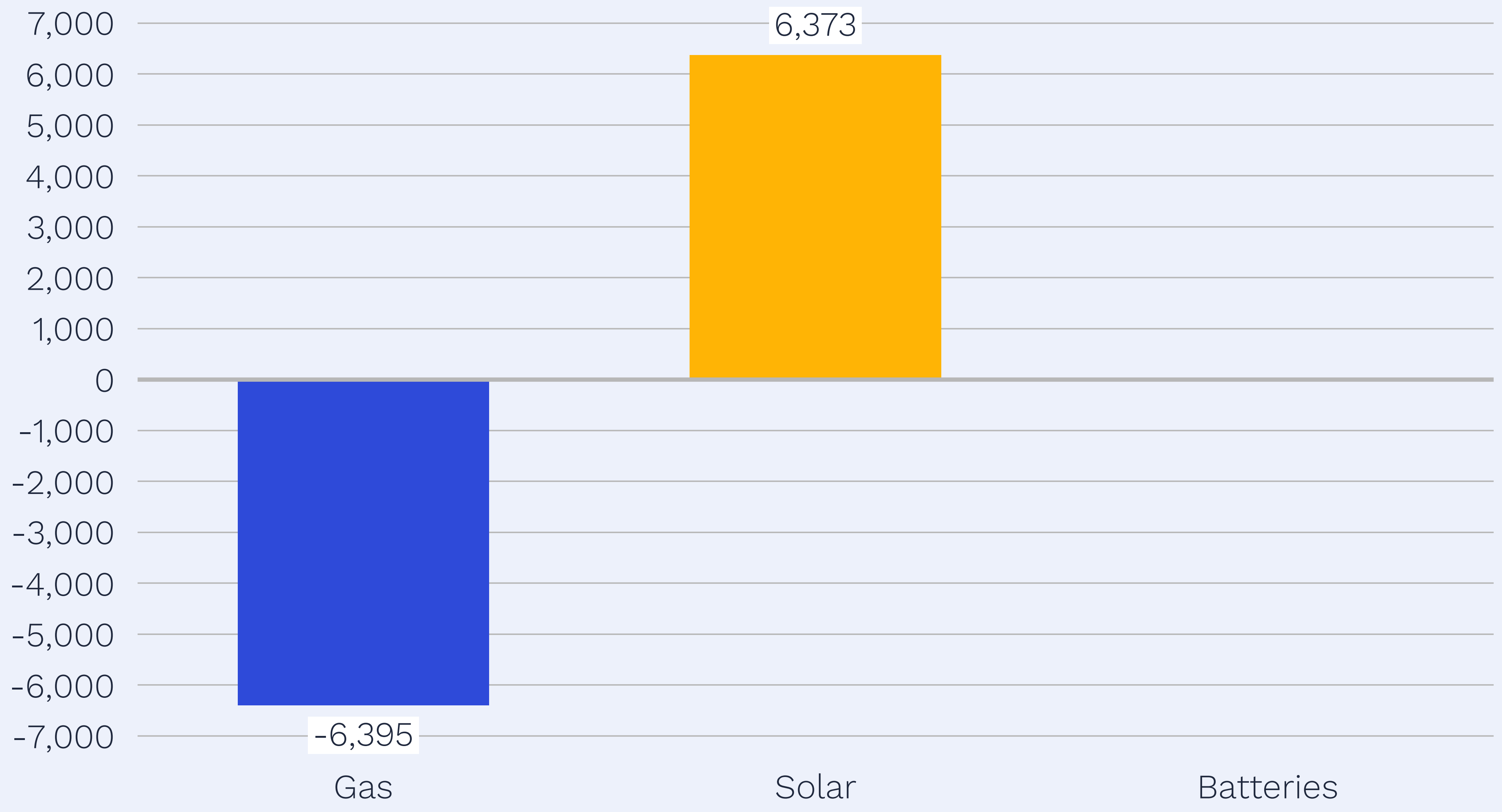
1. **Interconnection can boost Singapore's baseline CFE score, underscoring the importance of regional collaboration and the ASEAN Power Grid.** Singapore's local grid mix is dominated by gas. As part of its long-term strategy, Singapore aims to import up to 6 GW of low-carbon electricity by 2035, already granting 3 GW of import licences to Indonesia. In our model, we assume that by 2030, Singapore imports 4 GW of solar backed by 1.7 GW of batteries from Indonesia and up to 500 MW from Malaysia.
2. **Solar imports from Indonesia through a 1 GW interconnection would increase Singapore's base CFE score from 2.7% to 10%.** While the model does not account for C&I procurement in 2030 being met by direct PPAs from imports, clean imports to the Singapore grid lift the starting point of CFE. This decreases gas-power annually by 6 TWh, saving Singapore approximately US$440 million in fuel costs and avoiding 2.8 $MtCO_2$ emissions in comparison to a scenario where the interconnector is not available.
3. **Imports supplement Singapore's limited domestic clean energy options by unlocking a more diverse portfolio of clean energy.** Land and resource constraints cap the scale of solar and storage capacity in the country. Imports provide reliable power — delivered either through grid-to-grid interconnections, as with Malaysia, or via generator-to-grid like Batam.
4. **Ensuring imports are sourced from clean power can drive investment in regional clean generation and interconnector projects**. Expanding cross-border electricity links with Indonesia and utilising existing ones with Malaysia while ensuring imports are genuinely clean is essential, as importing fossil-based or untracked power neither guarantees decarbonisation nor supports hourly matching.
5. **Power imports are strategic to C&I consumer's Singapore decarbonisation.** Imports linked with time-based energy attribute certificates (T-EACs) can give Singapore corporates access to hourly clean energy from regional grids, improving their reported CFE scores at lower cost while stimulating regional investment.

Benefits of interconnection to 24/7 CFE

Hourly average of CFE score with and without Batam Solar (%)



Difference in Generation in a Scenario with vs. without Batam Solar (GWh)



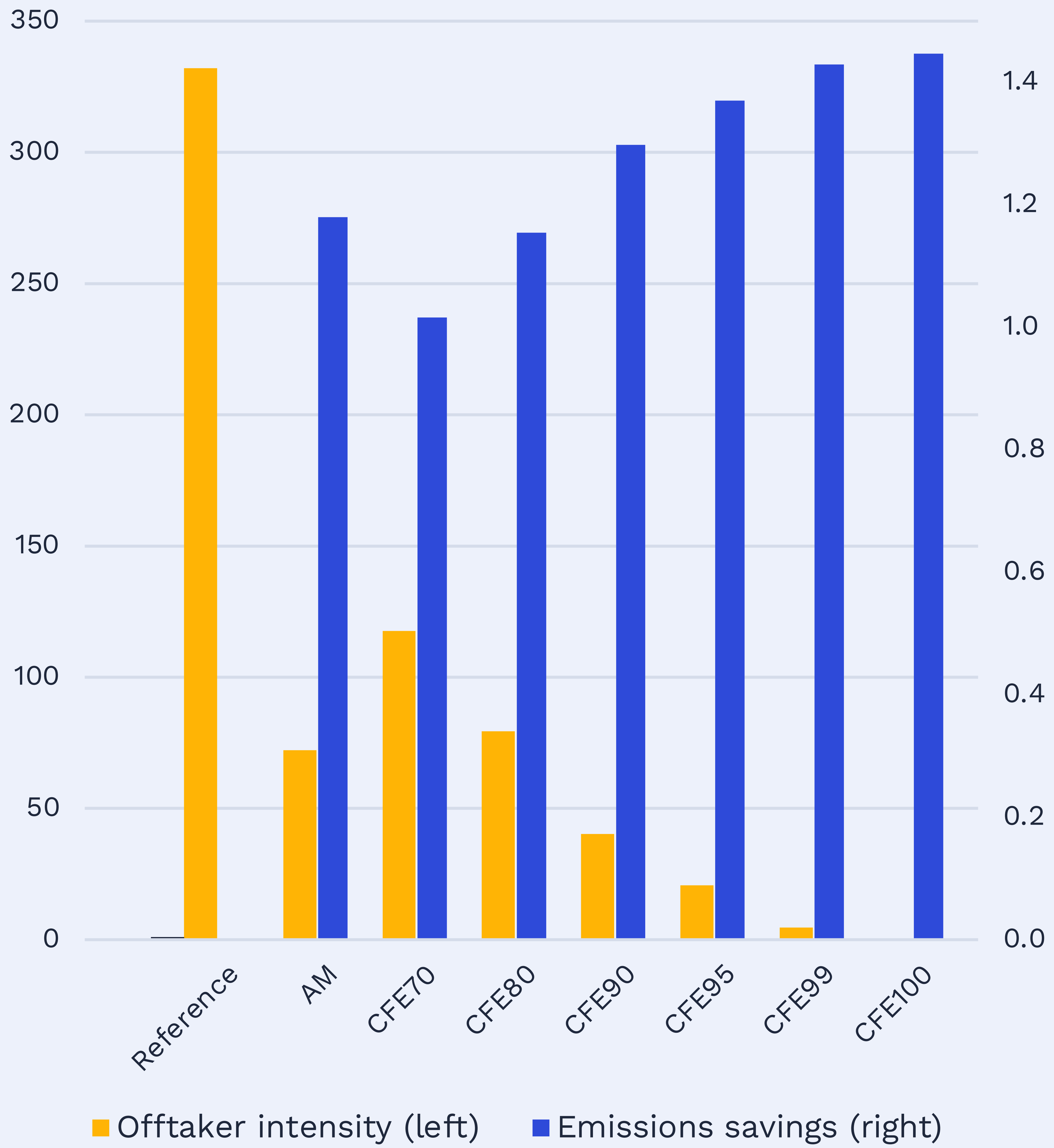
Hourly matching is better at driving down emissions

Higher CFE scores reduce emissions intensity for C&I consumers and the wider system more effectively than annual matching

1. **System-wide emissions consistently fall as matching stringency increases.** This indicates that C&I consumers can contribute significantly to emissions reductions from the Reference scenario, even at the lowest hourly matching score of 70% with further improvements delivering even greater benefits.
2. **Annual matching achieves greater nationwide emissions reductions from 70-80% CFE.** Annual matching requires more renewable build-out than lower CFE scores (around 3.6 GW versus 2.9 GW under 70% CFE), raising clean electricity availability across the year. In contrast, 70% CFE still relies on fossil-backed grid imports to cover hourly gaps, which drives up its emission intensity despite being cheaper for participating C&I consumers. In other words, 70% CFE strikes a balance: it is cost-effective and yields lower net system costs, but its nationwide decarbonisation contribution is 14% lower than that of annual matching.
3. **Hourly matching at 90–100% of hours cuts more system-wide emissions than annual matching.** At 80% CFE, hourly matching delivers comparable emissions reductions to annual matching. From 90% CFE onwards, hourly matching widens the gap and cuts 16-22% more emissions than under annual matching. By 99-100% CFE, hourly matching delivers approximately 1.44 $MtCO_2e$ in emissions savings for Singapore.
4. **The marginal cost of each additional megawatt-hour declines at higher levels of CFE.** While the final 20% of decarbonisation drives steep cost increases, it is also able to deliver deeper decarbonisation for both the system and C&I consumers, highlighting the efficiency of hourly matching in cutting emissions per unit of electricity consumed.
5. **Alternative technology palettes do not decrease national emissions more than solar and battery storage but increase the risk of leakage.** Gas with CCS, and gas–hydrogen co-firing result in larger gross reductions in grid emissions owing to slower growth in renewables. However, net reductions are constrained by users' responsibility for residual emissions from CCS.

Total abatement and emissions intensity

C&I consumer carbon abatement (gCO_2/kWh) and emissions intensity ($MtCO_2e$)



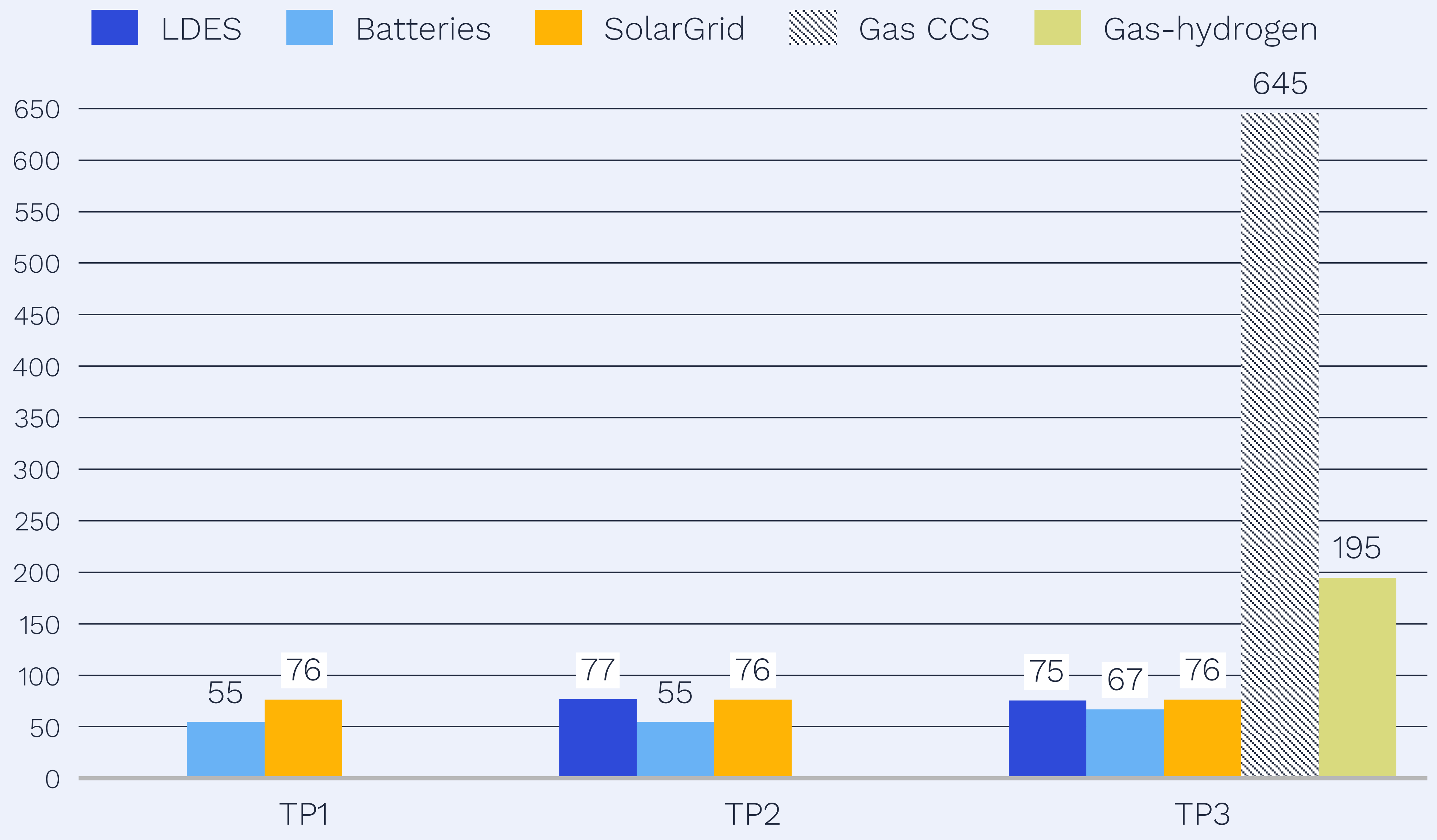
Technology risk

Limited role for CCS and blending keep it a distant reality

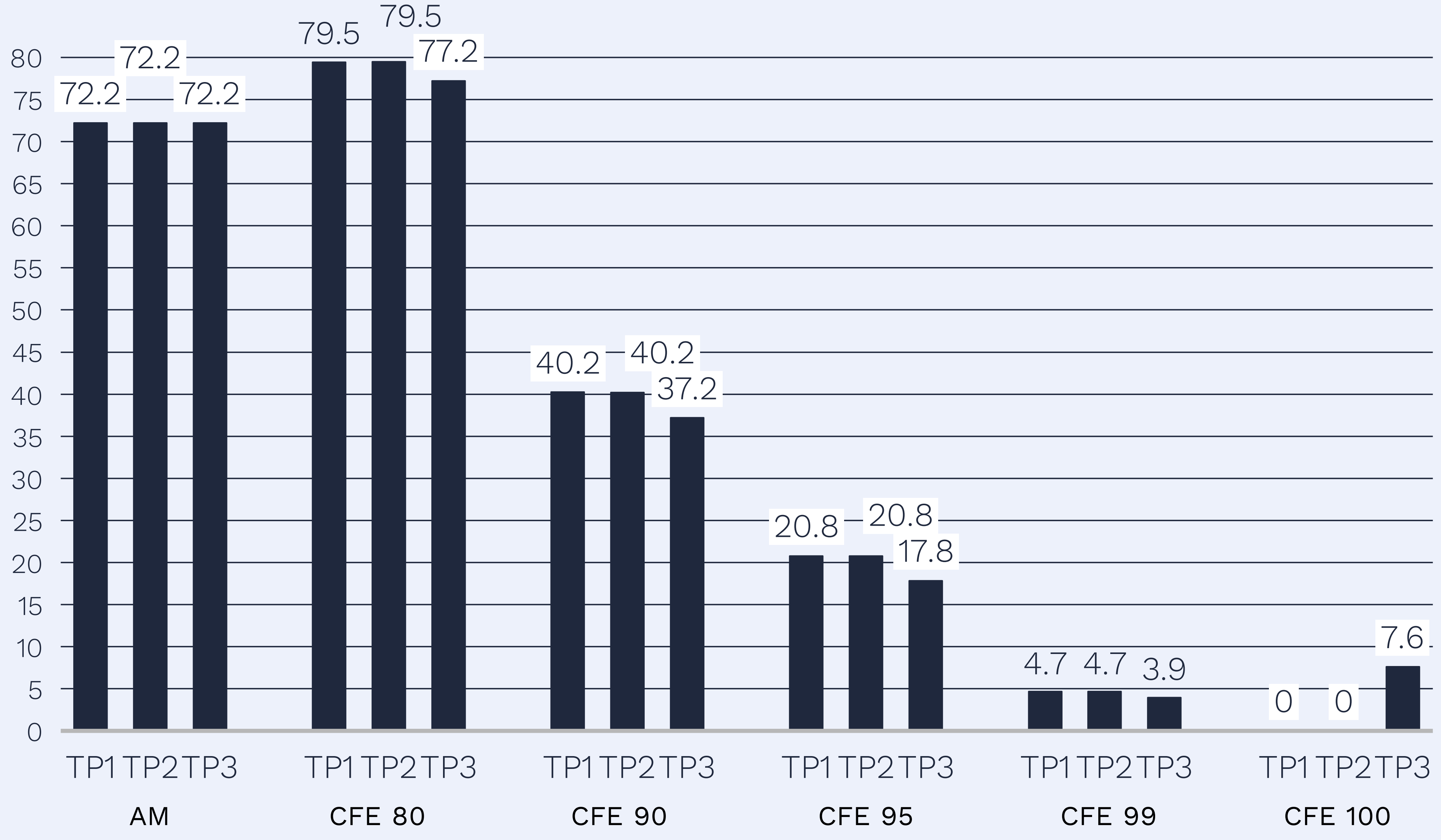
1. **While CCS and blending technology uptake appears at 99% CFE at very low capacities, the technologies are unlikely to be viable for C&I demand in Singapore.** Despite its technical fit and ability to reduce solar and battery overbuild, both remain expensive and geographically constrained solutions with total annual cost per unit capacity at 645k US$/MW — dramatically higher than all other technologies. Given Singapore's limited land and lack of proximate CO_2 storage basins, CCS would require long-range shipping, raising both infrastructure complexity and costs — making it a long-term, rather than near-term, investment option for meeting corporate decarbonisation needs.
2. **CCS deployment is highly sensitive to sequestration rates and transport costs.** We assume a 70% CO_2 capture and storage rate, higher than what is currently commercially achieved and assuming domestic storage availability. The costs resulting from our modelling likely underestimate real-world dynamics.
3. **The estimated marginal abatement cost of CCS for CFE in Singapore is relatively high — estimated at SGD 145 per tonne of CO_2 (108 US$/t CO_2),** often exceeding the current carbon tax of SGD 25/tCO_2 as of 2024. This is set to rise to SGD 50–80/tCO_2 by 2030. At these levels, CCS is unlikely to be a cost-effective option for CFE compared to renewables, storage, and clean imports.
4. **CCS has limited system-level emissions benefits under current assumptions.** CCS reduces renewable curtailment by displacing some excess clean generation and the need to oversize the system. However, this results in less displacement of fossil generation on the regular grid. Moreover, under current assumptions, CCS is a 'leaky' solution — meaning the more it's used, the more the associated clean energy procurement (e.g., through a CFE PPA) becomes a net source of emissions rather than a sink.
5. **Gas-hydrogen sees extremely low utilisation,** used at a 4% capacity factor as a 'last-resort' clean firm capacity, due to the high cost of hydrogen and very low round-trip efficiency from electrolysis, storage losses and reconversion.

Gas CCS results in dramatically higher costs and leakage risks

Total annual cost per unit capacity (thousand US$/MW)



National emissions impact from greenfield (gCO_2/kWh)



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[1] *Defined as the capture rate of CO_2 resulting from fuel combustion, times the sequestration rate for the captured CO_2.*

[2] *The project economics for pipeline transport did not affect CCS uptake during initial runs due to insufficient differentiation from other competing CFE technologies.*

[3] *Conversion uses average of 2023, where 1.34 SGD = 1 USD*

Policy guidance

Optimal CFE targets, solar-plus-storage, and regional interconnectivity can unlock decarbonisation wins for both corporates and Singapore

01

Supporting corporate 24/7 matching initiatives with robust hourly accounting standards can accelerate clean technology uptake.

By adopting time-based emissions accounting, regulators can ensure that corporate 24/7 carbon-free electricity goals translate into real system benefits. This would align procurement with actual avoided emissions, incentivise investment in storage and demand response, and strengthen the credibility of Singapore's role as a leader in corporate clean energy action.

02

Focusing on proven technologies — solar and battery storage — for both domestic rollout and regional imports is the most cost-effective solution.

Solar-plus-storage remains a highly viable option for meeting C&I demand, especially as technologies like LDES, CCS and blended thermals remain less competitive in 2030 due to high investment costs.

The deployment and utilisation of domestic solar potential — including rooftop, floating and mobile systems — can be accelerated towards 2030. These installations should be made accessible to corporate buyers through clear roadmaps and well-designed allocation or procurement schemes. This can include fast-tracked regulatory approvals for floating solar projects on reservoirs, paired with 4-hour battery storage to provide firm capacity and improve grid reliability.

03

Deepening regional interconnection facilitates a more diverse portfolio of clean power for Singapore.

Stronger interconnection creates the foundation for a regional market in time-based clean energy attributes, enabling corporates in Singapore to access a wider pool of carbon-free supply while curbing reliance on volatile gas markets and improving resilience against variability.

Near-term priorities should include optimising the existing link with Peninsular Malaysia and establishing new grid connections with Batam Indonesia.

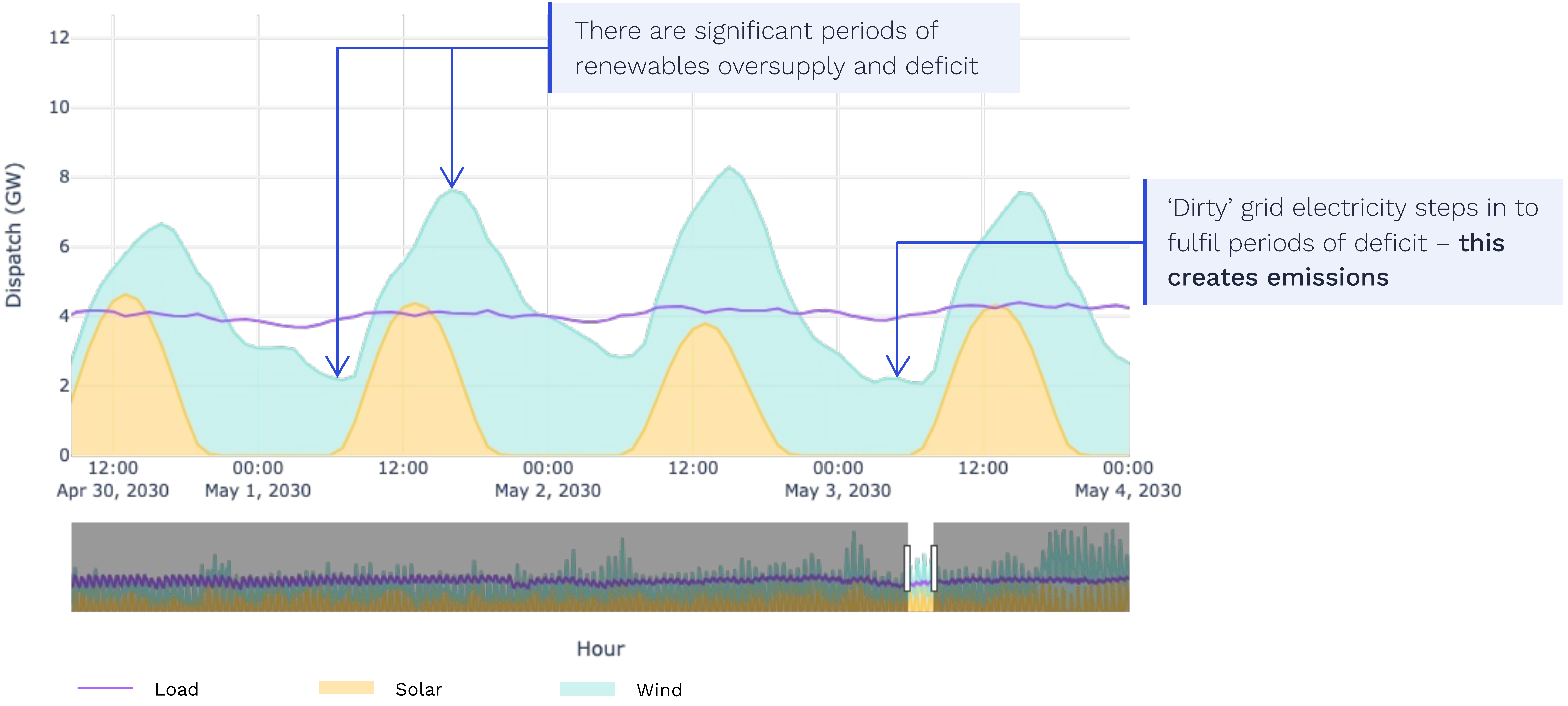
Policies supporting C&I consumers' dedicated access to clean energy imports can help expedite the development of new interconnection projects.

TransitionZero

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?



There are significant periods of renewables oversupply and deficit

'Dirty' grid electricity steps in to fulfil periods of deficit – **this creates emissions**

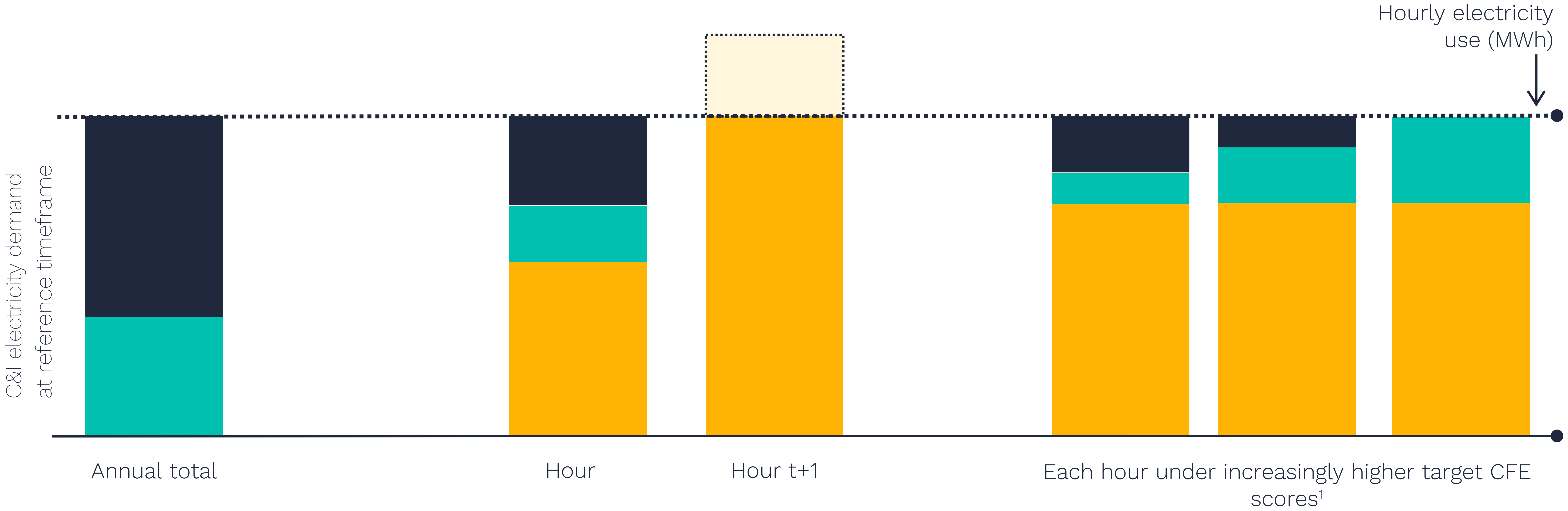
Sources: Google. IEA (2022), Advancing Decarbonisation through clean electricity procurement.

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, allowing corporates to procure diverse and flexible clean technologies, and helping the overall grid integrate higher shares of solar PV and batteries.

Shifting guidance on emissions reporting

The GHG Accounting Protocol is evolving, requiring 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 percentage of generation that comes from carbon free sources. In the case of Singapore, this is a single grid zone with an hourly CFE % score.
- 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.

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[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 Singapore 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
Onshore wind[3] and solar	✓	✓	✓
Battery storage	✓	✓	✓
Long-duration energy storage[1]	✗	✓	✓
Gas with CCS	✗	✗	✓
Hydrogen (H_2) & Ammonia (NH_3) co-firing	✗	✗	✓

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.
- In response to feedback from our Working Group participants, we will explore treating storage output as CFE only if it was charged exclusively with CFE.

---

[1] *Pumped storage hydro and Redox flow batteries are grouped under this option for Singapore and Malaysia. Liquid air storage is the technology made available in our Japan, Taiwan and India models.*

[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.*

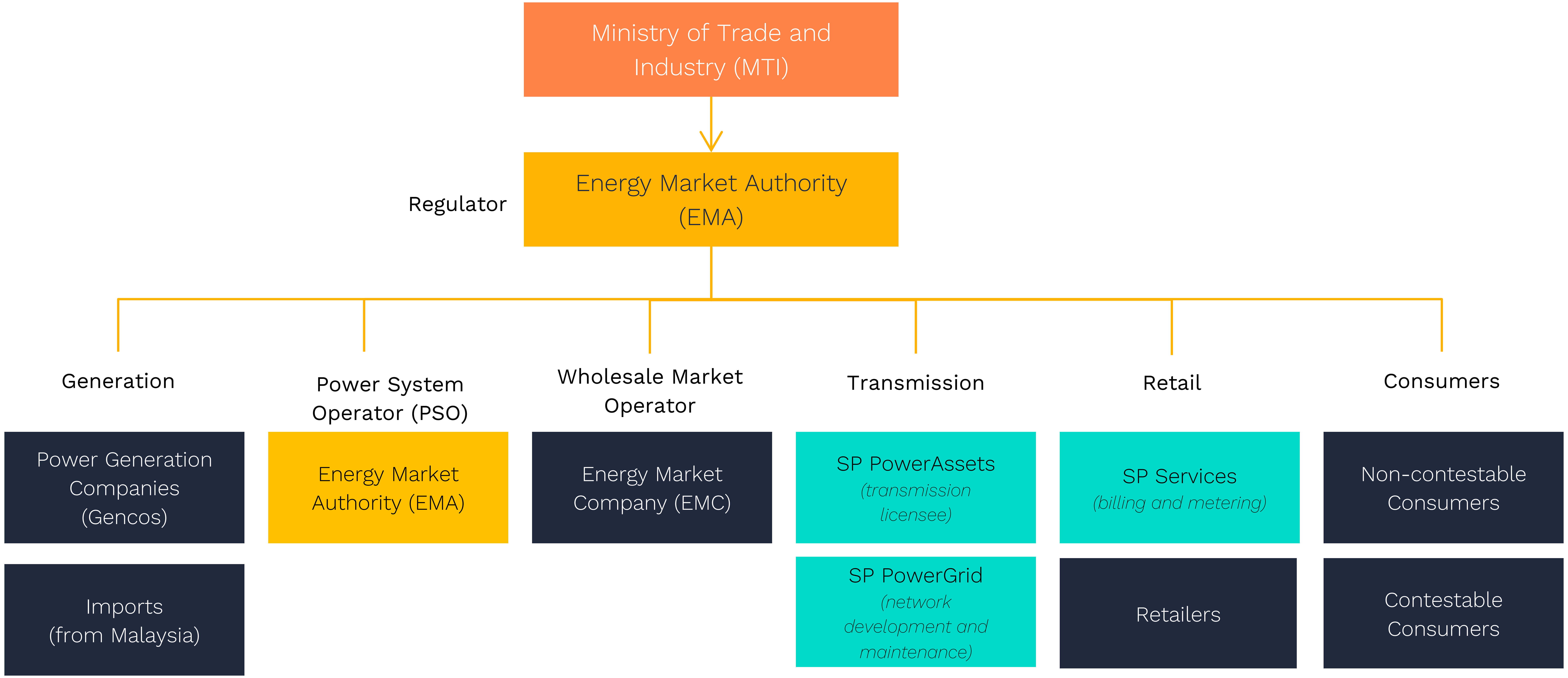
[3] *We have not considered onshore wind for Singapore, following feedback from stakeholders.*

TransitionZero

Overview of the Singapore power sector

Overview of the Singapore power sector (1/2)

Southeast Asia's first fully liberalised electricity market



Ministry of Trade and Industry (MTI)

Regulator

Energy Market Authority (EMA)

Generation
- Power Generation Companies (Gencos)
- Imports (from Malaysia)

Power System Operator (PSO)
- Energy Market Authority (EMA)

Wholesale Market Operator
- Energy Market Company (EMC)

Transmission
- SP PowerAssets *(transmission licensee)*
- SP PowerGrid *(network development and maintenance)*

Retail
- SP Services *(billing and metering)*
- Retailers

Consumers
- Non-contestable Consumers
- Contestable Consumers

SP PowerAssets, SP PowerGrid, SP Services are members of SP Group.

