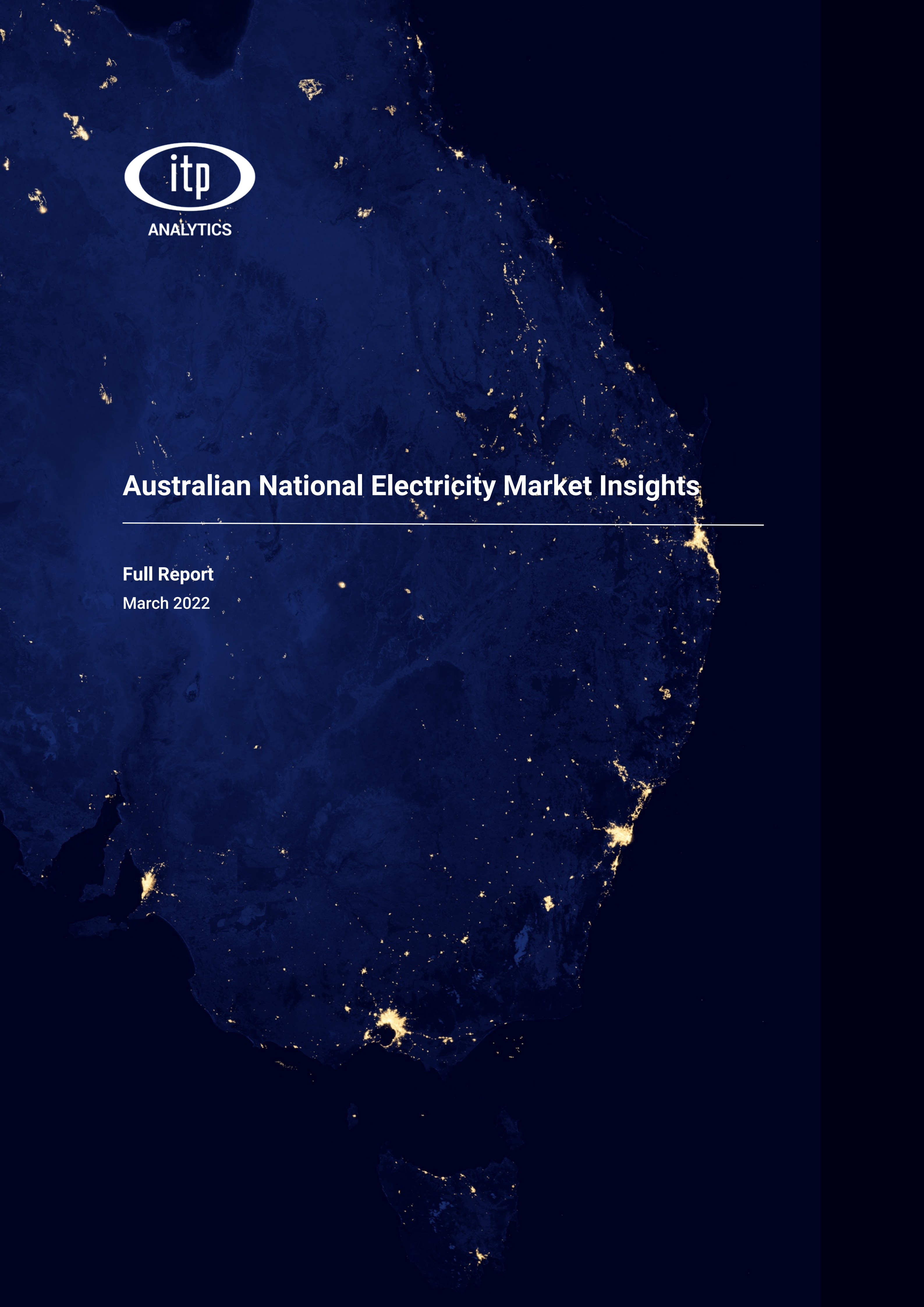

Australian National Electricity Market Insights

Full Report

March 2022

About Us

ITP Analytics offers a range of consulting services in energy market analytics:

> **National and state-wide capacity expansion modelling** – revealing least-cost energy transition pathways and delivery cost forecasts, facilitating the testing of regulatory reform and the implications of technological change.
>
> **Distribution level capacity expansion modelling** – analysing the implications of DER uptake (including EVs) and policy measures driving the gas to electricity transition.
>
> **Mini- and micro-grid feasibility and optimisation** – collaboratively with our engineering division, taking into consideration trends such as falling storage costs, emerging regulatory reform to drive fringe-of-grid disconnection and novel ownership models.
>
> **Generation and storage project feasibility and optimisation** – using sophisticated, bespoke modelling tools to assess the optimal management of generation, storage, and loads, taking into consideration complex tariff structures.
>
> **Regulatory environment analysis** – providing recommendations to government about reform processes or opportunities, and advice to industry about the implications of forecast change.

You can read about our recent and ongoing work at itpau.com.au/projects.

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Introduction

ITP Analytics is publishing quarterly reports analysing potential pathways for the transition of the Australian National Electricity Market (NEM). Our intent is to inform policy-making and public discussion. This report is the first of the series.

The analysis published in each report will be based on our openCEM model. openCEM is a freely available open-source electricity grid modelling tool developed by ITP. It is designed to be used by decision makers, energy system planners, regulators, project developers and investors to determine how policy objectives (such as electrification, renewable energy, or emission reductions targets) can be achieved at least-cost, while maintaining energy security. For a given policy objective, it reveals, for example:

- when, where, what type and how much generation, storage and transmission capacity should be added;
- how new generation and storage need to be operated in coordination with existing generation capacity to satisfy demand at the least cost.

Model outputs include all capacity and dispatch decisions for the system under consideration, as well as a breakdown of capital and operating costs, utilisation, capacity, energy, and transmission statistics.

Each quarterly report has two parts. The first part will describe how the NEM may transition to an increasingly renewable energy future using scenarios based on the published climate and energy policies of the federal government and opposition parties. These scenarios will be revised each quarter with updated input assumptions.

The second part of the report will be a more in-depth study of a specific topic of interest. In this report we examine the potential for hydrogen-fuelled open cycle gas turbines to displace solar and wind capacity and reduce total electricity system costs. Hydrogen turbines may also provide additional services for the electricity market, such as fault current and capacity for peak events.

The development of openCEM was partially funded by the Australian Government (ARENA) and the Governments of NSW, Victoria, and South Australia. Our development partners were the Centre for Energy and Environmental Markets at the University of New South Wales; the Climate and Energy College at the University of Melbourne; software development specialists ThoughtWorks, and the US Strategic Energy Analysis Center of the National Renewable Energy Laboratory.

Further detail about how openCEM operates is available in Appendix C and at opencem.org.au.

In this report we have included detailed openCEM output, including electricity delivery cost forecasts for each State. In future reports this, and more detailed and granular information, including retail and spot price forecasts, will be available via subscription.

Policy Comparison

Introduction

In this section, we compare three scenarios based approximately on the published federal energy policies of the Australian Liberal Party, Labor Party, and the Greens. Broadly, these represent net-zero emissions targets in the electricity sector of 2050 and 2030[1]. We also compare a policy that adopts the carbon price recommended for advanced economies by the International Energy Agency (IEA).

Inputs

The table below summarises the key inputs to openCEM for each scenario.

Scenario	Emissions Target	National Renewable Energy Target	Rebates & Schemes	Technology Costs	Carbon Price	Generator Retirements
No Net Zero Target	28% reduction from 2005 – 2030	33,000 GWh by 2030 23.5% in 2020	None	AEMO 2020 ISP Step Change	None	AEMO 2020 ISP Central
Net Zero by 2050 ("Coalition")	28% reduction from 2005 – 2030 Net-zero by 2050	33,000 GWh by 2030 23.5% in 2020	None	AEMO 2020 ISP Step Change	None	AEMO 2020 ISP Central
Net Zero by 2050 ("Labor")	45% reduction from 2005 – 2030 Net-zero by 2050	50% by 2030	Additional transmission infrastructure[2]	AEMO 2020 ISP Step Change	None	AEMO 2020 ISP Central
Net Zero by 2030 ("Greens")	75% reduction from 2005 – 2030 Net-zero by 2030	100% by 2030	Additional transmission infrastructure[3]	AEMO 2020 ISP Step Change	None (specific pricing not announced)	Accelerated retirement of coal[4]
IEA Carbon Price	28% reduction from 2005 – 2030	None	None	AEMO 2020 ISP Step Change	IEA carbon price for advanced economies[5]	AEMO 2020 ISP Central

[1] It is important to note that announced policies change frequently (especially close to an election) and may be often silent on some aspects required for modelling. In these cases, ITP makes an informed estimate, described above or in the Appendices. This report has been updated since its release to reflect a change in the Labor party policy.
[2] $5 billion transmission infrastructure fund from the ALP 2019 election policy
[3] $6 billion Grid Transformation Fund from Greens 2019 election policy
[4] See Appendix B for a list of coal stations retired early
[5] IEA (2021), Net Zero by 2050, IEA, Paris https://www.iea.org/reports/net-zero-by-2050

Carbon Price

The carbon price used in our IEA Carbon Price scenario is based on the International Energy Agency's proposal for advanced economies:

Carbon Price (AUD/t)	2022	2026	2030	2035	2040	2045	2050
IEA Advanced Economies	58	120	181	233	285	316	348

AEMO ISP Scenario

In consultation with Australia's major electricity market stakeholders, the Australian Energy Market Operator (AEMO) has found that their Step Change scenario, a high-renewables, aggressive fossil fuel retirement objective, is the most likely pathway forward for the Australian electricity market. We based price pathways on the Step Change scenario for fuel, technology builds and maintenance, and technology adoption speed. 2022 AEMO ISP scenarios are still under review, so 2020 Step Change assumptions were used for the modelling in this report.

Emissions

Net-zero emissions targets were implemented as a constraint of zero tonnes of emissions in the year that the policy aims for. Where there are no additional, intermediate targets proposed by a policy, the emissions target stays constant throughout the years from the last year it was specified. This allows openCEM to calculate the cheapest pathway to net-zero while meeting all other constraints.

Economy-wide net-zero targets differ in timing from net-zero targets in the electricity sector. 100% renewables in the electricity sector implies that the sector is also producing net-zero emissions. Generally, policies have more ambitious net-zero targets for the electricity sector than the rest of the economy, as it is simpler and less costly to reduce emissions in the electricity sector.

