Australia's National
Science Agency

GenCost 2019-20: preliminary results for stakeholder review

Draft for review

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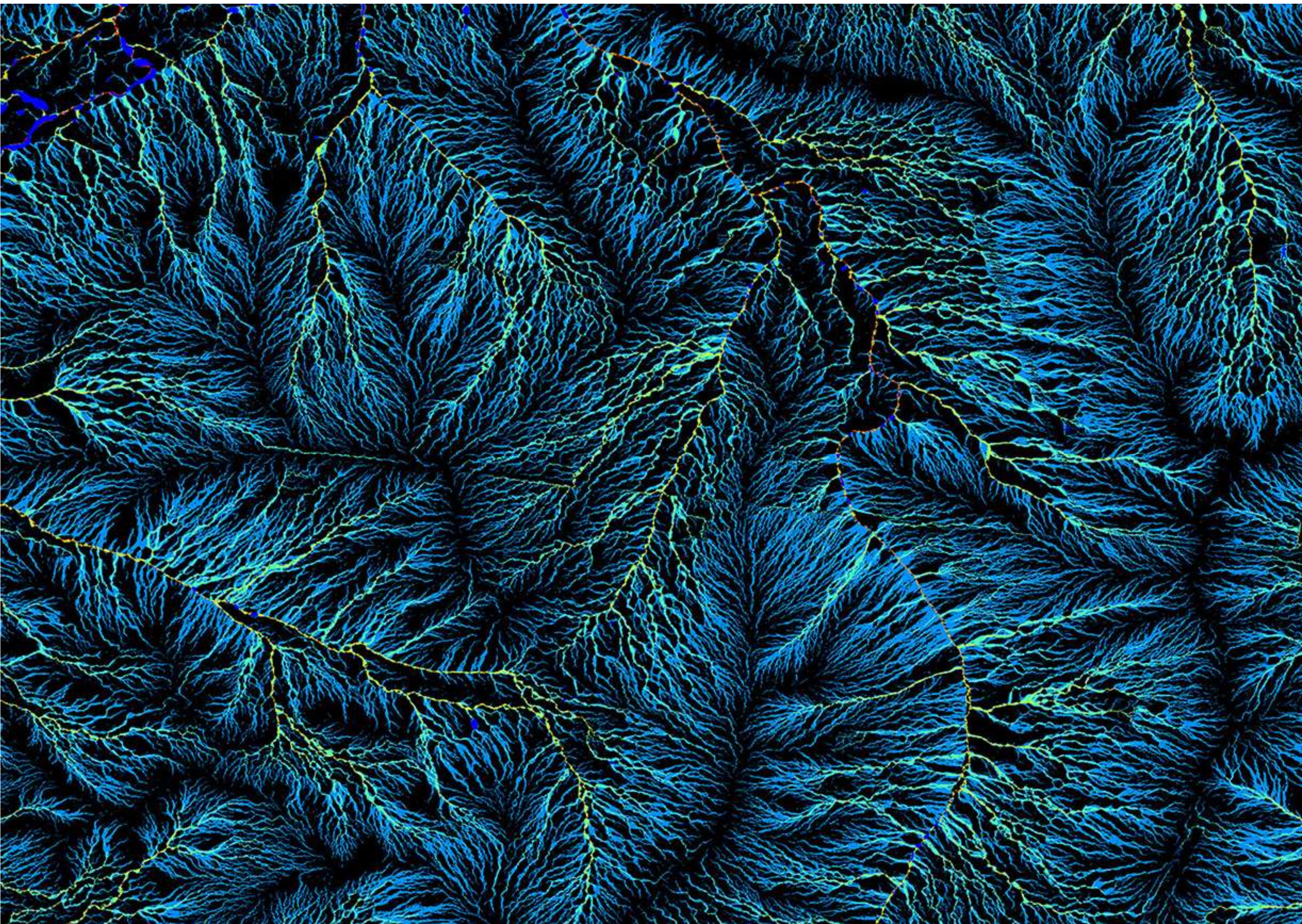
December 2019



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Acknowledgments

The report has been improved by input from a stakeholder workshop in August 2019.

Executive summary

GenCost is a collaboration between CSIRO and AEMO, together with stakeholder input, to deliver an annual process of updating electricity generation and storage costs. In this draft report, we are providing preliminary results for stakeholder review. The preliminary results are based on updated current cost estimates and new global electricity scenarios that were co-designed by stakeholders at a workshop in August 2019. The updated current cost estimates were commissioned by AEMO and delivered by Aurecon.

The projection methodology is grounded in a global electricity generation and capital cost projection model recognising that cost reductions experienced in Australia are largely a function of global technology deployment. The global generation mix is expected to be dominated by wind and solar photovoltaic (PV) by 2050 in all three scenarios explored in this report: Central, High CRE and Diverse technology. The implementation of scenarios that include a broader set of global technology drivers has resulted in a wider range of potential capital cost reduction paths for wind and solar PV. The new scenarios also indicate that in some scenarios carbon capture and storage and nuclear small modular reactors could play a larger role than previously projected.

In this report, CSIRO's projection model was extended to include offshore wind and hydrogen reciprocating engines. Both technologies are relevant where a country's onshore renewable resources are too constrained to meet all of their needs. The global modelling finds that these technologies are generally preferred compared to other options already included in the modelling such as fuel cells, geothermal and wave power. In the storage technologies, pumped hydro remains the lowest cost option for the present. However, battery storage experiences the greatest capital cost reductions to 2050.

Compared to GenCost 2018, the updated current costs for 2019-20 indicate that solar PV capital costs continue to fall, but no faster than was expected in 2018. However, onshore wind capital costs in 2019-20 are lower than were anticipated in 2018.

To improve the quality of the report, we are seeking feedback on these preliminary results before finalising the report in early 2020. In particular, input is requested on the following questions:

Do the scenarios adequately explore the plausible range of outcomes with regard to technological change of known technologies?

Are the updated current capital cost assumptions reflective of current project costs?

Are the inputs and assumptions for the capital cost projection model reasonable?

Are the inputs and assumptions for the levelised cost of electricity calculations reasonable?

1 Introduction

Current and projected electricity generation and storage technology costs are a necessary and highly impactful input into electricity market modelling studies. Modelling studies are conducted by the Australian Energy Market Operator (AEMO) for planning and forecasting purposes. They are also widely used by electricity market actors to support the case for investment in new projects. Governments and regulators require modelling studies to assess alternative policies and regulations. There are substantial coordination benefits if all parties are using similar cost data set for these activities or at least have a common reference point for differences.

1.1 Scope of the GenCost project and reporting

The GenCost project is a joint initiative of the CSIRO and AEMO to provide an annual process for updating electricity generation and storage cost data for Australia. The project is committed to a high degree of stakeholder engagement as a means of supporting the quality and relevancy of outputs. This preliminary report for feedback is part of delivering on that commitment.

The project is flexible about including new technologies of interest or, in some cases, not updating information about some technologies where there is no reason to expect any change, or if their applicability is limited. GenCost does not seek to describe the set of generation technologies included in detail.

1.2 CSIRO and AEMO roles

AEMO and the CSIRO jointly fund the GenCost project by combining their own in-kind resources. AEMO commissioned Aurecon to provide an update of current electricity generation and storage cost and performance characteristics (Aurecon, 2019). These were used as a starting point for discussions with a wide range of stakeholders including a workshop in August 2019.

Project management, workshops, capital cost projections (presented in Section 3) and this final report are primarily the responsibility of the CSIRO.

1.3 Incremental improvement and focus areas

There are a large number of assumptions, scope and methodological considerations underlying electricity generation and storage technology cost data. In any given year, we are readily able to change assumptions in response to stakeholder input. However, the scope and methods may take more time to change, and input of this nature may only be addressed incrementally over several years, depending on the priority.

For GenCost 2019-20, we have prioritised extension of Levelised Costs of Electricity (LCOE) estimates to include the costs of balancing variable renewable energy. A separate process will be followed to gain stakeholder feedback on this work.

CSIRO's cost projection methodology, inputs and assumptions are discussed in Appendix A. Appendix B provides data tables for those projections.