Key statistics

12 GW
Total installed capacity

58 TWh
Total demand

95%
Gas generation share

9%
Renewables capacity share

1,540 MW
Total installed solar capacity, of which 119 MW was added in 2024

Figures as of end-2024
Source Singapore Energy Market Authority (2025)

Overview of the Singapore power sector (2/2)

Corporate clean energy procurement avenues

C&I consumers in Singapore currently have several options for procuring clean electricity:

- Installing 'behind-the-meter' solar assets;
- Signing long-term Power Purchase Agreements (PPAs) with the Gencos; and
- Purchasing Renewable Energy Certificates (RECs).

However, the limited indigenous renewable energy resources and current supply mix constrain the availability of clean electricity for corporates.

To structurally decarbonise its energy system, the Singapore government has outlined an energy transition strategy built on three key pillars: distributed solar PV deployment, hydrogen adoption, and clean electricity imports through regional grid interconnections.

The strategy is being backed by concrete policy actions. This include, for instance, the December 2024 inaugural electricity import from Malaysia, and recent granting of conditional licenses for up to 3GW of transmission capacity from Indonesia's Riau Islands, with deployment targeted from 2029.

Despite the unprecedented scale and complexity of the subsea interconnectors involved, electricity imports - particularly of firm solar power - are expected to play a critical role in helping C&I consumers in Singapore meet their decarbonisation goals.

In addition to corporate procurement strategies, the Singaporean government has a target to deploy 2 GWp of solar by 2030, import 6 GW of clean electricity by 2035, and ensure all new gas plants are hydrogen-compatible.

Select moments in Singapore's renewable procurement journey

2013 **Transition to half-hourly settlement**

Uniform Singapore Energy Price (USEP) in the National Electricity Market of Singapore (NEMS) shifted to 30-minute intervals, improving market responsiveness and enabling finer tracking of clean energy use.

2014 **Renewable Energy Certificates (RECs)**

RECs were launched and integrated into the electricity market via SP Group's digital marketplace, allowing corporates to offset grid emissions with verifiable RE attributes.

2021 **Green electricity import RFPs & REC aggregators expand**

EMA opened a Request for Proposal (RFP) for long-term clean electricity imports, marking a step in the broader plan to import up to 6 GW by 2035; REC platforms began scaling voluntary markets and aggregator models.

2023 **24/7 CFE pilots & granular tracking**

EMA launched industry consultations and pilots for 24/7 CFE tracking using granular hourly matching, with tools to support clean procurement for corporates.

2024 **2024 — Carbon tax**

Carbon tax increases from SGD \$5 to \$25/tCO_2e spurred greater private sector interest in clean electricity sourcing and bundled PPA imports.

Singapore's interconnectivity pivot

Emerging import framework and regional partnerships support its 2035 and 2050 decarbonisation goals

- A self-sufficient grid until 2022, Singapore is targeting 6GW of low-carbon electricity imports, enough to meet 30% of the country's demand by 2035.
- To date, signed bilateral agreements amount to imports of up to 7.4 GW of low-carbon electricity by 2035 from Indonesia, Cambodia, Vietnam, and Australia, all via newly built subsea cables.
- Interconnection projects for the importing of clean energy are required to meet EMA's 75% load factor — signalling a policy shift toward reliability in regional power trade. Conditional licenses have so far only been granted to projects from Indonesia, and these will require more regulatory approvals and financial close before being considered for an import license.
- EMA has signalled readiness to issue 30-year import licences to support long-term investments required for large-scale infrastructure like subsea cables and solar/battery setups; a crucial step for investor confidence.
- Under the Singapore Green Consortium, a 1 GW interconnector is planned by 2030. Realising these regional interconnections involves an estimated US$20–30 billion in investments across solar farms, batteries, and subsea cables across ASEAN.

Sources: EMA, Reuters, Pinsent Mason

List of existing and proposed import initiatives

Company	Planned imports	Project details	Status
Laos–Thailand–Malaysia–Singapore Power Integration Project	0.2 GW	Hydropower from Lao PDR, transmitted via Thailand and Malaysia. Import started in June 2022.	Active
Sembcorp Power Pte Ltd	0.05 GW	Green electricity sourced from Malaysia's Energy Exchange (ENEGEM) Platform. Import started from December 2024 and will run for a 2-year pilot.	Active
Pacific Medco Solar	0.6 GW	Located in Bulan Island, Indonesia. 2,000MWp of solar PV and 500MW of BESS. Target operational from 2028.	Conditional license
Adaro Solar International Pte Ltd.	0.4 GW	Details not yet disclosed.	Conditional license
EDP Renewables APAC	0.4 GW	Details not yet disclosed.	Conditional license
Vanda RE Pte Ltd	0.3 GW	Located in the Riau Islands, Indonesia. 2GW of solar capacity and 4,400MWh BESS. Target operational in phases by 2032.	Conditional license
Keppel Energy Pte Ltd	0.3 GW	Located in the Riau Islands, Indonesia. 2GW of solar PV integrated with BESS.	Conditional license
	1 GW	Import electricity to come from various RE sources in Cambodia. Import expected to commence after 2030.	Conditional approval
Singa Renewables	1 GW	Located in the Riau islands, Indonesia. Undisclosed capacity of solar PV and BESS. Target operational from 2029.	Conditional license
Shell Eastern	0.4 GW	Located in the Riau islands, Indonesia. 2 GW of solar PV and 8000 MWh of BESS. Target operational after 2030.	Conditional approval
Sembcorp Utilities Pte Ltd	1.2 GW	Imported electricity to come from offshore wind power and other sources in southern Vietnam. Target operational after 2030.	Conditional approval
Sun Cable (Singapore) Assets Pte Ltd	1.75 GW	Imported electricity to come from solar power in Australia's Northern Territory. Target operational after 2035.	Conditional approval

Methodology

How we modelled CFE across the project and for Singapore

Key modelling design features

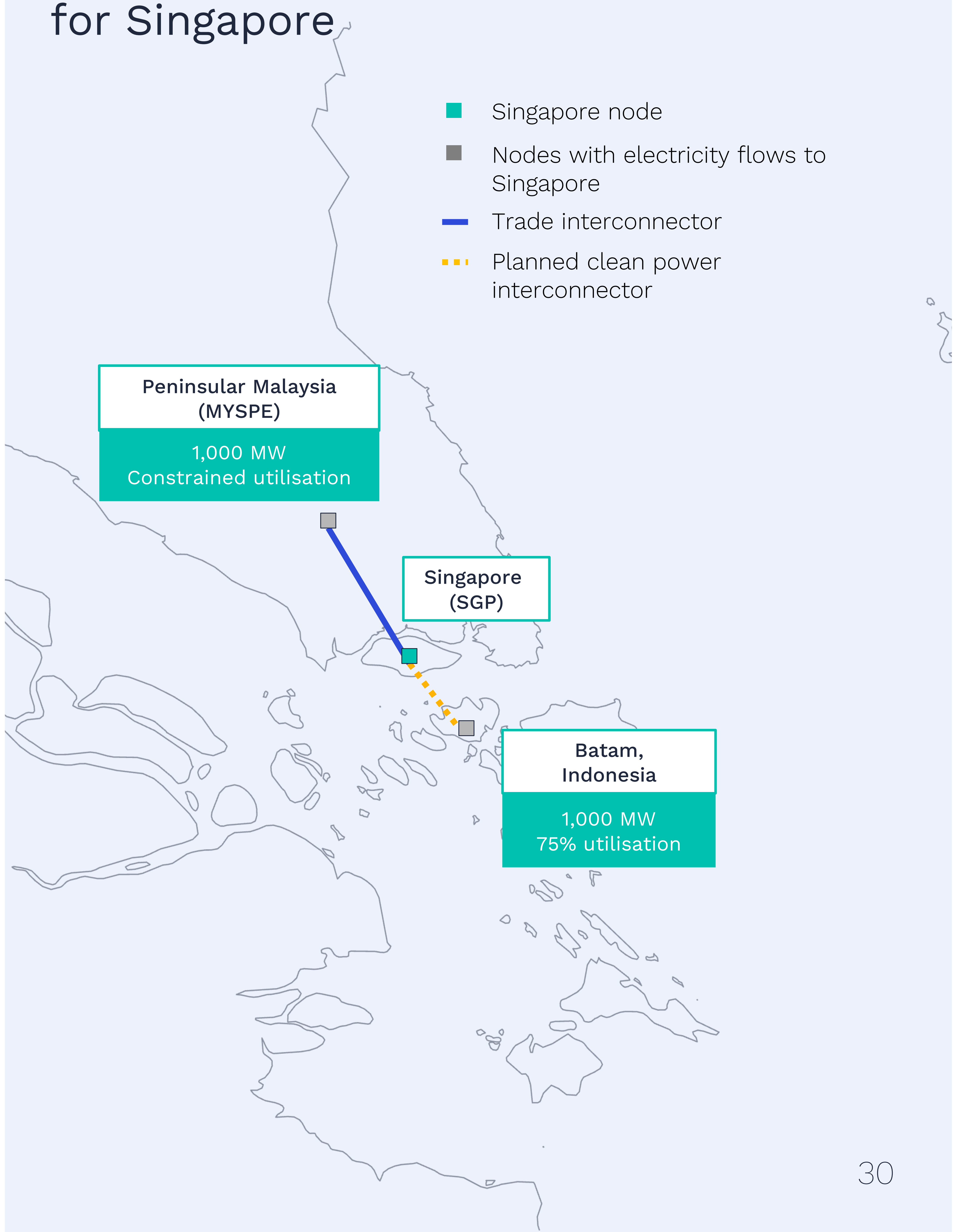
Relevant parameters of the 24/7 CFE model

- **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:** Projected national demand, plus increased growth from emerging sectors.
- **CFE demand profile:** Proportional to overall demand profile in each grid region.
- **Interconnectors:** 2 international interconnectors with different utilisation requirements. Adhering to Singapore's targets, we place a 75% flow requirement for planned clean power imports from Indonesia. The existing line to Malaysia is assumed to operate at lower utilisation, as it serves only as balancing capacity.

Explore the full methodology

A detailed explanation of our modelling assumptions and methodology, along with other TransitionZero CFE country reports, is available at: www.transitionzero.org/cfe

Nodes & interconnectors modelling for Singapore



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]

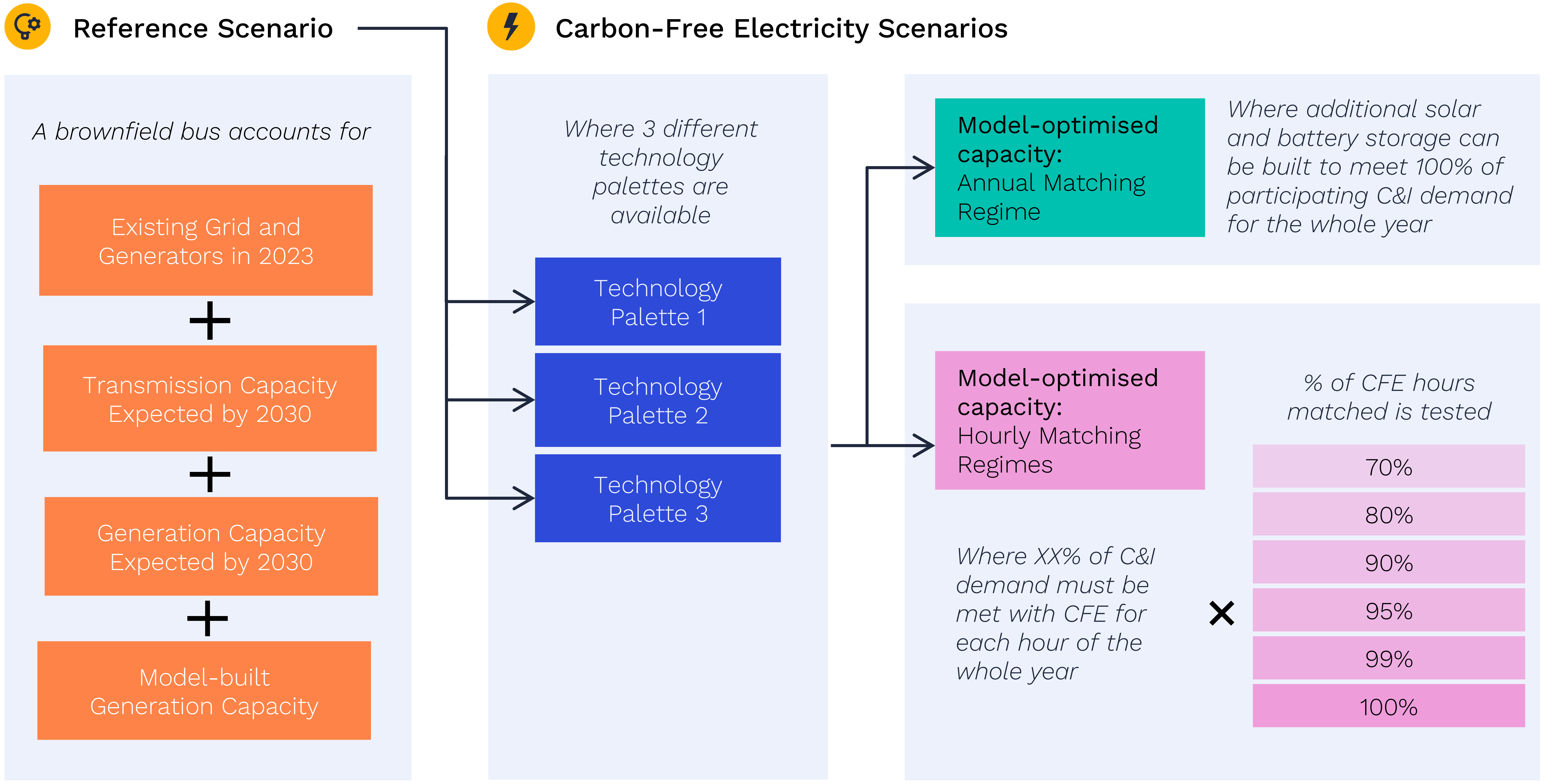
- Planned expansions
- Capacity mix targets
- Decarbonisation targets
- Transmission plans

---

[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.

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



Reference Scenario

A brownfield bus accounts for

Existing Grid and Generators in 2023

\+

Transmission Capacity Expected by 2030

\+

Generation Capacity Expected by 2030

\+

Model-built Generation Capacity

Carbon-Free Electricity Scenarios

Where 3 different technology palettes are available

Technology Palette 1

Technology Palette 2

Technology Palette 3

Model-optimised capacity: Annual Matching Regime

Where additional solar and battery storage can be built to meet 100% of participating C&I demand for the whole year

Model-optimised capacity: Hourly Matching Regimes

Where XX% of C&I demand must be met with CFE for each hour of the whole year

×

% of CFE hours matched is tested

70%

80%

90%

95%

99%

100%

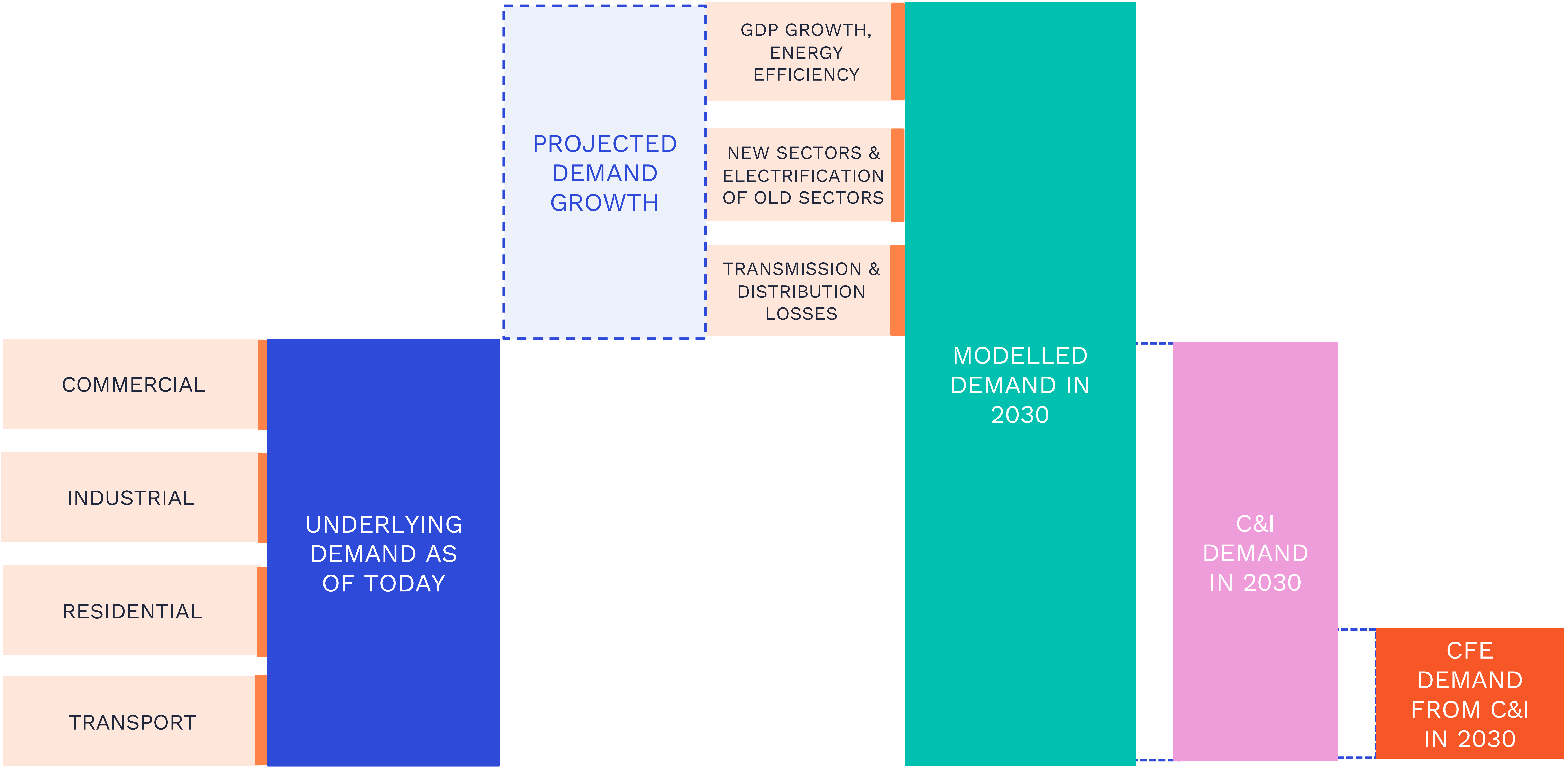
Notes

- 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.

Demand in 2030

Our model considers demand for both conventional electricity and CFE

Illustration of components contributing to modelled final demand



COMMERCIAL

INDUSTRIAL

RESIDENTIAL

TRANSPORT

UNDERLYING DEMAND AS OF TODAY

PROJECTED DEMAND GROWTH

GDP GROWTH, ENERGY EFFICIENCY

NEW SECTORS & ELECTRIFICATION OF OLD SECTORS

TRANSMISSION & DISTRIBUTION LOSSES

MODELLED DEMAND IN 2030

C&I DEMAND IN 2030

CFE DEMAND FROM C&I IN 2030

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.
- To reflect structure changes in electricity consumption, we incorporated incremental demand beyond GDP-linked growth, accounting for emerging high-load activities and firm C&I demand.
- 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%

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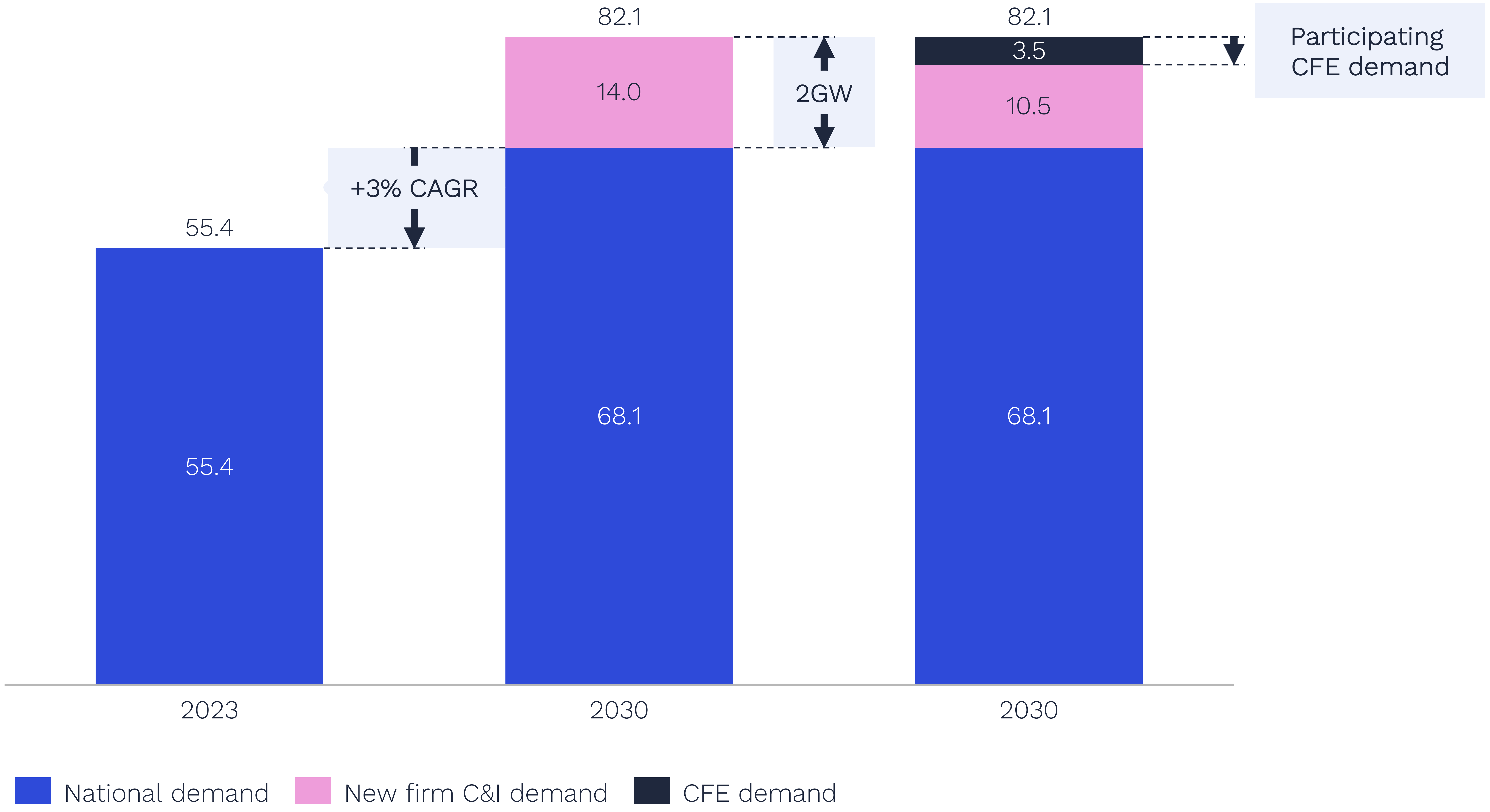
[1] Bottom-up in-house projection done for Japan only.

3.5 TWh of Singapore's 2030 power demand is assumed to participate in 24/7 CFE

Singapore's demand (TWh) in 2023 and 2030



Notes

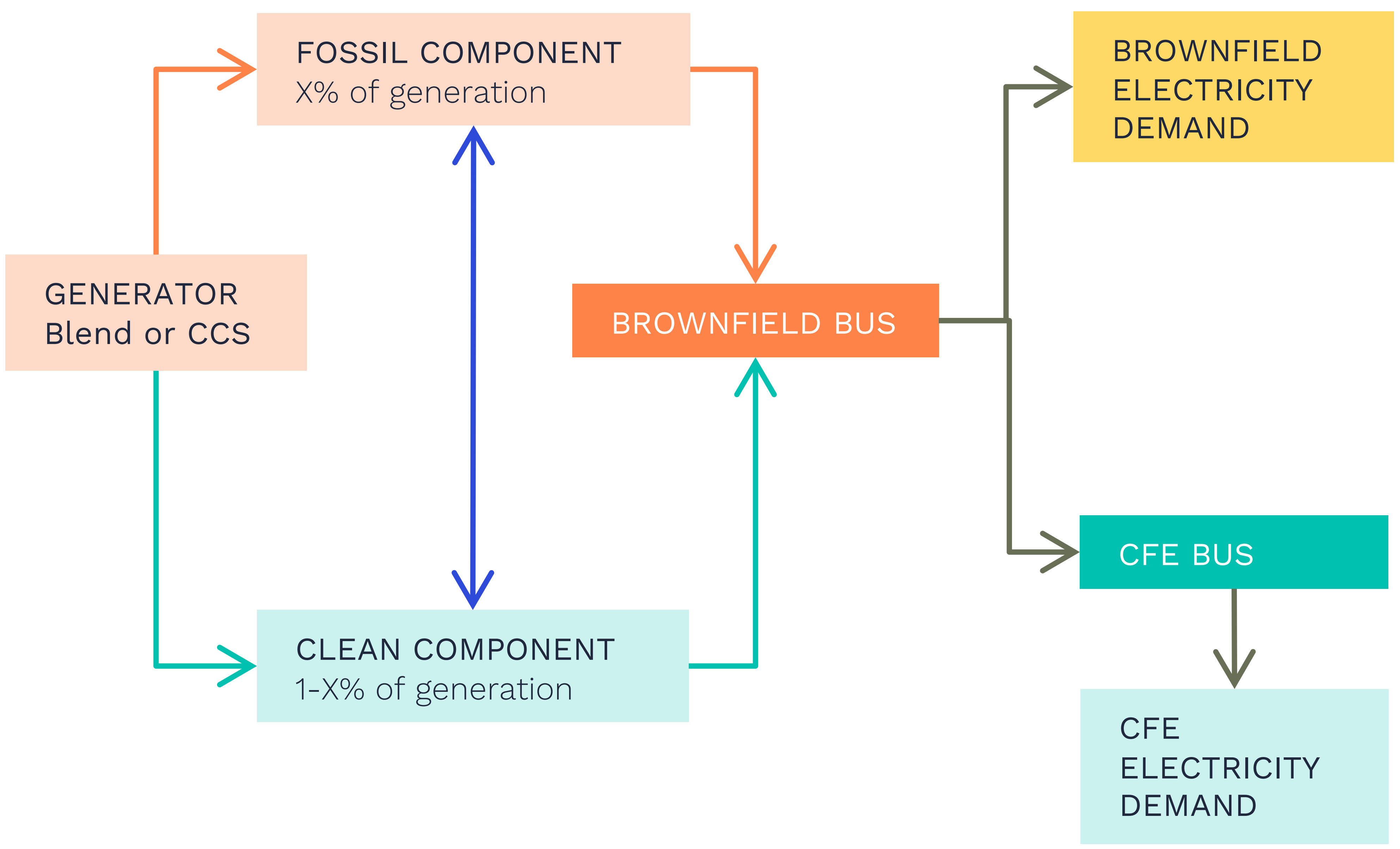
- We assume national electricity demand growth between 2023 and 2030 is 3% CAGR, in line with EMA' estimates.
- In addition to new sources of electricity demand accounted for in the national growth estimate, an additional 2GW of firm C&I demand is projected to come online by 2030, based on current market data and government plans.
- In our CFE scenarios, we assume the portion of demand is 25% of firm C&I demand – or 3.5TWh.

Source: EMA for 2023 data, TransitionZero for 2030 projection

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



GENERATOR
Blend or CCS

FOSSIL COMPONENT
X% of generation

CLEAN COMPONENT
1-X% of generation

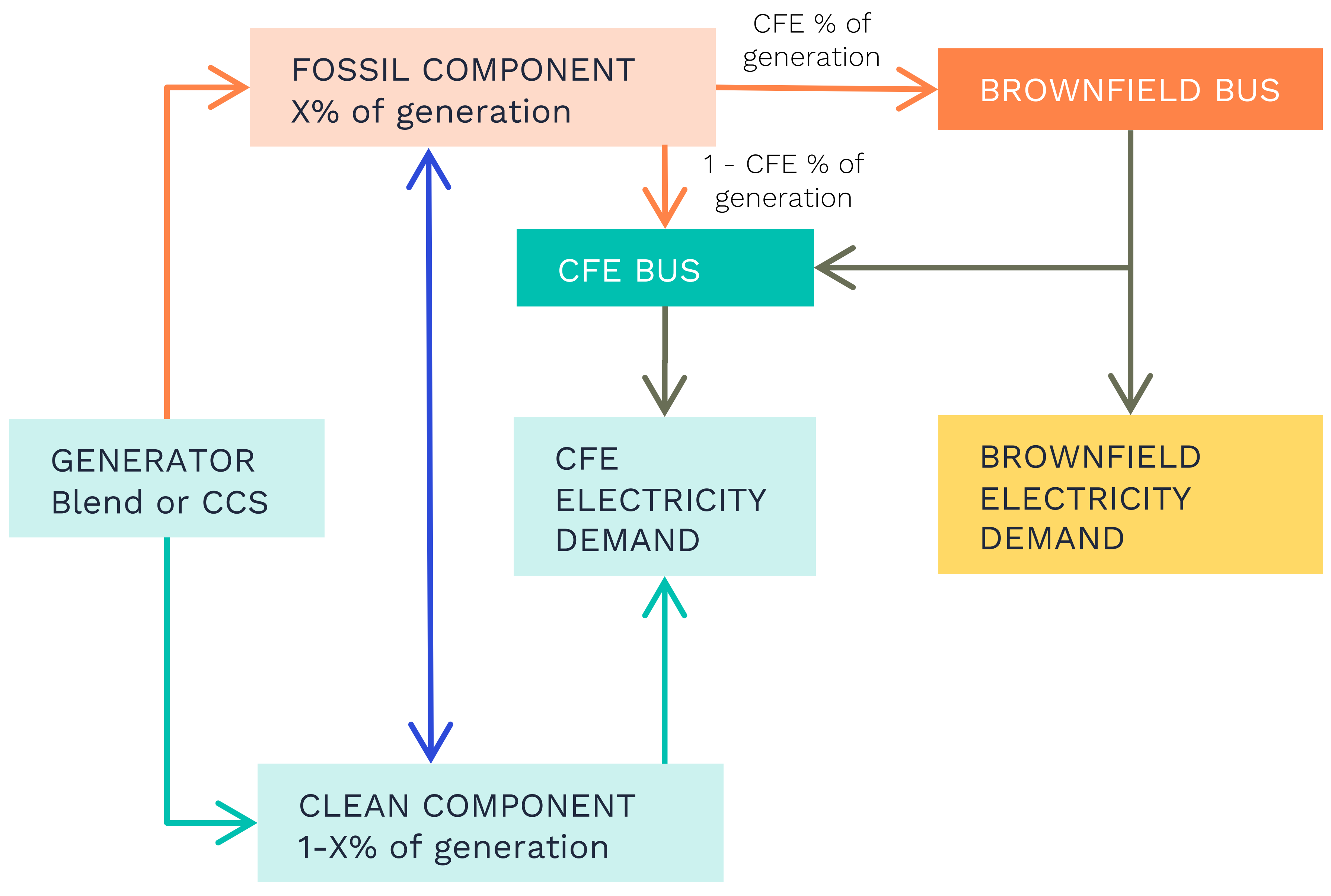
BROWNFIELD BUS

BROWNFIELD ELECTRICITY DEMAND

CFE BUS

CFE ELECTRICITY DEMAND

Built on the greenfield



GENERATOR
Blend or CCS

FOSSIL COMPONENT
X% of generation

CFE % of generation

BROWNFIELD BUS

1 - CFE % of generation

CFE BUS

CFE ELECTRICITY DEMAND

BROWNFIELD ELECTRICITY DEMAND

CLEAN COMPONENT
1-X% of generation

🟦	CFE ratio of generation
🟩	CFE generation
🟧	Non-CFE generation
▬	CFE share of brownfield mix
🟨	Non-CFE share of brownfield mix

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, again, on the target matching regime.