Results

Marginal Cost of Delivery

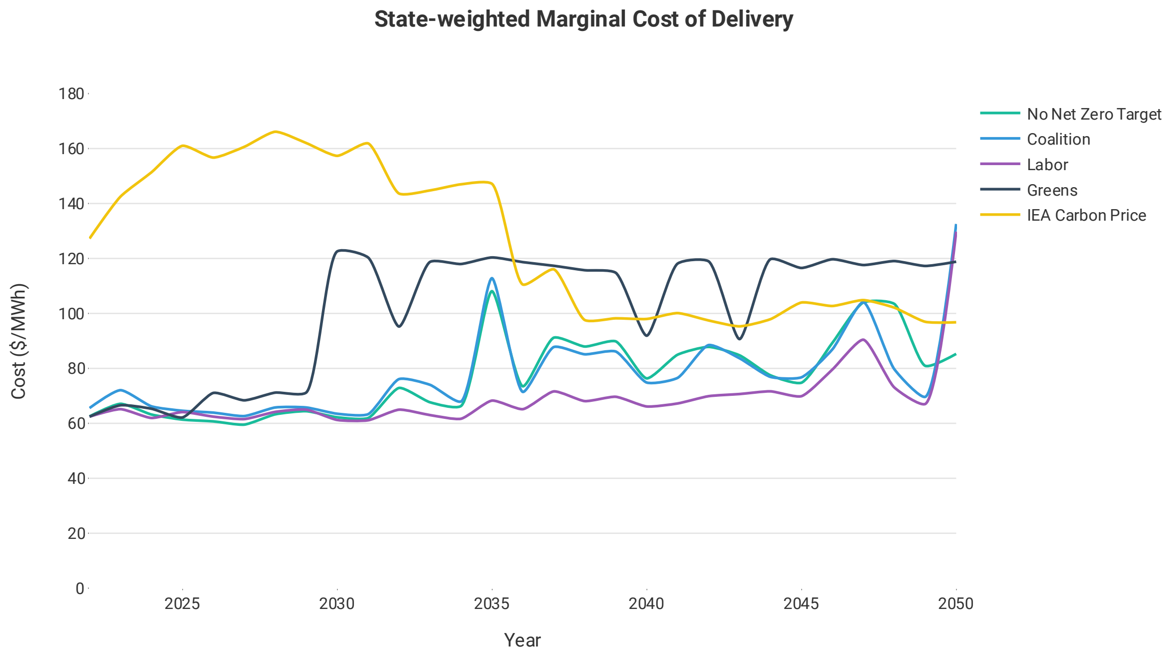


Figure 1

openCEM calculates a marginal cost of dispatching each technology based on its fuel costs, other operating costs, repayment costs, and a profit margin, and makes a “stack” of prices for each timestep based on this. As there are no competitive market mechanisms, this is not the same as a spot price in the actual market, but it offers a way of comparing the cost of delivering electricity for each scenario. It can be construed as a proxy for wholesale prices because it embodies a combination of short and long running marginal costs for the system. We discuss the challenge of forecasting wholesale prices in high renewables grids in Part Two of this report.

Figure 1 shows the average of all the regional marginal prices in a year, weighted by the total demand in each region. Peaks in the delivery cost occur at different times for each scenario. For example, in the Greens scenario, the delivery cost is highest in 2030, when the model must achieve 100% renewables. In the years before 2030, substantial wind, solar, and battery capacity is built to achieve this, and the additional build repayment costs contribute significantly to the higher delivery cost from 2030 onwards.

The other scenarios follow this trend. In the Labor and Coalition scenarios, reaching net zero in 2050 requires substantial expenditure on renewables and storage in the years leading up to 2050, so the delivery cost peaks in 2050.

The Labor scenario maintains a lower cost of delivery throughout most of the years due to increased transmission infrastructure resulting in more efficient use and building of generators.

Technology Mix

In 2050, the technology mix is almost identical in all scenarios with net-zero emissions, and all scenarios are satisfying the same demand growth. This results in the total system cost converging in 2050 for all but the No Net Zero Target scenario. openCEM arrives at roughly the same technology mix in every scenario with a net-zero constraint in 2050, regardless of the starting point.

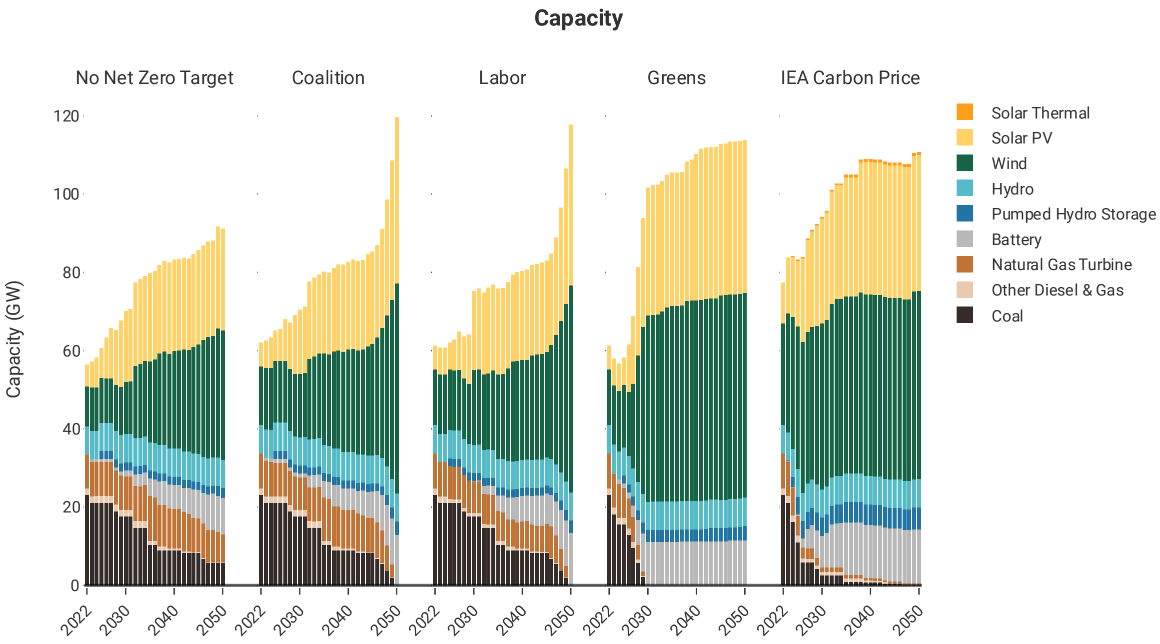


Figure 2

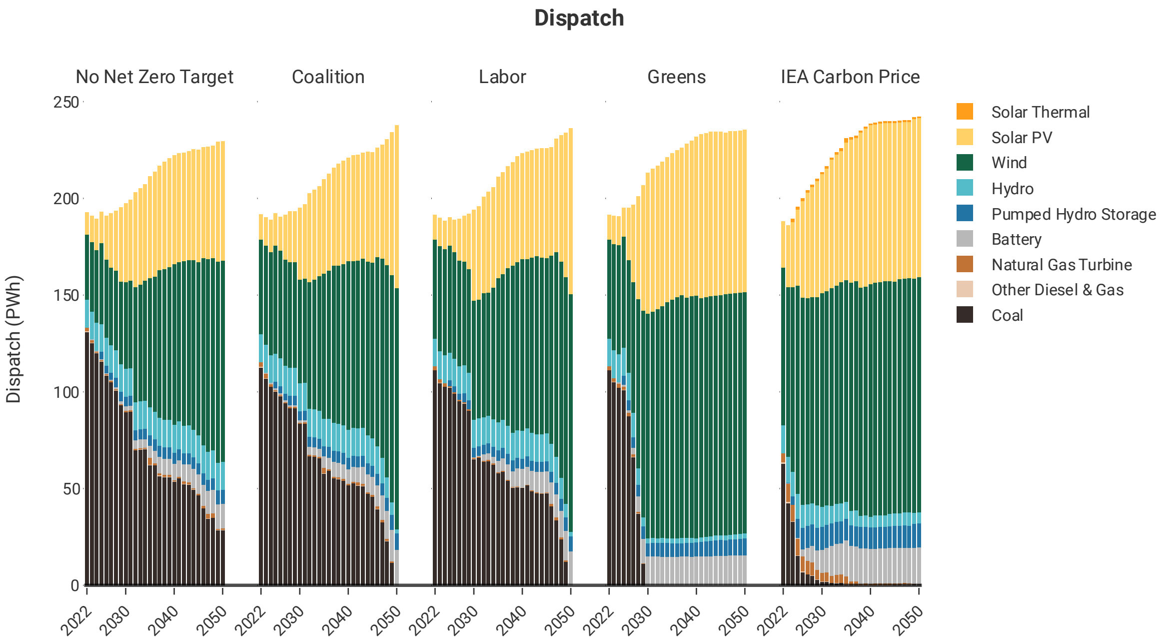


Figure 3

None of the policies specify a rate of increase in renewables before they reach net-zero. In an unconstrained model, the least cost approach results in almost all the required renewables being built in the year before net-zero is required. In our modelling, we have not constrained each scenario so that it cannot build more than is practical in a single year. openCEM still builds most of the renewables in the few years preceding a net-zero target. Whether this transition would occur in the same way in practise depends heavily on the investment decisions of developers.

In general, solar and wind dominate the generation mix as emissions reduce, due to their low cost, which is predicted to continue decreasing. To match supply with demand, these technologies need support from storage, and the results show that the least-cost, zero-emissions way to do this is with a combination of batteries and pumped hydro.

In the Coalition policy scenario, coal retirements are only significantly impacted in 2050, with retirements accelerated to a greater degree by Labor and Greens policies. In the IEA Carbon Price scenario, openCEM deploys solar thermal generation with 12-hour storage, to help reduce emissions further and avoid paying the carbon price. In the other scenarios, the cost of solar thermal with storage is too high for it to be deployed.

Cost Breakdown

System costs in scenarios with increasing amounts of renewables are dominated by loan repayment, and operation and maintenance costs. openCEM avoids paying a carbon price in the IEA Carbon Price scenario, as it is cheaper to build renewables to reduce carbon emissions than to continue emitting and pay the carbon price in either scenario.

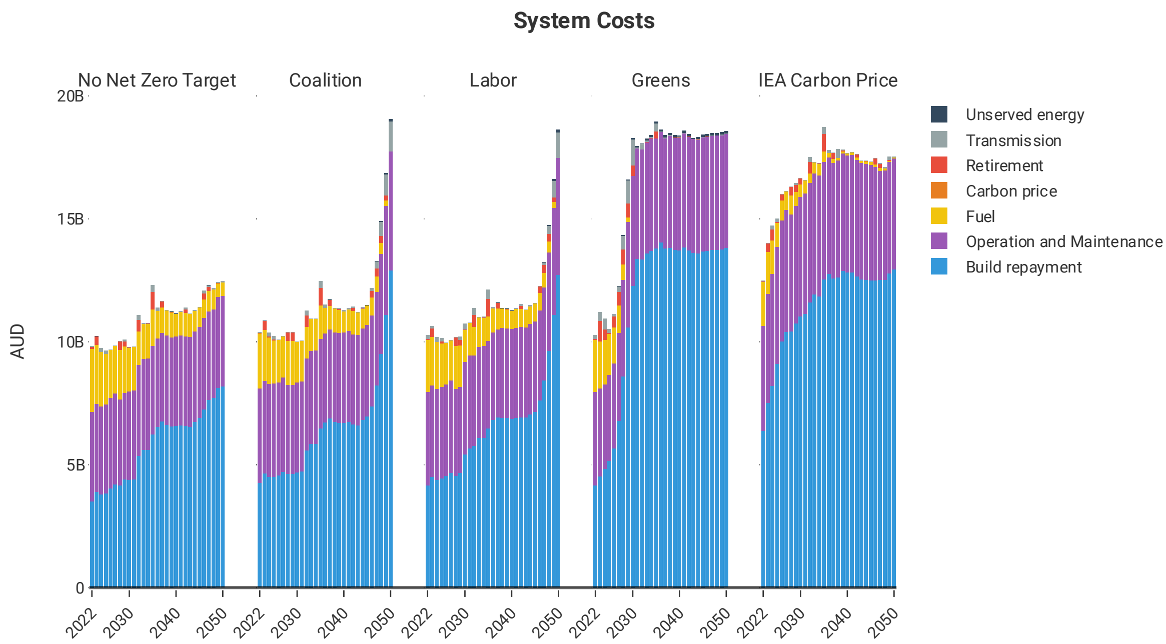


Figure 4

The graph above shows that the No Net Zero Target scenario has the lowest costs, as expected, as it is unconstrained by emissions targets and carbon prices, and openCEM can utilise the cheapest available combination of technologies to meet the demand in the NEM in each year.