2 Current technology costs

AEMO commissioned Aurecon (2019) to provide an update of current electricity generation and storage technology cost and performance data for existing and selected new electricity generation and storage technologies. This data is used in this report as the starting point for projections of capital costs to 2050 and for calculations of the levelised cost of electricity.

Compared to GHD (2018) who updated costs for this project in 2018, the Aurecon (2019) technology list has changed. Costs for coal and nuclear technologies have not been updated since there have been no major developments in these technologies since the previous report (however there are changes in their projected future costs– see Section 3). Additional technologies updated by Aurecon, but not included in GHD (2018), are fuel cells[1], electrolysers[2], offshore wind and additional durations for lithium ion batteries. Pumped hydro has not been updated and is sourced from Entura (2018).

Feedback from stakeholders on GenCost 2018 (Graham et al., 2018) suggested that large generation units of any kind (nuclear, coal and gas) will be more difficult to deploy because of falling minimum demand and the greater redundancy required to cover both planned and unplanned outages of a large plant. Consequently, assumed gas plant sizes are smaller in Aurecon (2019) than GHD (2018).

CSIRO also received feedback on nuclear small modular reactor (SMR) costs that the source of GHD's estimated cost was not clear and that other estimates are lower. In reviewing this issue, we found that, while GHD's source was unclear, there is no hard data[3] to be found on nuclear SMR. While there are plants under construction or nearing completion, public cost data has not emerged from these early stage developments.

In lieu of hard data, estimates are only available from vendors or from applying engineering principles. Past experience has indicated that vendor-based estimates are often initially too low[4]. Constructing first-of-a-kind plant includes additional unforeseen costs associated with lack of experience in completing such projects on budget. SMR will not only be subject to first-of-a-kind costs in Australia but also the general engineering principle that building plant smaller leads to higher costs. SMRs may be able to overcome the scale problem by keeping the design of reactors constant and producing them in a series. This potential to modularise the technology is likely another source of lower cost estimates. However, even in the scenario where the industry reaches a scale where small modular reactors can be produced in series, this will take many years to

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[1] CSIRO provided an estimate for this in 2019 to supplement the GHD data.

[2] These are relevant for hydrogen production and storage. Although hydrogen could be relevant a storage technology, we do not currently include it in our global modelling.

[3] Hard data refers to public cost data from completed projects. There are other categories of technologies which have no hard data such as biomass with carbon capture and storage

[4] For example, early cost estimates for enhanced geothermal began at around $7000/kW but over time increased to $12,000/kW as more was learned about this technology. https://pangea.stanford.edu/ERE/db/WGC/papers/WGC/2015/04025.pdf

achieve and therefore does not impact estimates of current costs. Therefore, while we share stakeholder concerns that SMR costs are uncertain, we have not taken vendor cost estimates or costs at some future date under ideal manufacturing conditions as estimates of current costs. However, future SMR cost projections, outlined in Section 3, do take these factors into consideration, resulting in significant cost reductions in one of the scenarios explored.

2.1 Current generation technology capital costs

Figure 2-1 provides a comparison of current (2019-20) cost estimates (drawing primarily on the Aurecon (2019) update) for electricity generation technologies with the three most recent previous reports: GenCost 2018, Hayward and Graham (2017) (also CSIRO) and CO2CRC (2015) which we refer to as APGT (short for Australian Power Generation Technology report). All costs are expressed in real 2019-20 Australian dollars and represent overnight costs since it would not be possible to build and financially close projects before July 2020.

CSIRO's estimate for 2019-20 rooftop solar PV cost is included in the "Aurecon/CSIRO" data as that technology was not part of Aurecon (2019). Rooftop solar PV costs are before subsidies from the Small-scale Renewable Energy Scheme. For the coal and nuclear technologies, the data has not changed since GenCost 2018. However, it has been adjusted for inflation.

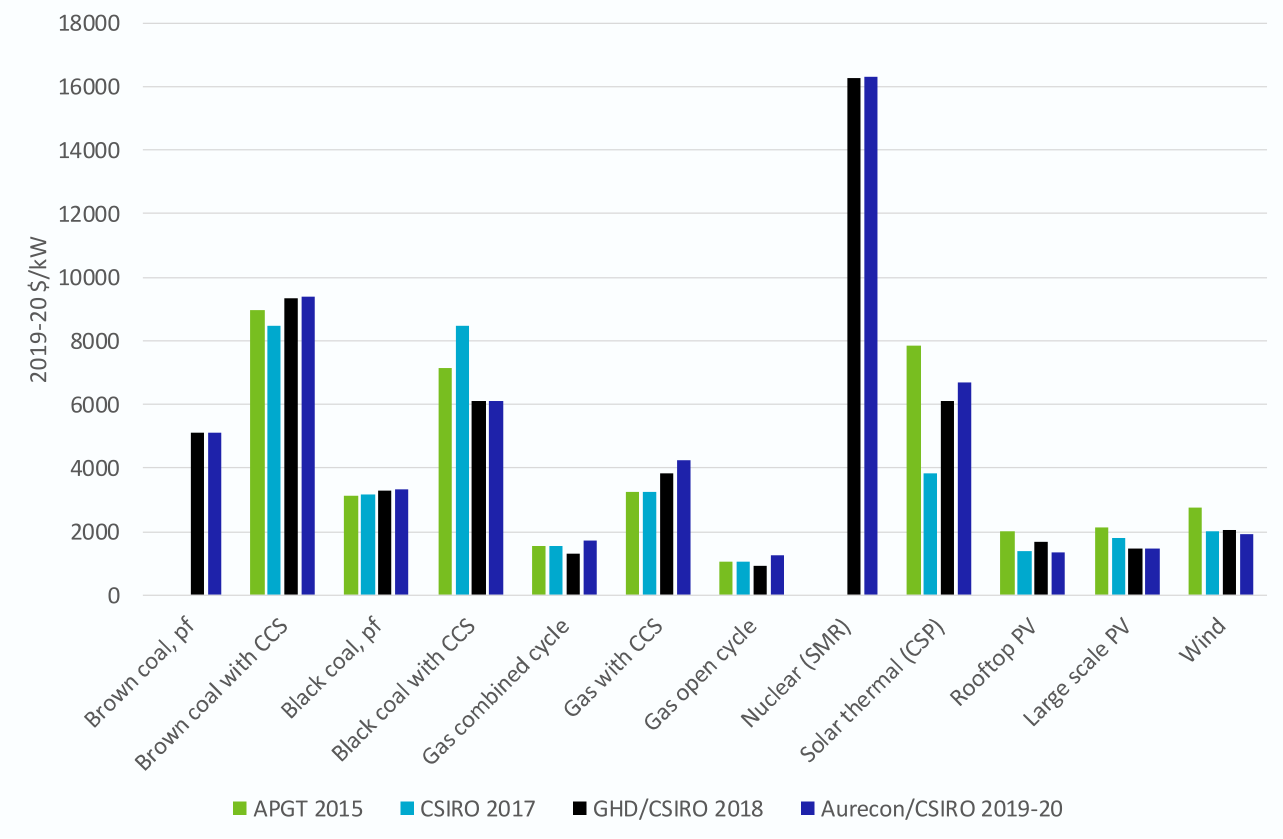


Figure 2-1 Comparison of generation technology capital cost estimates for 2019-20

There are three main changes since GenCost 2018. The first is that capital costs for gas-fired plant are higher. This is because the standard generation plant sizes for gas have been revised downward to better reflect sizes being considered by investors. Given the engineering principle that smaller generation plants are higher cost, this has led to an upward revision in gas generation technology capital costs.

The second change is that solar thermal capital costs have increased. During GenCost 2018, it was considered that a major solar thermal plant may be built in South Australia. Now that this plant is not proceeding, this reduces local learning and results in a higher cost to build new solar thermal plant in Australia.

The third change is that wind capital costs are slightly lower than anticipated, indicating that we underestimated the amount of cost reduction in wind over the last year. However, large-scale solar PV cost reductions over the past year were more accurate. The cost of rooftop solar PV has also been stable, but we have reverted back to representing a 5kW system (which is closer to the average new residential system size) which is lower cost, through economies of scale, than the 3kW system included in 2018.