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

---

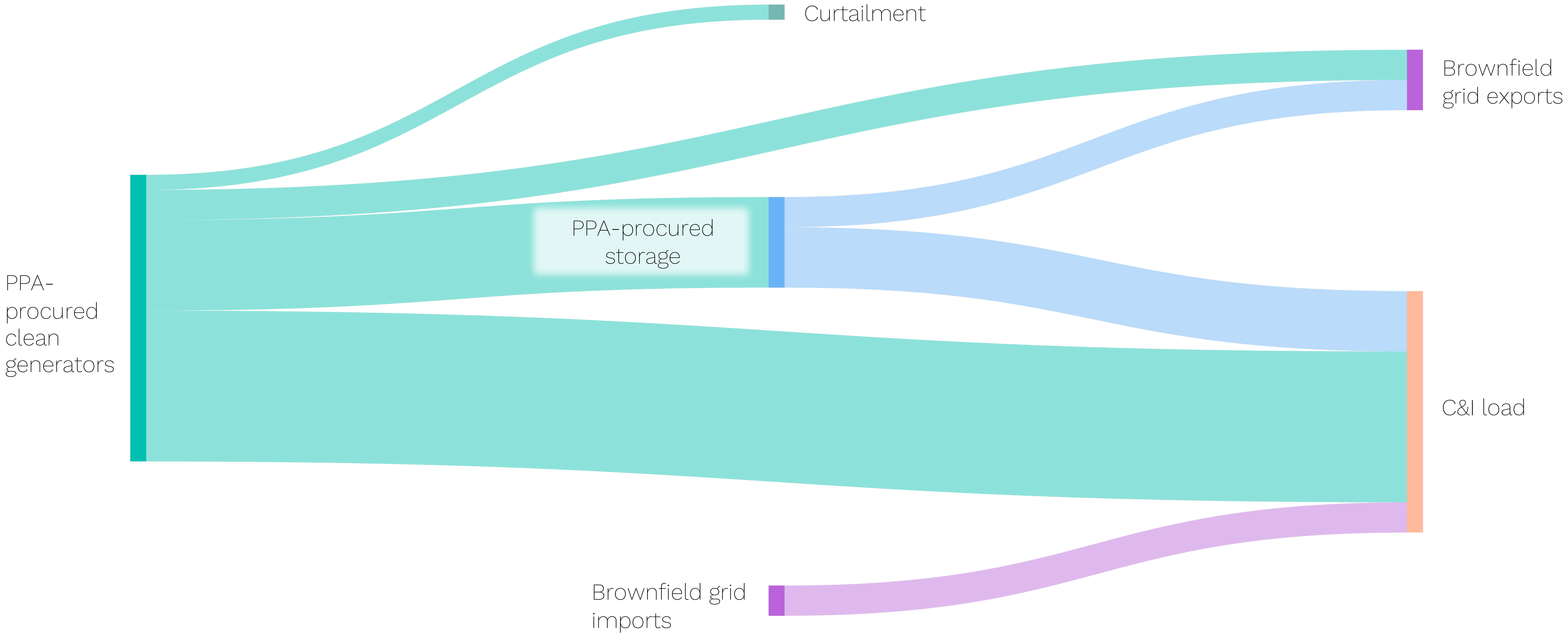
[1] Expressed as the CFE share of the hourly matching regime.

[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.

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:

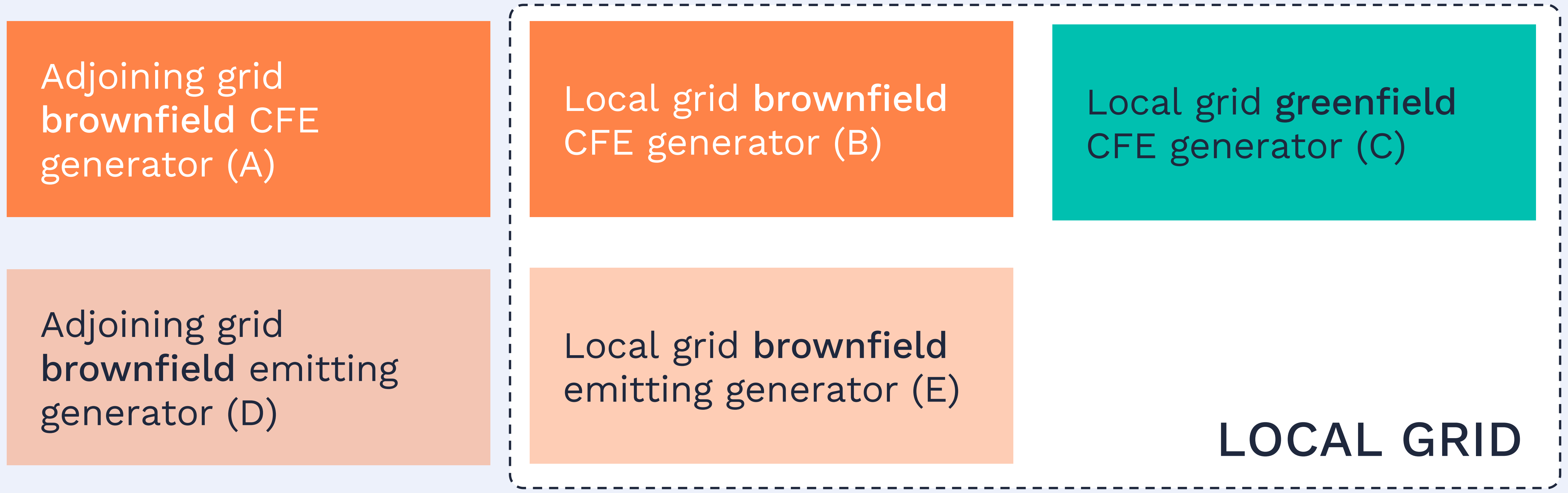
$$\text{Unit cost} = A \times \frac{\text{capex + opex + grid export revenue}}{\text{C\&I load} - \text{grid imports} + \text{grid exports}} + (1-A) \times \frac{\text{grid import costs}}{\text{grid imports}}$$

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

- 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



Adjoining grid **brownfield** CFE generator (A)

Local grid **brownfield** CFE generator (B)

Local grid **greenfield** CFE generator (C)

Adjoining grid **brownfield** emitting generator (D)

Local grid **brownfield** emitting generator (E)

LOCAL GRID

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

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

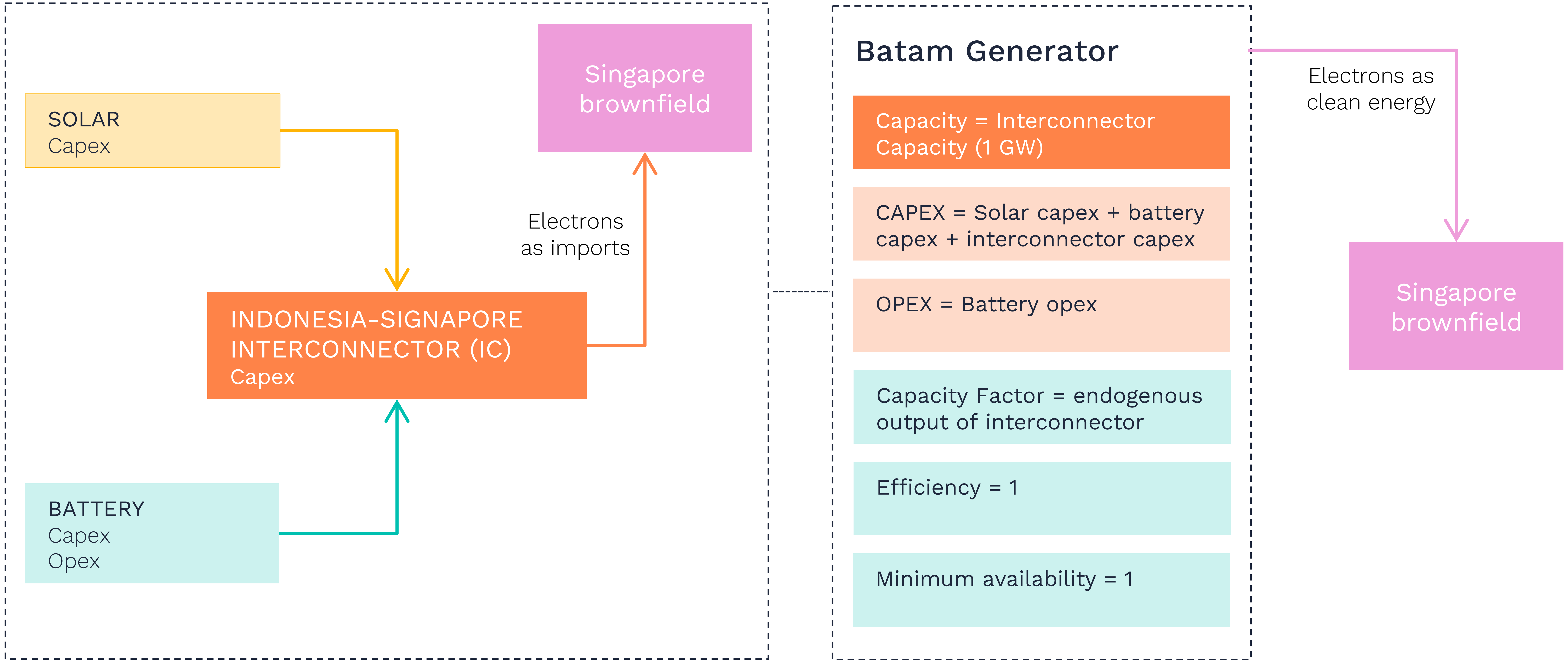
- To determine whether C&I consumers can use the brownfield grid to meet their target CFE score, we calculate a 'grid CFE score', showing what ratio of all brownfield generation comes from CFE sources.
- When C&I consumers use brownfield procurement to top up insufficient PPA generation, if their local 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.

Solar Imports to the brownfield

We implement a 2-step process to represent Batam solar contributions in the CFE score

Model run 1: Indonesia-Singapore interconnection

Model run 2: Batam solar as a generator



SOLAR
Capex

BATTERY
Capex
Opex

INDONESIA-SIGNAPORE INTERCONNECTOR (IC)
Capex

Electrons as imports

Singapore brownfield

Batam Generator

- Capacity = Interconnector Capacity (1 GW)
- CAPEX = Solar capex + battery capex + interconnector capex
- OPEX = Battery opex
- Capacity Factor = endogenous output of interconnector
- Efficiency = 1
- Minimum availability = 1

Electrons as clean energy

Singapore brownfield

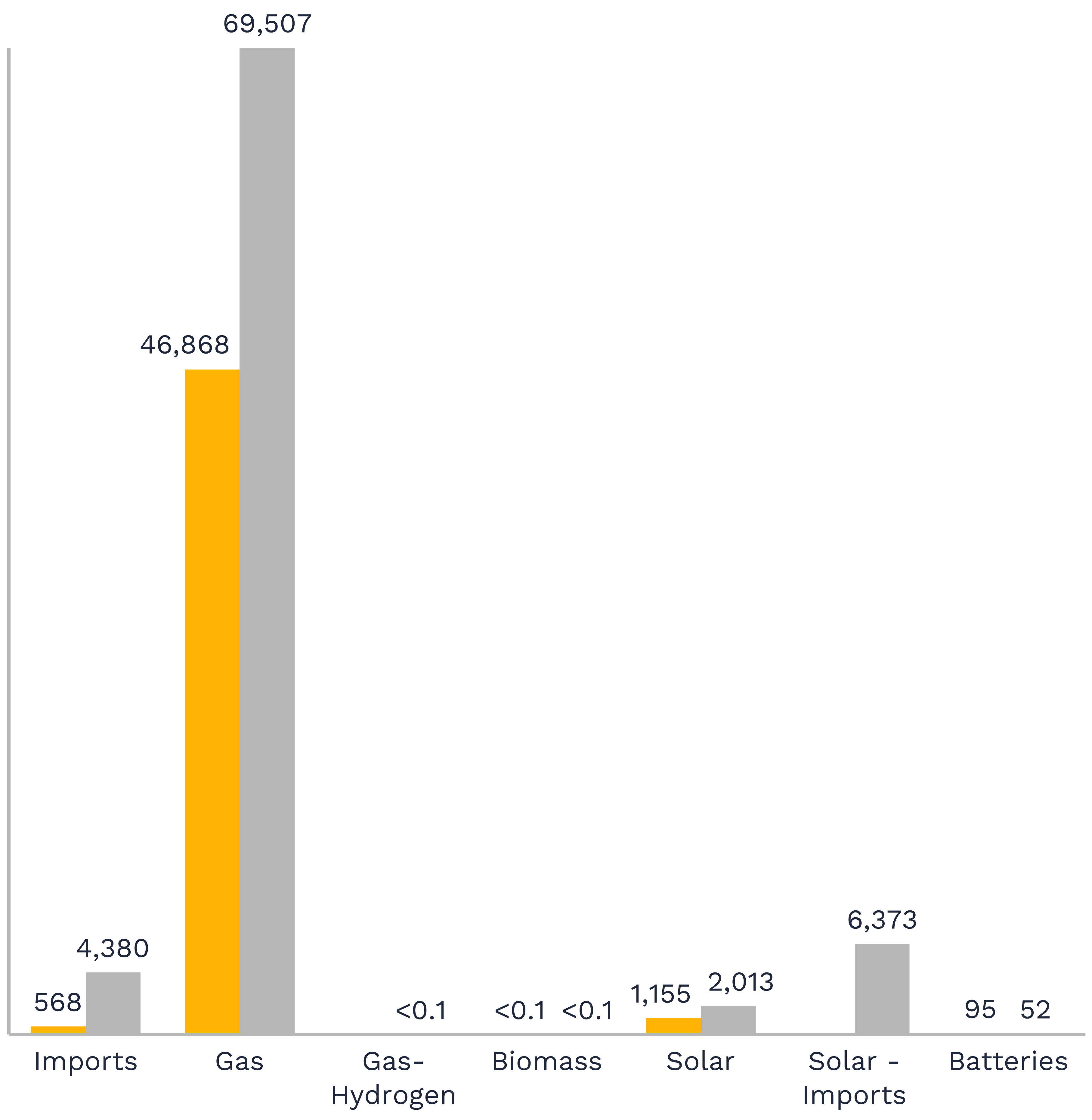
Notes

- The model architecture sees imports as a neutral generator that does not count towards the base grid CFE score.
- To ensure that solar from Batam was recognised as clean, and able to contribute to CFE demand, we ran a two-step process.
- A first run was done to endogenously determine the solar and battery capacity that will allow the connector to meet the 75% utilisation requirement. This also determined the full project investment cost, tech parameters and profile.
- This was added as a clean generator in a second model run.

Creating the 2030 reference scenario (1/2)

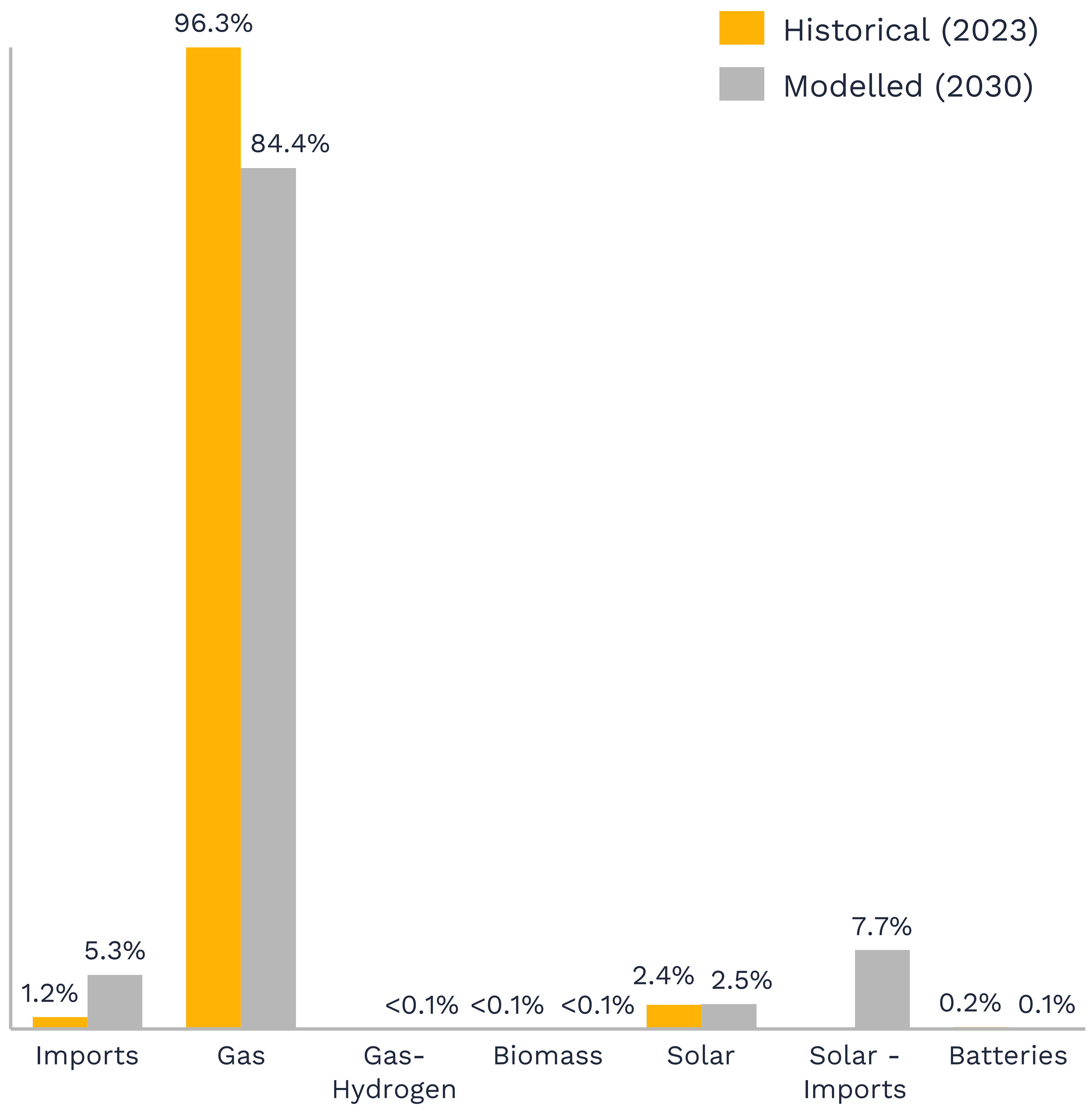
Solar grows, gas dominates, and imports rise to meet future demand

Total Generation (GWh)



[1] *Capacity factors*

Share of Generation (%)



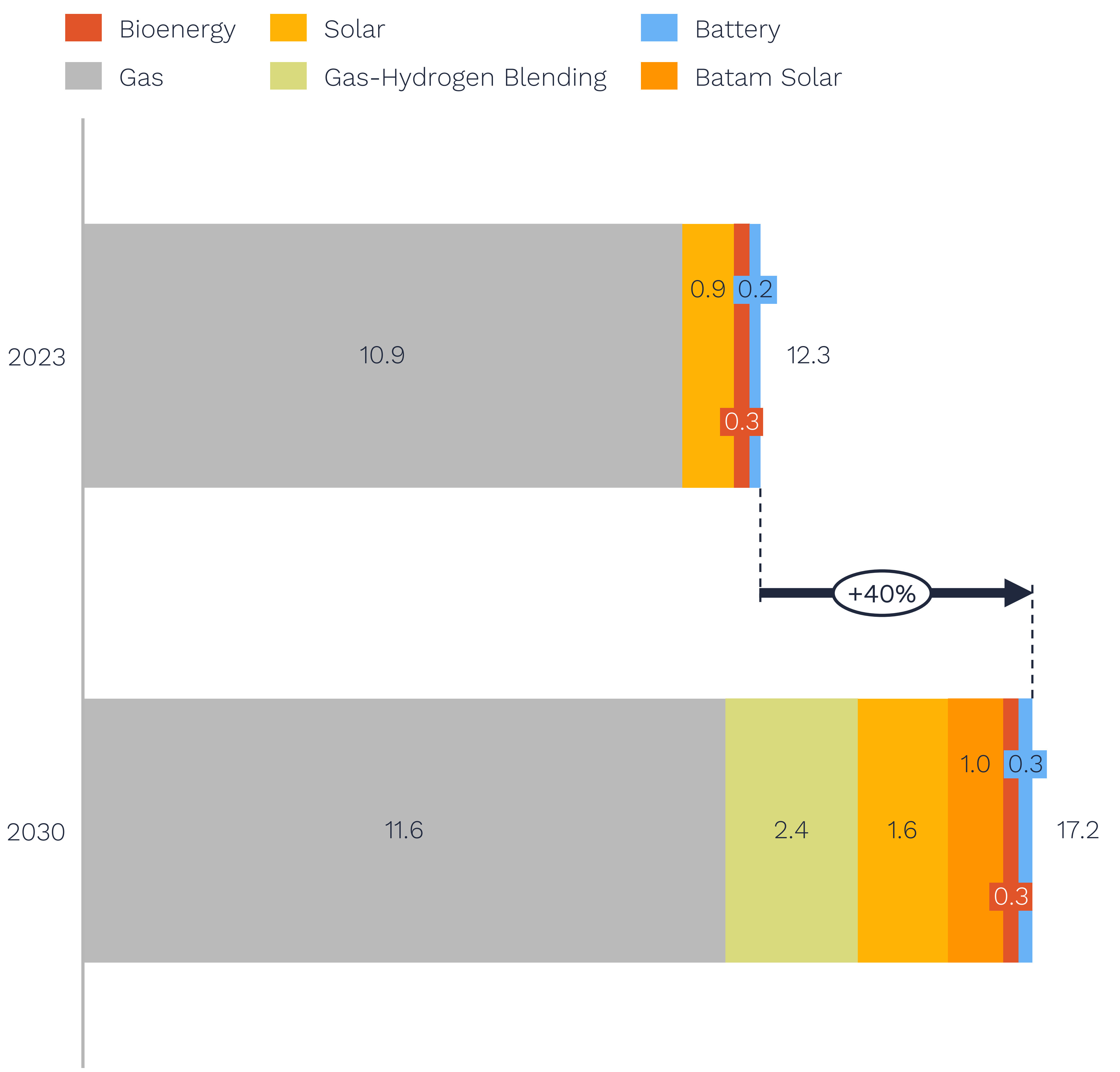
2030 capacity guidelines

- **Calibration**: Historical data in 2023 was used to represent the generation pattern reported by Singapore's EMA.
- **Policy targets**: 1.6 GW of solar capacity, a 60 $MtCO_2$ emissions peak in the power sector, and a 30% minimum hydrogen blending have been added as constraints.
- **Technology expansion**: Gas generation is allowed to expand in 2030, while RE resources remain limited in Singapore. As a result, gas continues to be the main source of electricity generation, even though solar output almost doubles.
- **Innovative thermal technologies:** Blended gas and hydrogen plants begin to contribute to the generation mix in 2030, but their role remain minor.
- **Batam solar:** A 1 GW interconnector is powered by 4 GW of solar and 1.6 GW of batteries, contributing nearly 8% of clean power to the 2030 Singapore grid.
- **Interconnectors**: Singapore may import up to 4.3 TWh of electricity from Malaysia Peninsular by increasing utilisation of the existing line to 50%. As generation sources for imports are currently unspecified, imports from this line do not contribute directly to CFE.
- **The role of imports in meeting increasing demand and decarbonisation**: Total imported generation will account for approximately 13% of demand, which is expected to increase by 61% between 2023 and 2030.

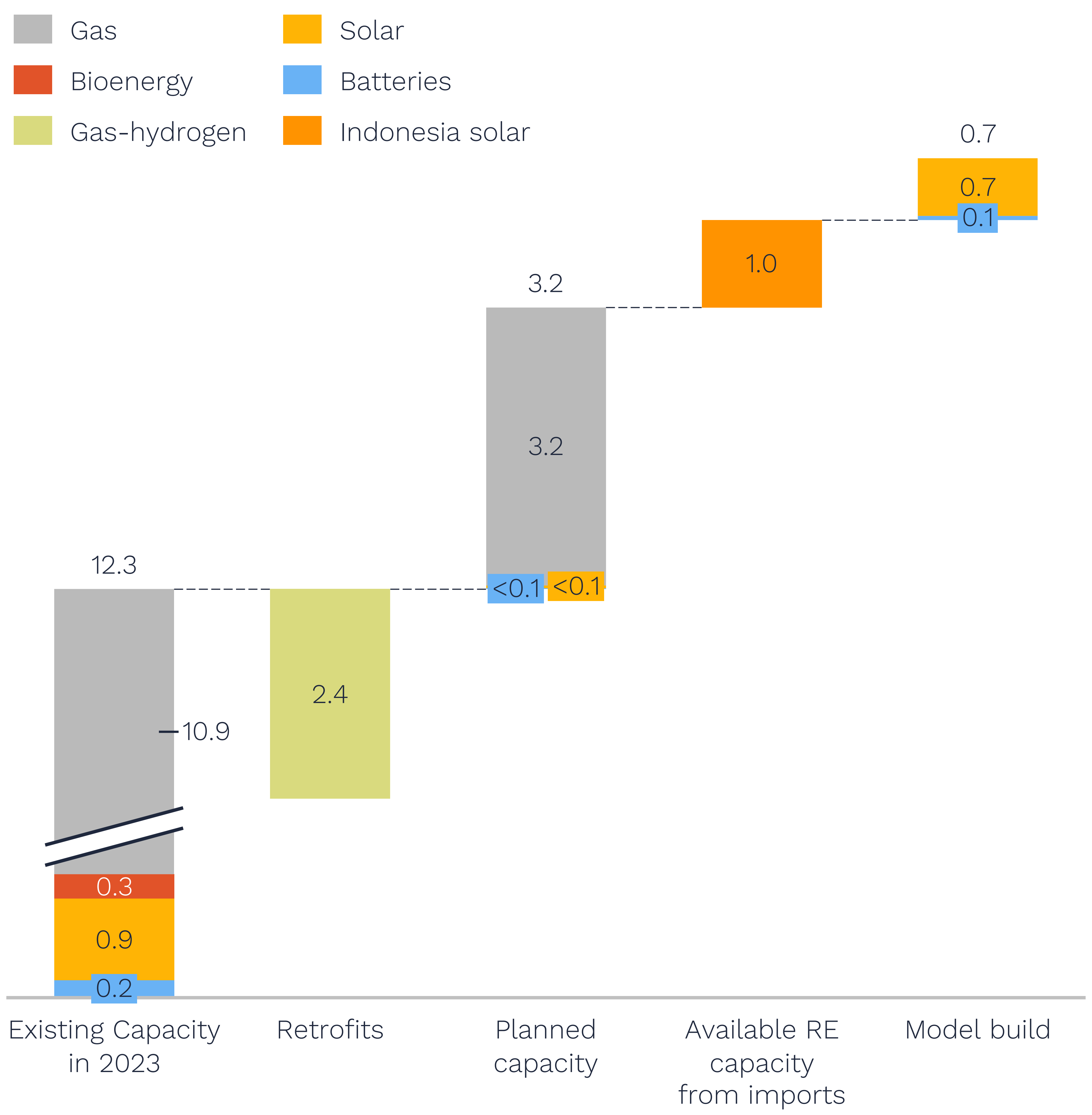
Creating the 2030 reference scenario (2/2)

Installed capacity expands by 40%, with clean energy generation share increasing to 32%

Installed capacities (GW)



Breakdown of 2030 installed capacities (GW)



2030 capacity guidelines

- Our dispatch model incorporates the planned capacity announced by the project developers and optimises the need for any additional build needed to meet projected demand, which we estimated to increase by 3% CAGR between 2023 and 2030. (See Annex for detailed input data).
- Installed capacity is projected to grow by 40% (4.6 GW) by 2030, dominated by gas and solar expansion.
- Singapore plans to retrofit 2.4 GW of existing gas capacity with hydrogen blending turbines, as well as add 3.2 GW of new gas capacity. Taken together, the planned gas fleet by 2030 totals 14.8 GW.
- An additional 0.7 GW of unassigned projects is built by the model to cover remaining demand on the brownfield grid.

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 power mix. As with any forecast, the evolution of Singapore'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, as well as higher build out of firm C&I could increase demand projections to higher than expected. 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, though in practice profiles between consumer types will differ. Commercial demand is daytime-heavy and easier to serve with solar and with weekend shutdowns creating lower demand on the grid. Industrial demand is flatter and harder to match without wind or long-duration storage — implying very different 24/7 CFE challenges. 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. **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 15% (this prevents optimising for the grid rather than the C&I load); and iii) participating CFE demand is 4% of total electricity demand. These assumptions represent our best judgement of how to faithfully model CFE in the Singapore power sector, but these assumptions can also have a large impact on the modelling results. The sell-back criteria is based on previous literature, meaning 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.