In all scenarios, the rate of increase in renewables in the years preceding a net-zero target influences the resulting unserved energy cost in those years. This is influenced by the trajectory for emissions reduction, which we have assumed in this analysis to have a steep increase in the years approaching a net-zero target. It will be influenced by future policy and investment decisions. The unserved energy costs seen in the cost graph could also in practise be reduced by demand management.

The Coalition and Labor policy scenarios demonstrate how openCEM finds the least-cost pathway to meet a net-zero target in 2050 with minimal other constraints. It builds the most renewables in 2049 and begins paying them off in 2050. The Labor policy is distinct from the Coalition policy in 2030 due to its 50% emissions reduction target over 2005 levels at that time.

Total system costs are similar across all scenarios in 2050, and the rate at which they increase is linked to the rate of emissions reduction. Total system costs step up significantly in years when a scenario requires an emissions target to be met. In contrast, the IEA scenario, with no emissions target but an increasing carbon price, results in a smoother increase in costs, capacity expansion, and emissions reductions.

The costs presented above are financial costs and they ignore externalities such as damage caused by emissions of greenhouse gas emissions.

Social Cost of Carbon

A Social Cost of Carbon (SCC) assigns a dollar value to the damage caused to the environment and society from each additional ton of carbon dioxide equivalent emissions (tCO_2e). Various methods for estimating a social cost of carbon have been published. These methods assess the cost of climate change on various parts of the economy, including labour productivity and agriculture, human health, and impacts on natural ecosystems that are typically unpriced.

Below we compare four different proposals for an SCC:

- $30 and $150/$tCO_2e$, held constant, simply for illustration.
- $73/$tCO_2e$ based on a value adopted by the Biden administration (as an interim measure) in 2021[a].
- A trajectory proposed to the Australian Capital Territory government by the ACT Climate Change Council in 2021[b]. The authors note that their recommendation is similar to trajectories published by the then interim United States Intergovernmental Working Group (IWG) on the Social Cost of Greenhouse Gases, and further that the IWG warned that all its interim working values for the Social Cost of Carbon, including a 152 USD (about 200 AUD) 2020 precautionary value were likely underestimates.

	Social Cost of Carbon (AUD/tCO_2e)						
Trajectory	**2022**	**2026**	**2030**	**2035**	**2040**	**2045**	**2050**
$30/$tCO_2e$	30	30	30	30	30	30	30
United States Government	73	73	73	73	73	73	73
$150/$tCO_2e$	150	150	150	150	150	150	150
ACT Climate Change Council	204	213	222	233	243	254	265

To explore the wider economic costs of each policy scenario, in the graph below we sum electricity system costs and the total carbon dioxide equivalent emissions of each scenario in tonnes, multiplied by the four different proposals for a social cost of carbon.

This graph illustrates that striking the optimal balance between financial system costs and emission costs depends on assumptions about the SCC. It is apparent that while the cost of damage caused by greenhouse gas emissions is difficult to definitively assess, it is worthy of much greater focus and public discussion.

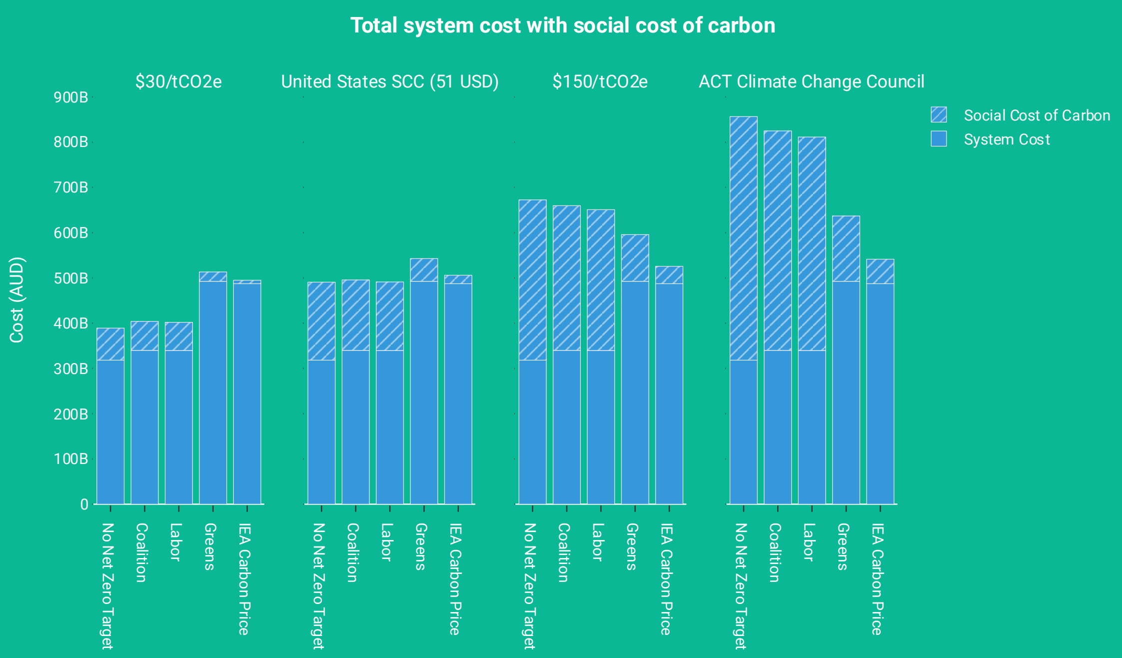


Figure 5

Note that this analysis sums electricity system costs and climate damage costs only. Broader economic impacts are not assessed by openCEM. These wider effects may be beneficial, such as the value of increased investment and employment, or negative such as the impact of higher electricity prices on energy intensive industry.

[a] https://www.washingtonpost.com/climate-environment/2021/02/26/biden-cost-climate-change/ and https://www.whitehouse.gov/wp-content/uploads/2021/02/TechnicalSupportDocument_SocialCostofCarbonMethaneNitrousOxide.pdf

[b] The Social Cost of Carbon and Implications for the ACT, ACT Climate Change Council (2021) https://www.environment.act.gov.au/cc/act-climate-change-council/council-publications

Marginal Cost of Abatement

The marginal cost of abatement per ton of CO_2e emissions can be determined when scenarios emit less than the base case in a year. To calculate it, the reduction in emissions is divided by the increased cost. The Labor policy scenario has a negative cost of abatement in 2035, as in that year it is emitting less and costs less than the No Net Zero Target scenario.

We have excluded the extreme values from this graph, when the difference in emissions between the base case and the comparison is small or a large jump in renewables suddenly occurs, which makes the marginal cost of abatement less meaningful.

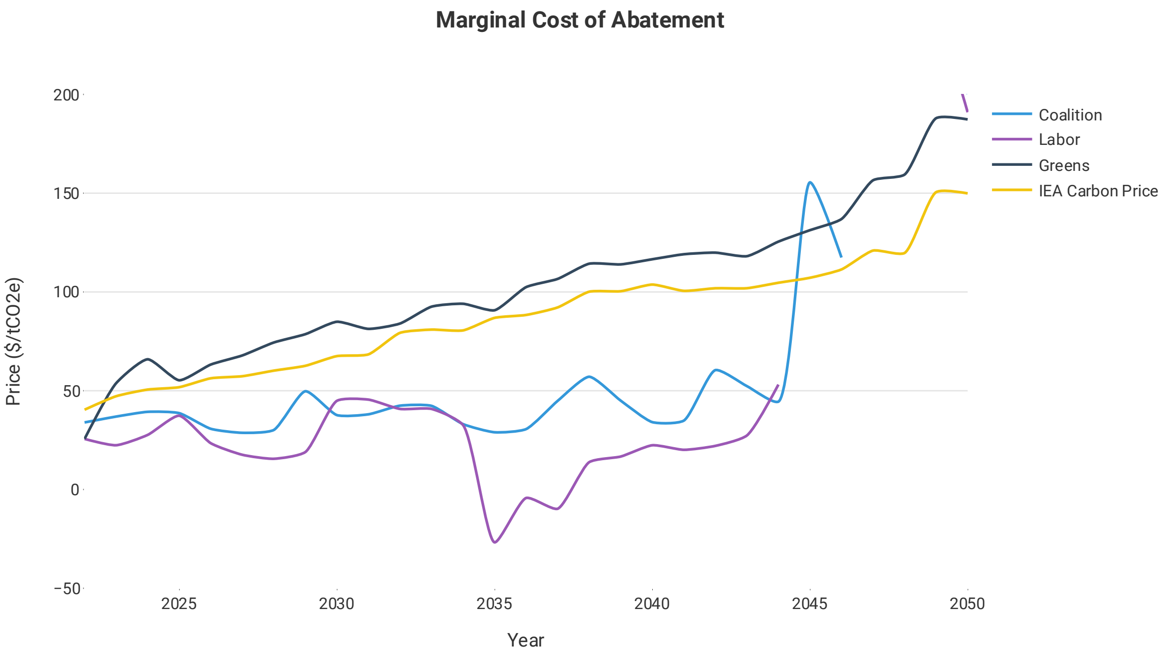


Figure 6

Marginal Cost of Abatement figures are often compared to carbon prices and the social cost of carbon, to see whether the price we are paying to reduce our emissions is in proportion to the cost of the damage we are avoiding.

This analysis shows that the type of dispatchable generation used as a scenario reduces its emissions affects its cost-effectiveness for emissions abatement. The IEA scenario achieves a lower cost of abatement than the Greens scenario, using a very small amount of residual coal and gas, more pumped hydro, slightly less wind and solar, and notably, is the only scenario to use solar thermal.

Emissions

Scenarios with a net-zero emissions target in a particular year reach that target along a reverse-sigmoid trajectory, as seen in Figure 7. openCEM and other models often determine this trajectory to be the most efficient when performing these kinds of optimisation problems. The IEA Carbon Price scenario does not follow the first half of this trajectory, however, as it must immediately begin reducing emissions as quickly as possible.

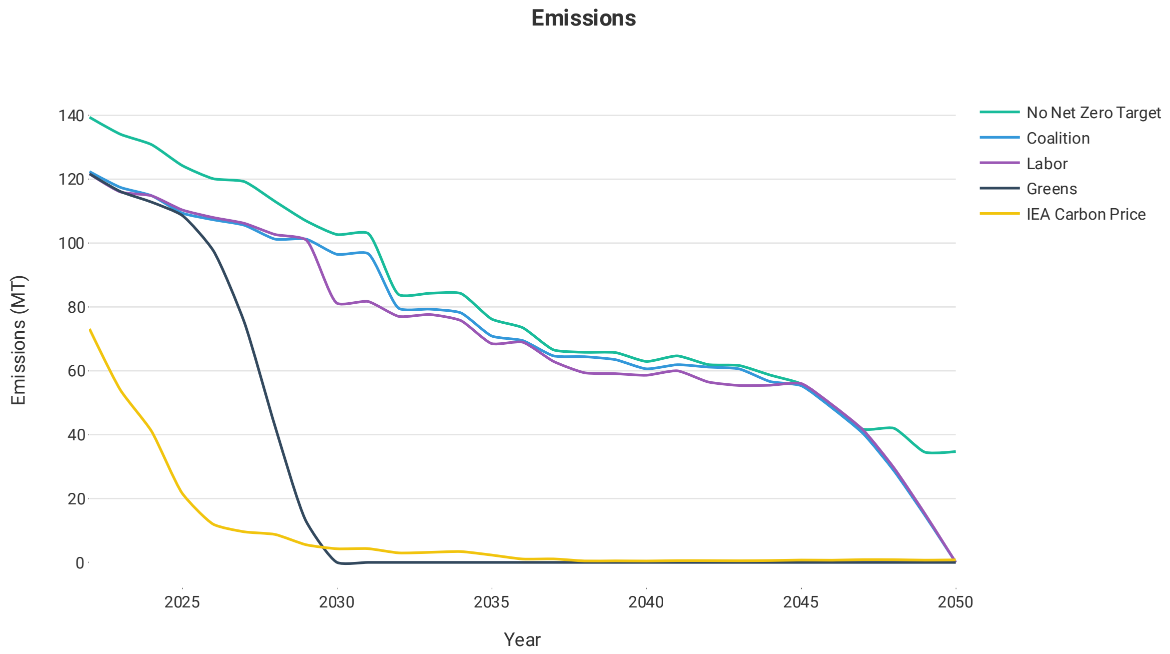


Figure 7

Australia's updated national carbon budget from 2021–2050 is 3521 MT for 1.5 °C global warming, and 6161 MT for 2 °C[6]. Subtracting 499 MT emitted in 2021[7], this leaves us with 3022 and 5662 MT from 2022–2050. In 2021, electricity generation contributed 32.9% to Australia's total emissions[7], and the NEM provided approximately 85% of total generation in Australia[8]. For this analysis we assume that the electricity sector will maintain its proportion of emissions out to 2050, even though it is likely that the electricity sector will reduce its emissions faster than other sectors like transport, agriculture, and industrial processes, and reach 2050 with a smaller share of emissions. This is because the mature renewable generation technologies offer low-cost abatement opportunities, compared to changing technology in other sectors.