2.2 Current storage technology capital costs

The current capital cost of storage from Aurecon (2019), GHD (2018), CSIRO (2017) and Entura (2018) is shown in Figure 2-2 and tabled in Appendix B. All data has been converted to 2019-20 Australian dollars. Storage capital costs can be presented in two ways. One is as separate component costs: for power ($/kW) and energy ($/kWh); where the costs must be multiplied by the power and energy capacity of a project and added together to calculate the total project cost. Alternatively, they can be presented as a total cost where either the power or energy capacity has been divided through the total project value. For example, a storage project that costs $40m and has a power capacity of 20MW and energy capacity of 40MWh. The cost for this project can then be expressed as either $2000/kW or $1000/kWh on a total cost basis. This total cost approach is the basis of costs shown in Figure 2-2.

Aurecon (2019) has provided battery costs for 1, 2, 4 and 8 hour energy duration. The 1 hour battery costs are 5% lower than the 2018 costs estimated by GHD (2018). However, the 2 hour batteries are higher than CSIRO (2017) estimates. However, Aurecon’s estimate is likely to be more accurate given there has been more completed projects since 2017.

It is interesting to note that both the 4 hours and 8 hours battery costs are higher than the cost of pumped hydro with 6 hours storage. This indicates that pumped hydro energy storage (PHES) has a distinct competitive advantage in longer duration storage applications at present. Entura (2018) costs are an average across the top 25% of projects in the NEM. There are a number of local project site assumptions that impact PHES costs.

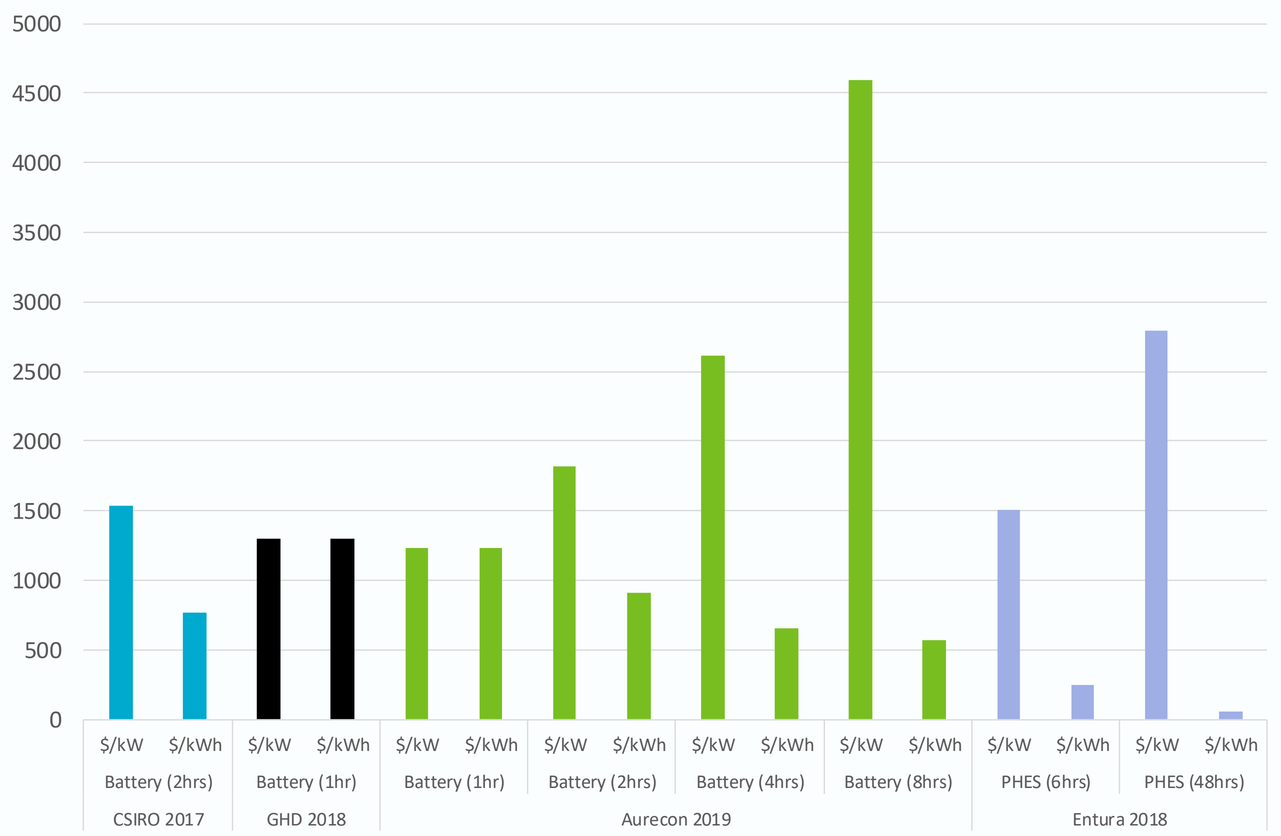


Figure 2-2: Capital costs of storage technologies (total cost basis)

The cost of compressed air was not updated by Aurecon (2019) but was reported by GHD (2018) to be $2467/kW or $51/kWh on a total cost basis for 48hrs storage. Aurecon (2019) report the current cost of electrolysers as being $1620/kW. This would be an important component of a hydrogen storage system. Another storage technology that could potentially be deployed is thermal storage which uses electrical resisters and a steam turbine to store and discharge electricity. Costs have been estimated for a graphite based system at $250/kWh for 8 hours electrical storage, 42% round trip efficiency and a 25 year economic life[5].

[5] Solastor graphite thermal battery presentation, May 2019.

3 Capital cost projections

3.1 Scenarios

In August 2019, we asked GenCost workshop participants to identify key global drivers of electricity generation technological change and design scenarios that could be implemented in GenCost 2019-20. This was in recognition that the climate change policy scenarios that were applied in previous technology cost projection modelling were not successful in exploring a wide enough range of outcomes. For most electricity generation technologies, the projection results from 4 degrees and 2 degrees climate policy scenarios were difficult to separate. We would expect there to be minimal variation in the outlook for mature technologies but for emerging technologies there should be a broader range of plausible outcomes.

Three new scenarios are described in Table 3-1. They are based on the scenarios and drivers suggested by stakeholders, together with insights from the modelling team on what would most likely deliver a broader range of technology cost outcomes. We acknowledge that there are potential wild card events that are not included in the scenarios such as completely new technologies and inter-regional high voltage interconnection. However, we chose to exclude wild cards. We also considered the possibility of aligning scenarios with other globally recognised scenarios. However, we found that drivers for other scenarios were not well targeted at producing changes in technology outcomes.

The Central scenario applies a moderate 4 degrees consistent climate policy with no extension to current renewable energy policies globally. Existing constraints (Hayward and Graham, 2017) were applied with respect to renewable energy resources and technical approaches for managing balancing of variable renewable electricity. Demand growth is moderate with some electrification of transport.

Under the High VRE scenario we apply a strong climate policy (similar to but higher than the 2 degrees carbon price applied in GenCost 2018) that supports high electrification across sectors such as transport and buildings and subsequently high electricity demand. Renewable energy resources are less constrained (physically and socially) and balancing variable renewable electricity is less challenging.

The Diverse technology scenario assumes that physical and social constraints mean that access to renewable energy resources is more limited. Governments subsequently limit their renewable targets below the threshold required for major deployment of balancing solutions. Consequently, there is a greater reliance on non-renewable technologies and a carbon price consistent with a 2 degrees consistent climate policy provides the investment signal necessary to deploy these technologies. Hydrogen trade is higher allowing some regions to access a low emission imported fuel.