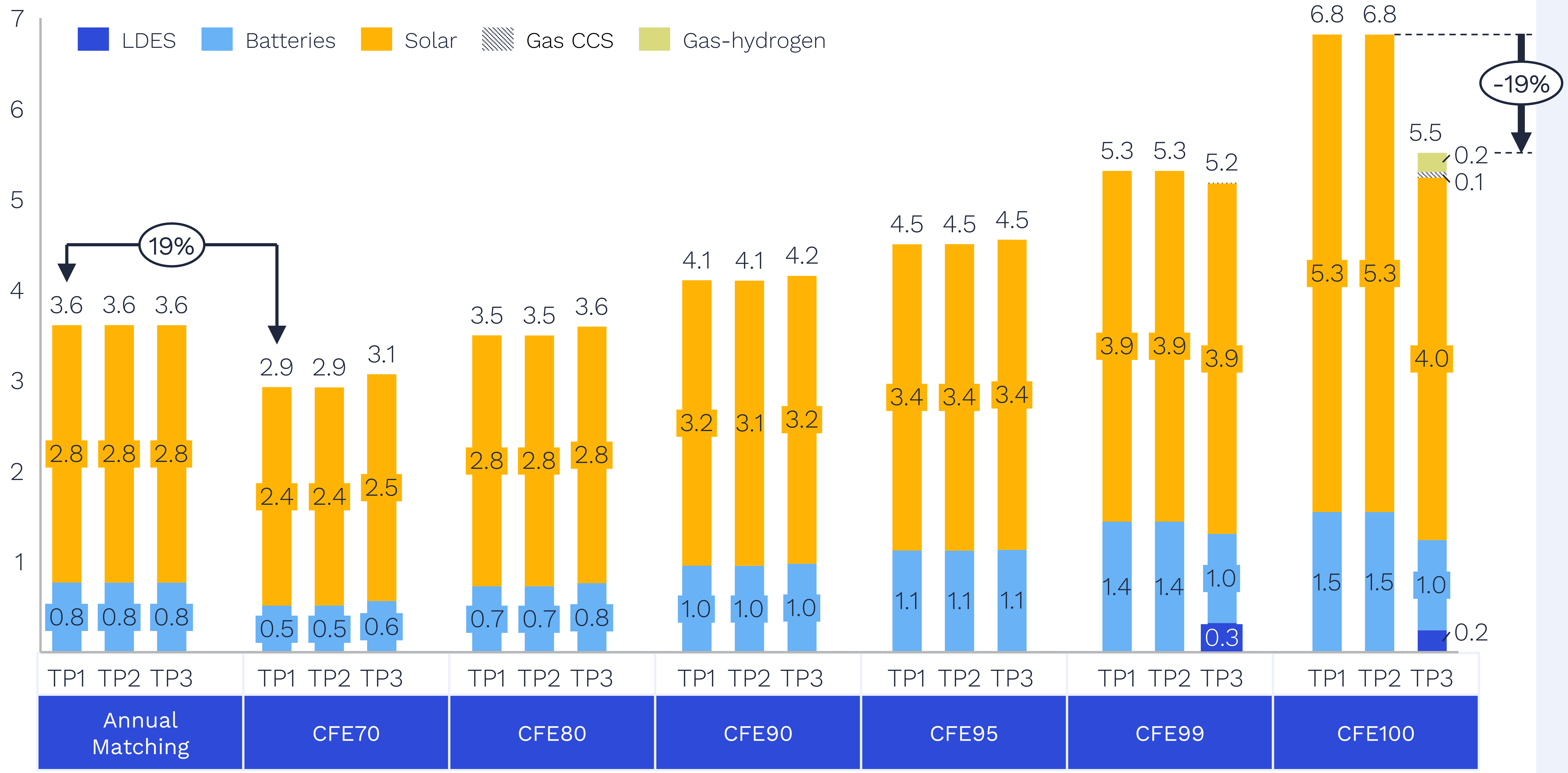
Modelling results

Deep-dive analysis into the findings

How much capacity does hourly matching need?

Solar & batteries dominate 24/7 clean power portfolios, as technologies like LDES and innovative thermal play niche roles in closing the final gap to 100% CFE

Greenfield capacity when 4% of national demand adopts CFE (GW)

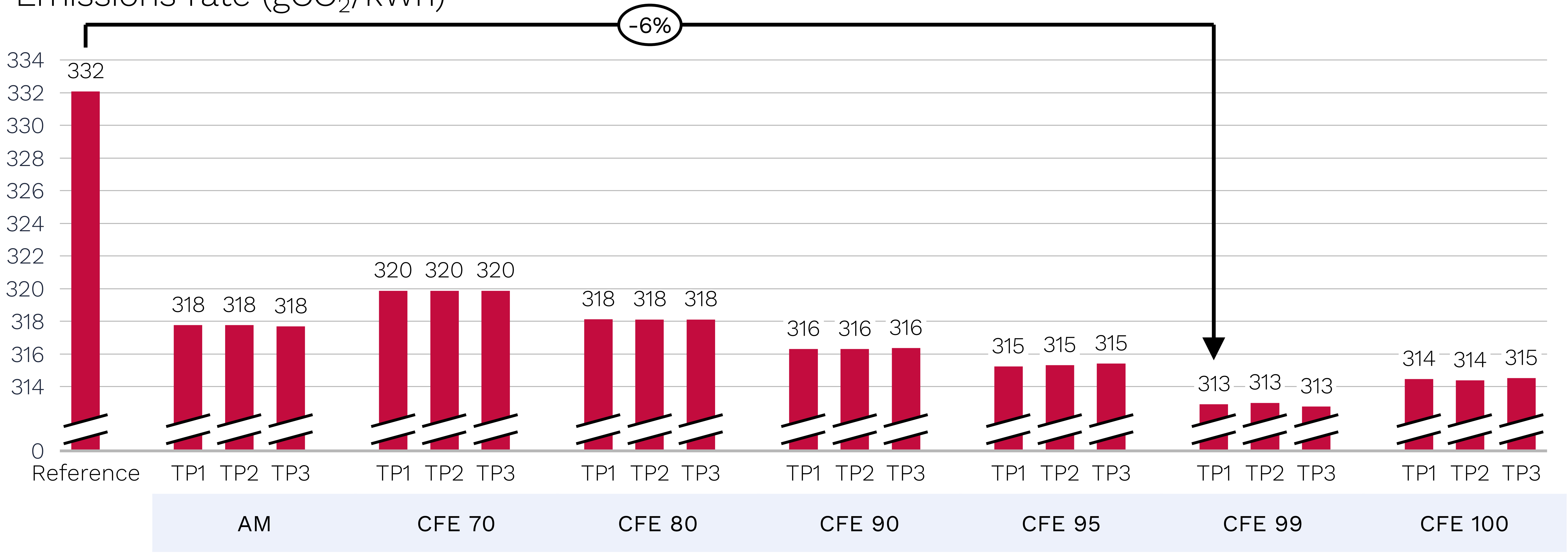


Notes

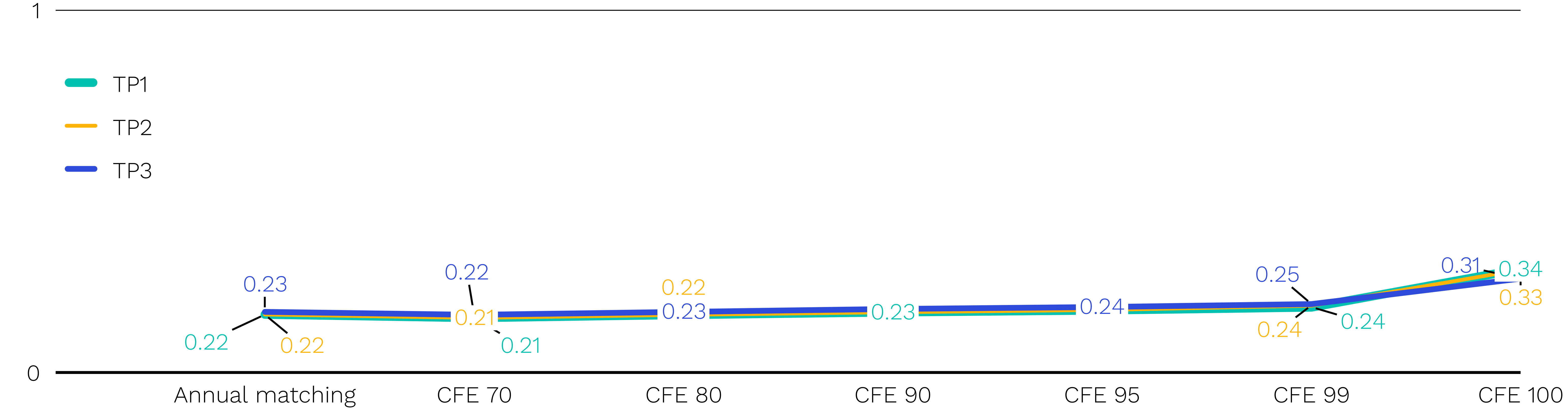
- Annual matching build-out of 3.6 GW closely resembles the capacity required to reach 80% CFE, which can be achieved with a relatively modest addition of 2.8 GW of solar and 0.7 GW of battery storage, along with some electricity purchased from the grid. Beyond this point, CFE investment rises sharply to enable more ambitious hourly matching.
- Solar and batteries form the backbone of CFE procurement, enabling cost effective matching of load and clean generation. Solar provides abundant, low-cost power during the day, while batteries shift this energy into non-solar hours. Both are mature and widely deployable with falling costs, making them a first-choice solution.
- LDES has a limited role, only deployed in TP3 at 99-100% CFE. Its low uptake reflects its high-cost relative to system value in this specific portfolio design. If longer durations — such as week-long — were available and integrated, it could alter the least-cost resource mix and reduce overbuild of solar and battery. Future improvements in LDES economics or policy support could shift this result.
- Gas-CCS in TP3 is deployed only to meet the most difficult-to-match hours for 100% CFE. The addition of 60 MW of gas-CCS and 212 MW of gas-hydrogen blending, along with 237 MW of LDES, helps reduce procured solar capacity by 30% and battery capacity by nearly 35% relative to TP1. These technologies are capital-intensive but provide flexible and firm capacity, reducing the need for overbuild of solar and storage.

Emission reductions

Clean exports aid decarbonisation, but storage and high CFE targets raise abatement costs when seeking to go beyond 90% CFE



Emissions rate (gCO$_2$/kWh)



Carbon abatement cost (US$/kgCO$_2$)

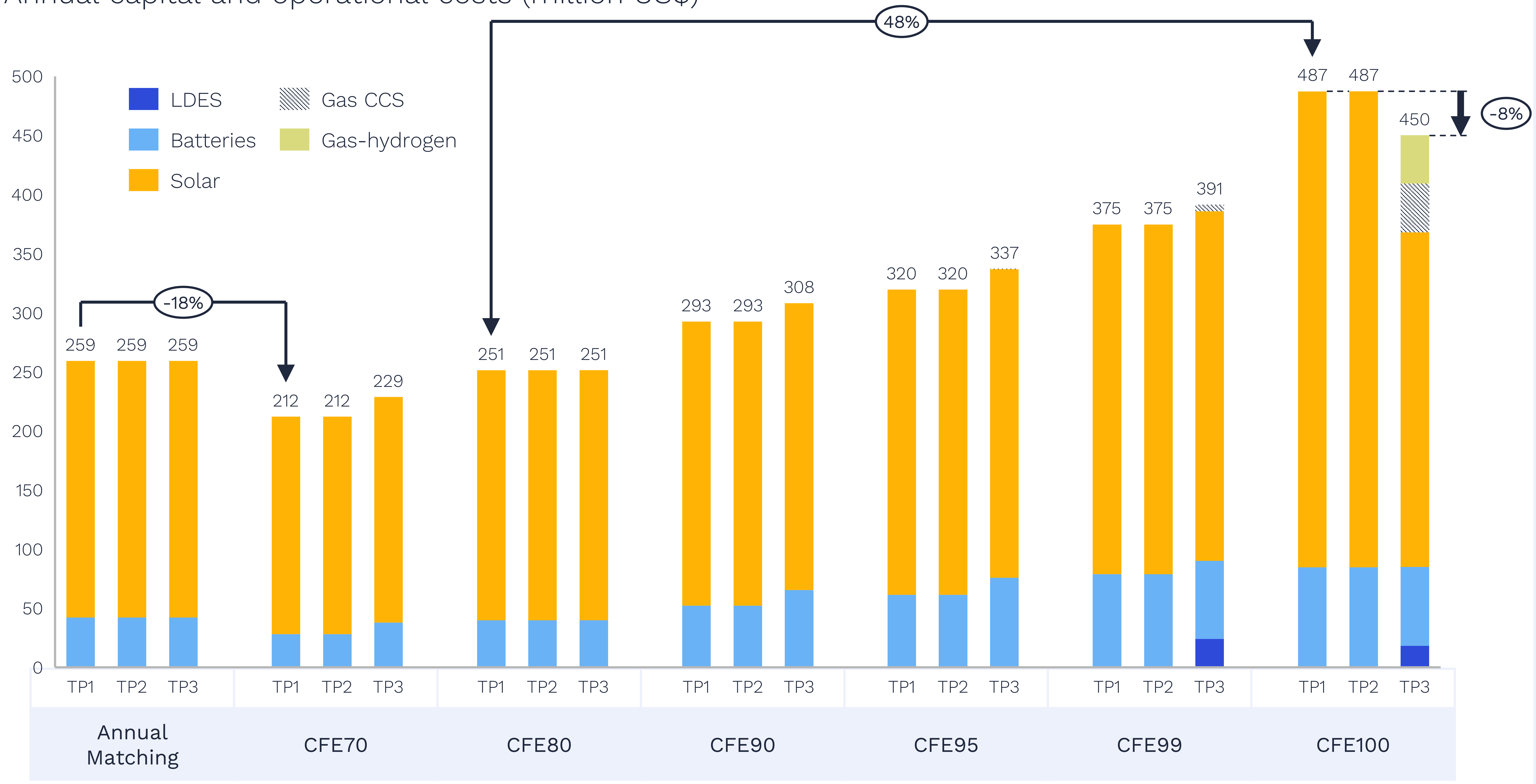
Notes

- Although greenfield emissions from participating C&I consumers account for just 4.3% of national electricity demand, it can enable up to nearly 6% of total system emission reductions.
- Carbon abatement cost is lower under from 70-90% CFE in comparison to annual matching. It progressively increases beyond 90% CFE, as a result of overbuild in procurement costs, rising sharply at 100% CFE as the model overbuilds solar and battery capacity well beyond cost-optimal levels — raising marginal abatement costs despite relatively modest additional emissions reductions beyond 95% CFE.
- Emissions associated with participating CFE loads under annual matching (318 gCO2/kWh) are lower than the total emissions in the Reference Scenario (332.1 gCO2/kWh), reflecting that potential of clean C&I procurement to offset the climate impact of new demand.
- While TP3 lowers direct C&I costs to reach 100% CFE relative to other palettes, it does so by adding dispatchable firm assets (e.g. gas with CCS or hydrogen), which introduce emissions 'leakage' into the system. This makes the approach somewhat counterproductive — trading lower C&I procurement costs for increased system emissions — and raises questions about whether it is a cost-effective use of resources at high CFE levels. Their use — although limited — contributes to a slightly higher system-wide emissions in comparison to TP1 and TP2 when deployed to meet 100% CFE (315 gCO2/kWh).

Pursuing 100% CFE Comes at a High Cost

Cleaner, high-CFE scenarios demand more solar and costly storage — making 100% CFE nearly twice as expensive as 80% CFE

Annual capital and operational costs (million US$)



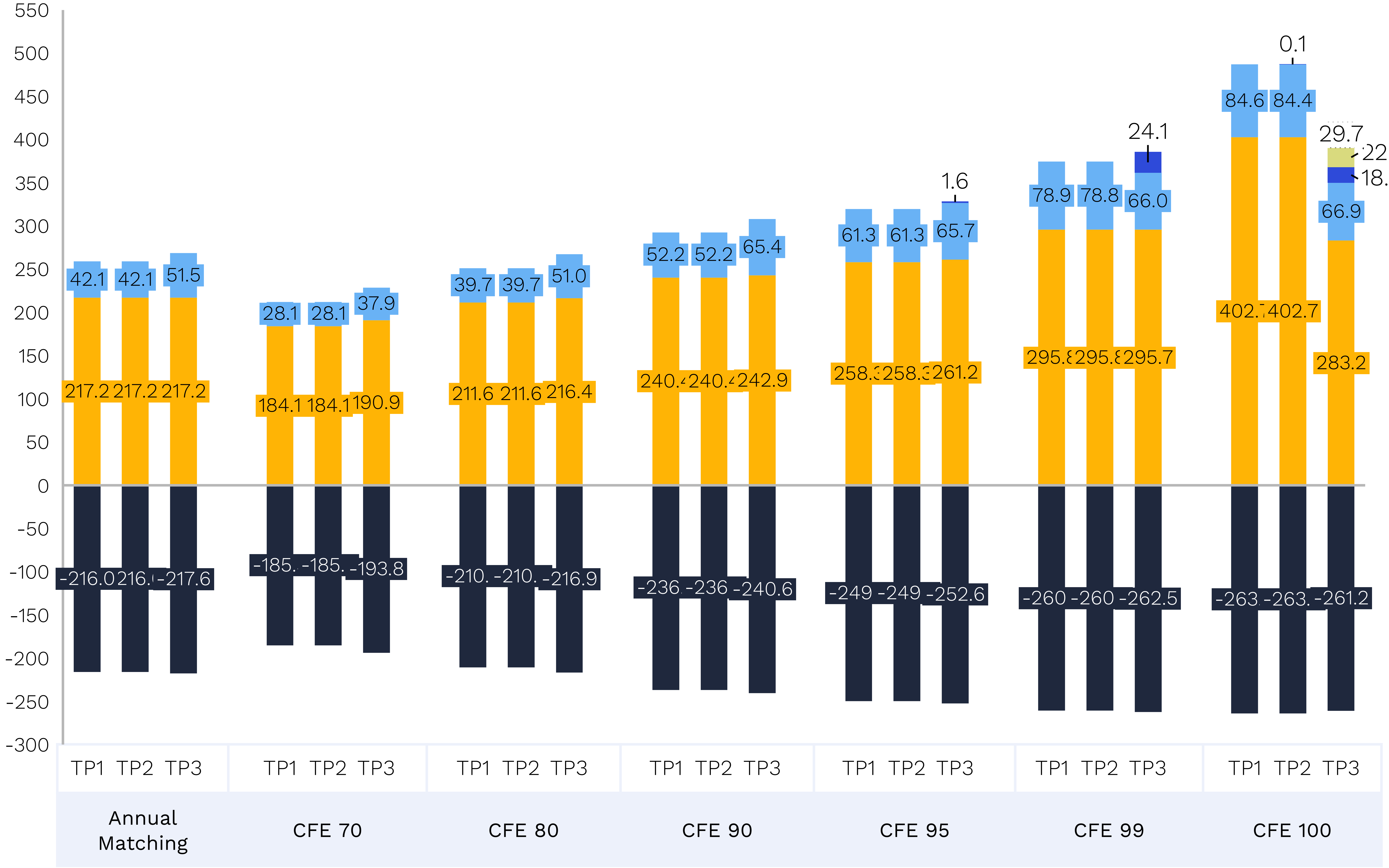
Notes

- A 70% CFE target is cost-effective against annual matching with 18% less capital and operational costs required (approximately US$47 million less).
- Achieving 80% CFE delivers similar costs, fuel savings and emissions reductions as annual matching. Pushing towards 100% CFE, however, brings greater emissions benefits for the system as a whole.
- Moving from 80% to 100% CFE nearly doubles total system costs, driven by the need to build solar-plus-batteries to extend cover to non-sunlight hours and reduce dependence on the grid to ensure hourly clean matching.
- LDES in TP2 is not deployed in most scenarios, seen to be useful only when other firm power is available. This is largely because vanadium redox flow batteries offer only modest storage duration gains — 6 additional hours — at significantly higher cost compared to lithium-ion batteries. The model finds it more cost-effective to overbuild solar and lithium-ion storage — even with higher curtailment and energy needs — than to scale up LDES. This is due to the limited marginal value of LDES and a sell-back cap which restricts revenue gains from discharging stored energy.
- Blending technologies could reduce costs associated with overbuilding solar for 100% CFE by US$36 million, but the breakdown of costs show a higher fuel cost burden in comparison to solar and battery only.

Higher CFE levels brings grid savings

70% CFE delivers US$16 million in net savings compared to annual matching, but higher targets unlock more fuel cost savings

Costs vs. savings to the Singapore's power system (million US$)



Notes

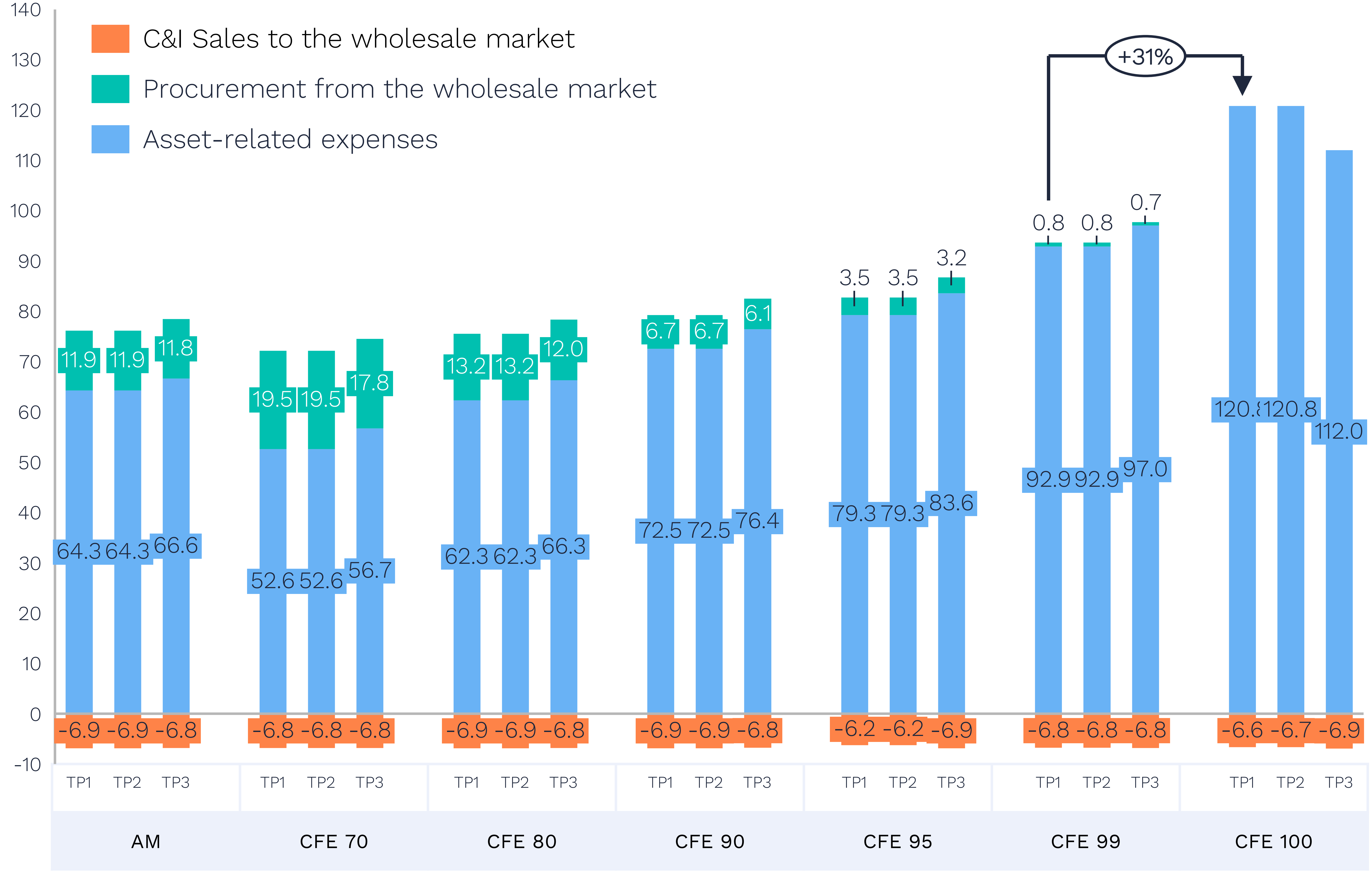
- In 24/7 CFE regimes, CAPEX reflects the upfront cost to C&I consumers for building or contracting dedicated clean capacity to meet hourly matching — costs that are not borne by the grid consumer. As C&I consumers can sell excess clean supply to the grid, they are able to contribute to a reduction on gas-fired generation, cutting fuel and dispatch costs which are often paid by the consumer.
- Surplus power from greenfield PPAs reduces LNG fuel cost between US$185 and 261. million, increasing with higher CFE scores and benefiting the entire system. On the other hand, annual matching fuel cost savings is capped at US$217.6 million.
- Achieving 70% CFE reduces net system costs by US$16 million compared to annual matching. These savings are sensitive to trade costs, which depend on policy and tariff design.
- Above 80% CFE, costs for hourly matching shifts to C&I consumers, as they must invest more heavily in dedicated clean capacity rather than rely on grid.
- With blended technologies, total and net system costs are only lowered at 100% CFE. However, their benefit to the grid decreases due to greater fuel costs associated with gas-hydrogen blending and gas CCS.
- While C&I consumers bear the upfront capital burden of hourly matching, operational savings — driven by reduced grid procurement — can be passed on to the grid operator and end-users through lower wholesale prices.

🟧 Solar CAPEX	🟨 Gas-hydrogen CAPEX
🟦 Battery CAPEX	▨ Gas-CCS CAPEX
🟦 LDES CAPEX	■ Fuel Cost

Costs to C&I Consumers

PPA costs escalate for C&I consumers at higher CFE targets

PPA Unit Cost (US$/MWh)



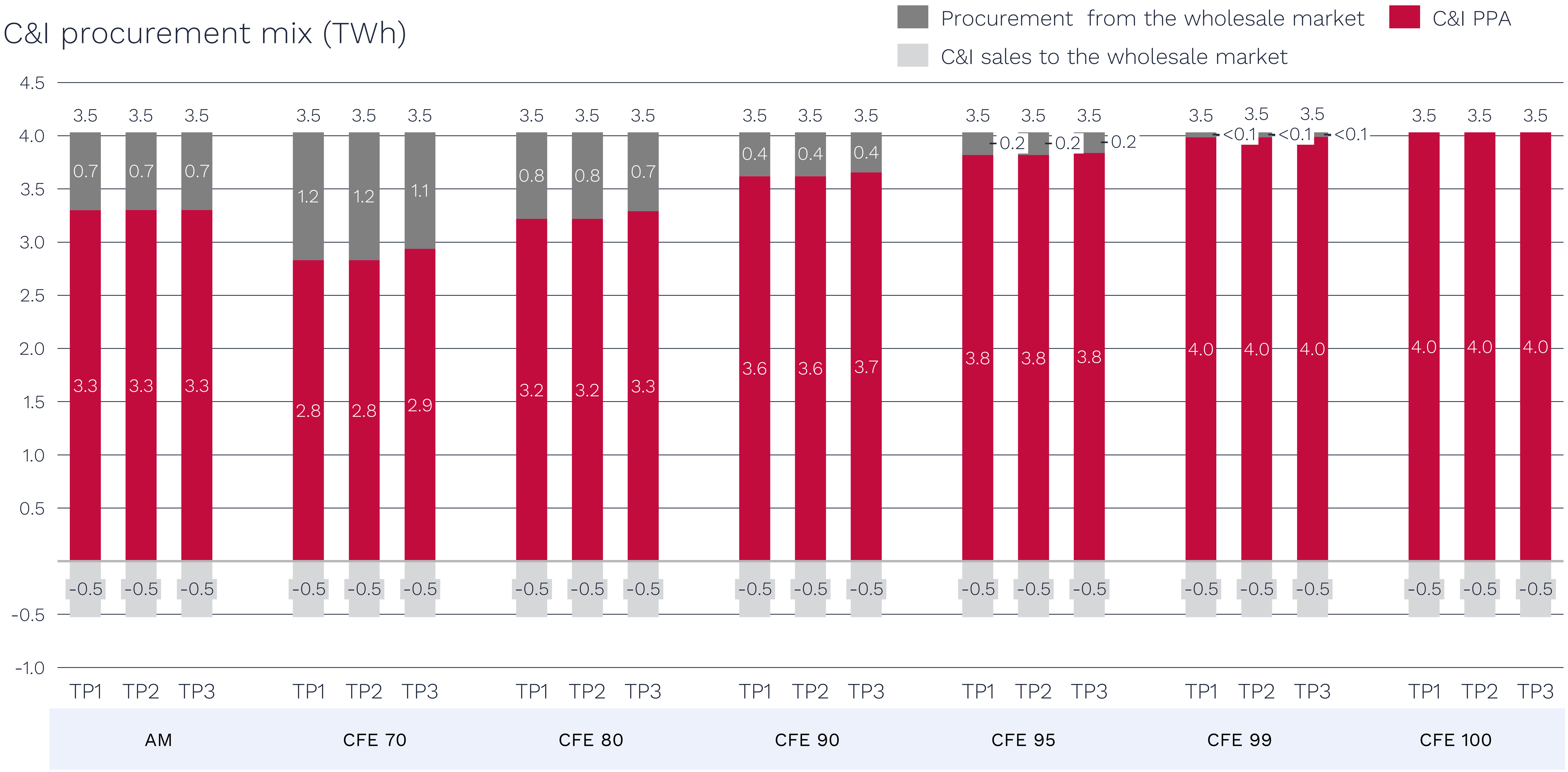
Notes

- Total nationwide costs borne by the C&I off-takers double in the transition from CFE 70% to CFE 100%.
- The highest escalation in PPA costs occurs in the last 1% of CFE with costs increasing compared to annual matching. A 31% increase is observed where solar and batteries are deployed, and 16% where innovative thermal technologies are available.
- Revenue from selling surplus power to the brownfield grid offsets some of the PPA cost. However, due to a 15% cap on sell-back, contribution to the reduction in PPA costs is consistent across scenarios. Sell-back to the main grid is maximised across all scenarios.
- CFE 95% appears to offer a cost-effective trade-off, with moderate increases in PPA costs compared with steep escalation beyond this threshold. At full hourly CFE, the PPA costs are the highest, indicating that the combination of 100% clean power and full self-sufficiency for C&I consumers will come at a premium. Cleaner grids help minimise this trend, emphasising the importance of decarbonisation on the main Singapore grid.

Higher CFE targets require less grid dependence and more clean PPAs

Grid supply fades at 99-100% CFE, as Singapore's gas-dependent grid limits its contributions to hourly matching

C&I procurement mix (TWh)



Notes

- The greenfield system can partially rely on electricity imports from the brownfield to support 24/7 CFE matching. However, because Singapore's grid is primarily gas-based, the carbon intensity of imported electricity significantly limits its contribution to hourly CFE matching.
- Supply from the brownfield grid is near zero at 99% CFE and disappears entirely at 100% CFE across all technology palettes. Achieving higher CFE targets involves greater investment in clean PPAs.
- To reflect operational realities and conservative technical assumptions, a 15% export or sell-back cap — applied in both annual and hourly matching scenarios — constrains the greenfield's ability to export excess clean electricity to the brownfield system in higher CFE scores. This limit is reached across all CFE levels and technology options.

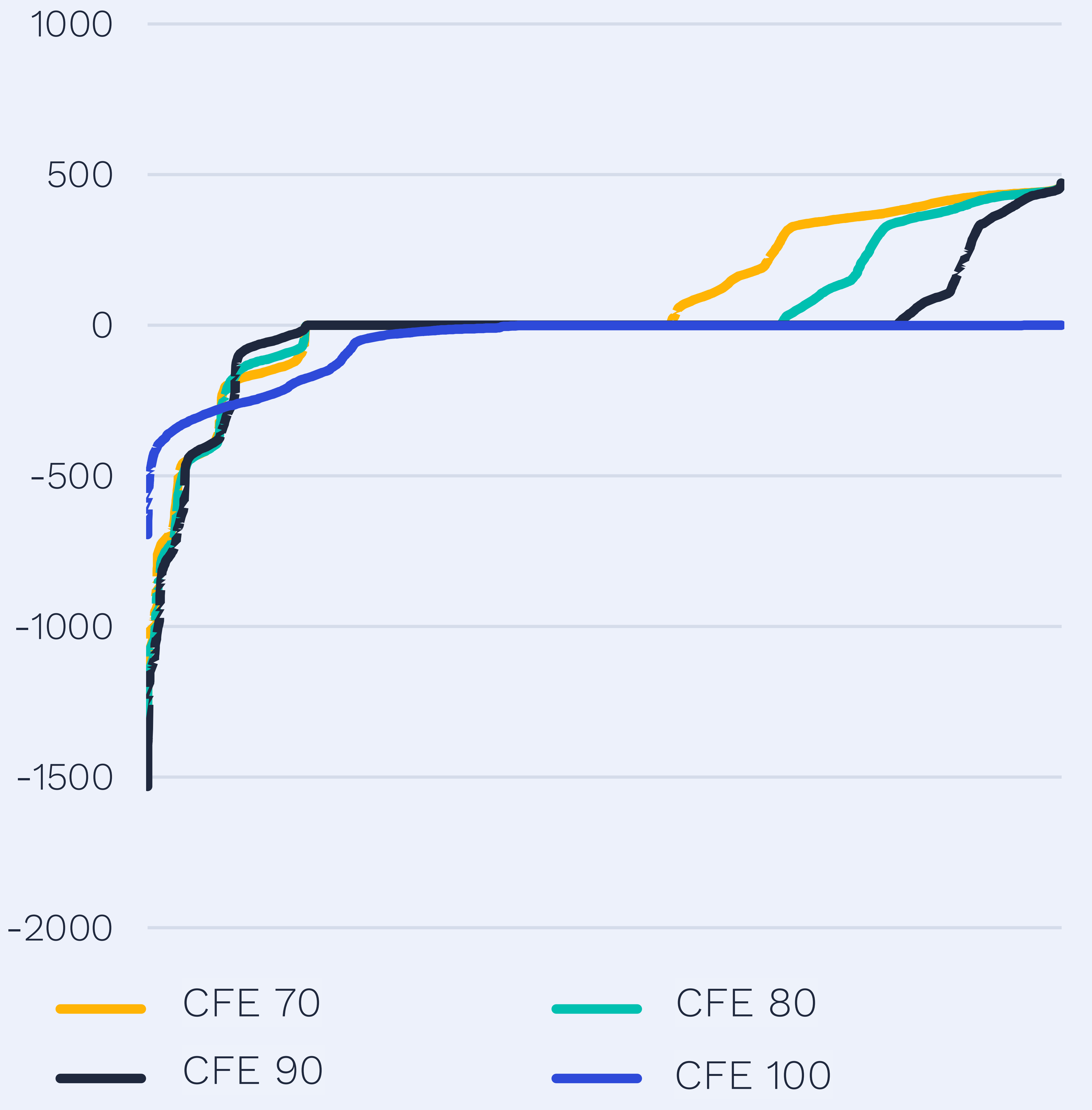
Import and export dynamics

Sell-back is critical to avoid curtailment and optimise clean energy use

- At lower CFE scores like 70%, the greenfield system frequently purchases power from the grid (positive values) to meet demand. As the CFE target increases from 70% to 100%, both the frequency and magnitude of imports decline. Under a 100% CFE regime, the system operates with near-total self-sufficiency, relying on dedicated clean PPAs.
- Total imports from the grid exceed exports — highlighting that while sell-back mitigates curtailment, the system remains a net importer of electricity up to the highest CFE levels.
- The full utilisation of the sell-back of surplus C&I generation to the grid is driven by both overbuilding of solar-plus-storage systems and additional revenues from grid sales and curtailment.
- The maximum hourly imports from the brownfield reaches nearly 500 MWh, reflecting that imports are useful at certain hours of the day.
- Large export events exceeding 1,000 MWh occur in less than 1% of hours, reflecting the rarity — but not insignificance — of curtailment risk without sell-back provisions. This is likely due to a short fall in demand during events such as Lunar New Year. Given the predictability of generation, this can be anticipated and managed by the utility.