Following the assumptions above, Australia's remaining quota for total CO_2e emissions in the electricity sector from 2022–2050 is 845 megatons to stay within 2°C global warming, and 1583 megatons to stay within 1.5°C. The Greens and IEA Carbon price allow our electricity network to beat

[6]https://www.climatecollege.unimelb.edu.au/files/site1/docs/%5Bmi7%3Ami7uid%5D/ClimateTargetsPanelReport.pdf
[7] https://www.industry.gov.au/data-and-publications/national-greenhouse-gas-inventory-quarterly-update-june-2021
[8] https://www.industry.gov.au/sites/default/files/2020-12/australias-emissions-projections-2020.pdf

these targets. The Coalition, Labor, and No Net Zero scenarios do not achieve the early emissions cuts that are required to stay within either limit, and allow the NEM to emit over 25% more emissions than required to stay within 2º.

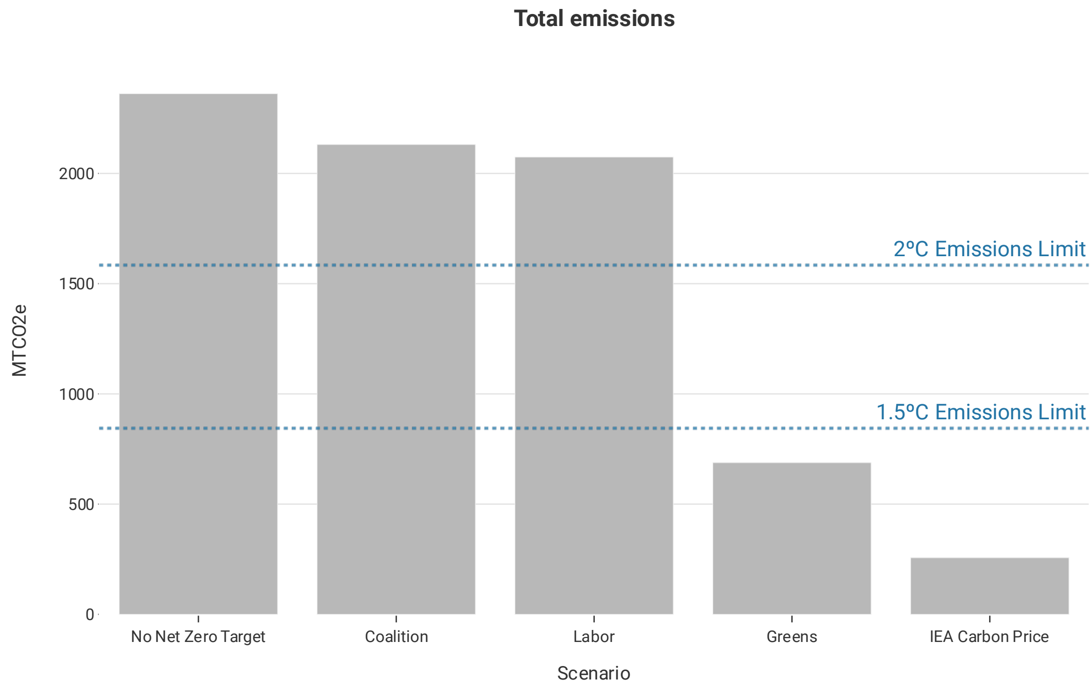


Figure 8

Though the IEA Carbon Price is designed to help developed economies limit their emissions to below 1.5º warming levels, it turns out that in Australia's electricity market, it causes more aggressive emissions cuts than are required to achieve the target.

Renewable Energy Fraction

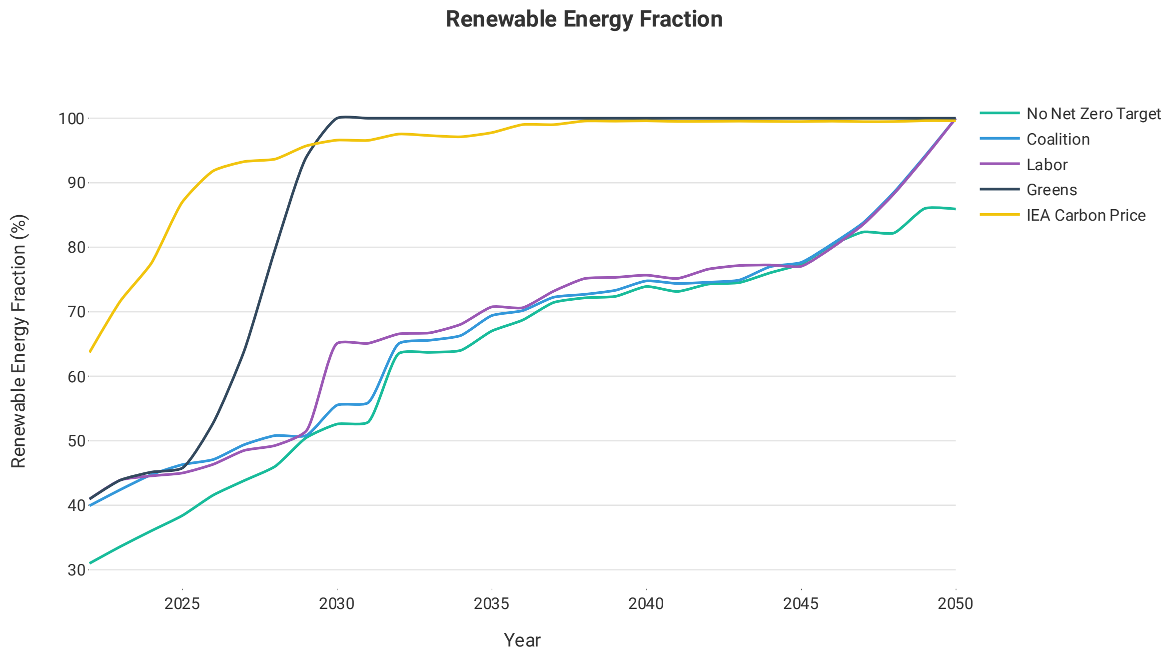


Figure 9

Until there is a carbon price, renewable energy target, or net-zero target, the renewable energy fraction in all scenarios follows a similar trajectory, shaped by technology costs. In the IEA Carbon Price scenario, the carbon price influences the building of renewables early on. The Greens policy reaches a 100% fraction of renewables by 2030 due to its net-zero target. The IEA Carbon Price creates a smoother but still relatively fast pathway to 100% renewables, reaching 95% by 2030, 99% by 2040, and 100% by 2050. The other two scenarios achieve 100% renewables in the year of their net-zero target, with Labor reaching its 50% target in 2030. The scenario without a net-zero target continues to build more renewables due to dropping prices to reach 80% by 2050.

In-depth

Hydrogen Gas Turbines

Introduction

In this section we analyse several scenarios in openCEM, with and without the ability to build hydrogen gas turbines. Hydrogen gas turbines are very similar to natural gas turbines, but burn hydrogen fuel instead of natural gas, and produce no emissions.

Inputs

The Labor scenario from Part 1 was selected for this analysis, adding only the option for openCEM to build new hydrogen gas turbines. The build and maintenance costs of these new generators were assumed to be the same as those for natural gas turbines on the basis that the fundamental technology is very similar.

Hydrogen Price

We based our hydrogen price pathway for 2022–2050 on forecasts from the Chief Scientist's Briefing Paper on Hydrogen for Australia's future[9]. These prices assume Polymer Electrolyte Membrane (PEM) electrolysis as the method for producing hydrogen, which produces "green" hydrogen with zero emissions.

	2022	2026	2030	2035	2040	2045	2050
Price ($/GJ)	21.25	19.55	17.86	15.74	13.62	11.50	9.38

The Chief Scientist's briefing paper states that hydrogen electrolysis will require dedicated wind and solar generators, so we have not assumed that the NEM provides this energy. Funding to build the dedicated renewable generators used for electrolysis, the electrolysis units, hydrogen storage, and transport, would likely come from private investment supported by government grants, which both the Coalition[10] and Labor[11] have announced.

[9] Hydrogen for Australia's Future, Commonwealth of Australia, 2018
[10] https://www.minister.industry.gov.au/ministers/taylor/media-releases/future-hydrogen-industry-create-jobs-lower-emissions-and-boost-regional-australia
[11] $1 billion hydrogen scheme from the ALP 2019 election policy

Results

In our modelling, hydrogen gas turbines provide zero-emissions base generation during the day as well as increased generation during peak periods and overnight when other renewables like solar and wind are not sufficient. Generally, in every state, their output doubles, compared to their lowest output, in the 14-hour period from 5 pm to 7 am.

The hourly dispatch of hydrogen gas turbines in our model illustrates its role in the NEM amongst other generation schedules. The hydrogen gas turbines still play a role during the day, though they are dispatched less because of the cheap wind and solar that dominates the market at those times.

Dispatch Timing

The following graphs show when the hydrogen turbines are dispatched in the Labor with Hydrogen Turbines scenario in 2050.

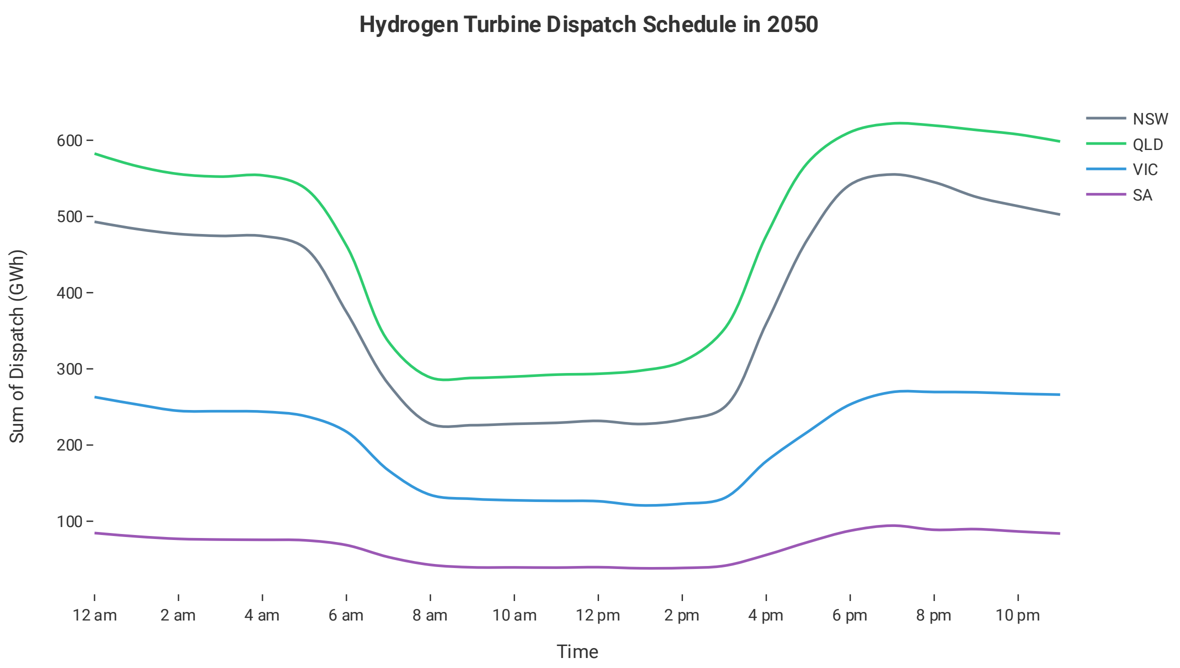


Figure 10

The hydrogen turbines are dispatched the most in winter, followed by autumn, spring, and summer, due to seasonal demand and availability of solar. They provide the most energy in Queensland, followed by New South Wales, Victoria, and South Australia, with a clear overnight peak in Queensland and New South Wales. This is because of the larger amount of coal being displaced by renewables in these states, requiring additional dispatchable capacity that the hydrogen turbines provide.