Table 3-1 Scenarios and their key drivers

Key drivers	High VRE	Diverse technology	Central
CO2 pricing / climate policy	High (to encourage electrification) Consistent with 2 degrees world	High (to support non-VRE technology) Consistent with 2 degrees world	Moderate Consistent with 4 degrees world
Renewable energy targets and forced builds / accelerated retirement	High (reflecting confidence in VRE)	RE policies go to no more than 50%	Current RE policies
Demand / Electrification	High	Moderate	Moderate
Learning rates	Higher for longer in solar and batteries	Normal maturity path	Higher for longer in solar and batteries
Renewable resource & other renewable constraints	Unconstrained	More constrained than existing assumptions	Existing constraint assumptions[1]
Constraints around stability and reliability of variable renewables	New low cost solutions	Conventional solutions but not needed	Conventional solutions
Hydrogen fuel price	High: Not needed, unconstrained domestic renewables	Low	Moderate
Decentralisation	Less constrained rooftop solar PV	Existing rooftop solar PV constraints[1]	Existing rooftop solar PV constraints[1]

1 Existing large-scale and rooftop renewable generation constraints are as published in Hayward and Graham (2017)

3.1.1 Global generation mix

The rate of technology deployment is the key driver for the rate of reduction in technology costs for all non-mature technologies. However, the generation mix is determined by technology costs. Recognising this, the projection modelling approach simultaneously determines the global generation mix and the capital costs. The projected generation mix consistent with the capital cost projection described in the next section is shown in Figure 3-1. The technology categories displayed are more aggregated than in the model to improve clarity. Wind includes both on- and offshore wind and solar includes solar thermal and solar photovoltaics.

Reflecting the lower carbon price, the Central scenario has less solar and wind and higher coal generation than the remaining 2 degrees consistent scenarios. Although not large enough to observe in Figure 3-1, the Central scenario also has a small amount of generation from coal with carbon capture and storage (CCS). Under the High VRE and Diverse technology scenarios almost all coal generation is retired and the favoured form of CCS is gas with CCS. The High VRE scenario has the largest share of wind and solar at 63% in 2050. However, gas with and without CCS still plays a role in the generation mix reflecting general constraints on building any one technology and the need to support variable renewables with other balancing technologies.

The Diverse technology scenario includes the largest amount of generation from renewables other than hydro, wind and solar. Hydrogen generation (using reciprocating engines), ocean/tidal current, wave and conventional geothermal are some of the technologies included here. Nuclear small modular reactors (SMRs) are included in the nuclear category and play a modest role in the Diverse technology scenario.

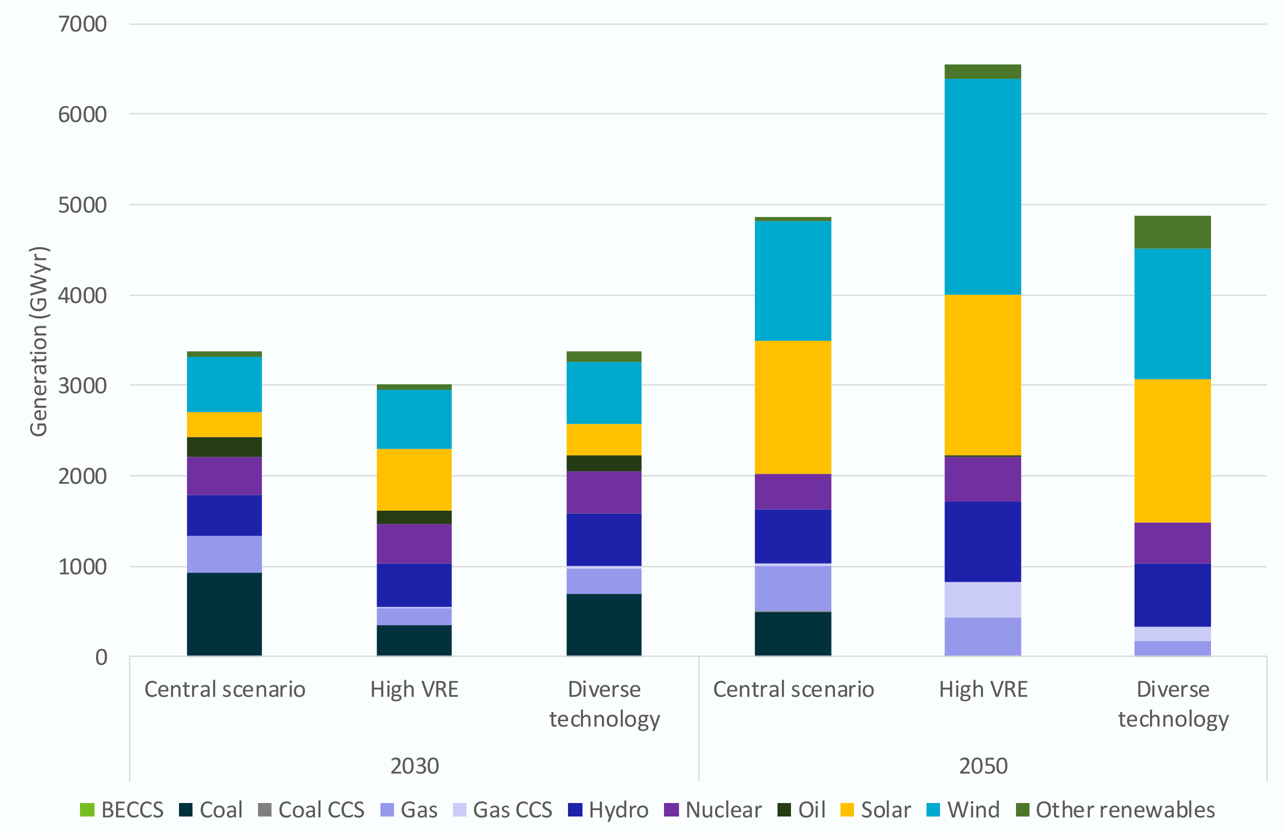


Figure 3-1 Projected global electricity generation mix in 2030 and 2050 by scenario

3.2 Changes in capital cost projections

This section discusses the changes in cost projections to 2050 compared to previous work. Comparable data from previous studies are only available for the main technologies. The projections for the three scenarios are compared to GenCost 2018, and CSIRO (2017). While the scenarios applied in this report include a larger set of drivers, like previous studies, the scenario can still be characterised as aligning with either a 4 degrees (Central scenario) or 2 degrees (High

VRE and Diverse technology scenarios) climate policy world. Note that the Global and Local Learning Model (GALLM) was the projection model in all three cases although there have been changes in both model structure and assumptions in each study.

For mature technologies, where the current costs have not changed and the assumed improvement rate is very similar, their projection pathways often overlap. The assumed annual rate of cost reduction for mature technologies is -0.01% in this report, which is close to that assumed in GenCost 2018. The rate of reduction in CSIRO (2017) was higher at -0.5%. The method for calculating the reduction rate for mature technologies is outlined in Appendix A.

Data tables for the full range of technology projections are provided in Appendix B.

3.2.1 Black coal supercritical

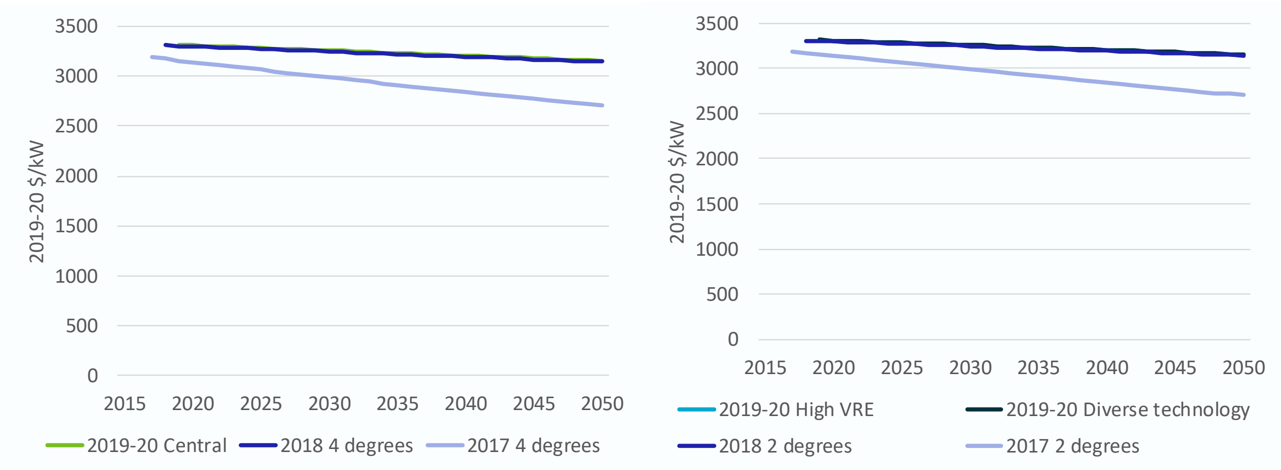


Figure 3-2 Projected capital costs for black coal supercritical by scenario compared to two previous studies

The projected capital costs for black coal supercritical plant have not changed compared to GenCost 2018 and do not vary by scenario. This is because the assumed rate of improvement in mature technologies remains the same, as does the assumed current capital cost which was sourced from GHD (2018).