Distribution of hourly net power exchange into greenfield in TP1 (MWh)

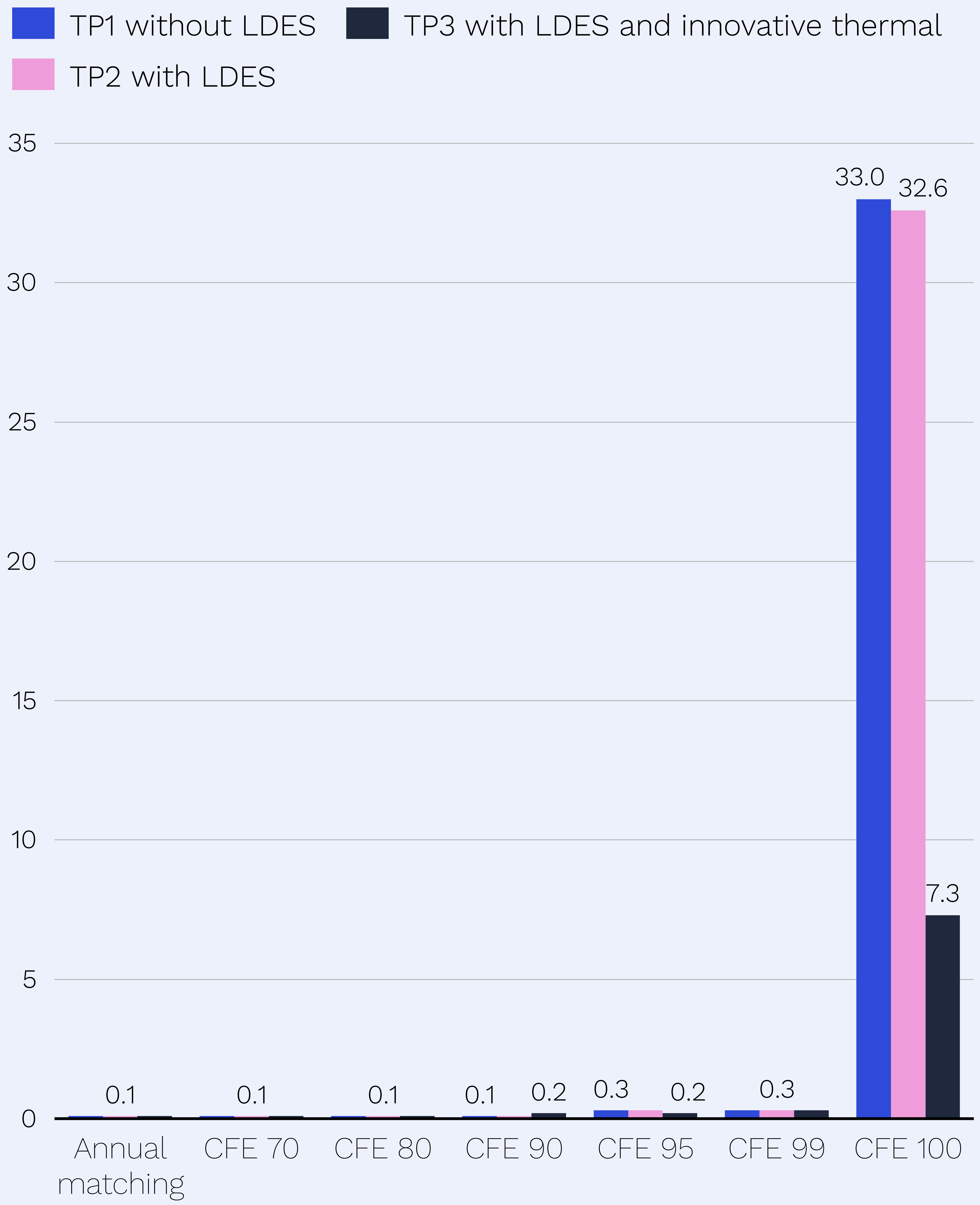
Positive = net grid power purchases, Negative = net sell-back



Solar curtailment

Relaxing the cap has cost and technical trade-offs

- Curtailment of PPA generators remains low under most matching regimes, growing as hourly CFE requirements increase.
- The 15% sell-back allowance is utilised in full across all scenarios due to the strategic oversizing of solar-plus-storage systems, which enables both hourly coverage and surplus sales. This cap remains sufficient to absorb excess generation until the highest CFE levels — 99% and 100% — where curtailment rises. Increasing the sell-back cap could reduce curtailment but would likely impose additional balancing and operational costs on the grid operator.
- Decisions to increase sell-back allowance from C&I grid to the main grid depends highly on the cost structure in both grids and thus national tariffs policies.
- Notably, the inclusion of LDES in TP2 and TP 3 has little to no impact on solar curtailment, as the excess generation occurs during sustained periods of oversupply that exceed the storage system's capacity or discharge windows.
- The inclusion of innovative thermal technologies in TP3 reduces solar capacity needed as Gas-CCS and Gas-hydrogen blending provides firm power, resulting in lower curtailment from 95% to 100% CFE in comparison to scenarios where only battery types are available.



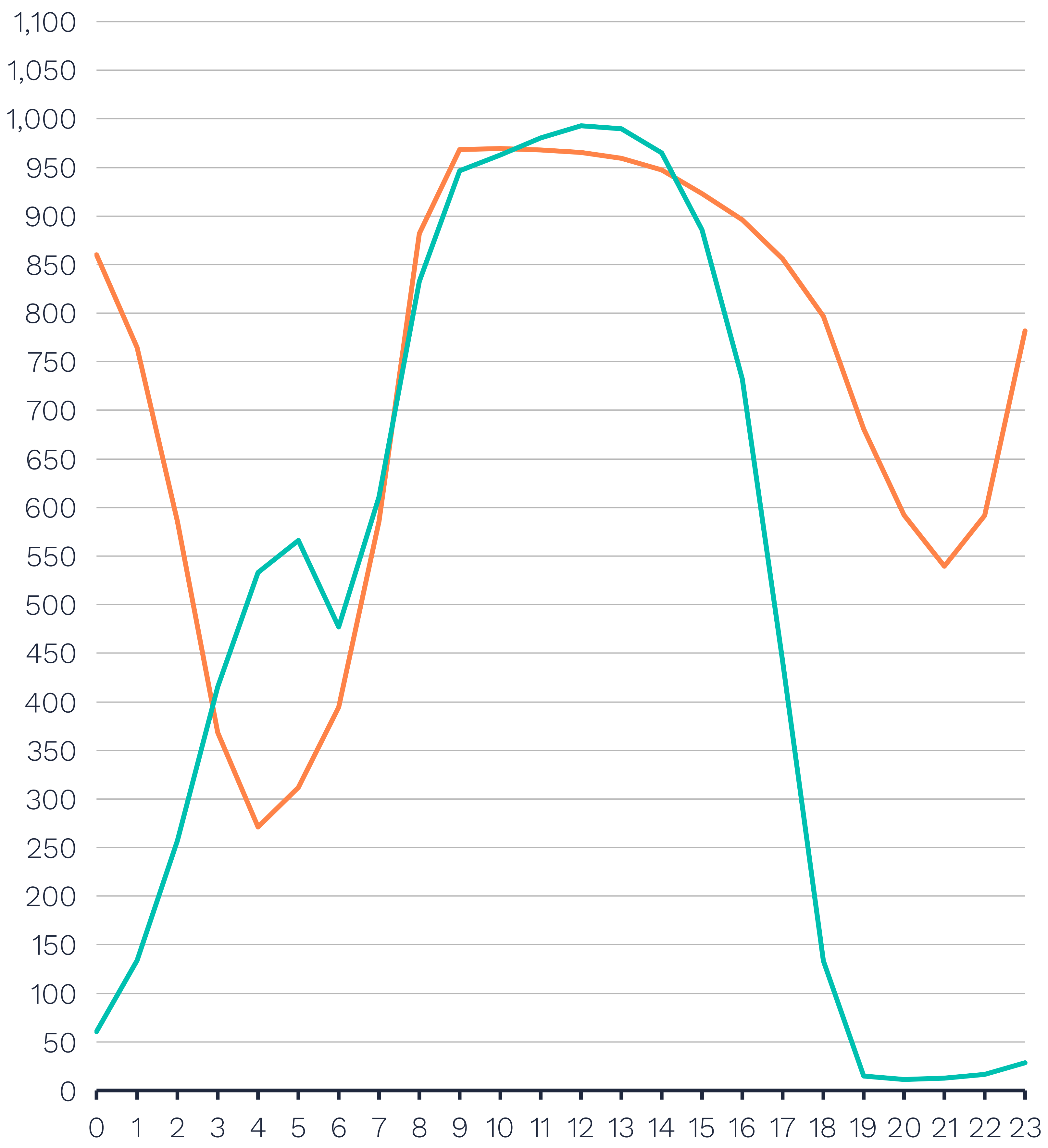
Solar power curtailment of PPA generators

(% of dispatched generation)

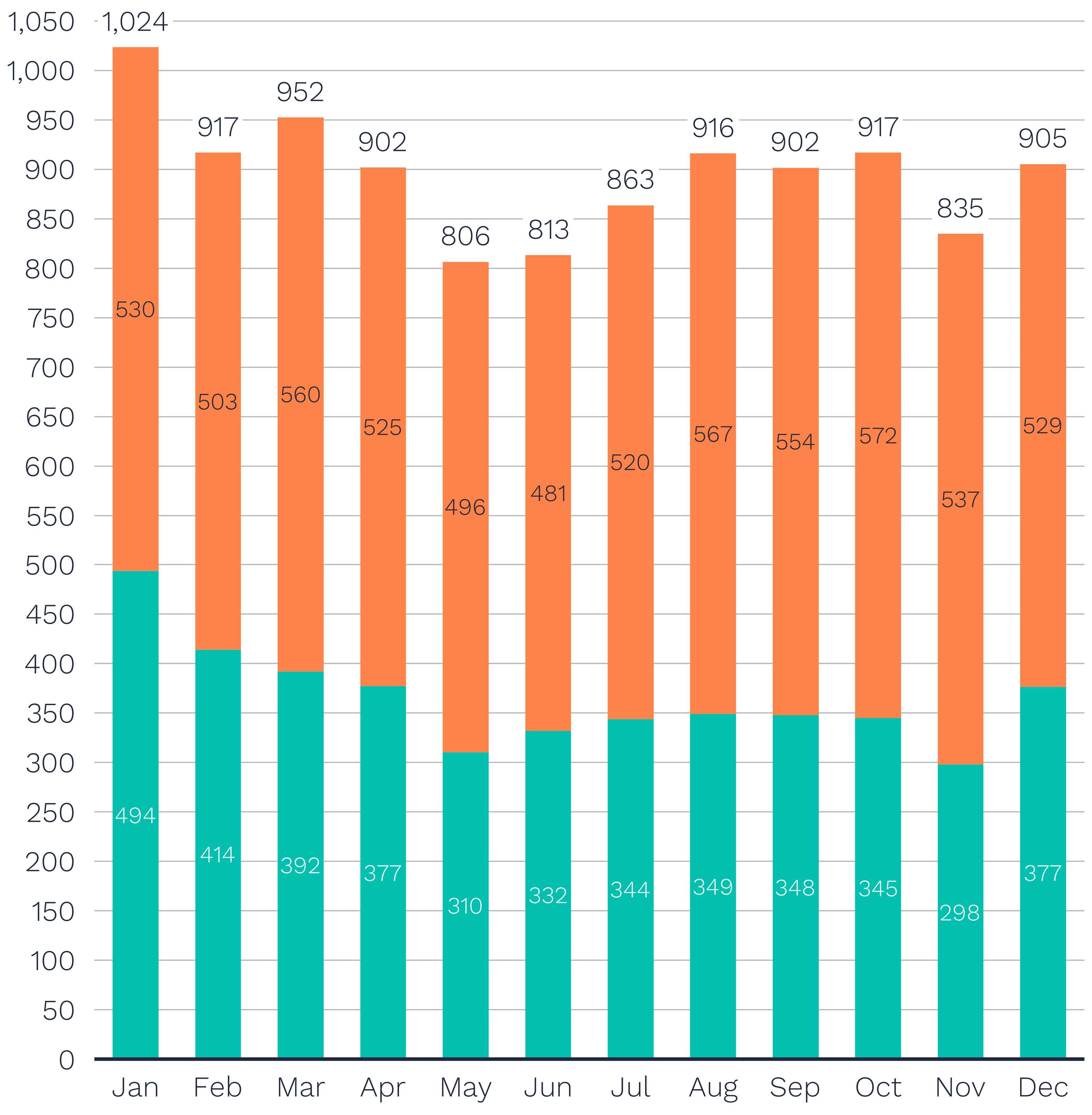
The role of interconnectors

Steady imports from Indonesia and Peninsular Malaysia help meet peak-hour demand

Hourly average imports (MWh)



Total imports by month (GWh)



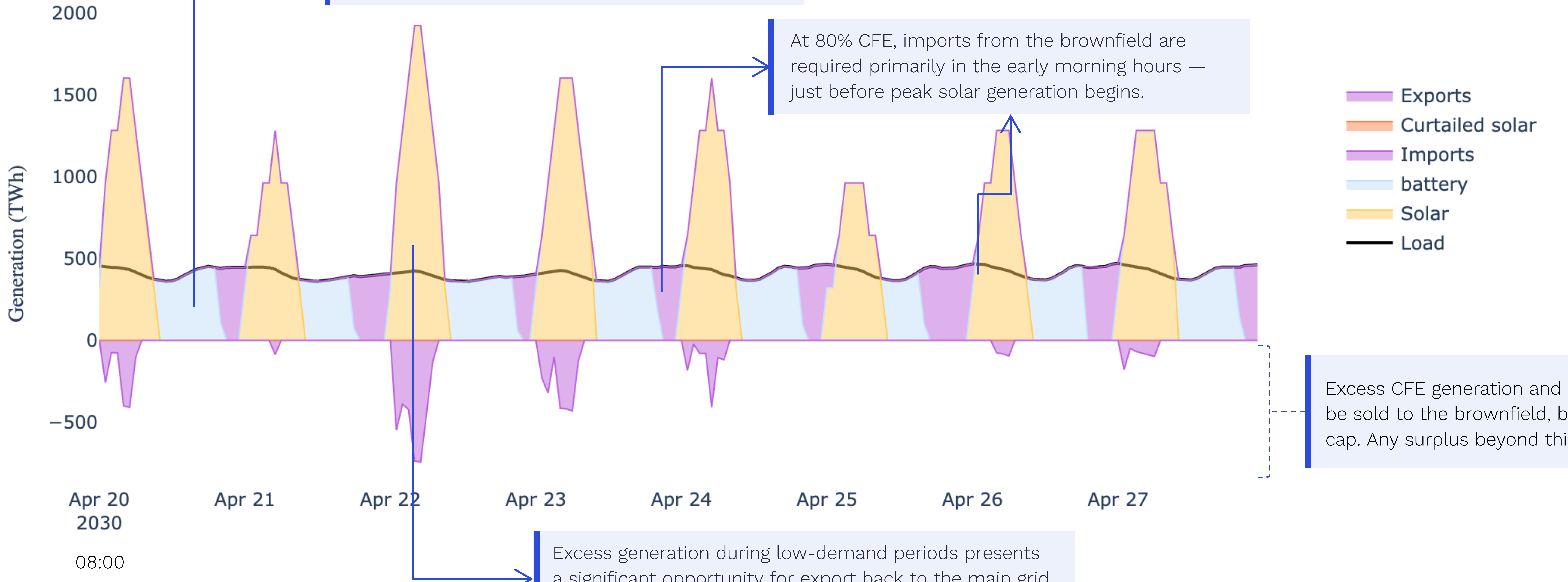
Notes

- Transmission lines can be expected to supply up to 10.6 TWh annually — covering around 13% of Singapore's grid demand and more than doubling its current imports.
- Most of the power imports occur during peak hours when demand is high. Battery storage in Batam allows a spread in the hours imports can be available, and thus supports the grid during early evening hours.
- Monthly power imports fluctuate throughout the year, with peak-to-trough variations of around 19% for Indonesia–Singapore. The variation is more pronounced for Peninsular Malaysia–Singapore, at 66%, where the interconnector is intended to balance supply and demand, and policy does not mandate a minimum load flow.
- Additional modelling will be required to assess the potential for interconnection to serve C&I consumers directly.
- Imports reduce the need for additional gas-fired generation on the brownfield system, contributing to lower-carbon electricity on the main grid. This was explored further in our Sensitivity Analysis.

🟧 Indonesia-Singapore
🟩 Peninsular Malaysia-Singapore

Examination of clean energy supply to C&I consumers

Sample hourly dispatch at 80% CFE using Technology Palette 1 (MW)



Battery storage is primarily used to meet evening and early morning demand, bridging the gap between solar generation cycles.

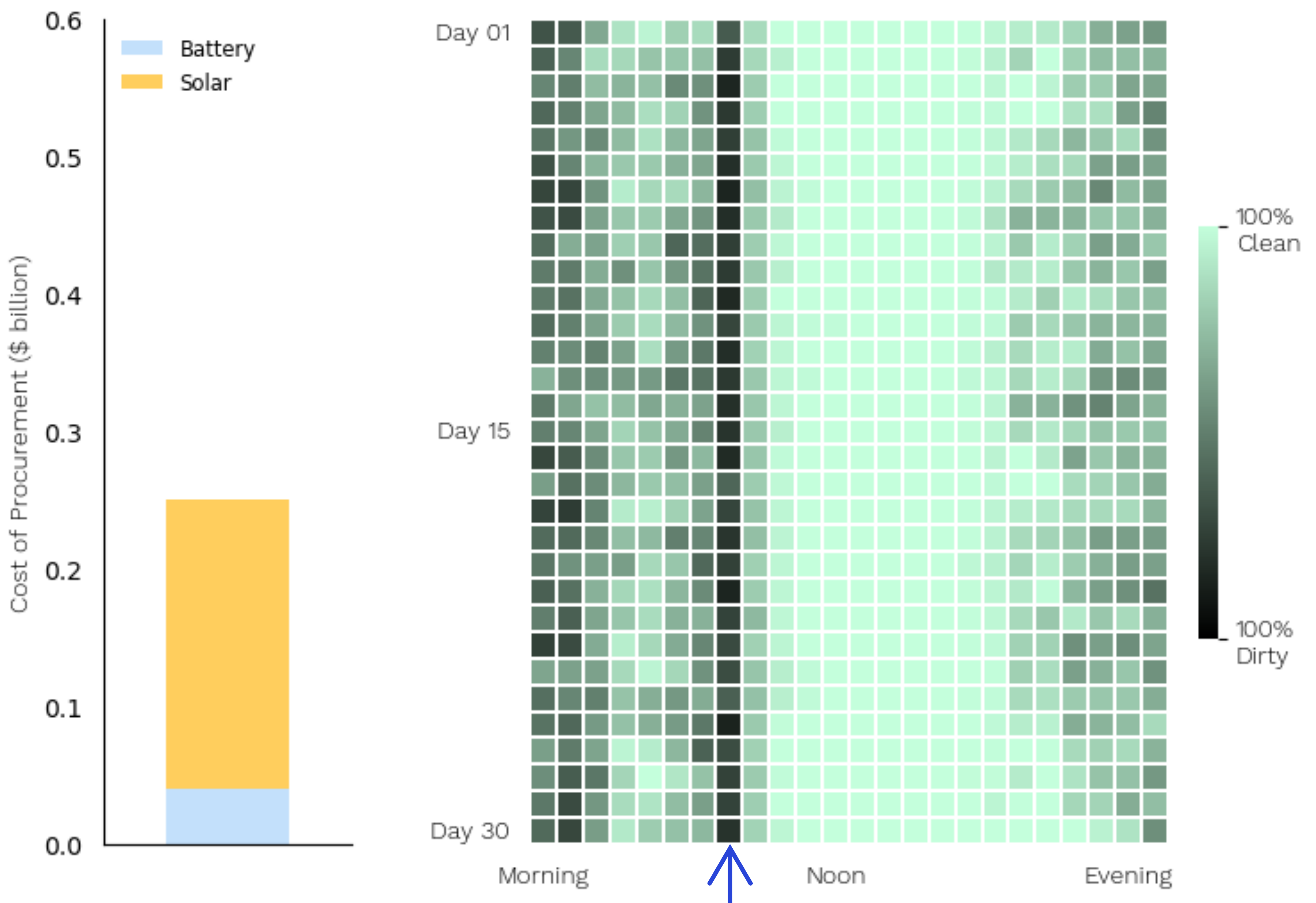
At 80% CFE, imports from the brownfield are required primarily in the early morning hours — just before peak solar generation begins.

Excess CFE generation and stored energy can be sold to the brownfield, but only up to a 15% cap. Any surplus beyond this limit is curtailed.

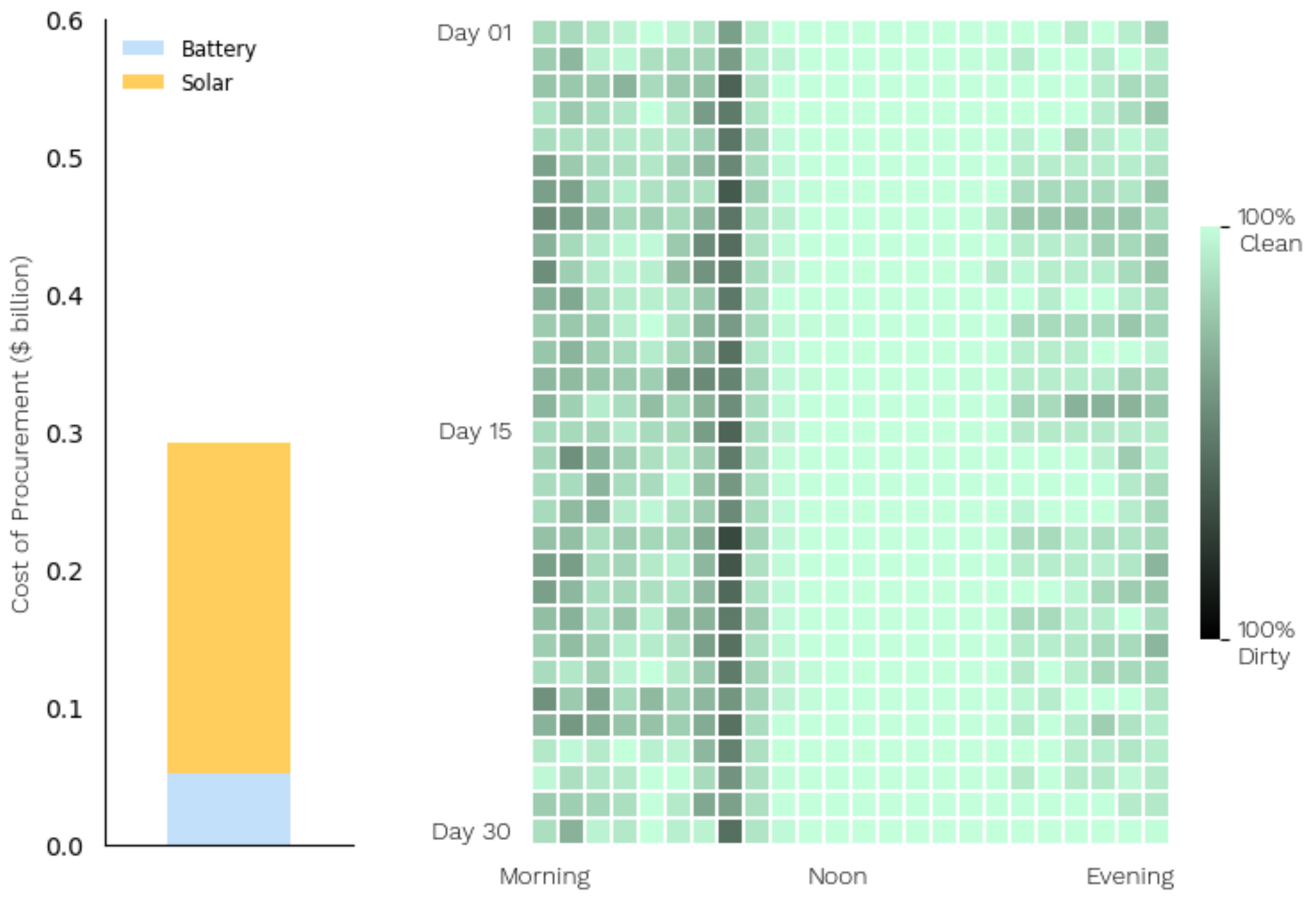
Excess generation during low-demand periods presents a significant opportunity for export back to the main grid, if policy permits greater sell-back flexibility.

Higher CFE targets bring greater costs and challenges

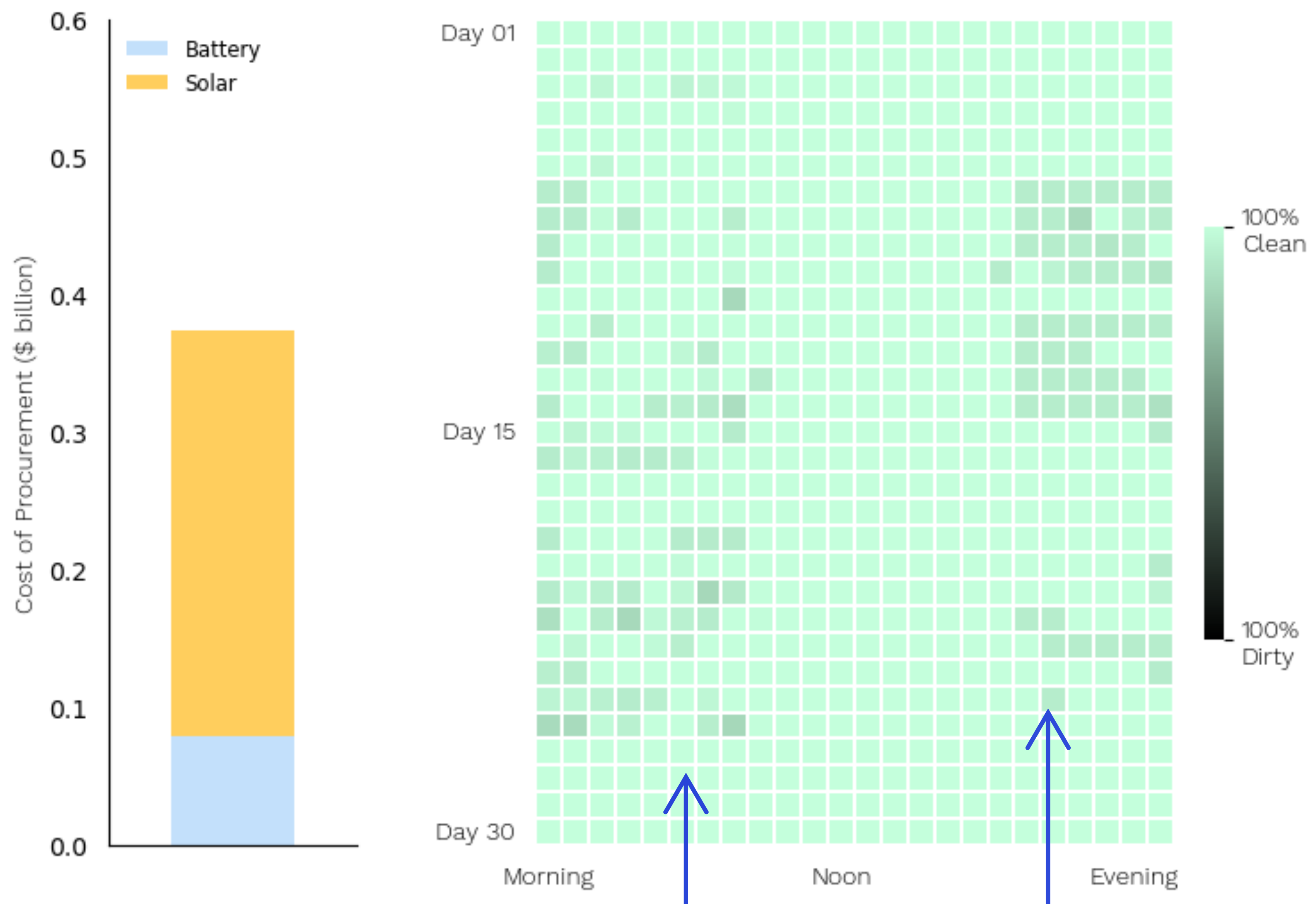
Hourly CFE scores by CFE level (%) for an average month, with annual procurement cost



80% clean procurement: hour-by-hour



90% clean procurement: hour-by-hour



99% clean procurement: hour-by-hour

Decarbonising early morning hours is challenging due to the absence of solar generation and likely depletion of battery storage from overnight use.