Hydrogen Turbine Dispatch Schedule in Winter

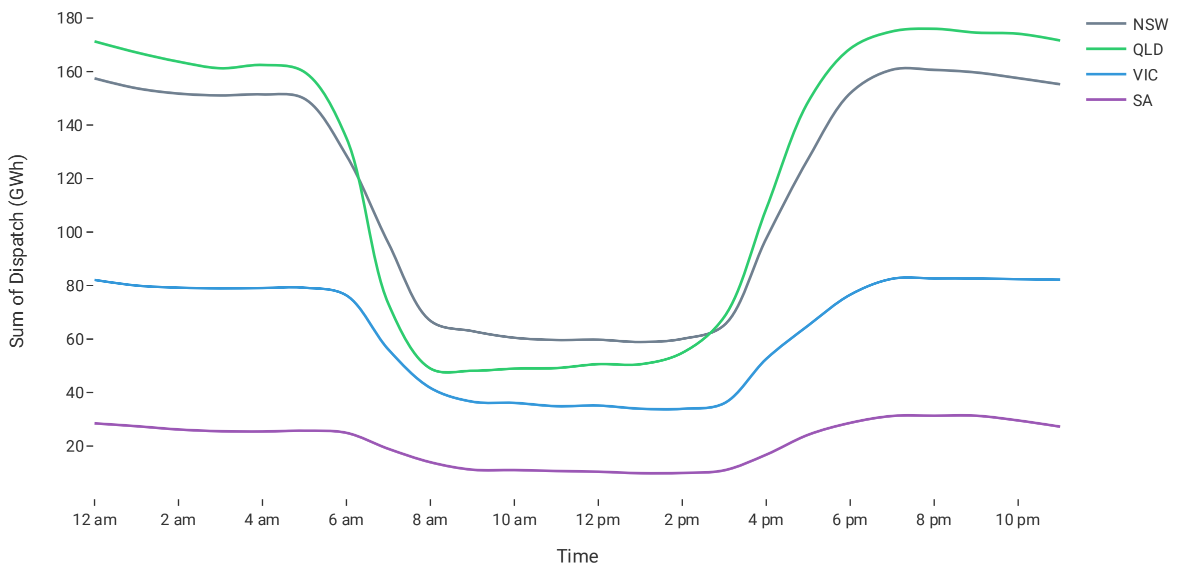


Figure 11

Hydrogen Turbine Dispatch Schedule in Summer

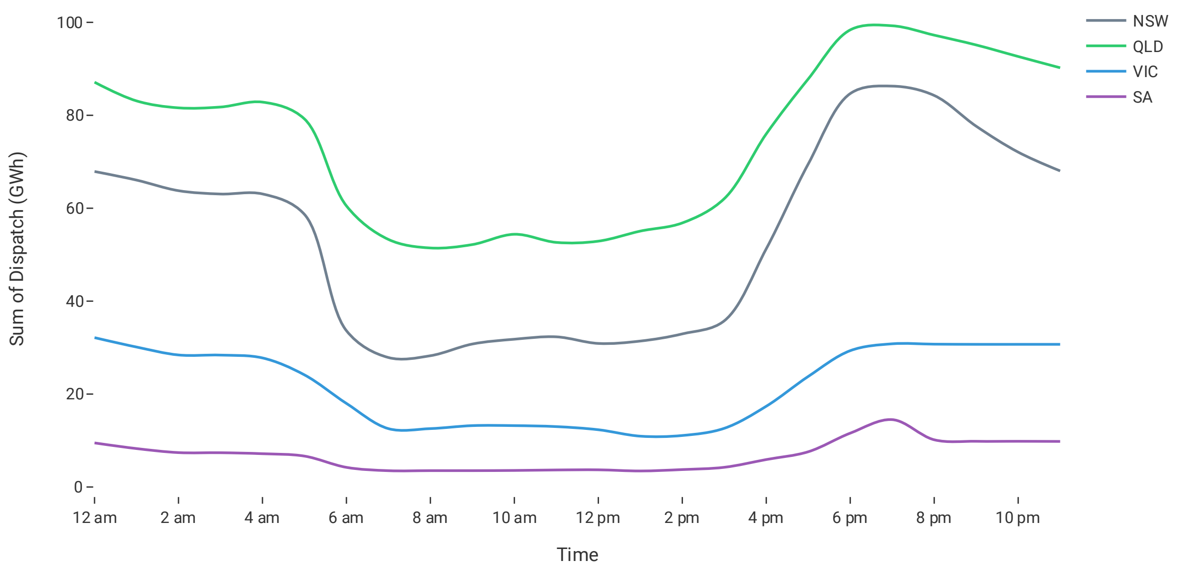


Figure 12

Technology Mix

openCEM builds hydrogen gas turbines in the year that the scenario requires net-zero emissions, and no earlier. In the Greens and the IEA Carbon price scenarios, we found that openCEM does not use hydrogen gas turbines, due to the higher assumed price of hydrogen in the years when the scenario requires net-zero emissions.

Capacity expansion decisions in openCEM are made to minimise the total system cost, not the wholesale price. Generation and other assets are built as soon as they are determined to be part of the least-cost mix.

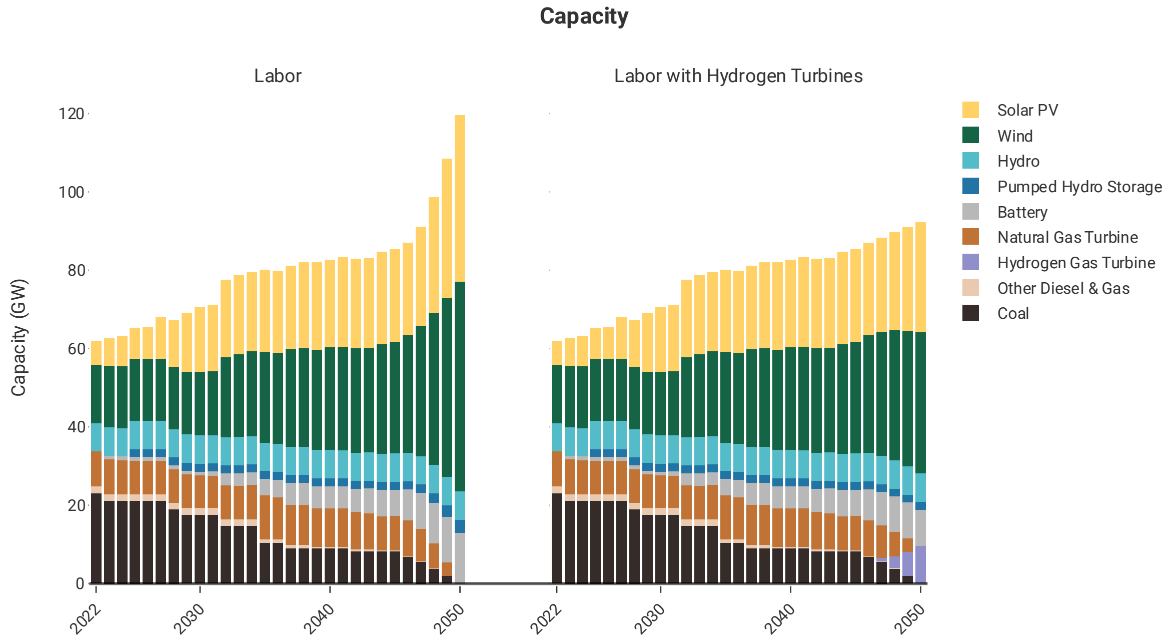


Figure 13

Hydrogen turbines reduce the amount of pumped hydro that openCEM builds. It mostly displaces a large amount of wind and solar relative to the additional capacity of hydrogen turbines that is installed. In the Labor with Hydrogen Turbines scenario in 2050, 10 GW of hydrogen gas turbines displaces almost 40 GW of solar, pumped hydro, and wind.

Approaching 2050, an additional barrier for solar and wind is that good sites will be increasingly difficult to find, which may cause their costs to increase and capacity factors to fall.

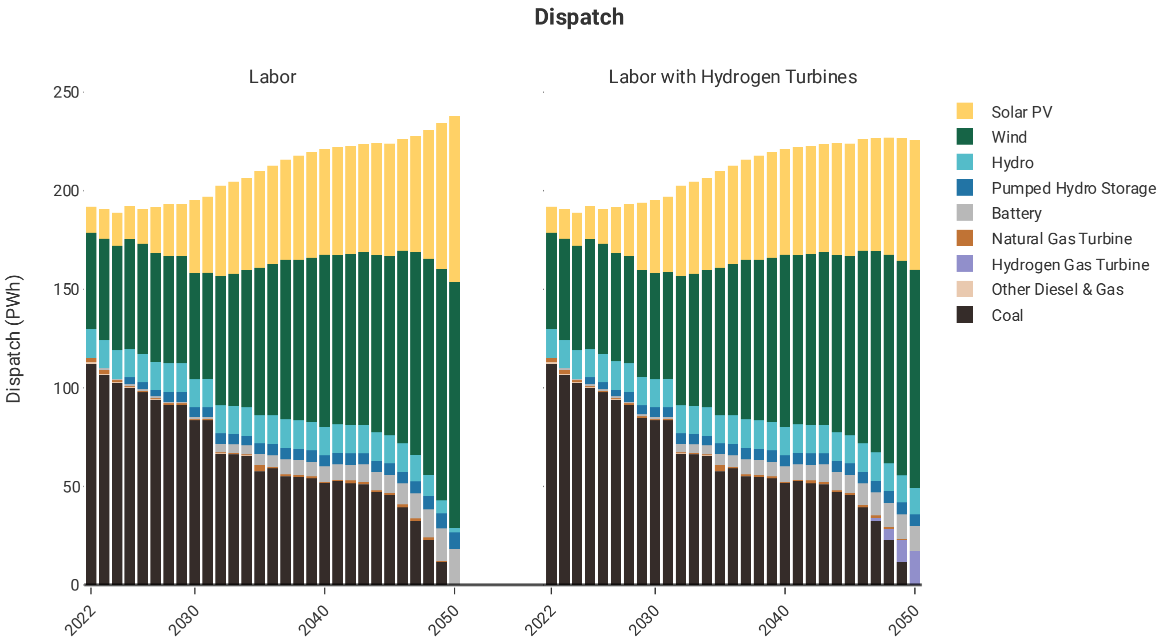


Figure 14

In the graph below, bars above zero indicate more capacity that was built in the hydrogen case than the base case, and bars below zero indicate less capacity being built in that year. It illustrates that a small amount of hydrogen turbine capacity can displace a relatively large amount of pumped hydro, wind, and solar PV capacity.