3.2.2 Black coal with CCS

The updated projections use the same 2019 capital cost as GenCost 2018 which was significantly lower than CSIRO (2017). Under the Diverse technology scenario, where renewable generation shares are constrained, costs fall the earliest (early 2020s) and to the greatest extent of all projections, to around $5000/kW in 2050. However, under the High VRE scenario, CCS deployment commences only a few years later (late 2020s). Under the Central scenario, deployment of CCS is delayed until the 2040s due to the lower carbon price. Subsequently, capital cost reductions are significantly delayed. This indicates that CCS deployment and cost reductions are mainly triggered by high carbon prices. However, the historical and future capital cost reductions in renewable generation means that the carbon price to trigger deployment has likely risen. This is indicated by the additional five-year delay in deployment in the Central scenario compared to GenCost 2018.

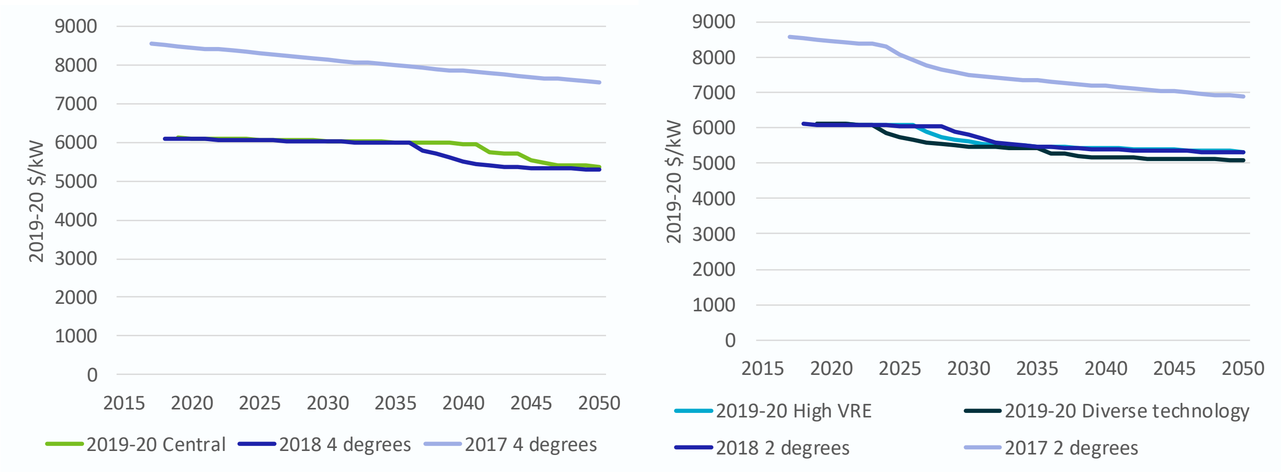


Figure 3-3 Projected capital costs for black coal with CCS by scenario compared to two previous studies

Black coal with CCS is largely a beneficiary of co-learning from deployment of gas with CCS in the High VRE and Diverse Technology scenarios with black coal with CCS a minor share of generation. However, under the Central scenario, black coal with CCS is up to half of total CCS capacity in some years.

3.2.3 Brown coal with CCS

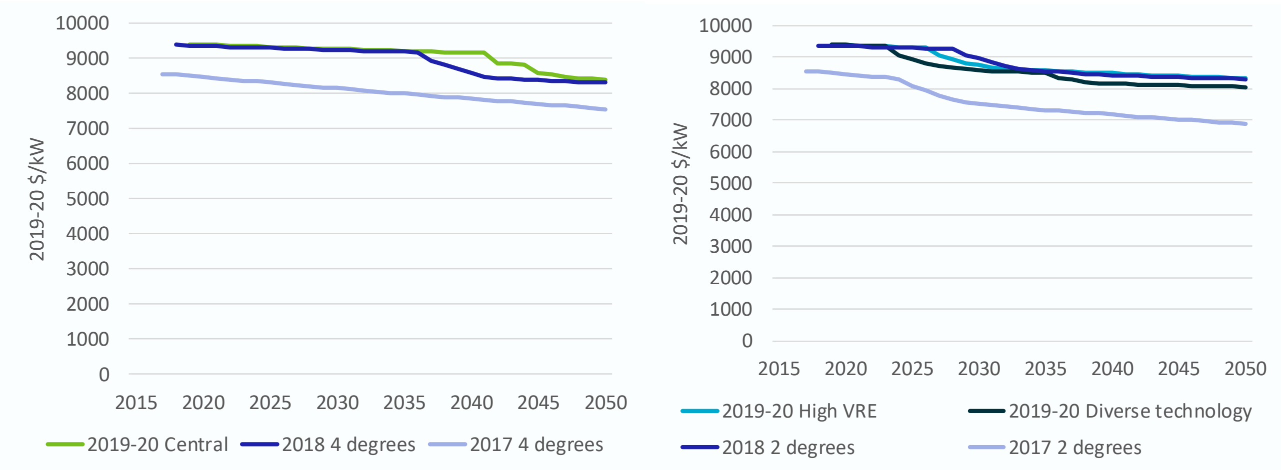


Figure 3-4 Projected capital costs for brown coal with CCS by scenario compared to two previous studies

Brown coal with CCS is projected to be a niche technology in terms of contribution to global electricity generation. The capital cost reductions achieved represent co-learning from deployment of gas with CCS in the High VRE and Diverse Technology scenarios and both black coal and gas with CCS in the Central scenario. Brown coal with CCS uses the same starting point for current capital costs as GenCost 2018 which was sourced from GHD (2018). This represented an increase compared to CSIRO (2017).

3.2.4 Gas combined cycle

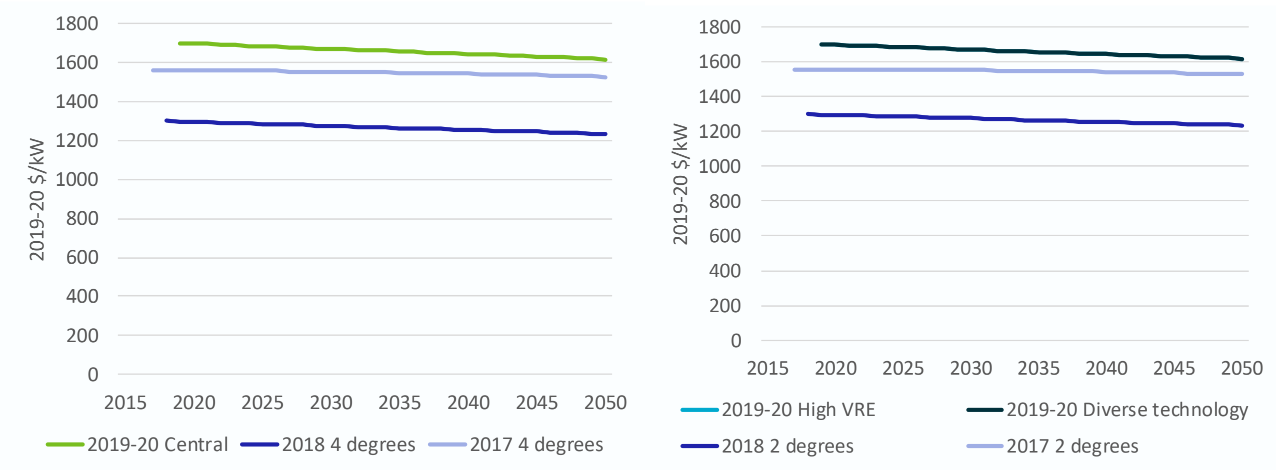


Figure 3-5 Projected capital costs for gas combined cycle by scenario compared to two previous studies

Gas combined cycle is classed as a mature technology for projection purposes and as a result its change in capital costs is governed by our assumed cost improvement rate for mature technologies. Consequently, the rate of improvement is constant across the Central, High VRE and Diverse technology scenarios. The current capital costs for gas combined cycle was updated by Aurecon (2019) and is higher because they are assumed to be smaller (reflecting feedback from stakeholders that plant sizes in GHD (2018) were higher than being considered by investors). Smaller plant are higher costs as they lose economies of scale. The outcome of these changes is that gas combined cycle capital costs are significantly higher than previous studies but closer to CSIRO (2017).