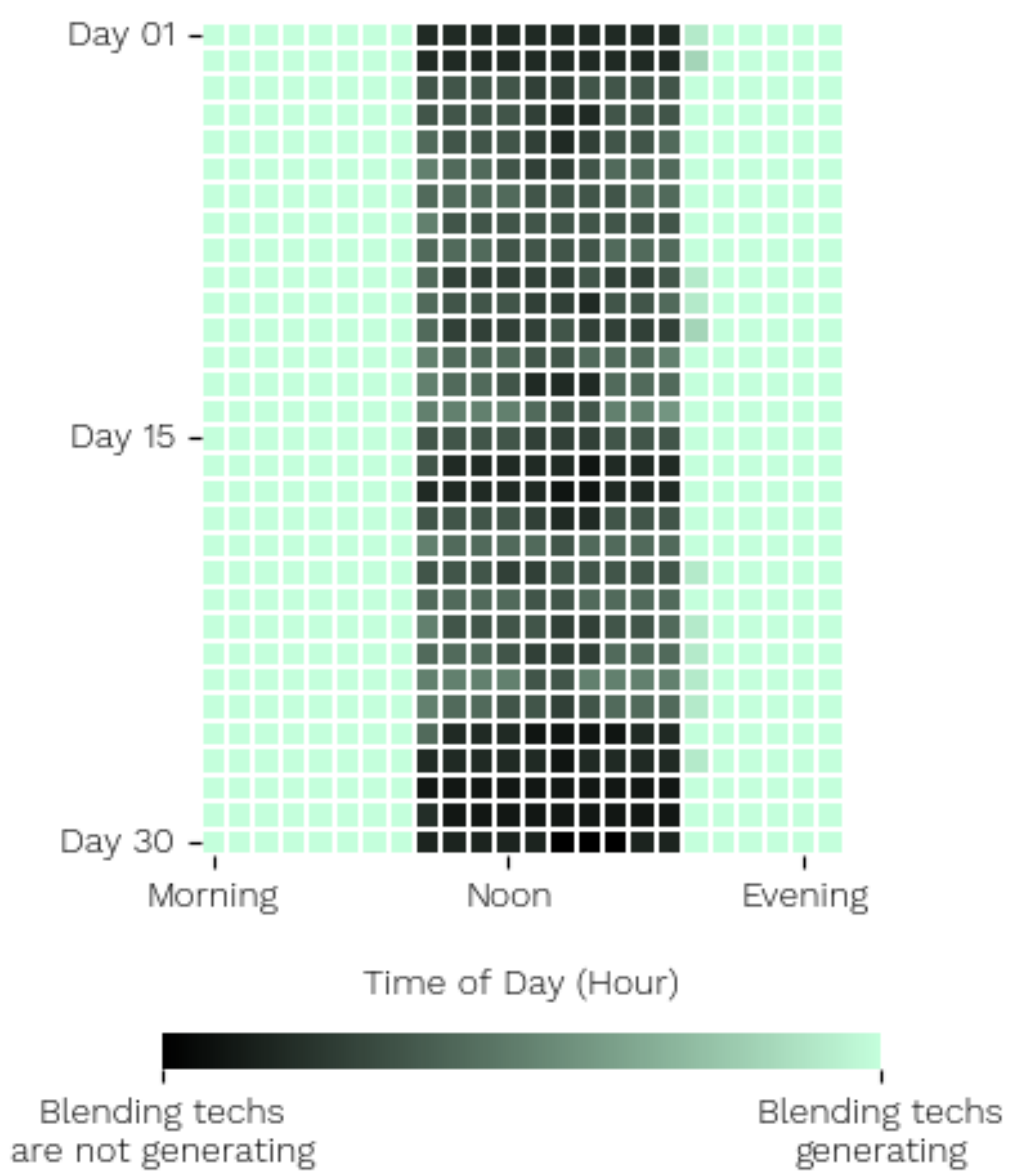
Evenings are easier to decarbonise, as batteries are typically freshly recharged with surplus CFE generation from earlier in the day.

Fully decarbonising these times is less cost-effective, as it involves adding more clean energy on top of clean energy rather than displacing costly fossil fuels from the main grid.

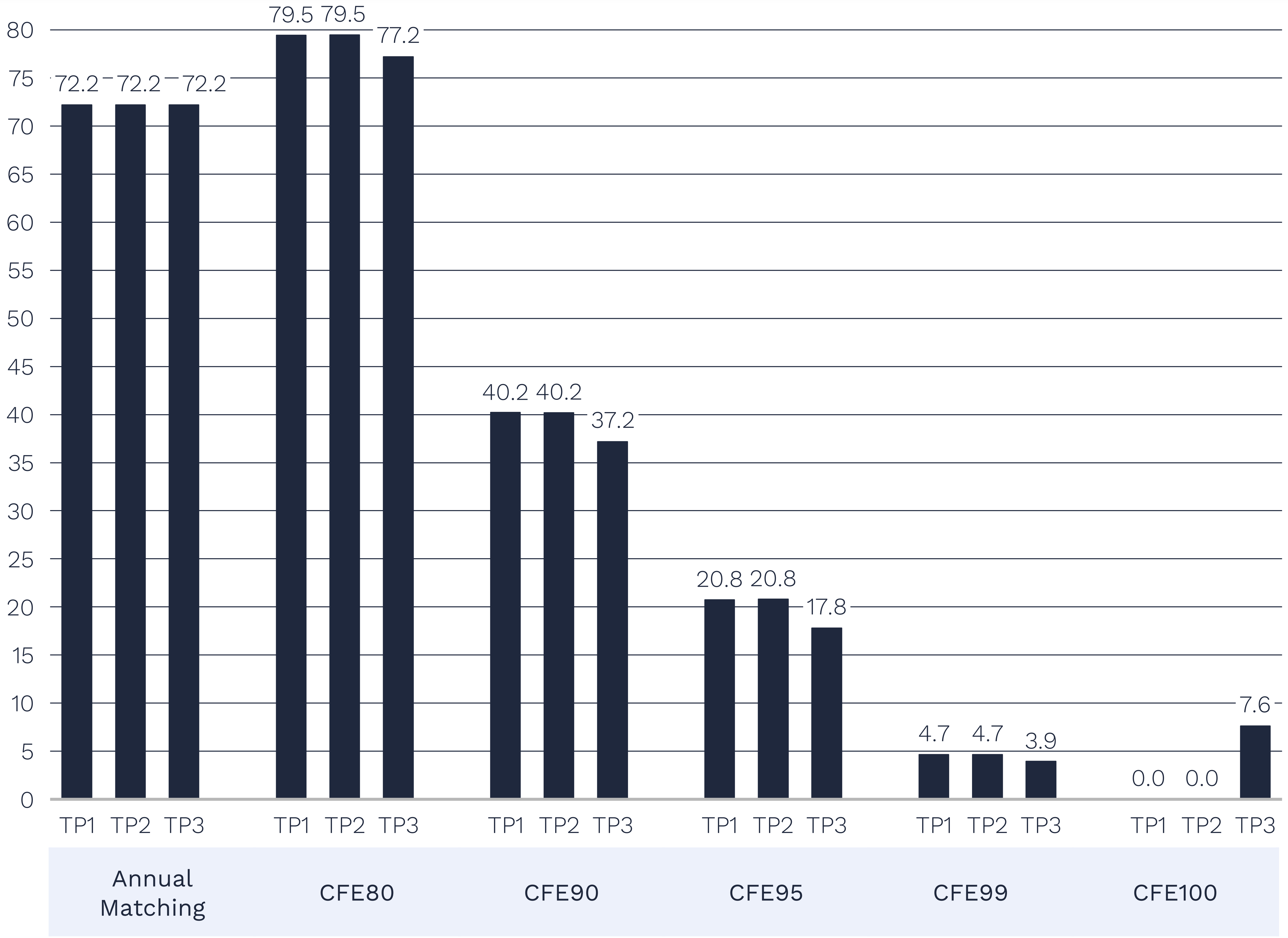
Technology risk of TP3

Innovative thermal technologies ensures reliability in hours when renewables are short, but adds emissions

Average of hours in TP3’s CFE 100



Greenfield emission rate (gCO2/kWh)



Notes

- During periods of low or no solar output — such as early mornings and evenings — blending technologies serve as firm, dispatchable sources when battery storage is unable to meet 100% CFE.
- As a complementary and relatively clean source of electricity, blending technologies reduce some overbuild of solar. However, they introduce emissions leakage, falling short of full decarbonisation. In 100% CFE, the greenfield emissions rate is 7.6 gCO2/kWh in TP3, but zero for TP1 and TP2.
- CCS uptake is particularly sensitive to two contentious variables that are not tested for sensitivities in this study: final sequestration rates, and storage and transportation costs. Our assumptions are provided in the Annex.
- This residual emissions burden raises the marginal cost of CO_2 abatement elsewhere in the system. As a result, any near-term cost savings from avoiding solar and battery overbuild must be weighed against longer-term climate and regulatory risks.

TransitionZero

Sensitivity analyses

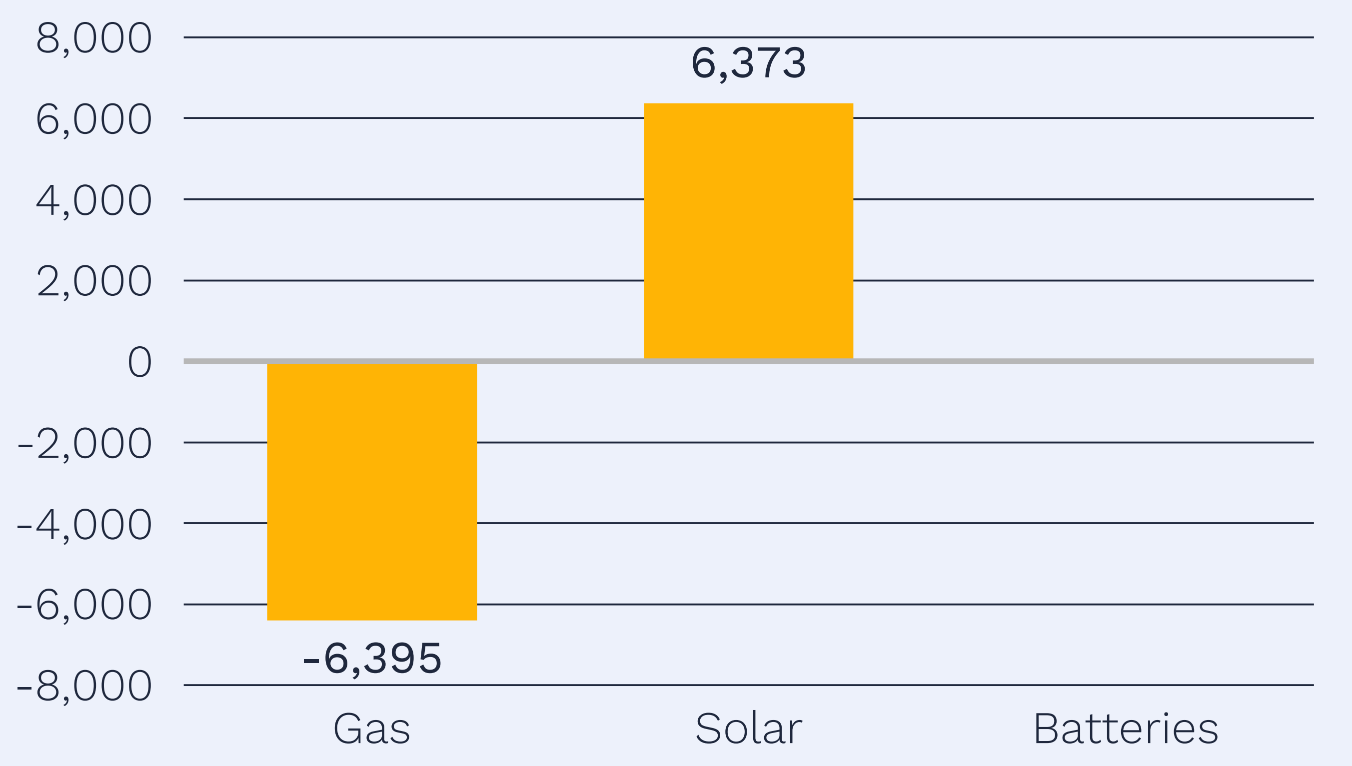
Deeper analysis on the sell-back constraint

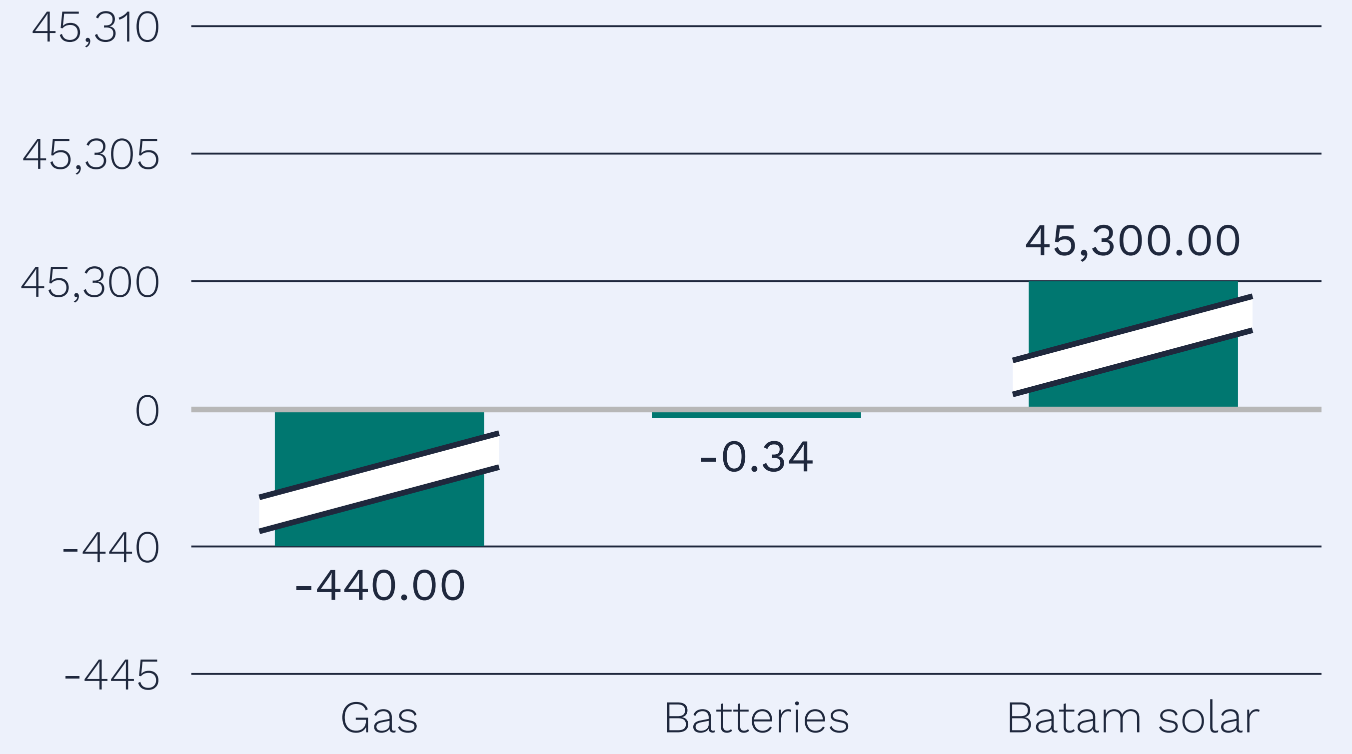
Benefits of clean-powered interconnection from Indonesia (2/2)

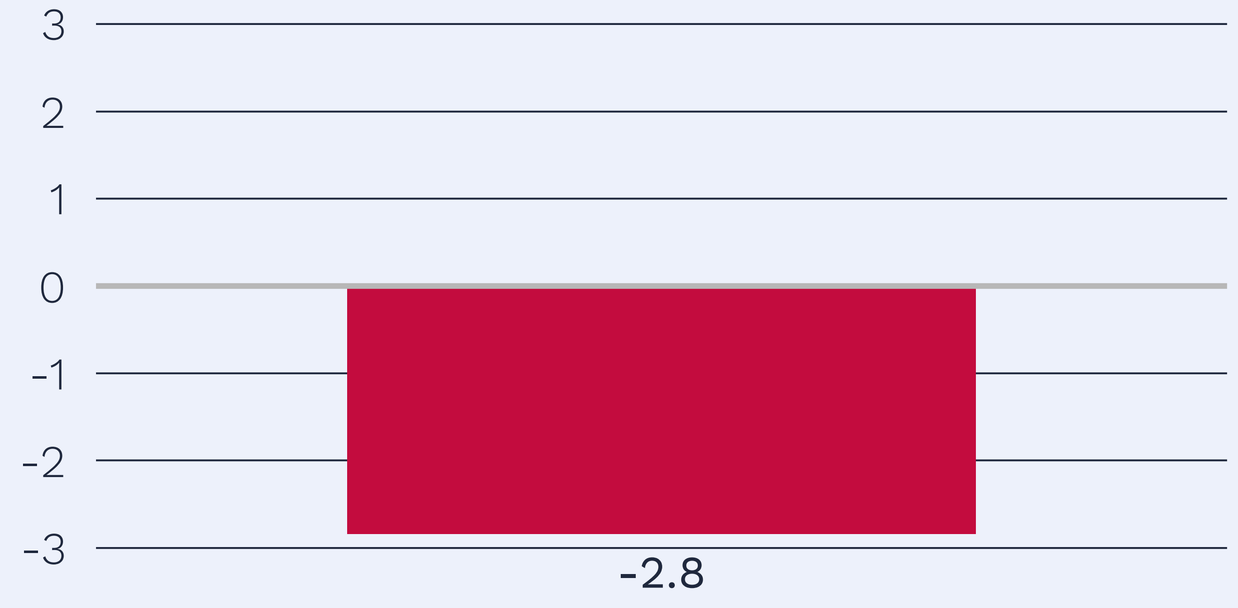
A 1 GW Batam interconnector provides an additional 6 TWh of solar-based power to Singapore's brownfield, avoiding 2.8 MtCO$_2$ emissions

- A sensitivity analysis of the brownfield without a 1 GW Indonesia-Singapore interconnector reveals a structural dependence on fossil generation in the absence of regional imports and supply diversification.
- For this interconnector to meet the 75% utilisation requirement of the EMA, at least 4 GW of solar-capacity and 1.7 GW of batteries would need to be built. This would result in over 6 TWh of clean power imports to Singapore. The total capital investment cost of such a project is estimated at US$45.3 billion.
- Without imports from the tested line, gas-fired power output increases by nearly 6 TWh, raising its share of generation on the main grid by 9 percentage points and pushing the utilisation factor of gas plants from 75% to 85%. This raises both emissions intensity and operational costs, as well as underscores the scale of lost clean generation and the challenge of replacing it with domestic alternatives. Fuel savings from the interconnector would be equivalent to 440 million annually.
- Without new interconnectors, Singapore must rely solely on imports from the existing Peninsular Malaysia interconnector to cover periods of supply deficit, which we found to be maximising the line with a 97% load factor if utilisation in the model is left uncapped. This decreases to 75% utilisation if the Indonesia-Singapore 1 GW interconnector is available.
- In the absence of imports from Batam, the generation and capacity factors of solar remain unchanged in both scenarios, as domestic solar capacity is prioritised and optimised for maximum output. There is a small increase in battery use with an additional 0.2 TWh of discharge annually.

Difference in scenario results with vs. without Batam solar


Generation (GWh)


Total costs (million US$)

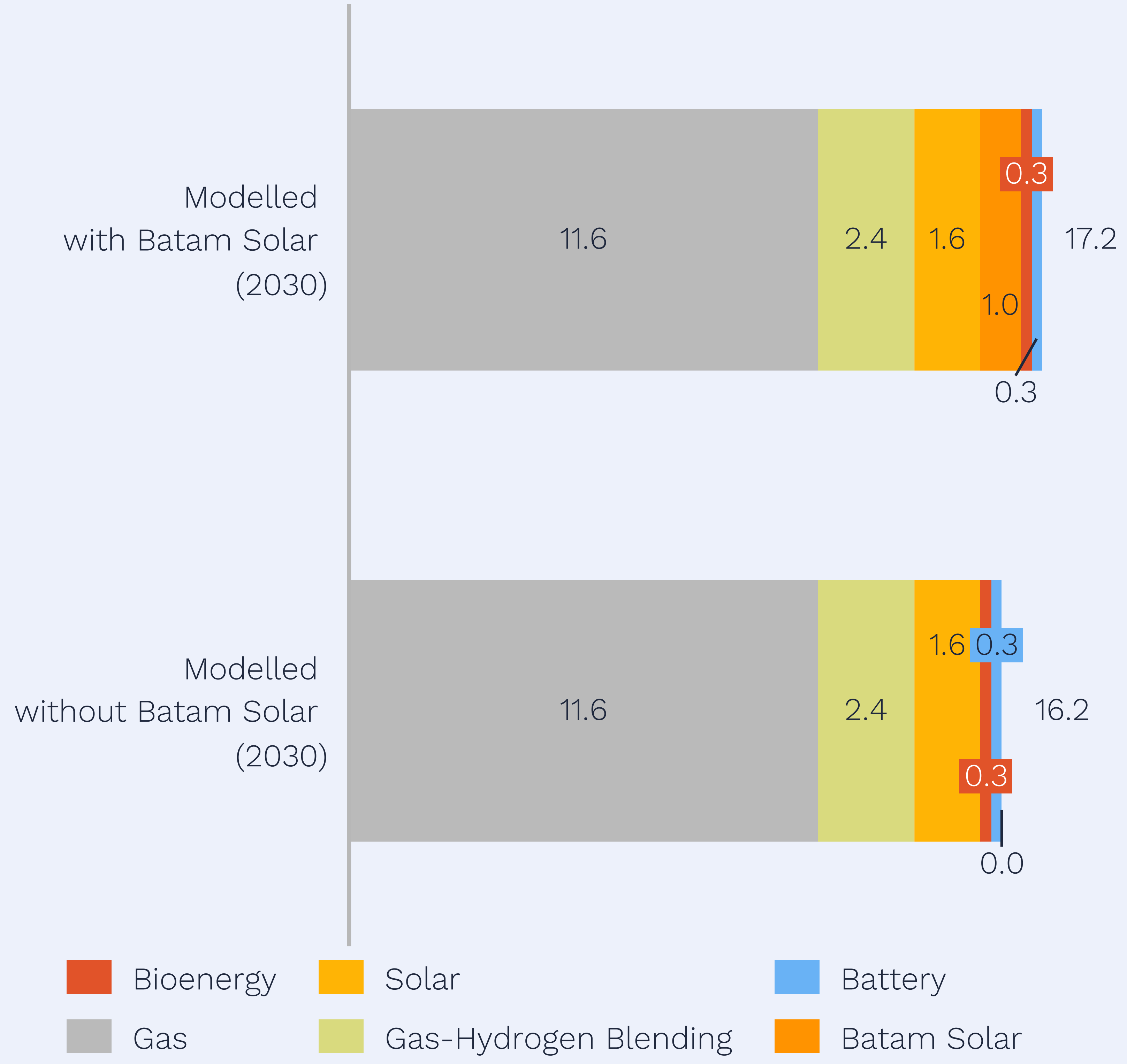

Emission (MtCO2)

Benefits of clean-powered interconnection from Indonesia (2/2)

Clean imports from Indonesia increases the base CFE available in Singapore

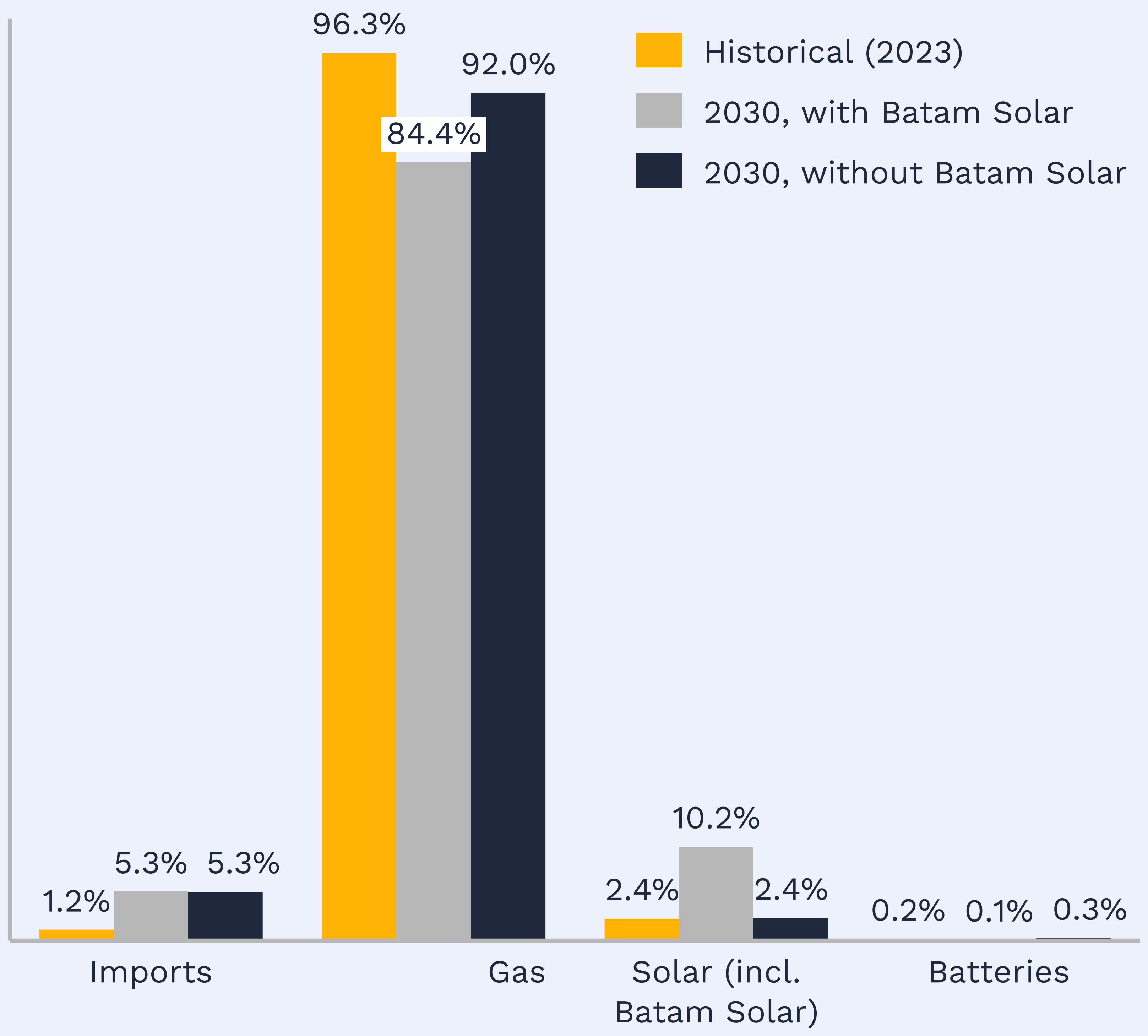
The capacity mix remains constant regardless of whether the 1 GW interconnector to Indonesia is available, but its inclusion shifts the generation mix considerably.

Installed capacity (MW)



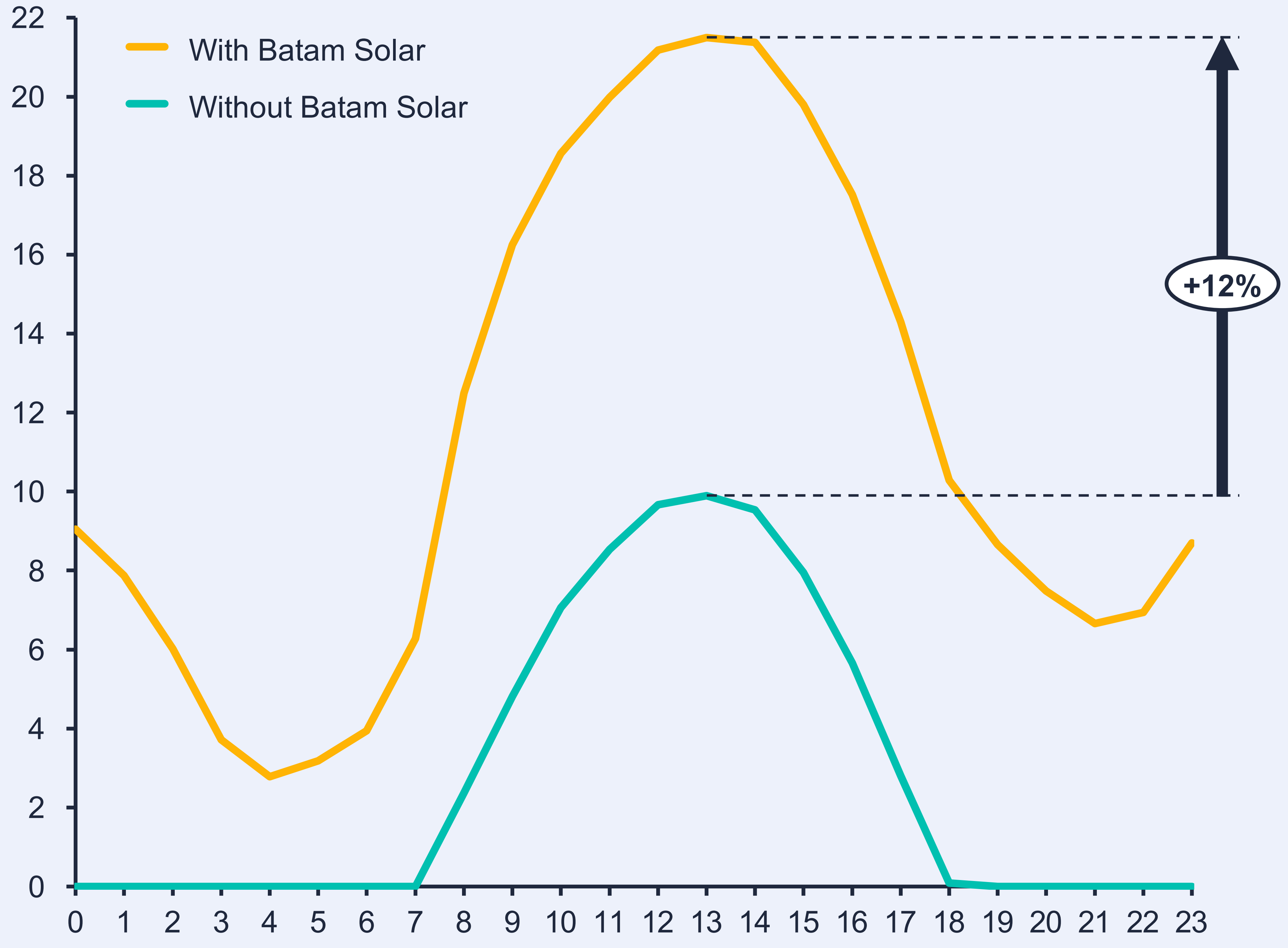
Solar imports shift generation away from gas, decreasing its share by 12% from 2023 and 7% in comparison to a scenario without Batam imports.

Generation share (%)



Batam solar imports raise Singapore's baseline CFE score by increasing the underlying cleanness of the grid, so hourly CFE can happen at a higher baseline and be available for C&I purchases for more hours.

Base grid CFE score (%)



Source TransitionZero modelling

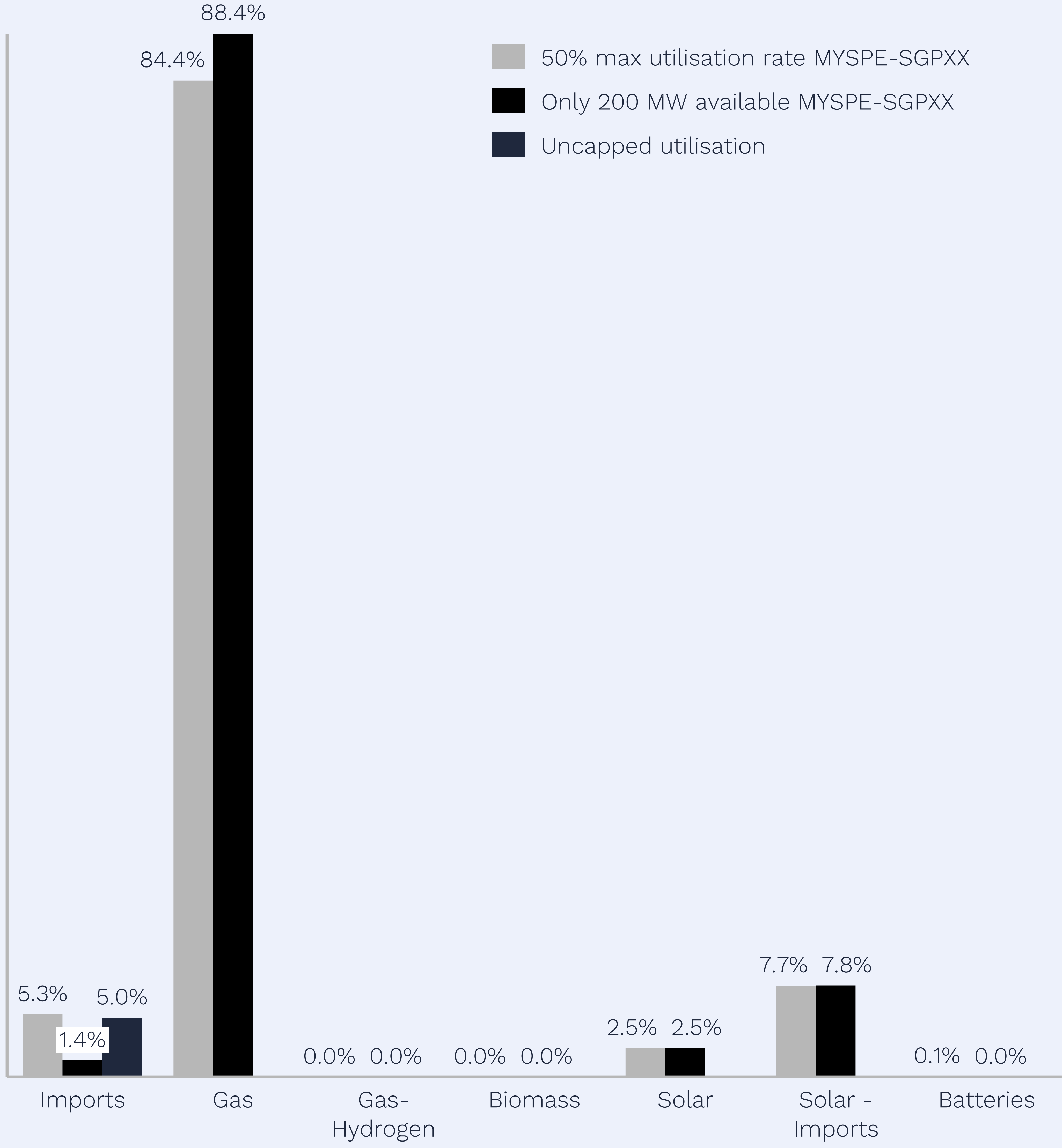
Benefits of utilising the Singapore-Malaysia interconnector (1/3)

Increasing imports through Singapore's existing interconnector can increase energy security and optionality

- We tested two sensitivities related to the utilisation of the Singapore-Malaysia interconnector. The 2030 baseline assumes 50% utilisation of the 1 GW line, increasing fivefold from a 10% utilisation for balancing today. The sensitivities explored include (1) a 20% maximum utilisation and uncapped utilisation to assess impacts on the generation mix, emissions and system costs.
- Higher interconnector utilisation supports decreasing gas use and has the potential to support decarbonisation and corporate procurement. At 50% maximum utilisation of the existing link with Malaysia, Singapore can draw ~5% of imports to displacing gas generation and raise the clean energy share available for CFE procurement.
- CFE benefits flatten under constraints. When capped at 200 MW, imports collapse to 1.4%, forcing corporates to rely more heavily on gas-dominated grid power, which raises hourly emissions intensity and makes 24/7 matching harder.
- Regardless of interconnector limits, solar-backed imports (~7.7–7.8%) provide corporates with a reliable clean source that helps smooth variability in domestic solar output.
- Limited important capacity reduces corporate flexibility to source tracked clean imports, leaving fewer procurement options in Singapore beyond local solar and batteries.
- Expanding and prioritising clean interconnector utilisation is essential — not just for system cost and resilience, but to enable corporates to scale 24/7 procurement and demonstrate real emissions cuts.