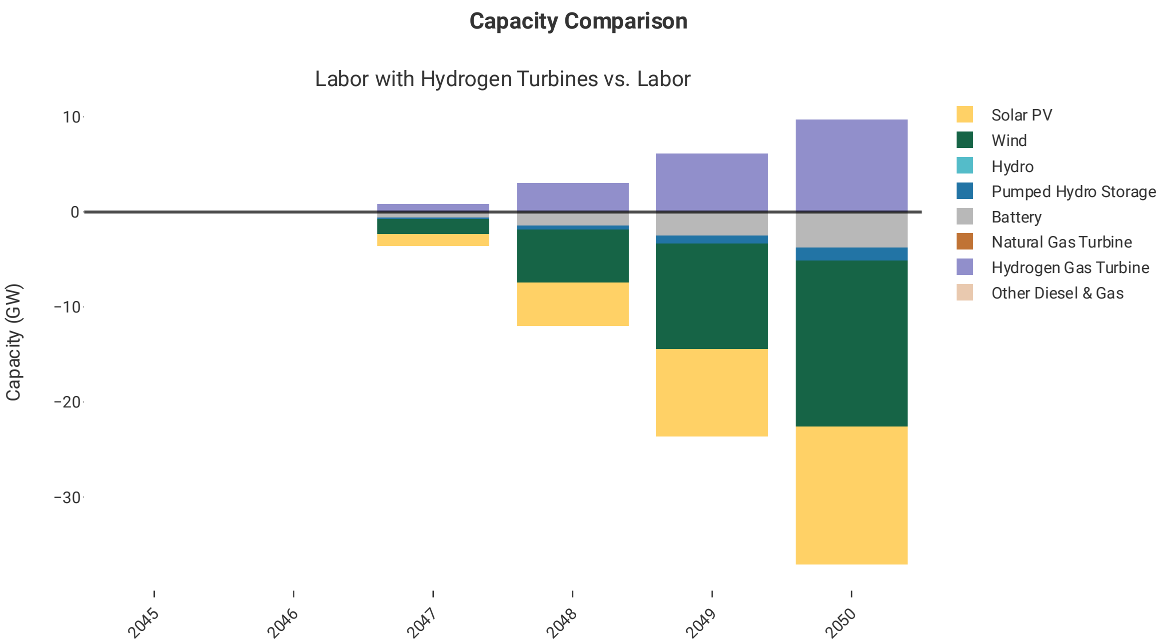


Figure 15

Costs

In the year that hydrogen gas turbines are built, the cost of delivering electricity per MWh in the NEM reduces by almost $20 in 2050. The hydrogen turbines also help to reduce unserved energy costs, and repayment costs for the wind and solar that is no longer needed.

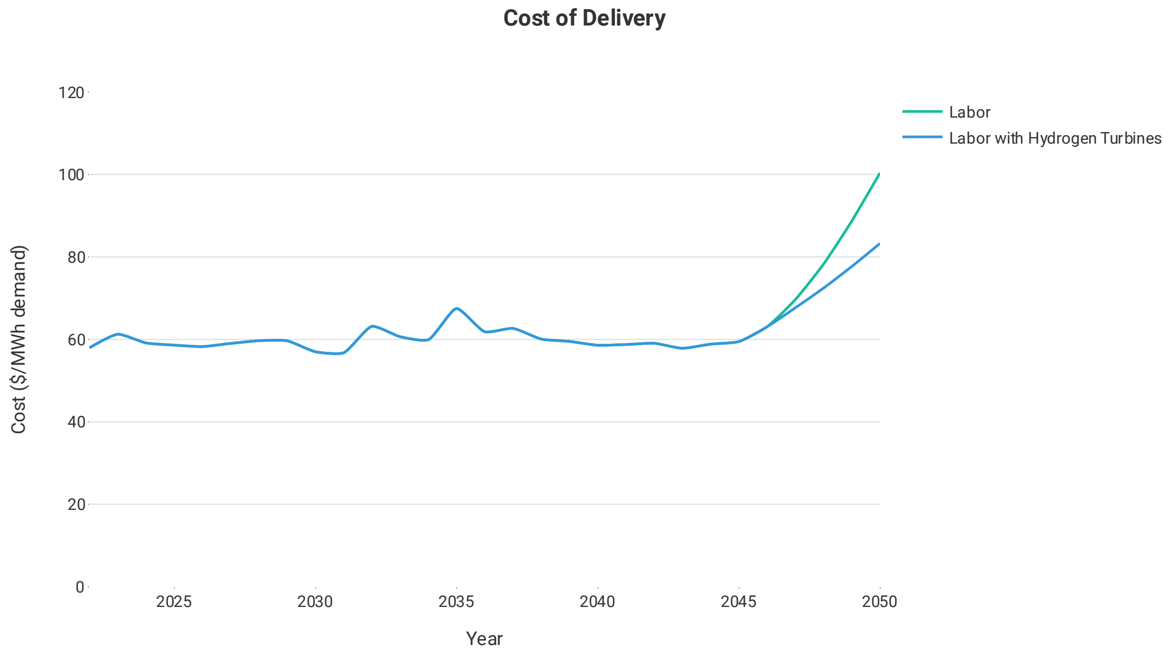


Figure 16

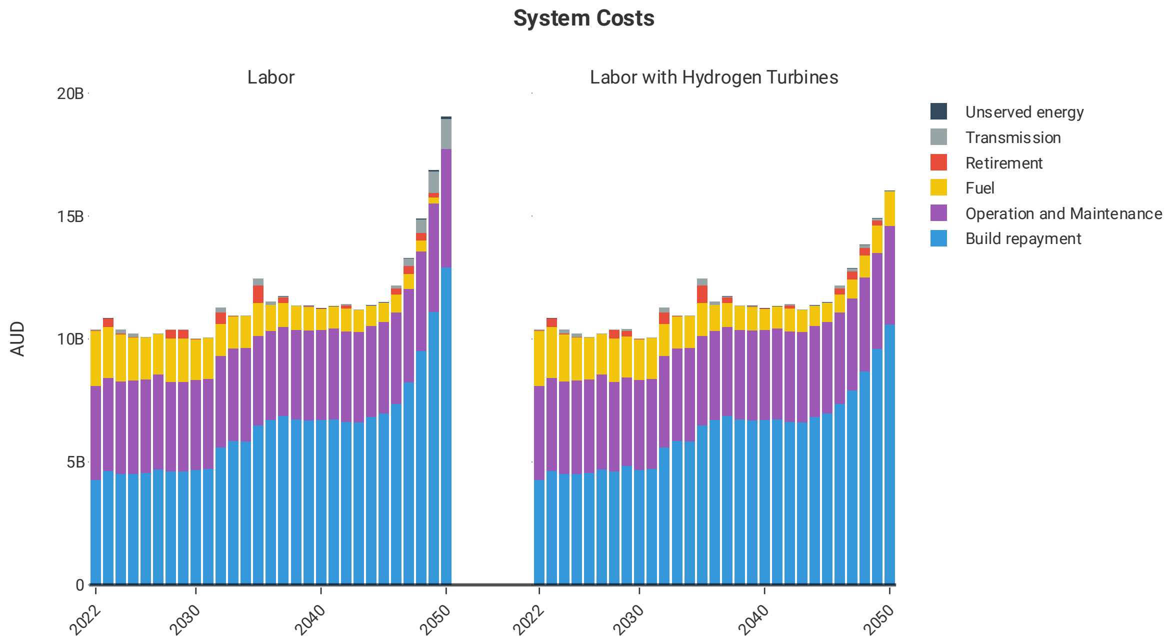


Figure 17

As hydrogen displaces solar, wind and pumped hydro, the hydrogen turbine scenarios show increased fuel costs after hydrogen is introduced.

The resource intensity of converting natural gas turbines to hydrogen is lower than manufacturing the alternative wind, solar, and hydro, as relatively little additional infrastructure needs to be built at the generation site[12]. We have not included costs of producing hydrogen or upgrading transport infrastructure. Research in the UK and US is underway for using existing natural gas pipelines to transport hydrogen, or a high concentration of hydrogen in natural gas to minimise costs[13].

Wholesale Prices with Zero-emissions Fuel-based Generators

Currently the wholesale electricity price in the NEM is determined by AEMO. For every 5-minute period, generators submit their bid and the amount of generation they can provide during that time. AEMO takes the lowest bids first, adding them up until demand is satisfied, with the highest bids being accepted last.

The spot price of electricity is calculated from the average of the highest bids required in each 5-minute increment required to fulfil demand. This is the price that the generators receive for production, and the price that electricity retailers pay for electricity during that period.

Generators that use fuel, like coal and gas power stations, will base their bid on expected fuel prices, maintenance costs, and loan repayments, while renewable generators like wind and solar will base their bid on maintenance costs and loan repayments.

Overnight, when cheap solar energy is unavailable and batteries have been depleted, the grid needs to be powered by dispatchable generators for a period of 12-15 hours, depending on the season. Currently, natural gas turbines and coal generation fill the gap during peak periods in the evening and early morning. In the high-renewables scenarios we simulate, renewable generators such as hydro, solar thermal storage, and hydrogen gas turbines provide dispatchable power as fossil fuel generators are retired.

These dispatchable renewable generators mean that a lot less wind, solar, and batteries are required in the system, as they can sustain their output for much longer than a significantly more expensive combination of wind, solar, and batteries. This means that the total system cost is lower with scenarios that have a range of dispatchable renewable generators, rather than just wind, solar, and batteries. However, compared to wind, solar, and batteries, the marginal cost of dispatching hydrogen generators is high because of the price of hydrogen, and is also high for pumped hydro and solar thermal because they need to recoup comparatively high build costs.

[12] https://www.ge.com/gas-power/future-of-energy/hydrogen-fueled-gas-turbines
[13] https://www.greentechmedia.com/articles/read/green-hydrogen-in-natural-gas-pipelines-decarbonization-solution-or-pipe-dream

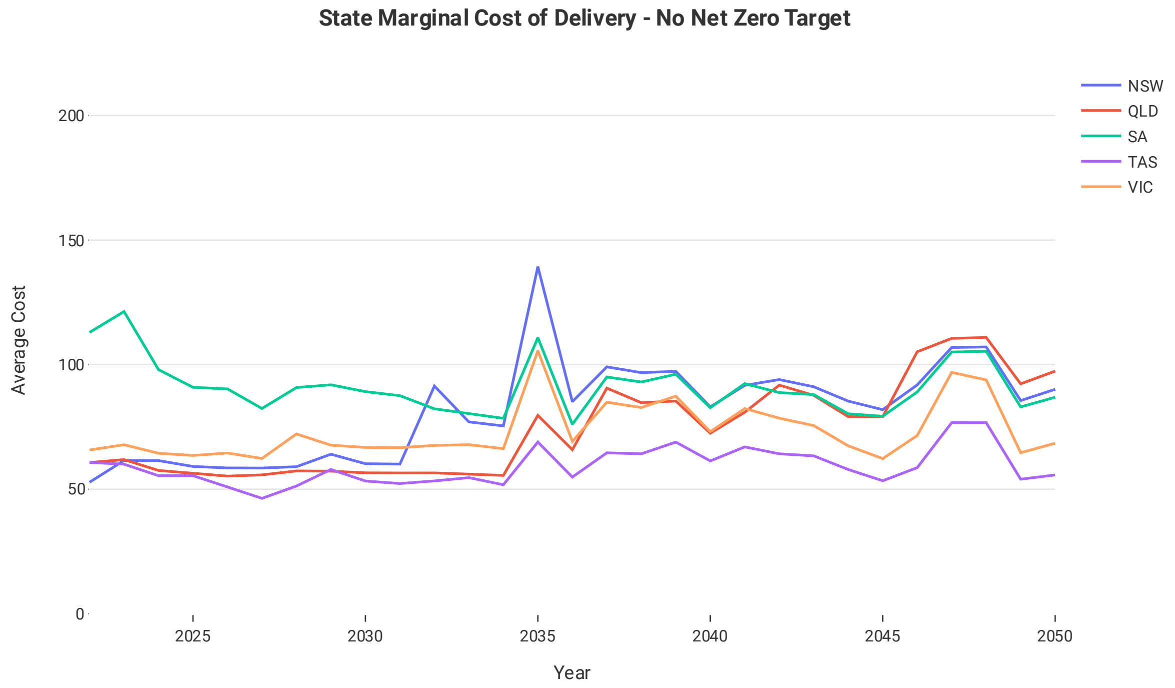
This results in the spot price being pushed up when the hydrogen generators are dispatching, and as they are providing consistent generation overnight, the price stays high for 12 to 15 hours. Even though the hydrogen generators are providing less than 10% of the total generation in the NEM during that time, they must dictate the price for all generation.