3.2.5 Gas with CCS

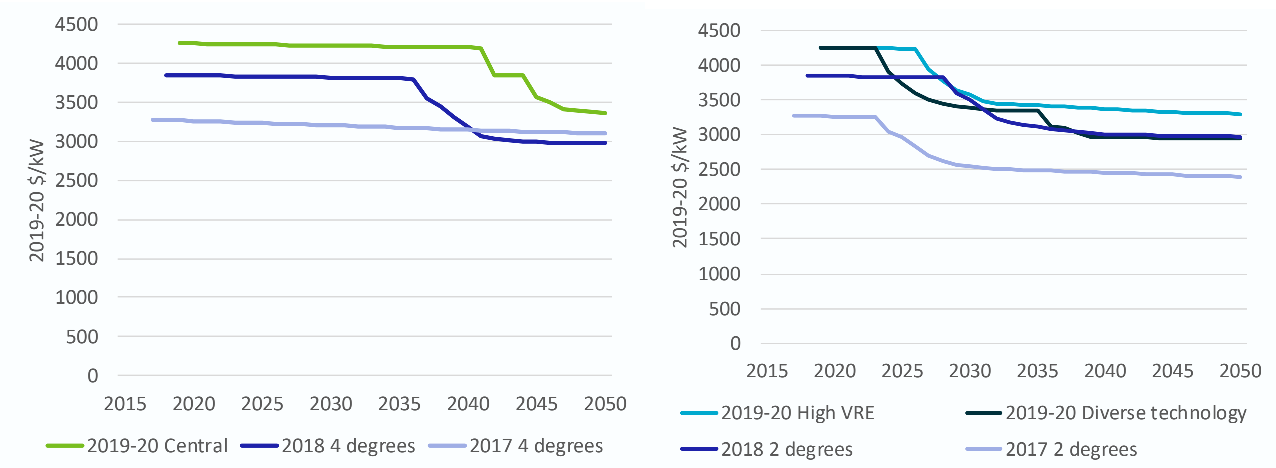


Figure 3-6 Projected capital costs for gas with CCS by scenario compared to two previous studies

The assumed smaller gas generation plant sizes that were included in Aurecon (2019) and adopted in the updated projections result in increased capital costs for gas with CCS compared with previous studies. However, under the Diverse technology scenario, gas with CCS is able to achieve a similar level of capital costs ($3000/kW) by 2050. Gas with CCS is the preferred CCS technology in all scenarios but is strongest in the 2 degrees scenarios of High VRE and Diverse Technological change. While gas fuel is generally higher cost than black and brown coal, the lower capital costs associated with gas with CCS make it the preferred CCS technology. Gas with CCS is also able to achieve a lower emission intensity than coal with CCS which is also a consideration under high carbon prices. Consequently, under the lower carbon price associated with the Central scenario, gas with CCS capacity is at a more equal share with coal with CCS capacity and each benefits from co-learning from deployment of CCS technology in the other plant type.

Gas with CCS deployment occurs sooner in the High VRE and Diverse technology scenarios compared to the equivalent 2 degrees scenario in GenCost 2018. This reflects in the former case the recognition that electricity demand is high and, while renewables are assumed to be abundant, there are still limits that mean a mix of technologies will be required to meet demand. In the latter case, it reflects the need to deploy a wider range of technologies at higher shares in a world with significantly limited renewable resources.

Gas with CCS deployment in the Central scenario is slower than the equivalent 2018 4 degrees scenario because the current and future capital cost of renewables is lower than projected in 2018, increasing the carbon price required to make gas with CCS competitive.

3.2.6 Gas open cycle

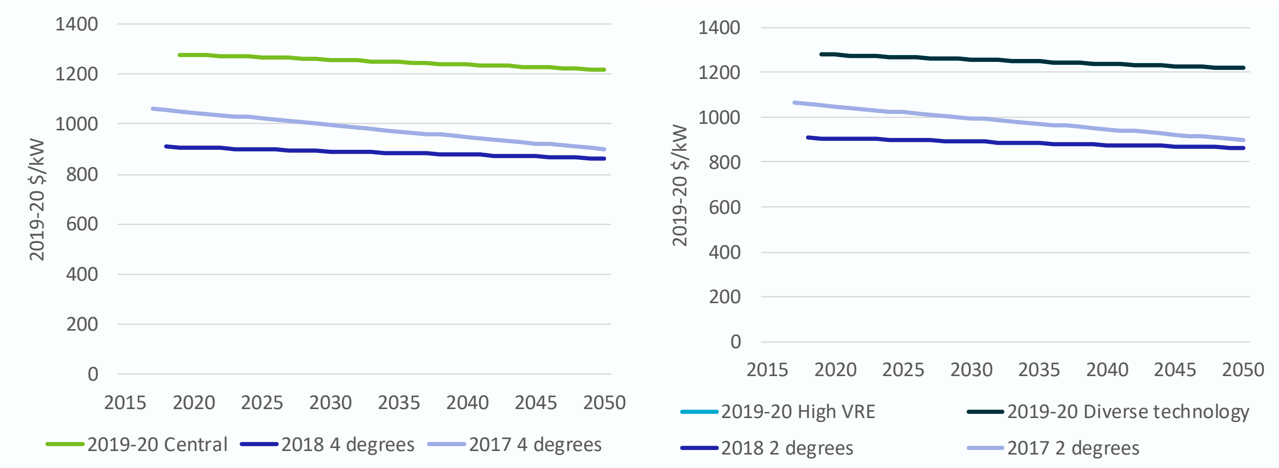


Figure 3-7 Projected capital costs for gas open cycle by scenario compared to two previous studies

Gas open cycle is classed as a mature technology for projection purposes and as a result its change in capital costs is governed by our assumed cost improvement rate for mature technologies. Consequently, the rate of improvement is constant across the Central, High VRE and Diverse technology scenarios. The current capital costs for gas open cycle was updated by Aurecon (2019) and is higher because they are assumed to be smaller (reflecting feedback from stakeholders that plant sizes in GHD (2018) were higher than being considered by investors). Smaller plant are higher cost as they lose economies of scale. The outcome of these changes is that gas open cycle capital costs are significantly higher than previous studies.