A case for regional imports to Singapore

Brownfield generation between scenarios (%)

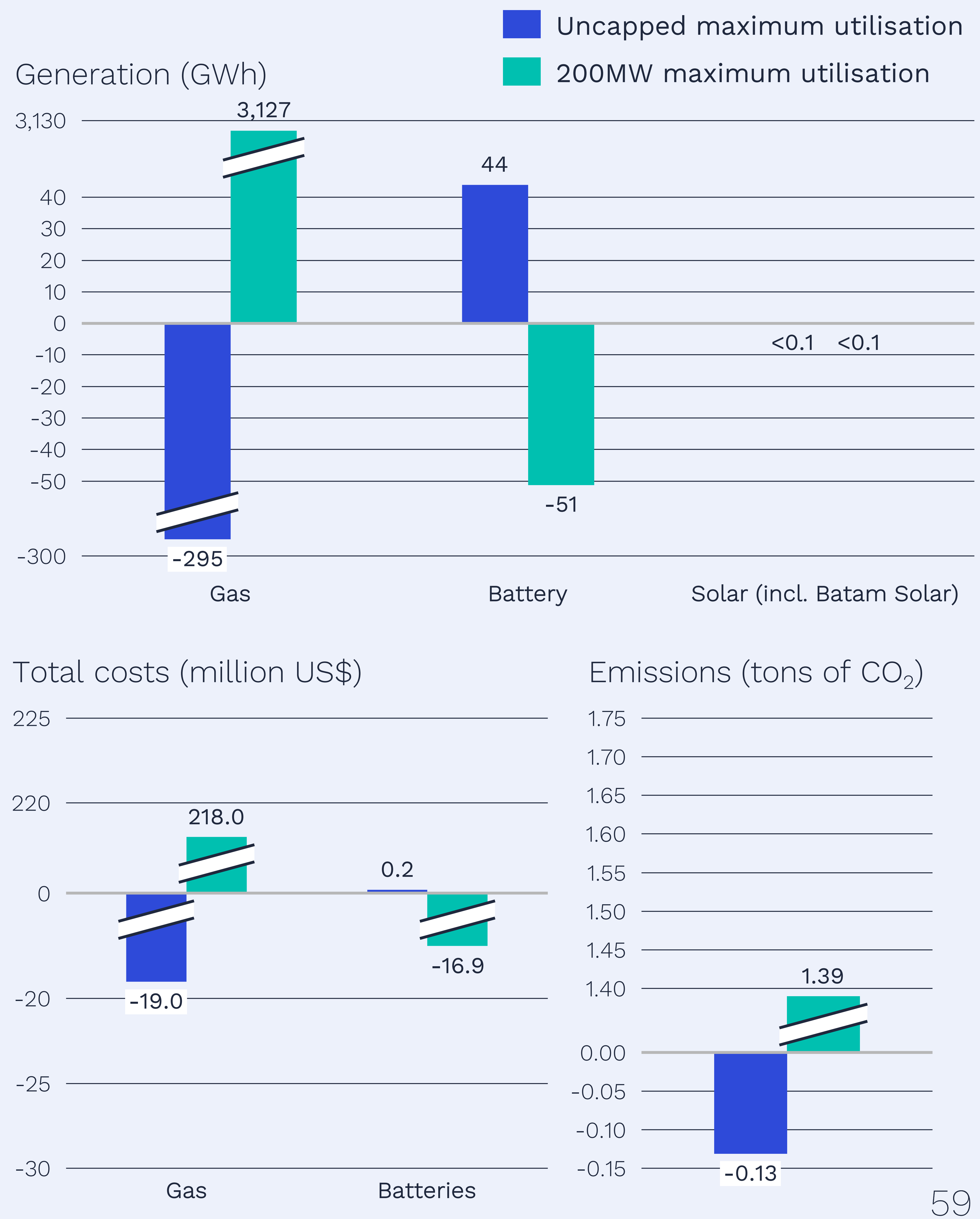


Benefits of utilising the Singapore-Malaysia interconnector (2/3)

Boosting use of the existing interconnector cuts gas reliance and system costs

- Ramping up use of the Malaysia-Singapore interconnector cuts gas use. With uncapped utilisation of the existing line, gas demand decreases, demonstrating that interconnectors reduce gas reliance by adding optionality. Gas generation falls 295 GWh, avoiding approximately US$19 million in fuel costs. Batteries provide modest balancing benefits, but savings are primarily driven by displaced gas burn.
- This is further demonstrated in the counter scenario of 20% maximum utilisation. In comparison to a scenario where the existing line is utilised at 50%, capping utilisation to 200MW increases gas generation by 3,100 GWh annually. This sees over US$218 million in additional fuel costs.
- Strengthening regional interconnectors is not just about imports: it directly reduces Singapore's exposure to volatile gas costs, improves CFE availability on the grid, and supports cost-effective decarbonisation.
- The interconnector today is mainly used for grid balancing, not clean power imports. With Singapore and Malaysia in talks on renewing the MOU and expanding utilisation, linking this to renewable and clean energy requirements could deliver dual benefits — strengthening grid reliability while cutting fossil fuel reliance and emissions.

Difference between MYSPE-SGP interconnector results of other utilisation levels to the base scenario

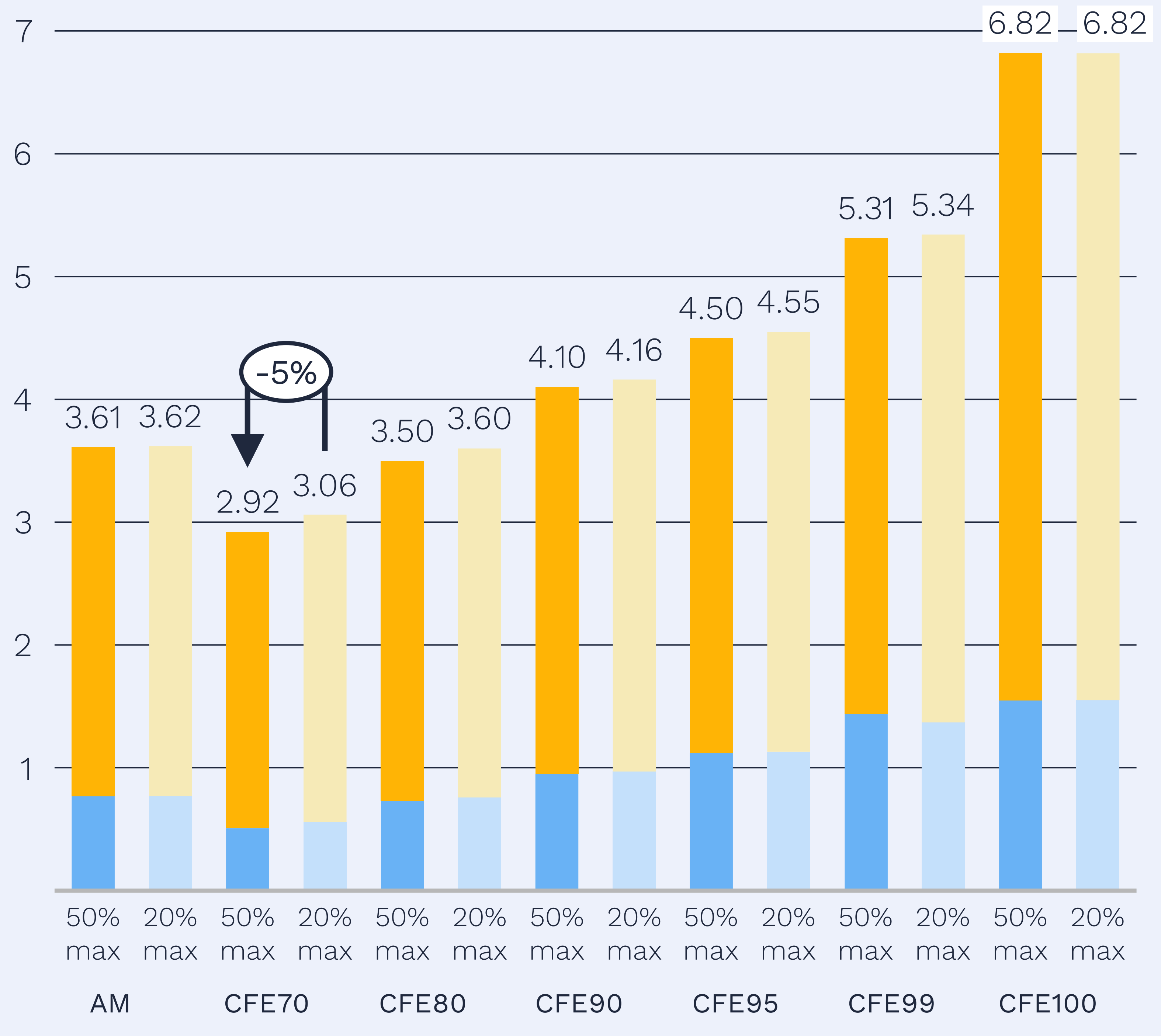


Benefits of utilising the Singapore-Malaysia interconnector (3/3)

Imports to the main grid will have limited impact on CFE unless those imports can be certified as clean

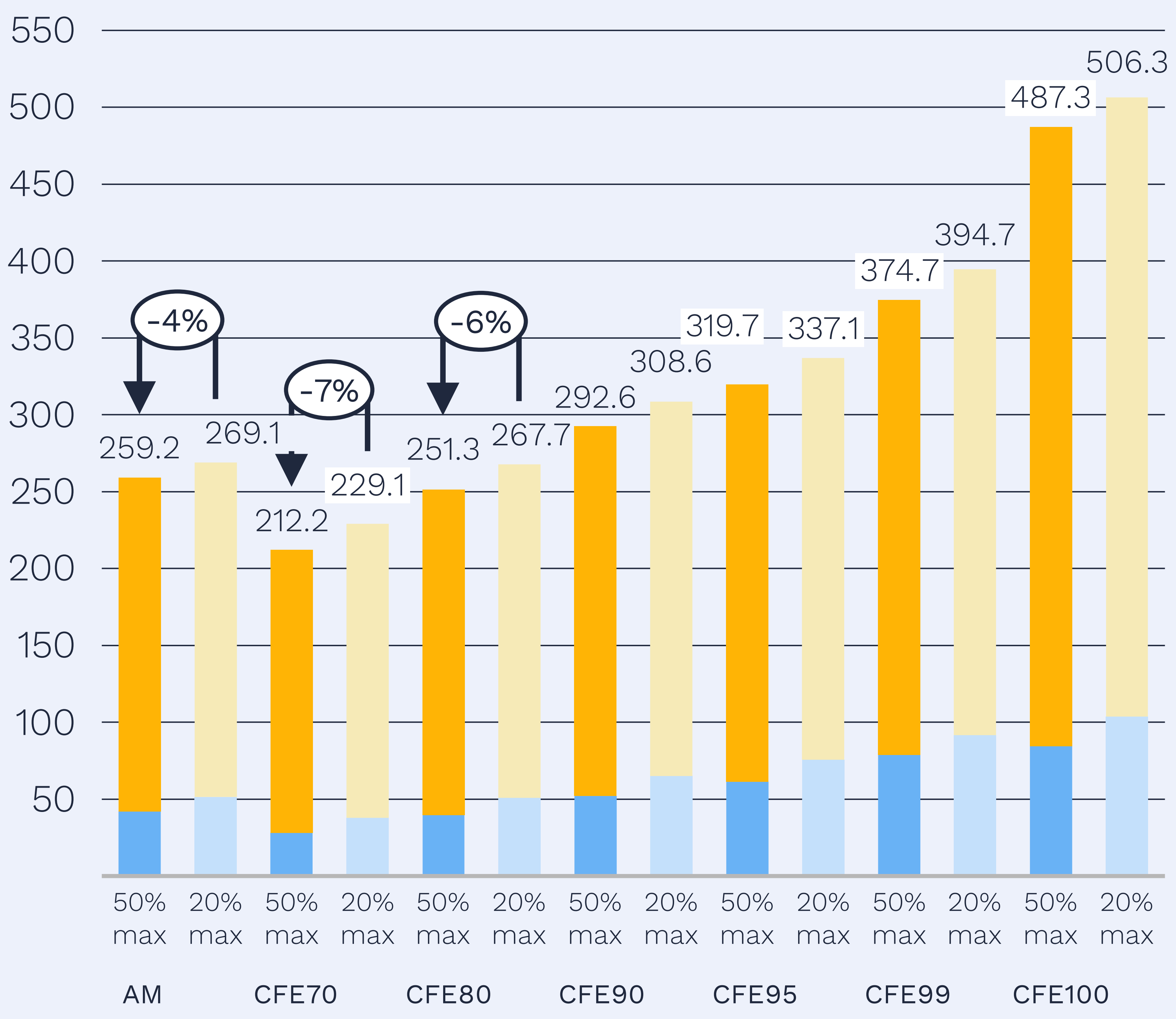
Comparing the capacity needs for C&I consumers when the SG-MYS line is utilised at 50% versus 20% shows that capacity needs fall only marginally, with imports impacting hourly matching results more than annual matching.

C&I procured capacity (GW)



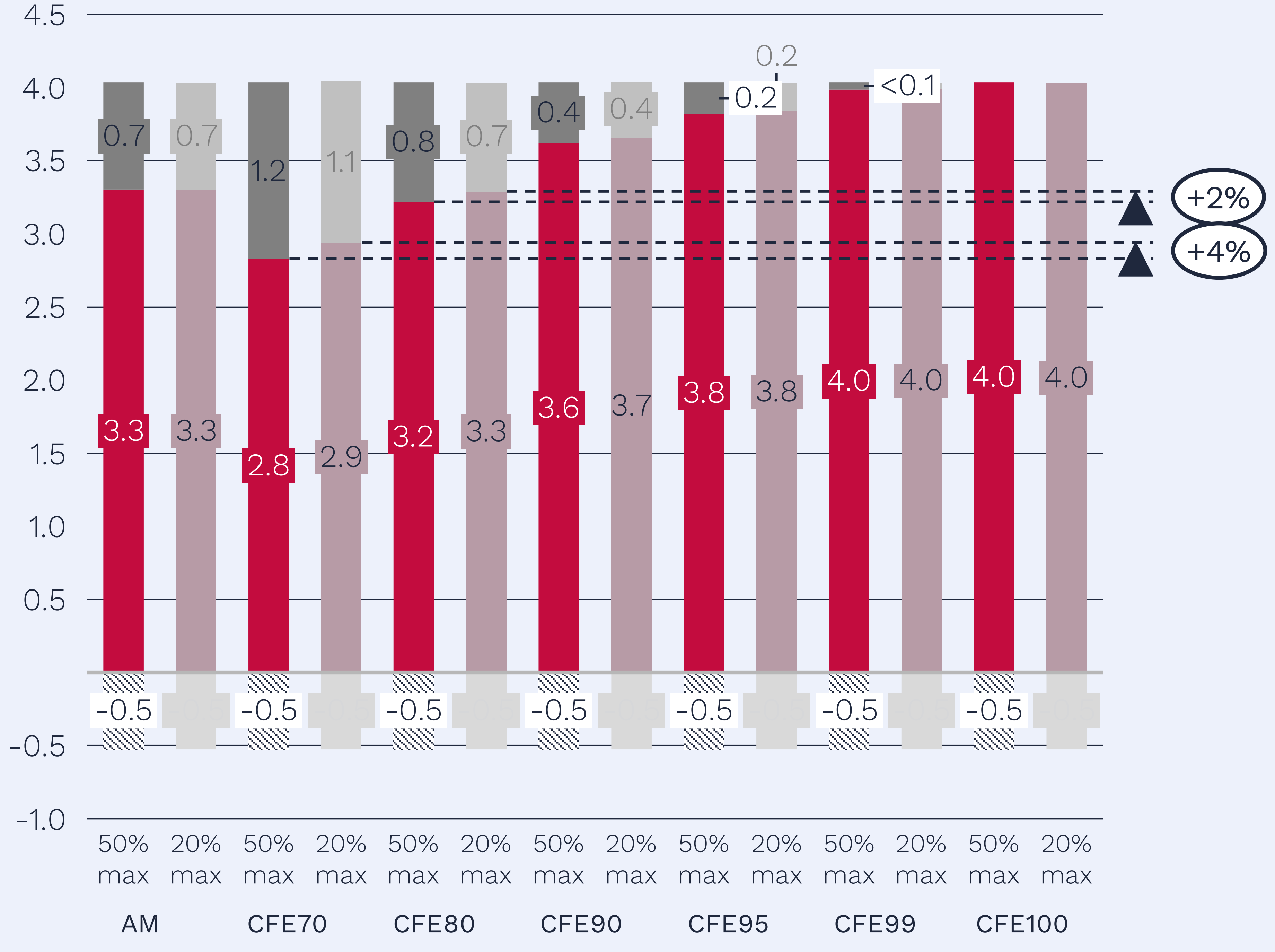
Investment costs are slightly reduced with more utilisation. The Batam interconnector sensitivity indicates that the result of this would be more pronounced if power through the line was clean, especially at lower CFE scores.

C&I procurement cost (million US$)



This is observed in the relationship between the grid and CFE, where C&I procurement from the wholesale is higher for 70-80% CFE when the SG-MYS link utilisation – and therefore imports – are higher and gas generation is displaced as a result.

C&I energy balance (TWh)



🟦 Batteries
🟧 Solar

⬛ Procurement from the wholesale
▨ Sales to the wholesale

🟥 C&I PPA
⬜ Procurement from the wholesale

⬜ Sales to the wholesale
🟪 C&I PPA

SOURCE: TZ Modelling

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Conclusion

C&I clean energy can deliver system benefits — when designed right

Optimal CFE targets, solar-plus-storage, and corporate PPAs unlock decarbonisation wins for both corporates and Singapore

01

70% CFE delivers a strong balance between cost, feasibility and emissions reduction.

Annual matching is often preferred by C&I consumers for its simplicity, but hourly matching introduces higher potential for emissions reduction for both C&I consumers and the wider system.

Achieving a 70% CFE score sees US$20 million less net system costs than annual matching. At 80% CFE, the costs and benefits nearly match those of annual matching, making it the optimal target for Singapore. Beyond 90%, capital costs rise for C&I consumers, but the system-wide gains — in emissions reduction and fuel savings — continue to increase.

02

Solar and battery — both domestic deployment and through imports — are key for clean energy supply.

Despite limited land availability, scaling solar-plus-storage remains a highly viable option for meeting C&I demand across matching regimes, especially as technologies like LDES, CCS and blended thermals remain less competitive in 2030 due to high investment costs.

Hence, enabling policies around clean power procurement for solar-plus-storage in the near-term, both domestically and via regional interconnection will be key to supporting a reliable, diversified pathway to 24/7 CFE.

03

C&I clean energy deployment gives benefit to both system cost and emissions mitigation.

For C&I consumers, contracting new PPAs and exporting excess clean energy to the grid helps reduce curtailment while contributing to the main grid's decarbonisation.

Policy recommendations

24/7 CFE can be aligned with the Singapore Green Plan 2030

Focus on proven technologies first

- Singapore can position itself as a regional leader in verifiable 24/7 clean energy procurement by prioritising proven solutions — namely solar, storage, and regional interconnections — as the backbone of its clean power system.
- Regulatory approvals should be fast-tracked for floating solar on reservoirs, paired with 4-hour battery storage to provide firm capacity and improve grid reliability.
- By focusing on proven renewables and storage first, Singapore can reduce near-term reliance and avoid long-term lock-in on costly and unproven options, such as carbon capture and storage or nuclear power.

Strengthen regional grid integration

- Near-term priorities include optimising the existing 1 GW interconnection with Peninsular Malaysia and ensuring the timely operationalisation of the planned 1 GW Batam interconnector with Indonesia. These projects would expand access to lower-cost renewable electricity, reduce exposure to imported LNG, and enhance system resilience.
- Over the medium-term, Singapore should work to deepen regional cooperation through ASEAN power trading frameworks, including the mutual recognition of green attributes associated with cross-border electricity flows.

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Annex

Further information, data and assumptions

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

Glossary (2/2)

Term	Definition
Grid CFE score	Hourly share of CFE within all brownfield generation from a single grid zone
Grid zone	A single grid zone in Singapore, i.e. SGP, representing the entire national power system as a unified bidding zone
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 with 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

National targets and planned capacity

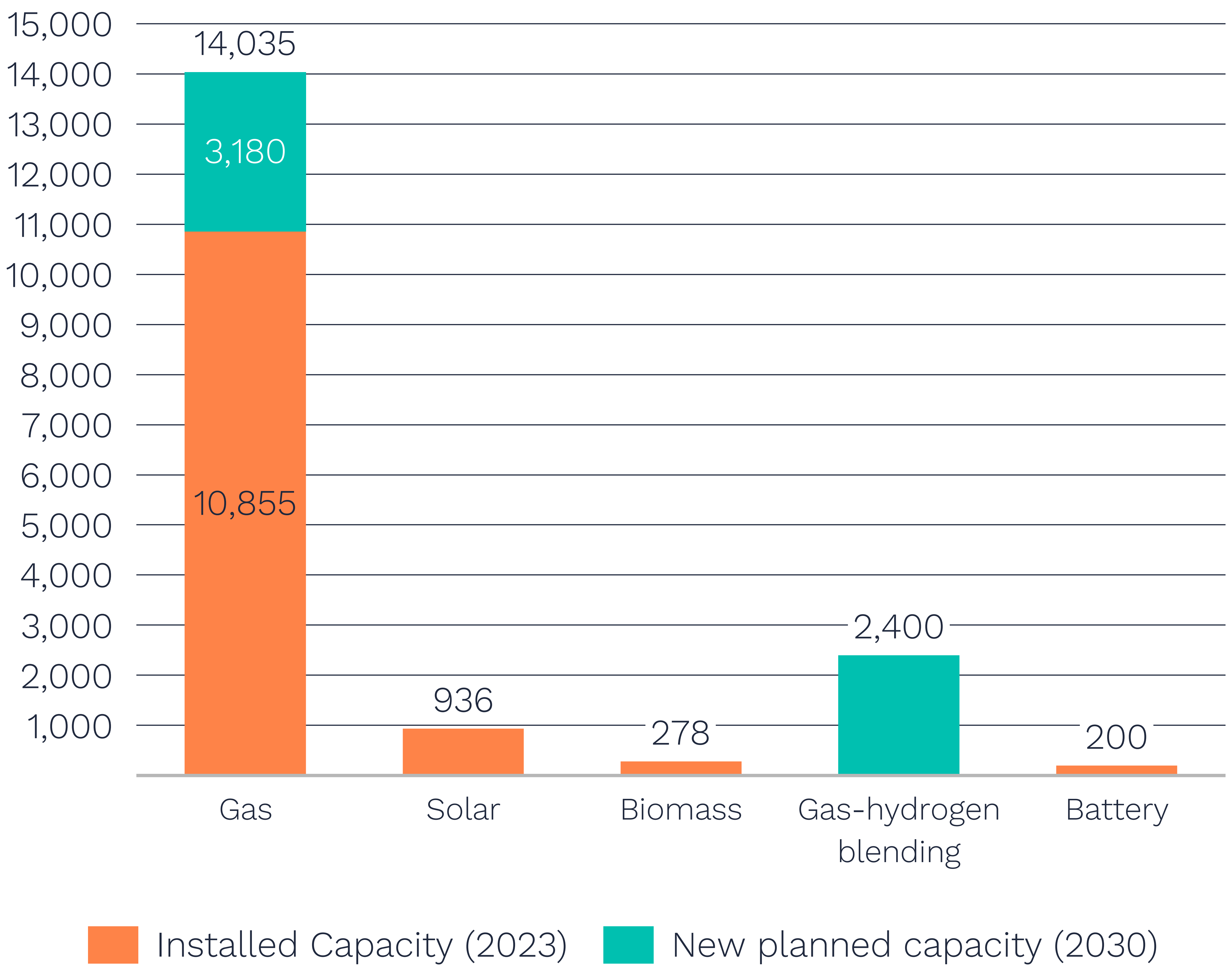
National decarbonisation targets and planned capacity are forced into the model to guide system development

Model constraints

Constraint type	Description
Solar penetration target	1,600MW (or 2,000MWp) of solar capacity
Emissions target	60 MtCO2eq power sector emissions peak
Fuel blending target	Gas-hydrogen blending at min 30% hydrogen

Source: Singapore Green Plan 2030, 2035 Nationally Determined Contributions, Project announcements, EMA

Existing and must-build brownfield capacity by technology (MW)



Notes

- We acknowledge that the Singapore Green Plan 2030 does not include explicit generation targets. This limited the calibration conducted for Singapore to matching our 2030 brownfield results to historical thermal generation patterns in 2023.
- We employ the government's 2030 planned capacity as a minimum build requirement for most technologies, with the exemption of solar where the target utility solar capacity is treated as a build constraint.
- National decarbonisation targets for renewable energy, emissions, and fuel blending were also applied. Only targets related to the power sector and applicable for 2030 are included.
- The 2030 pipeline of capacity reflected in government plans includes more than 3GW gas plants, maintaining gas' dominance in Singapore's system. On top of that, 2.4GW of existing gas plants will be retrofitted for gas-hydrogen fuel blending.
- Nationally, utility-scale solar is expected to exceed 1.6 GW as part of a strategy to reduce power sector emissions.

Tech build constraints

We seek to impose sensible limits on what type of capacity expansion we allow in the Reference Scenario for Singapore

Tech name	Planned new-build	Modelled additional build
Coal	✗	✗
Oil	✗	✗
Gas	✓	✓
Biomass	✓	✓
Co-firing Coal and Biomass / Ammonia	✗	✗
Co-firing Gas and Hydrogen	✓	✗
Gas CCS	✓	✗

Tech name	Planned new-build	**Modelled additional build**
Nuclear	✗	✗
Off-shore Wind	✗	✗
On-shore Wind	✗	✗
Grid-scale Solar	✓	✓
Conventional Hydro	✗	✗
Pumped Hydro	✗	✗
Batteries	✓	✓

Notes

- In addition to planned capacity based on government targets that are exogenously added, we allow the model to endogenously build new capacity for solar in the brownfield or Reference Scenario. This additional capacity is optimised on a least cost basis.
- Maximum endogenous build is capped by the renewable energy potentials.
- We exogenously add planned gas-based co-firing or CCS[1] capacity, and allow the model to build further capacity endogenously.
- To reflect long-term decarbonisation auctions and siting limitations, no additional capacity for coal-fired power plants – either exogenously or endogenously. This includes coal-based co-firing technologies.
- Technologies that are expandable in the greenfield to meet CFE are those included in the Technology Palettes presented in the methodology section.

[1] *For co-firing we allow only blue hydrogen and blue ammonia, but endogenously the model can build both blue or green capacity*

RE potentials & capacity factor assumptions

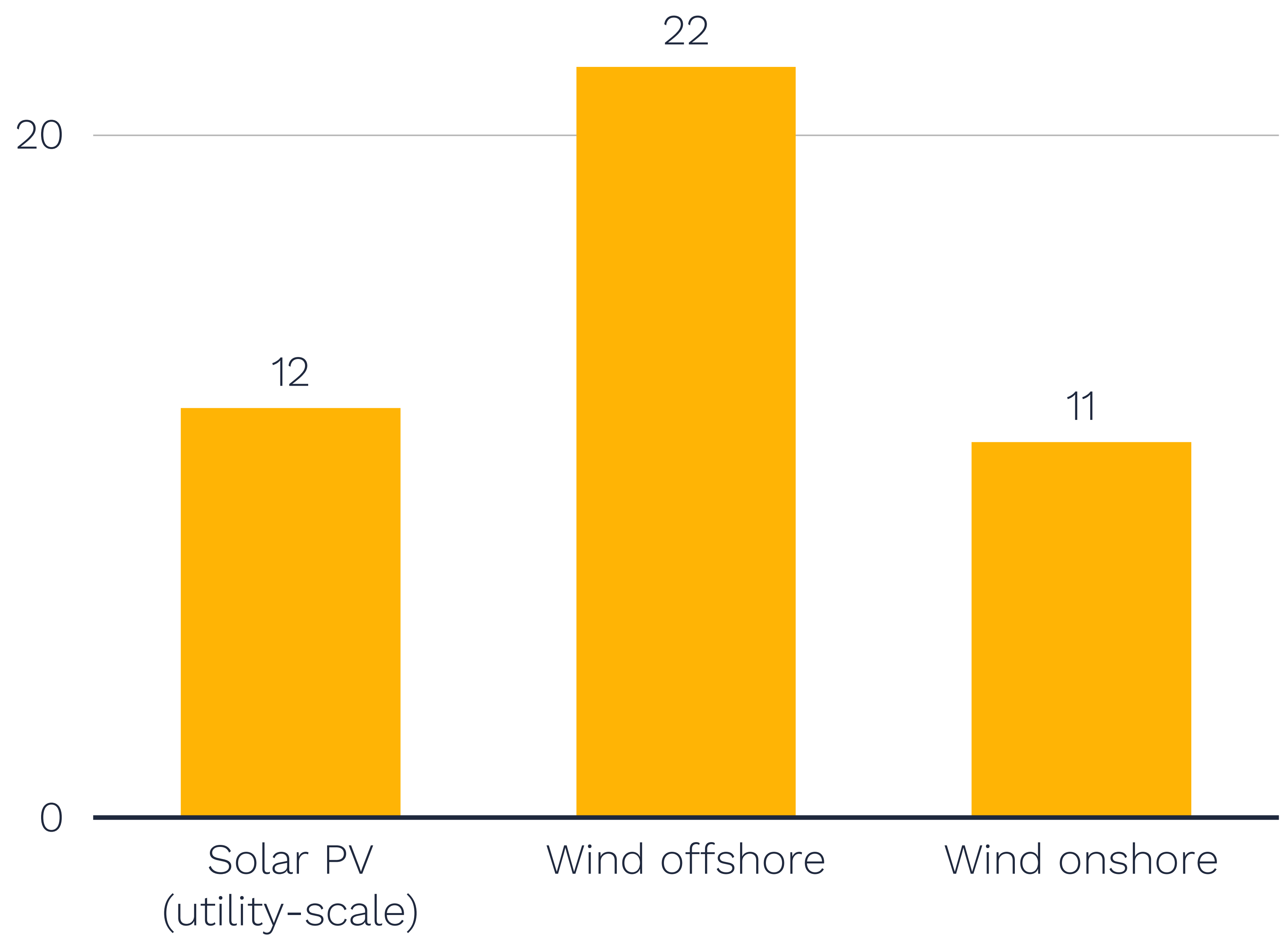
Technical capacity and generation potentials will constrain RE build-out and utilisation

RE Potentials

Technology	National potential (MW)
Bioenergy	280
Hydro	-
Solar PV (utility-scale)	6,900
Offshore wind	1,827

Sources: RE potential – TZ's in-house calculation
CF - TZ's in-house calculation scaled into renewables.ninja average values

Average capacity factor per technology (%)



Notes

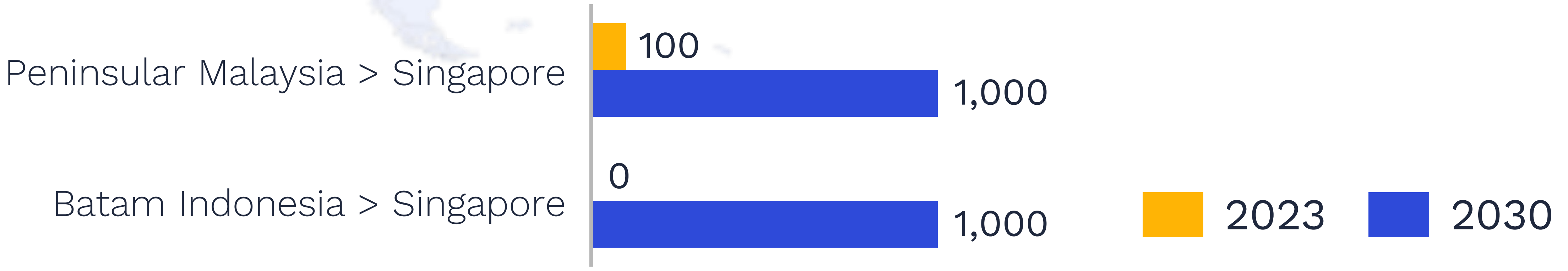
- Our in-house RE potential assessment indicates that Singapore has limited resources to fully meet its national decarbonisation targets. This is reflected in literature and government targets.
- To account for siting limitations, endogenous new build capacity of renewable energy is bounded by their respective technical potential.
- Utility-scale solar potential is limited to 7 GW, which may be insufficient to meet a 100% CFE score in addition to the 1.6 GW national solar target. Notably, imported solar capacity from Batam, Indonesia is made available in the model and is expected to contribute to the main grid and help bridge this gap.
- While data pertaining to wind is available and provided to the model, the technology has not been allowed to expand in the modelling, following stakeholder feedback on the feasibility of its deployment.