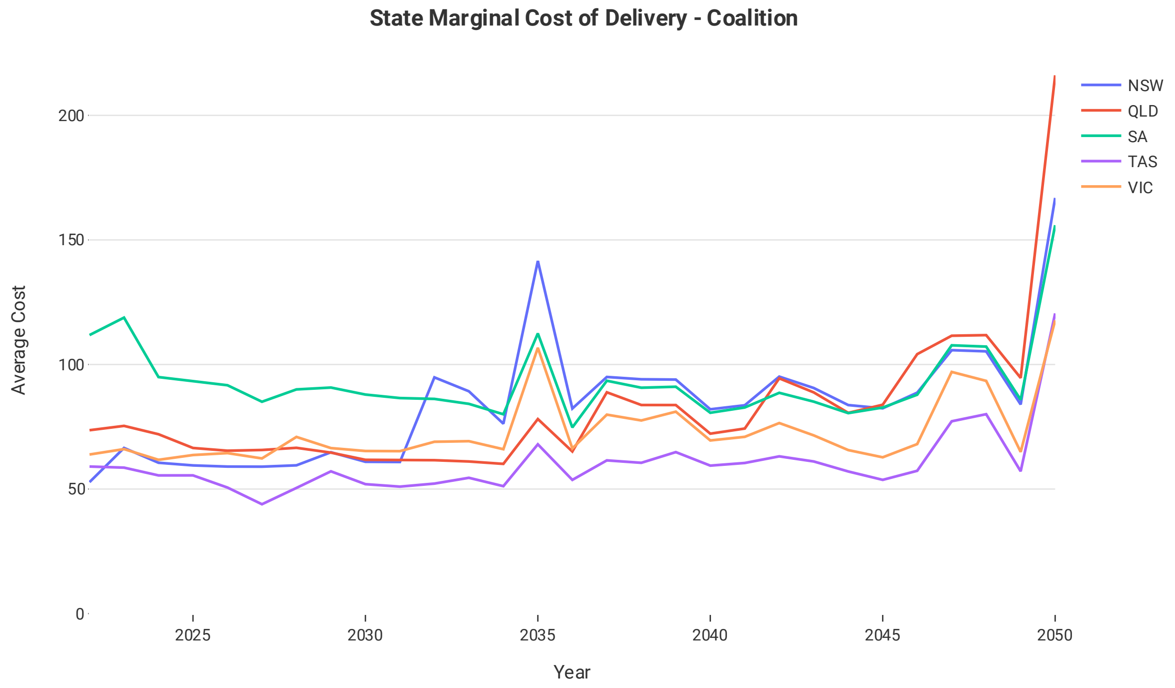
The factors above mean that a high renewables scenario with fuel-based dispatchable generators can have a lower total cost than one with more wind, solar, and batteries, but the wholesale price will be higher during the periods when those fuel-based dispatchable generators are operating. In other words, while dispatchable renewable generators serve to lower the overall system cost, and therefore electricity prices, under the current market arrangements investors may judge that they may not be able to bid competitively and new project development may stall.

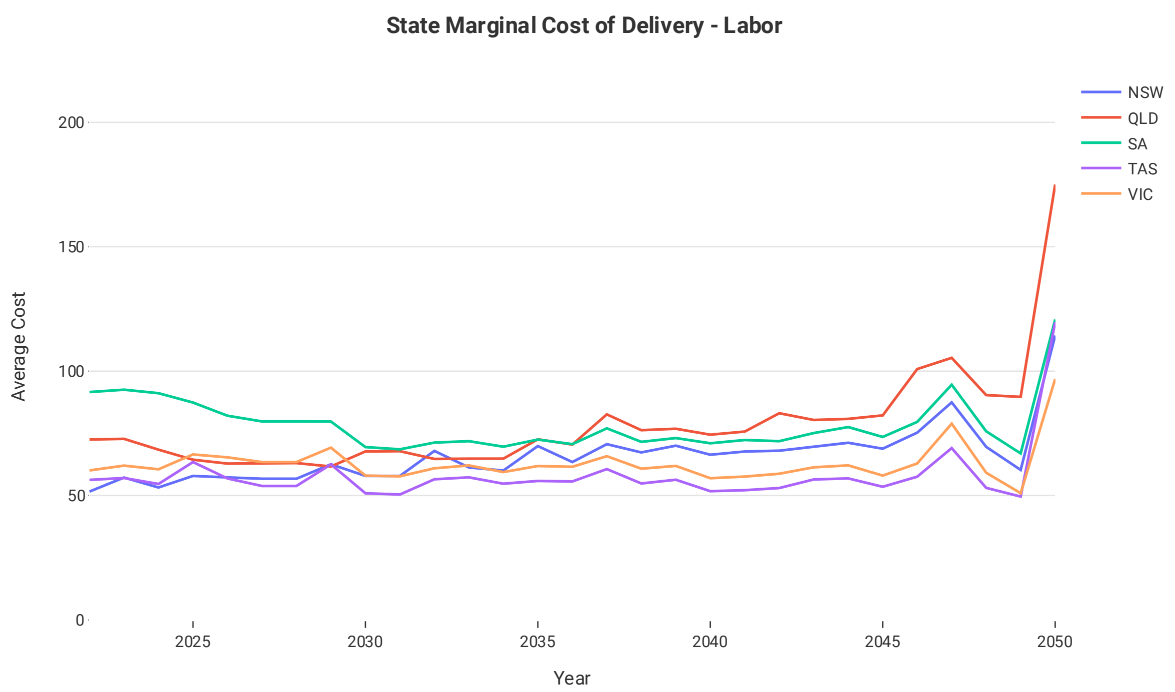
This is something that may need to be addressed by new policy or market mechanisms that seek to ensure that a least-cost electricity grid can be delivered while keeping viable technologies competitive, and wholesale prices that reflect the actual costs of generation.

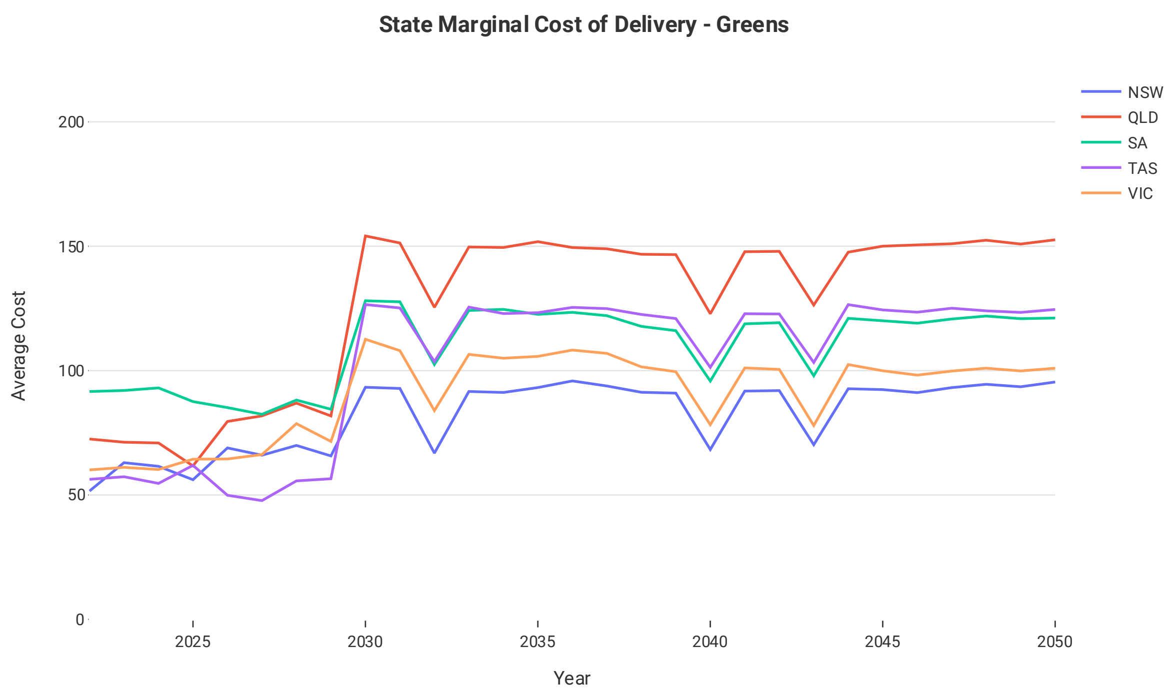
Appendices

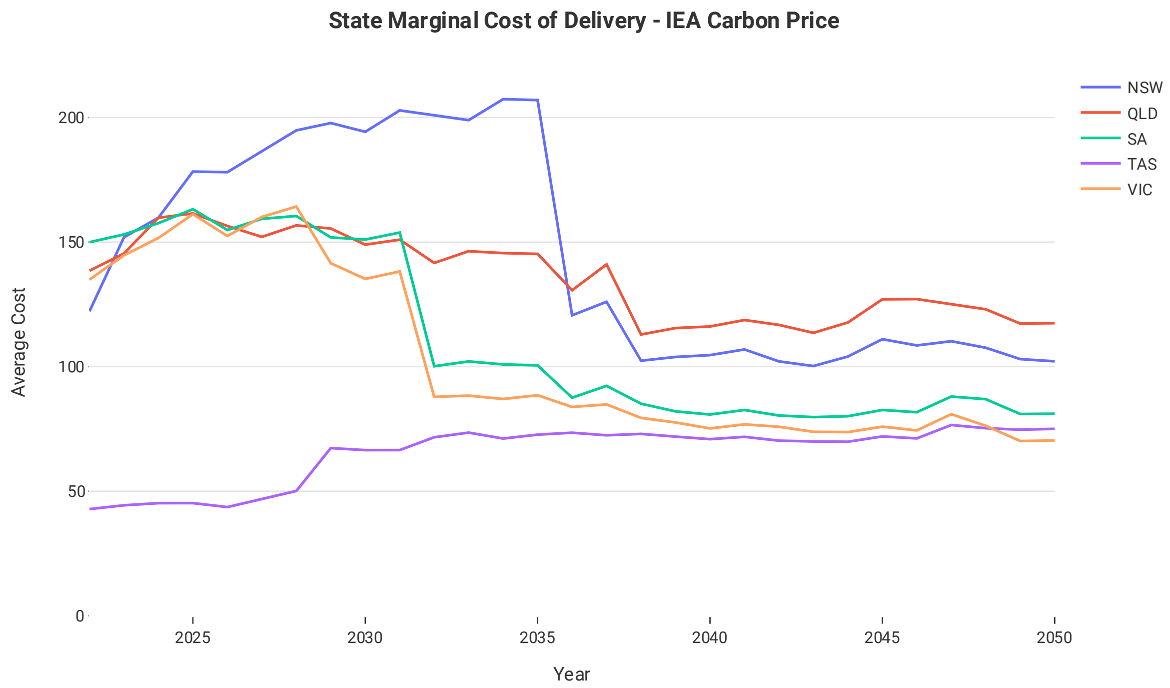
Appendix A. State Marginal Cost of Delivery