3.2.7 Nuclear SMR

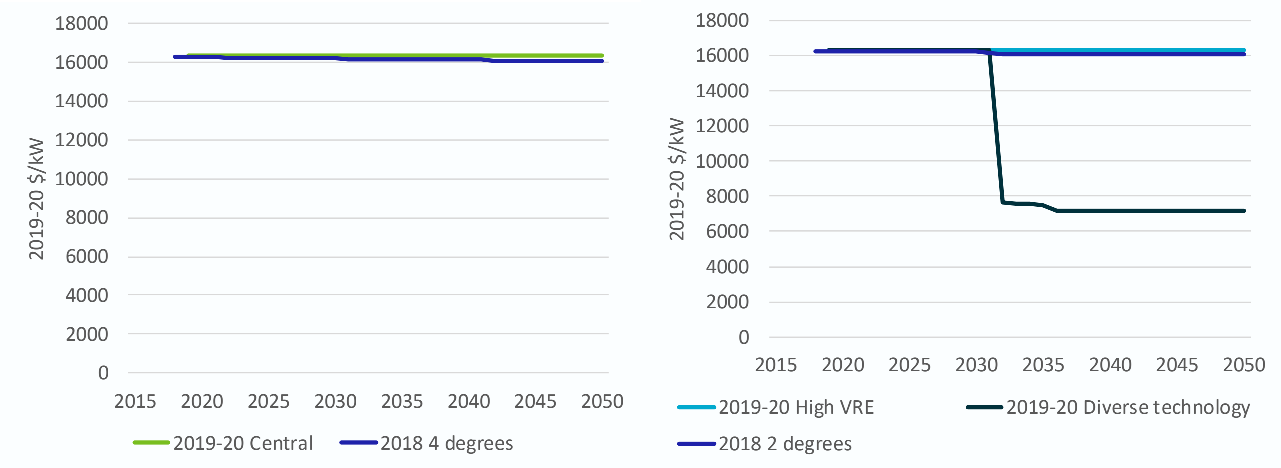


Figure 3-8 Projected capital costs for nuclear SMR by scenario compared to two previous studies

The assumed current capital cost for nuclear SMR remains the same as GenCost 2018 which was sourced from GHD (2018). As discussed in Section 2, while nuclear SMR costs are very uncertain due to the lack of public cost data on completed international projects, the GHD (2018) estimate remains reasonable for a technology at a low level of commercial deployment. However, GenCost 2018 cost projections were too narrow in their view because they did not allow for any improvement in costs over time. To address this, CSIRO's projection model was modified to include SMR as a separate nuclear technology category. This means that it was assigned its own higher learning rate (more consistent with an emerging technology) rather than being included in a broad nuclear category, with a low learning rate consistent with more mature large scale nuclear.

The impact of adding nuclear SMR as a technology separate from large scale nuclear is that we are now projecting a substantial cost reduction to around $7000/kW in the early 2030s in the Diverse technology scenario. This is the scenario where we would expect the cost reduction to be the largest given that renewable generation is more limited and carbon prices are high enough to encourage deployment of a wide variety of non-renewable generation technologies.

The capital cost reduction rate appears near vertical under the Diverse Technology scenario. However, the formulation of the learning rate function is the same as all other technologies. The sharp slope comes from the fact that technologies with near-zero existing capacity find it easier to increase their capacity several times relative to current capacity. This ratio of increased capacity to existing capacity is the mechanism by which capital cost reductions occur in the projection model.

Nuclear SMR does not make any significant cost reduction the Central and High VRE scenarios. In the former case, the carbon price is not high enough to warrant investment in bringing down nuclear SMR costs. In the High VRE scenario, the model has chosen investment in reducing costs of renewables and gas with CCS as the most efficient solution reflecting abundant renewable resources and greater existing progress on reducing CCS costs.

3.2.8 Solar thermal with 8 hours storage

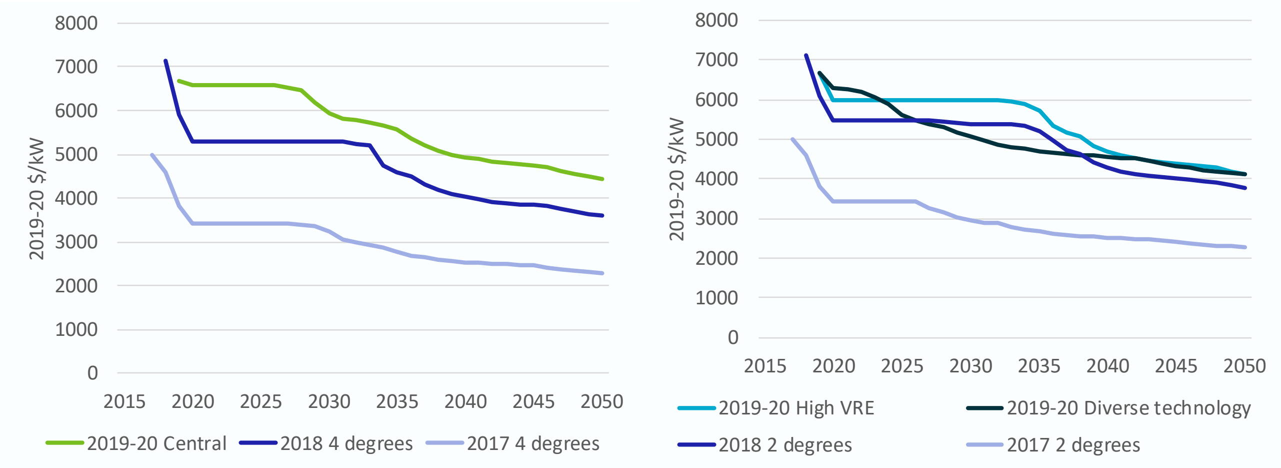


Figure 3-9 Projected capital costs for solar thermal with 8 hours storage by scenario compared to two previous studies

The capital cost projection for solar thermal with 8 hours storage is generally higher in the next five years compared to GenCost 2018 due to slower cost reductions. The fastest capital cost reduction occurs in the Diverse technology scenario. With variable renewables limited, solar thermal with storage is required to play a larger role in the global generation mix. Under the High VRE scenario, solar thermal with storage also plays a significant role, supporting the balancing of the system, and by the 2040s is following a similar capital cost reduction path, converging on $4000/kW by 2050. This is slightly above 2018 projections for the equivalent 2 degrees scenario.

Under the Central scenario, capital costs start higher and reduce more slowly than the equivalent 2018 4 degrees scenario. The increased capital costs for solar thermal most likely reflect improvements in the current and future capital costs of other renewables. Other renewables therefore compete more strongly with solar thermal with storage, reducing their deployment and subsequent cost reductions.

3.2.9 Large scale solar PV

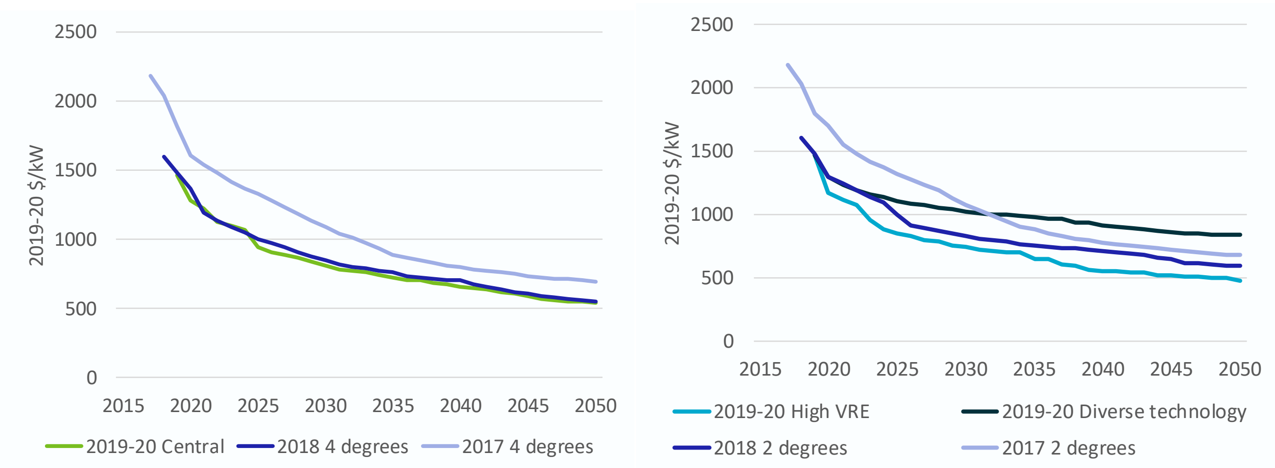


Figure 3-10 Projected capital costs for large scale solar PV by scenario compared to two previous studies

For perhaps the first time in several years, the current capital costs for large scale solar PV are consistent with the previous year's study. This means that the year ahead projection for large scale solar PV in GenCost 2018 was fairly accurate. This contrasts with previous years where the current costs required substantial downward revisions as was the case between CSIRO (2017) and GenCost 2018. For future years, the capital costs projections under the Central scenario are very similar to what was projected under the equivalent 4 degrees scenario in GenCost 2018. However, the projected capital costs under the 2 degrees scenarios, High VRE and Diverse Technology are different from the 2018 2 degrees projection. The High VRE scenario results in a faster and greater reduction in costs to $500/kW by 2050. The Diverse technology scenario tracks the 2018 projection until the mid-2020s but capital cost reduction slow thereafter and are above the CSIRO (2017) projection by 2050. There are tighter limits to solar adoption under this scenario and the reduced level of deployment means less capital cost reduction is achieved.