Interconnection constraints

We maintain a conservative view on inter-nodal transmission capacity expansion by 2030

🟩 Malaysia and Singapore nodes

■ Nodes with electricity trade with Malaysia and Singapore



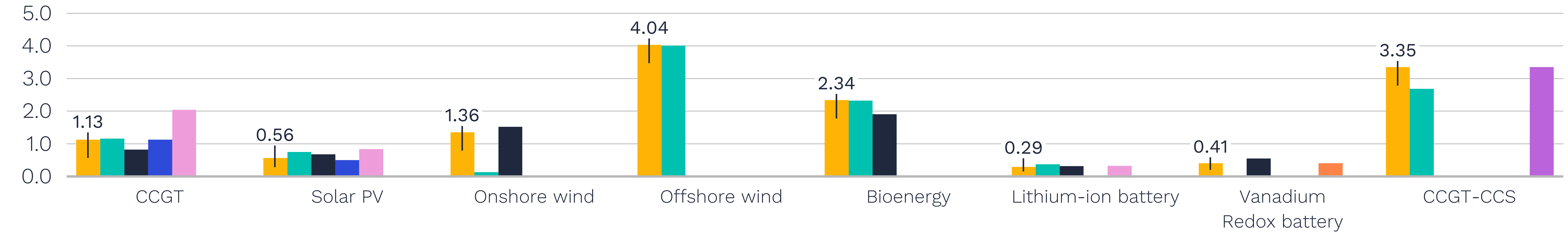
Notes

- We model Singapore as a single grid with interconnection to Peninsular Malaysia and Batam, Indonesia.
- The Singapore-Malaysia interconnector was utilised only at 100 MW in 2023, in line with bilateral agreements. In 2030, we allow the transmission capacity to reach 1,000 MW, reflecting the line's actual capacity following the 2022 upgrade.
- A 1,000 MW Singapore-Batam interconnector is introduced in 2030, representing a conservative estimate for the realisation of cross-border projects under the SG Green Consortium. A 75% utilisation load is applied, in line with EMA's requirements.

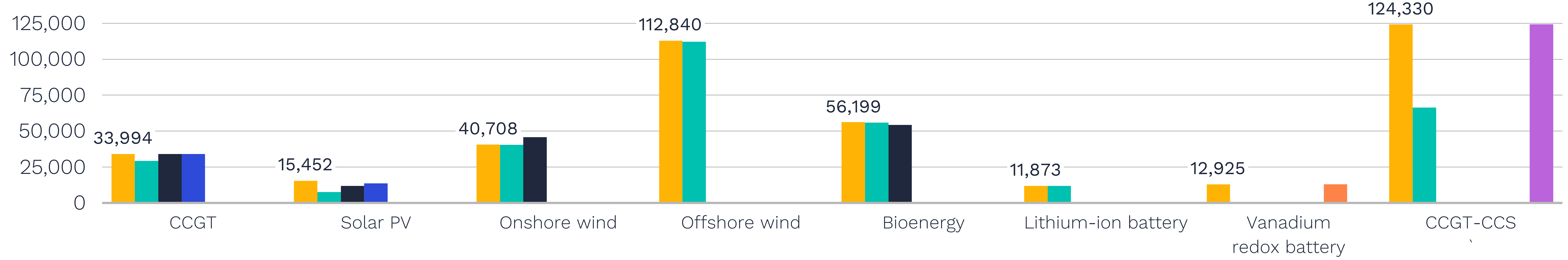
Technology cost assumptions

We consider various official and industry sources with ASEAN-specific technology costs

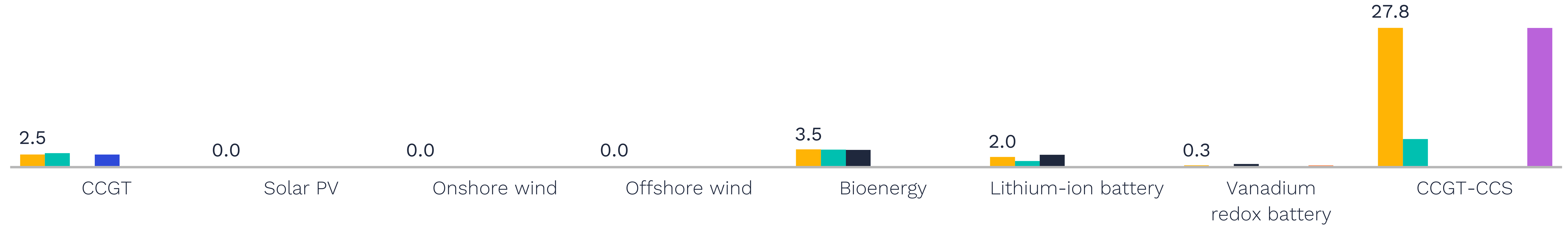
2030 CAPEX of select technologies (US$2023/MW, except US$2023/MWh for lithium-ion battery)



2030 Fixed O&M cost (US$2023/MW/year, except US$2023/MWh/year for lithium-ion battery)



2030 Variable O&M cost (US$2023/MWh)



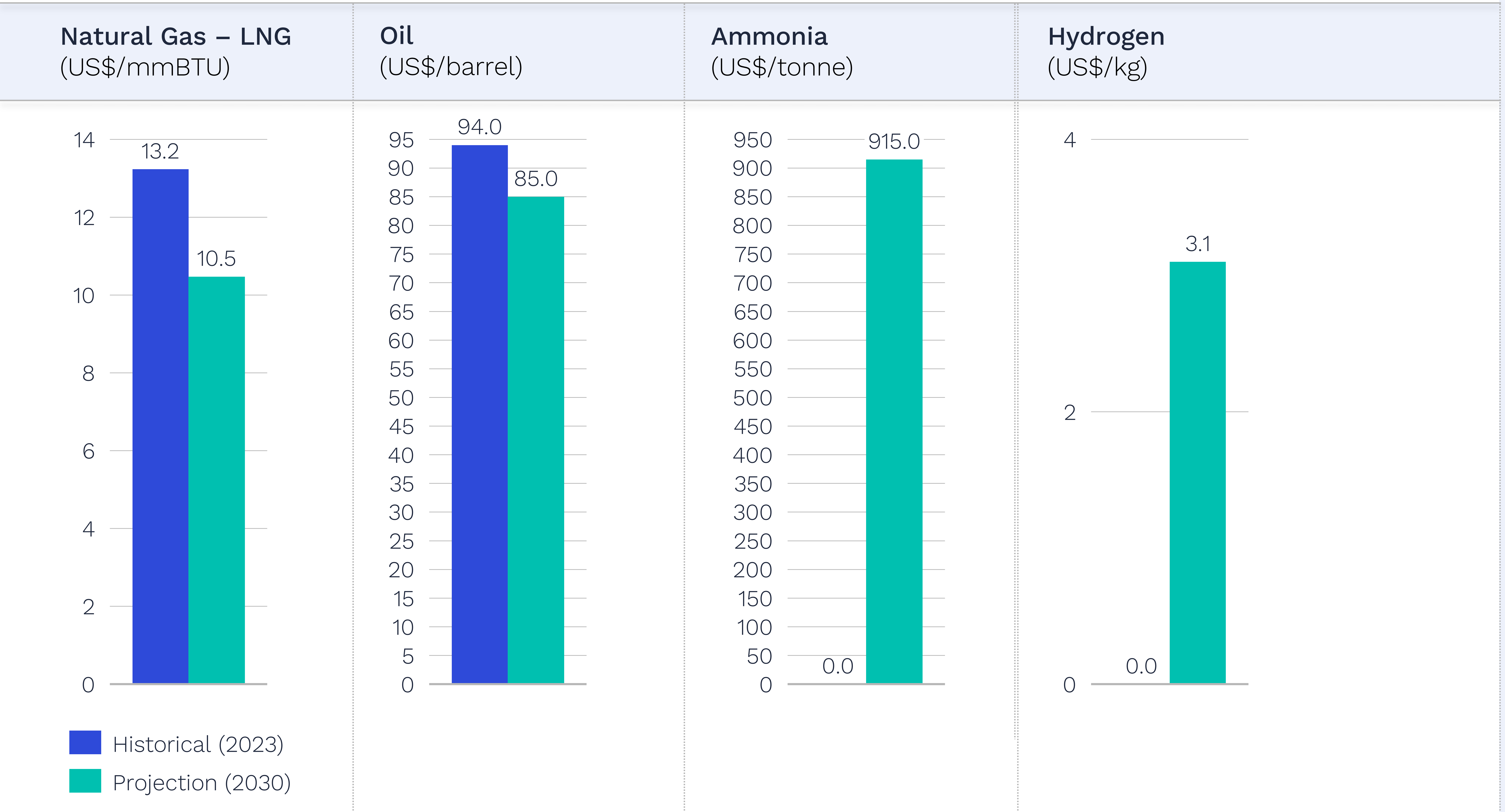
Notes

- Country-specific technology costs for Singapore were not publicly available to use as inputs in our model.
- We referenced technology costs that are specific to the region and released by trusted sources such as the Danish Energy Agency (with endorsement from local governments), ASEAN Centre for Energy, and Bloomberg New Energy Finance. Available data for the relevant technologies varied across these sources.
- We derived an average or the best-represented values for each technology, based on additional desk research and stakeholder consultations.
- Costs are expressed in US$2023 values.

🟨 Projection used in the current model
🟩 Indonesia Technology Catalogue by Danish Energy Agency
⬛ Vietnam Technology Catalogue by Danish Energy Agency
🟦 BNEF's Malaysia tech costs
■ ASEAN Center for Energy's AOR8
🟧 US DOE
🟪 METI Japan

Fuel costs

Cost projections account for Singapore's position as a net energy importer



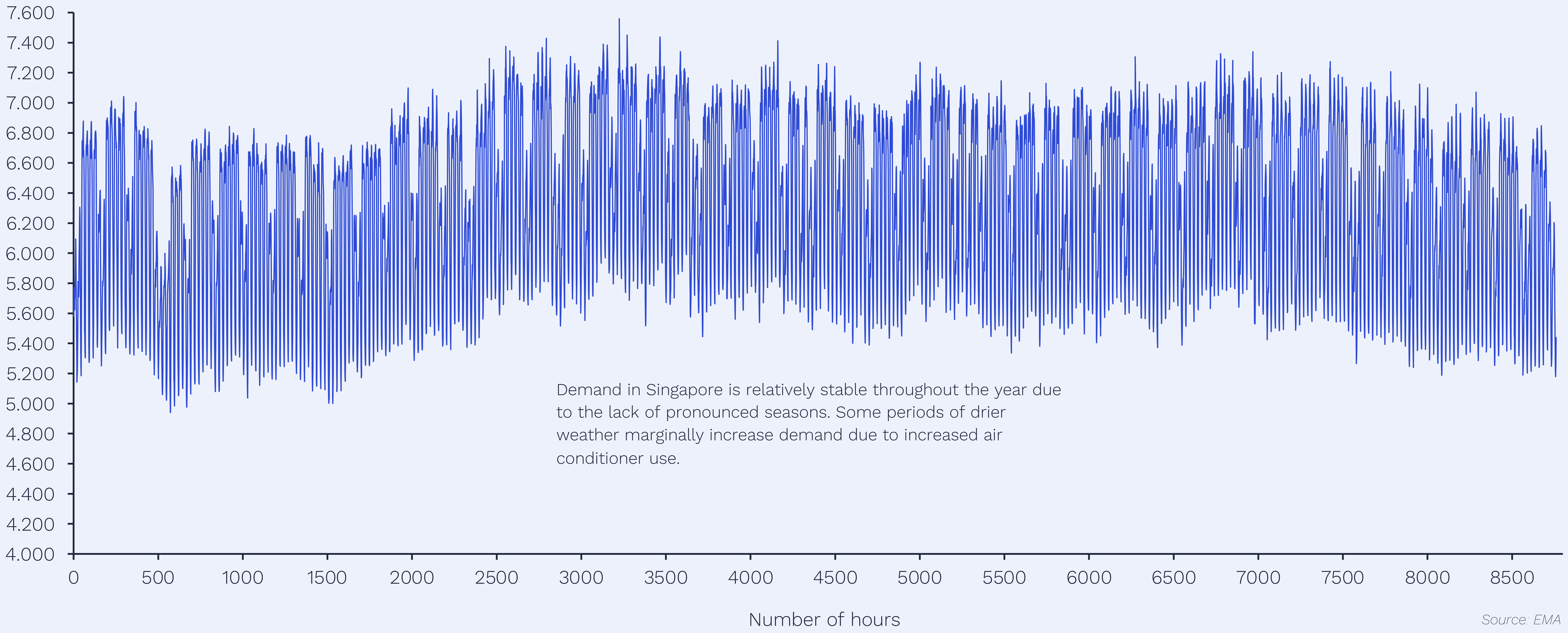
Notes

- Projected imported gas price is based on Japan's LNG import prices as a regional benchmark. Oil prices follow IEA crude oil price projections. We recognise both assumptions to be optimistic, given Singapore's reliance on imports for both fuels.
- Hydrogen costs are capped using IEA's STEPS supply cost curves for Asia.
- BNEF's ammonia cost estimates for Malaysia serves as the reference for ammonia pricing. Comparing with in-house TZ ammonia (renewable shipped) estimates and assumptions.

Sources:
Gas cost - S&P Global Commodity Insights for Japan
Diesel oil cost - IEA crude oil price projection
Hydrogen cost - IEA STEPS supply cost curve
Ammonia cost – BNEF projection for Malaysia

Hourly demand used follows recorded demand profile in 2023

This profile is applied to both brownfield and CFE demand across the country

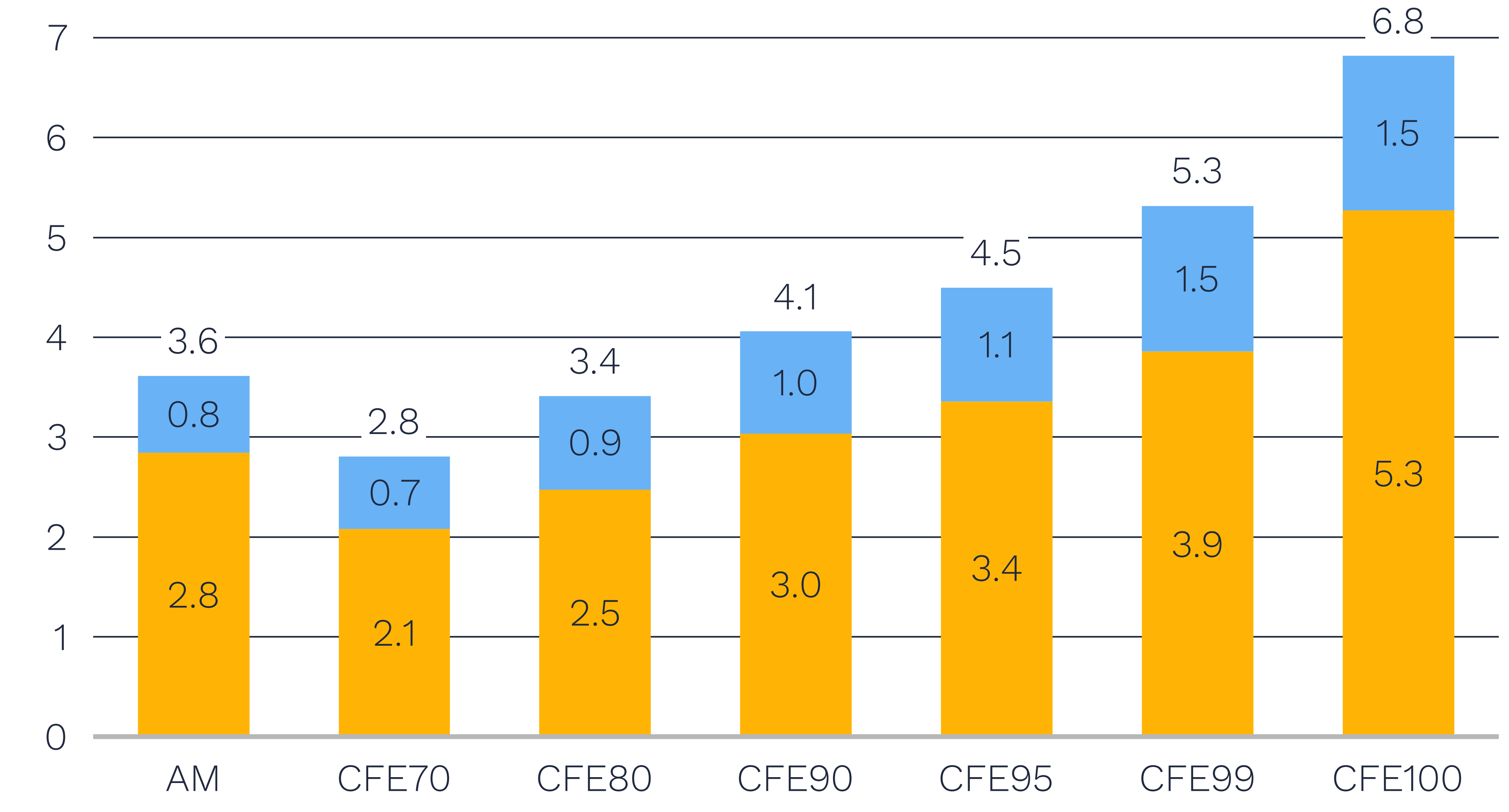


Demand in Singapore is relatively stable throughout the year due to the lack of pronounced seasons. Some periods of drier weather marginally increase demand due to increased air conditioner use.

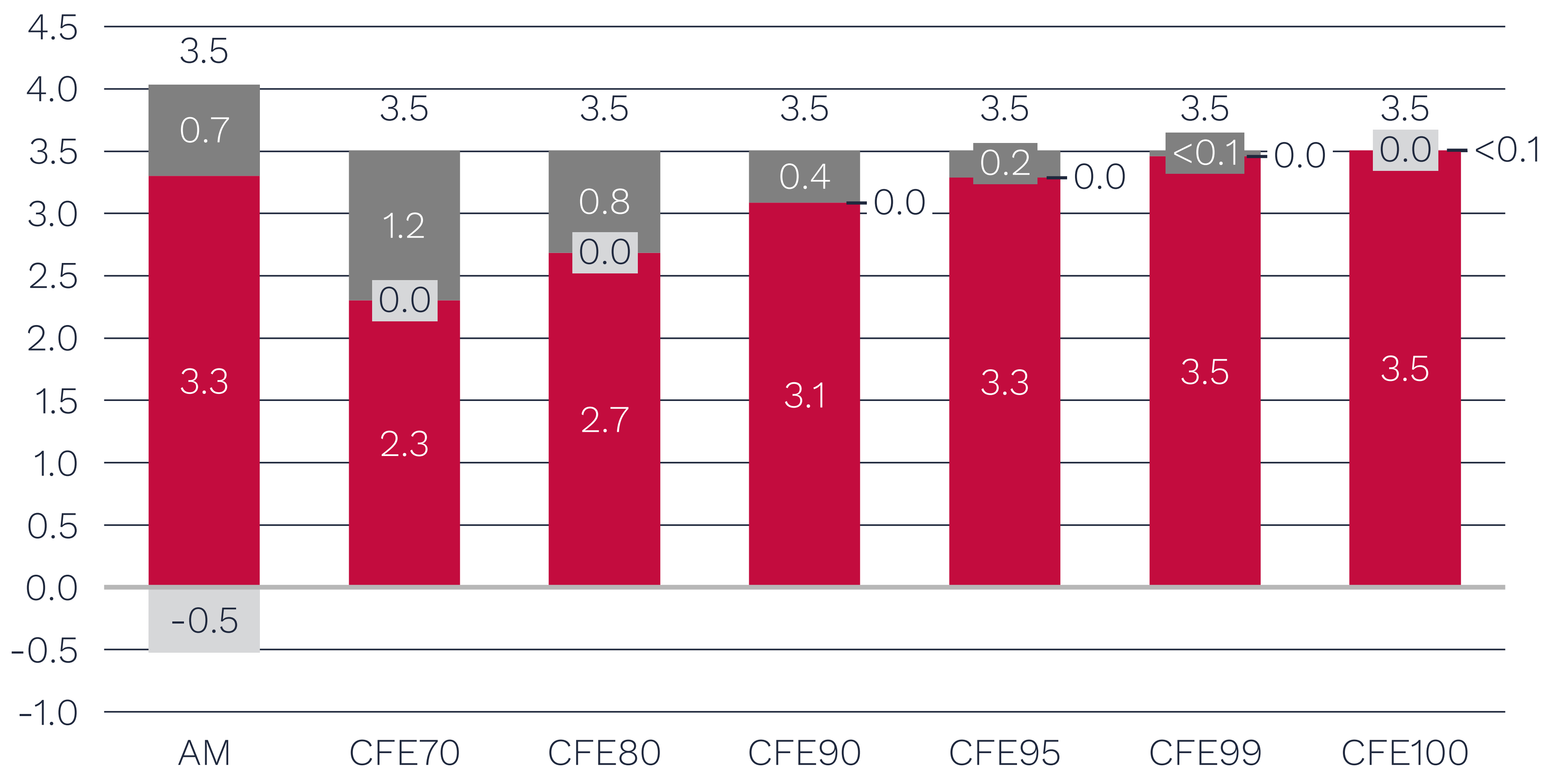
Source: EMA

Impact of sell-back on C&I procurement and the grid

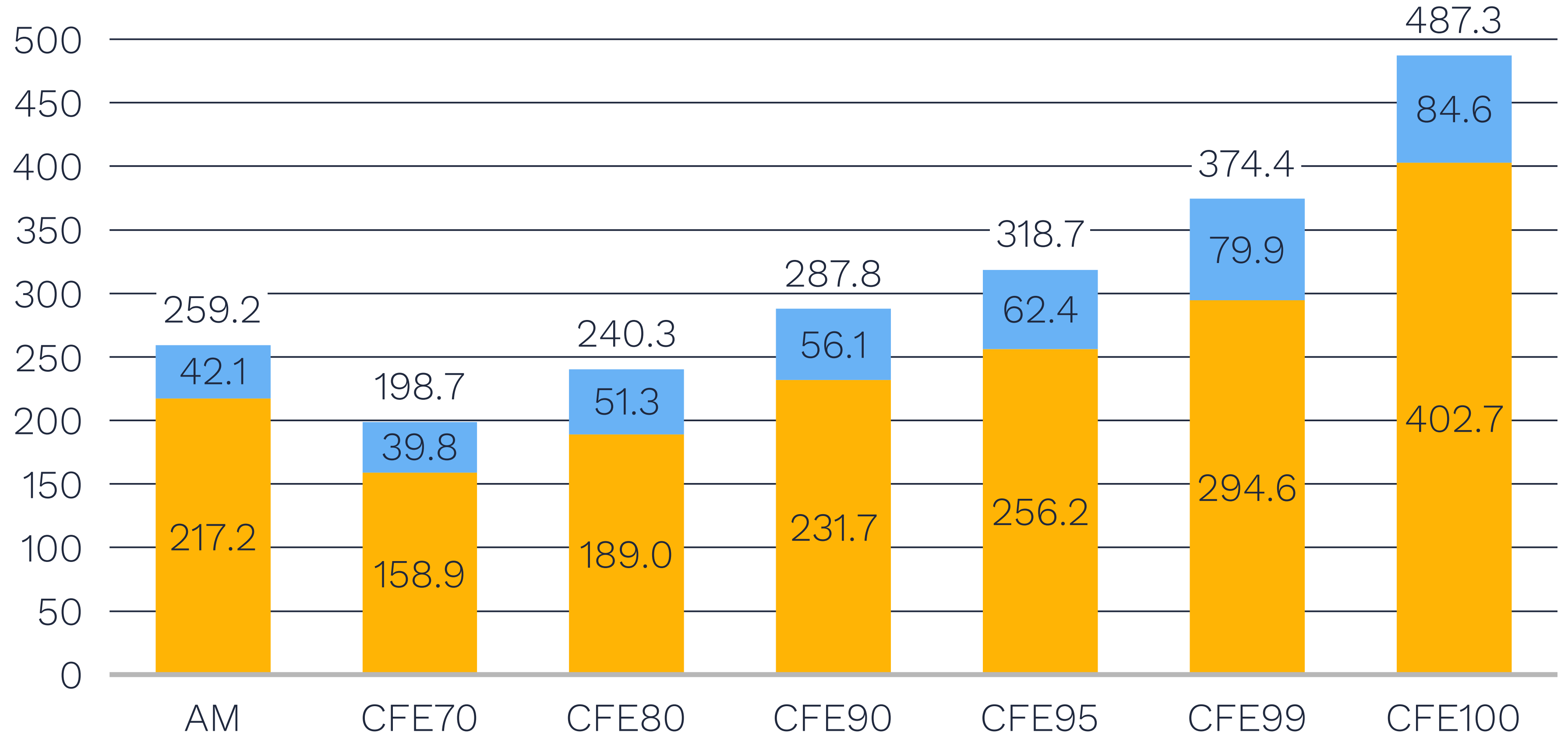
Procured capacity (GW)



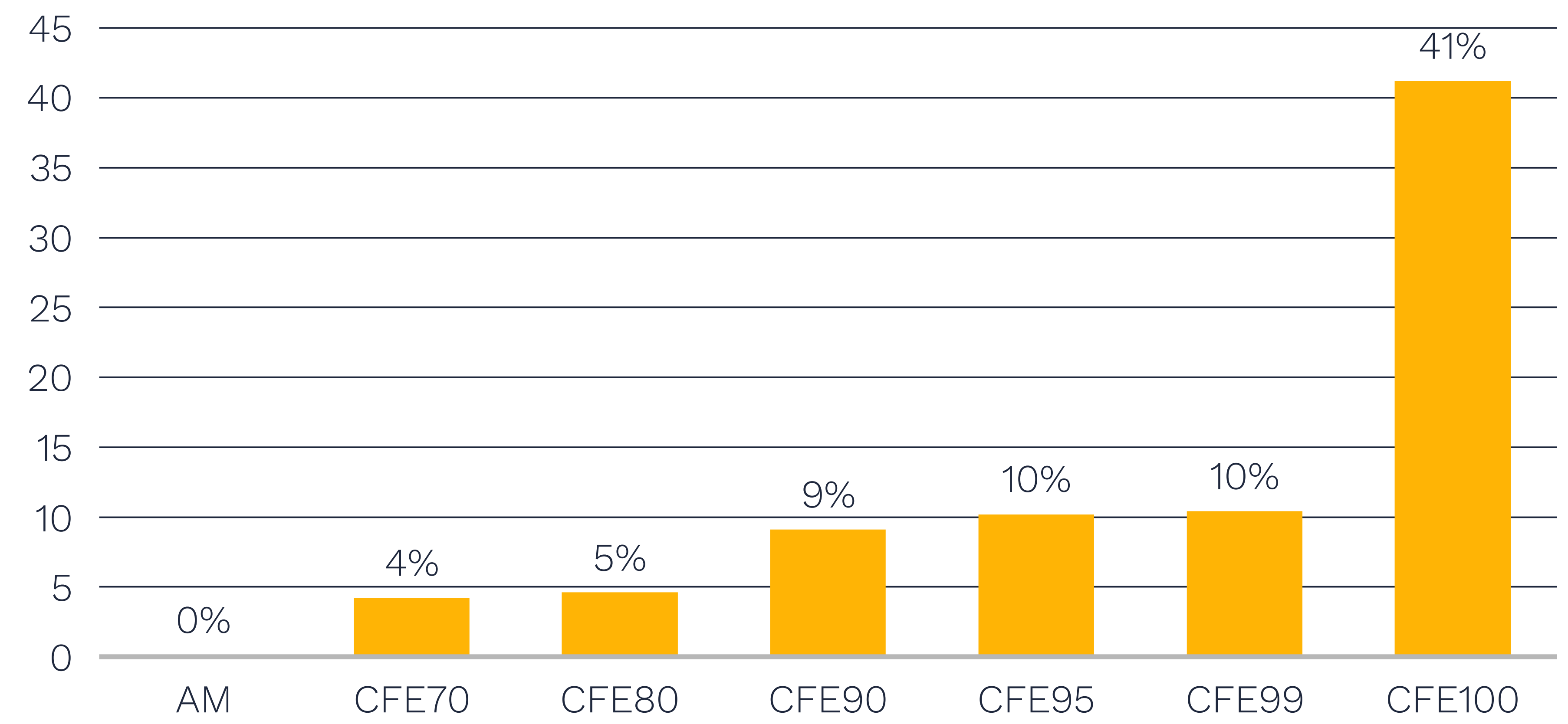
Greenfield – Brownfield trade (TWh)



Procurement cost (million US$)



Solar curtailment (%)



🟦 Batteries 🟨 Solar ⬛ Grid supply ⬜ Excess sold back to the main grid 🟥 C&I PPA

Notes

- Sell-back is key to minimising curtailment and maximising benefits in hourly matching scenarios.
- Allowing excess generation from procured capacity to be sold to the grid provides revenue for C&I developers to offset investment costs, and significantly reduces CFE curtailment.
- Total procured capacity and associated costs remain similar regardless of whether a 15% sell-back cap is applied.
- Without the ability to sell excess generation under hourly matching, less total CFE generation is observed compared to scenarios that allow sell-back. However, this is due in part to higher curtailment in a no-sell back scenario — rising exponentially to 40% at a 100% CFE target — as solar capacity must be oversized to meet hourly clean demand. At 100% CFE, the solar capacity required is more than double that of the 80% CFE scenario.

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.

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