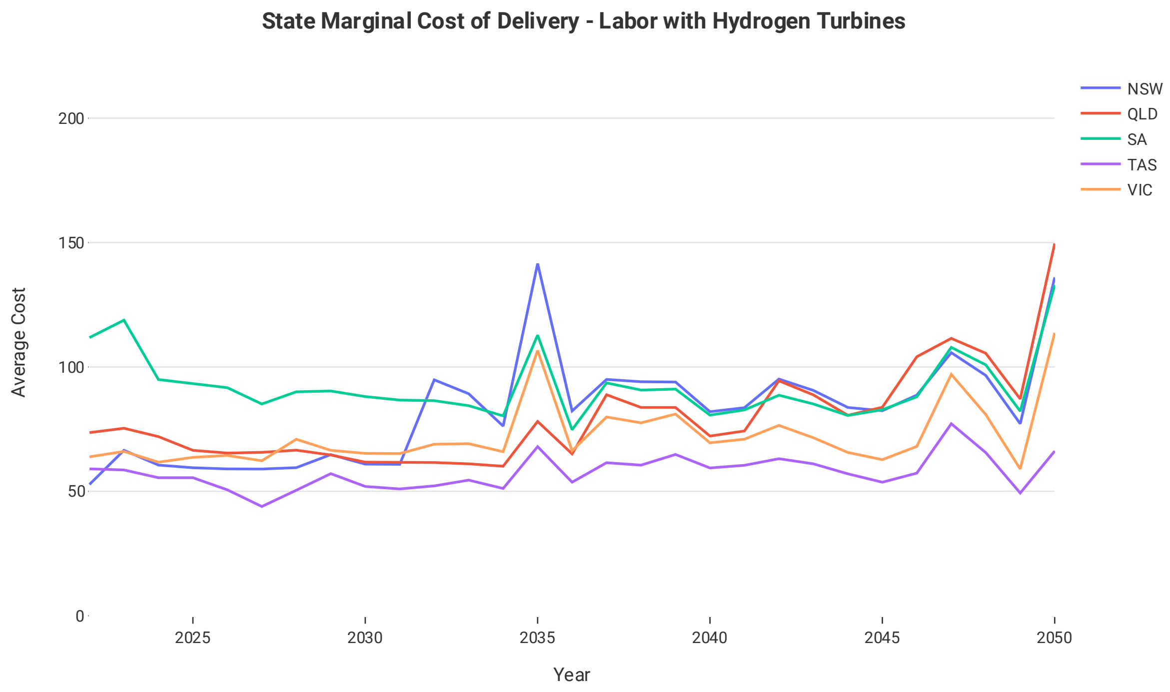





State Marginal Cost of Delivery - Labor
NSW
QLD
SA
TAS
VIC
200
150
100
50
0
Average Cost
2025
2030
2035
2040
2045
2050
Year


State Marginal Cost of Delivery - Greens
NSW
QLD
SA
TAS
VIC
200
150
100
50
0
Average Cost
2025
2030
2035
2040
2045
2050
Year


State Marginal Cost of Delivery - IEA Carbon Price
Average Cost
Year
NSW
QLD
SA
TAS
VIC
0
50
100
150
200
2025
2030
2035
2040
2045
2050


State Marginal Cost of Delivery - Labor with Hydrogen Turbines
Average Cost
Year
NSW
QLD
SA
TAS
VIC
0
50
100
150
200
2025
2030
2035
2040
2045
2050

Appendix B. Accelerated coal retirements from Greens 2019 election policy

NSW

- Decommissioning of Bayswater Power Station brought forward by eight years to 2024 at the age of 42.
- Decommissioning of Eraring Power Station brought forward by eight years to 2023 at the age of 42.
- Decommissioning of Vales Point Power Station brought forward by five years to 2026 at the age of 45.
- Decommissioning of Mt Piper Power Station brought forward by ten years to 2030 at the age of 37.
- Shutdown of two small waste coal mine gas power stations in 2025

VIC

- Decommissioning of Loy Yang A Power Station brought forward by five years to 2024 at the age of 40.
- Decommissioning of Loy Yang B brought forward by 13 years to 2030 at the age of 37.

QLD

- Decommissioning of Tarong Power Station brought forward by eight years to 2026 at the age of 42.
- Decommissioning of Stanwell Power Station brought forward by ten years to 2030 at the age of 37.
- Decommissioning of Callide B Power Station brought forward by 15 years to 2028 at the age of 35.
- Decommissioning of Kogan Creek Power Station in 2027.
- Decommissioning of Callide C Power Station in 2028.
- Decommissioning of Millmerran Power Station in 2029.
- Closure of the Braemar I and II and Moranbah coal mine gas power stations in 2025.

WA

- Immediate decommissioning of the Muja Power Station, foregoing plans to refurbish the power station (currently aged 52).
- Decommissioning of Collie Power Station brought forward by ten years to 2030 (earlier than currently proposed decommissioning date) at the age of 31.
- Closure of Bluewaters I and II in 2035.

Appendix C. Model Details

How openCEM works

openCEM is a capacity expansion and dispatch model that simulates the national electricity market (NEM) under a set of technical, cost and policy assumptions. Based on those assumptions, openCEM computes future capacity expansion (i.e. building large-scale generators and storage systems) and dispatch decisions over a number of years into the future that achieve a system-wide lowest annualised cost of operation.

openCEM divides the NEM into 16 planning zones to account for differences in renewable energy resources, fuel costs, electricity demand and connection costs. Each zone contains its own list of generator and storage capacity, and aggregates plants by technology in each respective zone. Wind and solar technologies in a given zone have their own hourly power output traces, building and fuel costs.

A cost minimisation search is performed sequentially for a number of future years in which a financial year is simulated using a time-sliced approach to compute capacity decisions and then in full to compute dispatch decisions. New capacity decisions are assumed to be operational during the simulated year. The net of all existing and new capacity computed for one year is carried forward as the starting point to the next. For the first year, initial capacity consists of reported firm capacity by the Australian Energy Market Operator (AEMO) in 2020.

Energy can flow without restriction between all the zones in a region but notional interconnectors of fixed capacity (marked red in the figure) limit the amount of energy transmitted between regions.

By default, openCEM uses AEMO Integrated System Plan (ISP) 2020 data for technology and fuel costs, build limits, existing generation, electricity demand traces and renewable energy resource traces (i.e. wind and solar). For CST, openCEM by default uses "collector" only traces that estimate thermal output performance from a collector field. With collector only traces, CST plants in openCEM can be configured to feature different storage sizes.

Notes on Assumptions

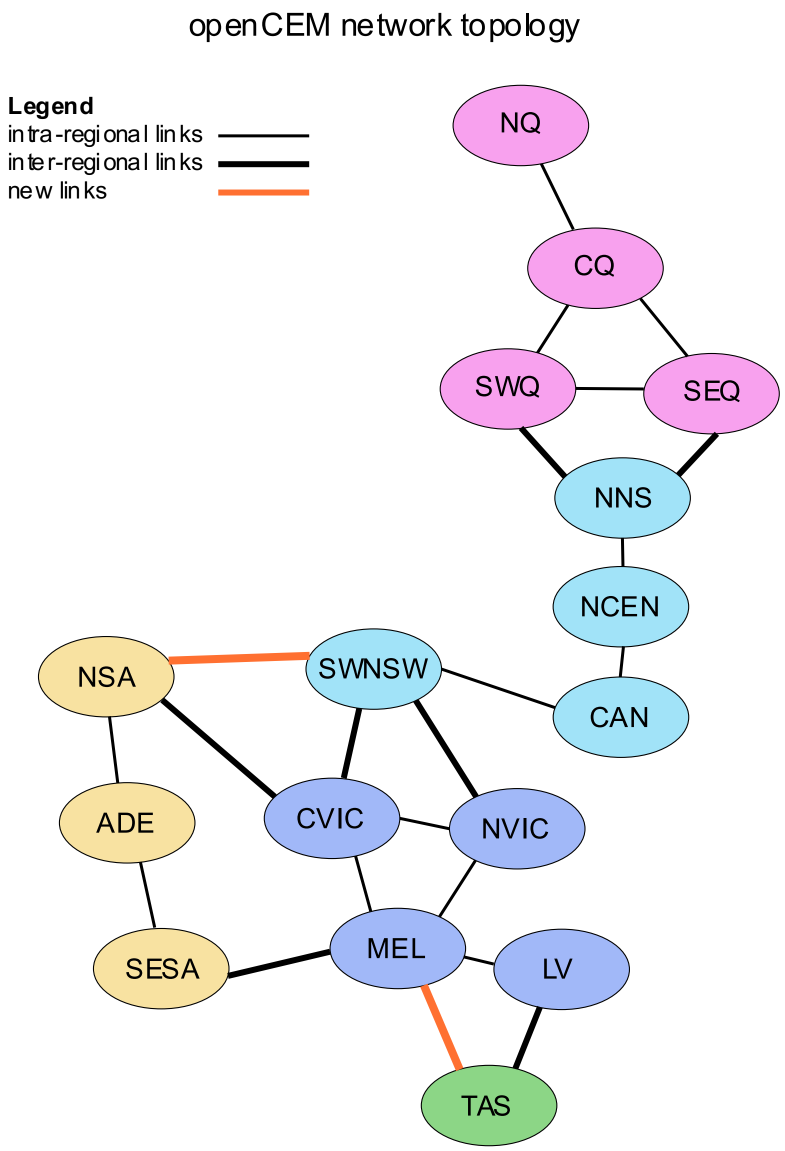
Hydrogen Gas Turbines

We did not provide a method in openCEM for it to convert existing gas turbines to hydrogen, instead requiring it to build new turbines at full cost. Overcoming this high cost in openCEM to build hydrogen gas turbines further illustrates that hydrogen gas turbines are a promising technology in a high-renewables electricity grid. In reality, the cost of converting a natural gas turbine to hydrogen may be lower than building new hydrogen turbines. This is something we will investigate in openCEM and analyse in a future report.

Emissions Pathways

The emissions pathways that openCEM produces are optimised for the lowest cost of the system, so they often start reducing slowly and are more aggressive closer to the emissions target in the scenario, when technologies are cheaper. This is typical of this kind of model, and reflects trends in emissions in the last 20 years, but is harder to predict with high confidence out to 2050. Things like investor attitudes towards certain technologies, and new technological and political developments can have a strong effect on the adoption of certain technologies, which openCEM cannot predict.

Network map



Appendix D. Other Reports and Additional Data

This report is released on a quarterly basis and will in future offer an option to purchase detailed output data from each scenario, including delivery costs broken down by state, detailed dispatch and capacity figures, and all other data shown in graphs, broken down by region, technology, and year.

ITP Analytics also has an employment model that works in tandem with openCEM to predict how different technology mixes, location, and timing affect jobs in each region in Australia. This information will also be included as an option for purchase in future reports.

Other publications from ITP Analytics and its parent company ITP Renewables are available at itpau.com.au/knowledge.

ANALYTICS