3.2.10 Rooftop solar PV

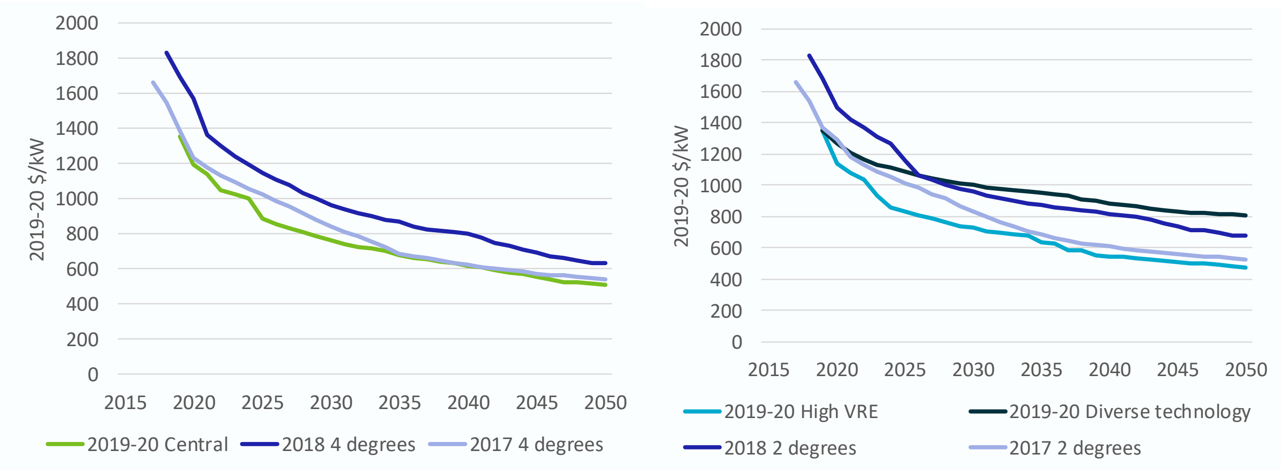


Figure 3-11 Projected capital costs for rooftop solar PV by scenario compared to two previous studies

Rooftop solar PV benefits from co-learning in the components in common with large scale PV generation plant and is also impacted by the same drivers for variable renewable energy across scenarios. As a result, we can observe similar trends in the rate of capital cost reduction. The capital cost projections under the Central scenario closely tracks the rate of cost reduction in the 2018 4 degrees scenario. However, the starting value has been adjusted to better align with a 5kW system and as a result it follows the 2017 path which was also based on a 5kW system.

The rate of capital cost reductions in the High VRE and Diverse technology scenarios differ from the 2018 2 degrees scenario. High VRE achieves the faster and greatest cost reduction indicating a world where solar PV deployment is very high. Under the Diverse technology scenario, emission reduction is achieved with a much lower reliance on variable renewable generation and subsequently deployment and capital cost reductions for rooftop solar PV are not as great.

3.2.11 Onshore wind

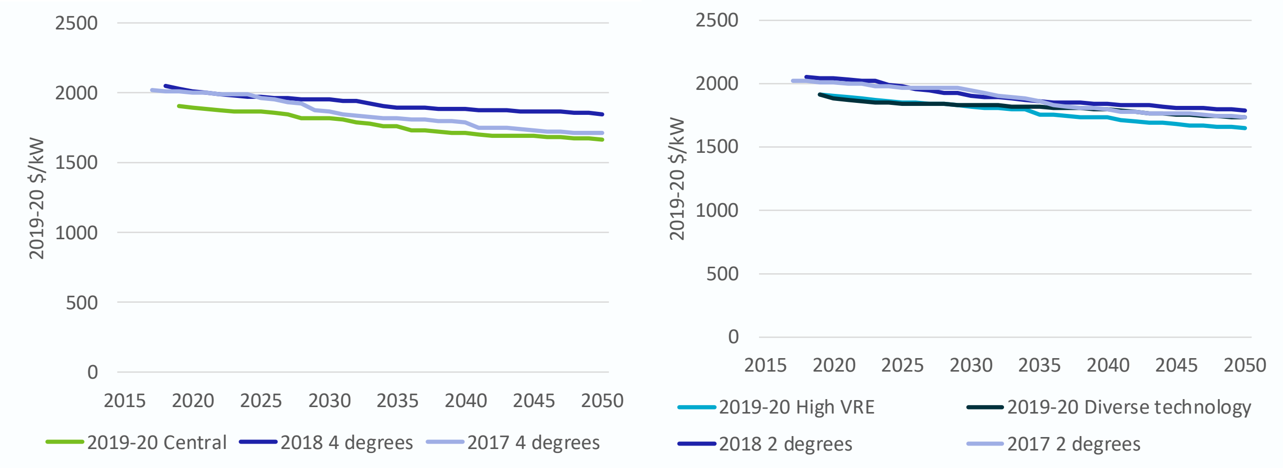


Figure 3-12 Projected capital costs for onshore wind by scenario compared to two previous studies

The 2019 capital cost for onshore wind has been revised downwards based on updated data from Aurecon (2019). Under the Central scenario, this has encouraged slightly more deployment and capital cost reductions than under the 2018 4 degrees scenario. Under the High VRE scenario the rate of reduction in costs is similar to the equivalent 2018 2 degrees scenario but the lower starting point means that the end-result by 2050 is lower. The rate of capital cost reduction under the Diverse technology scenario is slower than the 2018 2 degrees scenario reflecting a reduced reliance on variable renewable generation. However, the reduction in 2019 capital costs means that, even with this reduced annual rate of reduction, capital costs are lower than GenCost 2018 projections and similar to the values from CSIRO (2017) from 2035.

3.2.12 Battery storage

CSIRO first provided battery storage cost projections in a 2015 report to AEMC on energy storage trends (Brinsmead et a 2015). These were updated in 2016 for the Electricity Network Transformation Roadmap and were provided as part of generation costs projection reports in CSIRO (2017) and GenCost 2018. Whenever a technology is undergoing fast reduction in costs there is always significant uncertainty in the starting point for cost projections. Current costs for the battery only component of battery storage systems is around $250/kWh which is reasonably consistent with previous projections with the exception of CSIRO (2017).

The updated projection and those in 2018 tend to include a slowing down of cost reduction as the technology matures followed by an acceleration in the mid-2020s. This acceleration is associated with an expected large increase in global battery manufacturing associated with deployment of electric vehicles. Although there are differences between electric vehicle and stationary energy batteries, we assume they each benefit from some degree of co-learning from deployment of each other. Under the High VRE scenario, battery costs decline faster reflecting that the electrification of vehicles is progressing more quickly and also the global generation mix is increasing its share of variable renewables increasing demand for balancing technologies such as battery storage.

Under the Central and Diverse technology scenarios, the low carbon price and limits on variable renewables share respectively, reduce the need for balancing technologies so that battery cost reductions are delayed and more dependent on developments in the transport sector.

From 2018, CSIRO's projection methodology recognised that battery technologies, while mature, are still experiencing learning rates more consistent with emerging technologies. As a result, we have allowed higher rates of learning to apply for longer periods than previous CSIRO studies. The outcome of this assumption is that battery costs achieve a lower cost of $50/kWh by 2050 compared to an average of $100/kWh in the pre-2018 projections. The slightly higher costs for the High VRE scenario post-2030 reflect stronger competition from alternative technologies for balancing the system under high variable renewable generation.

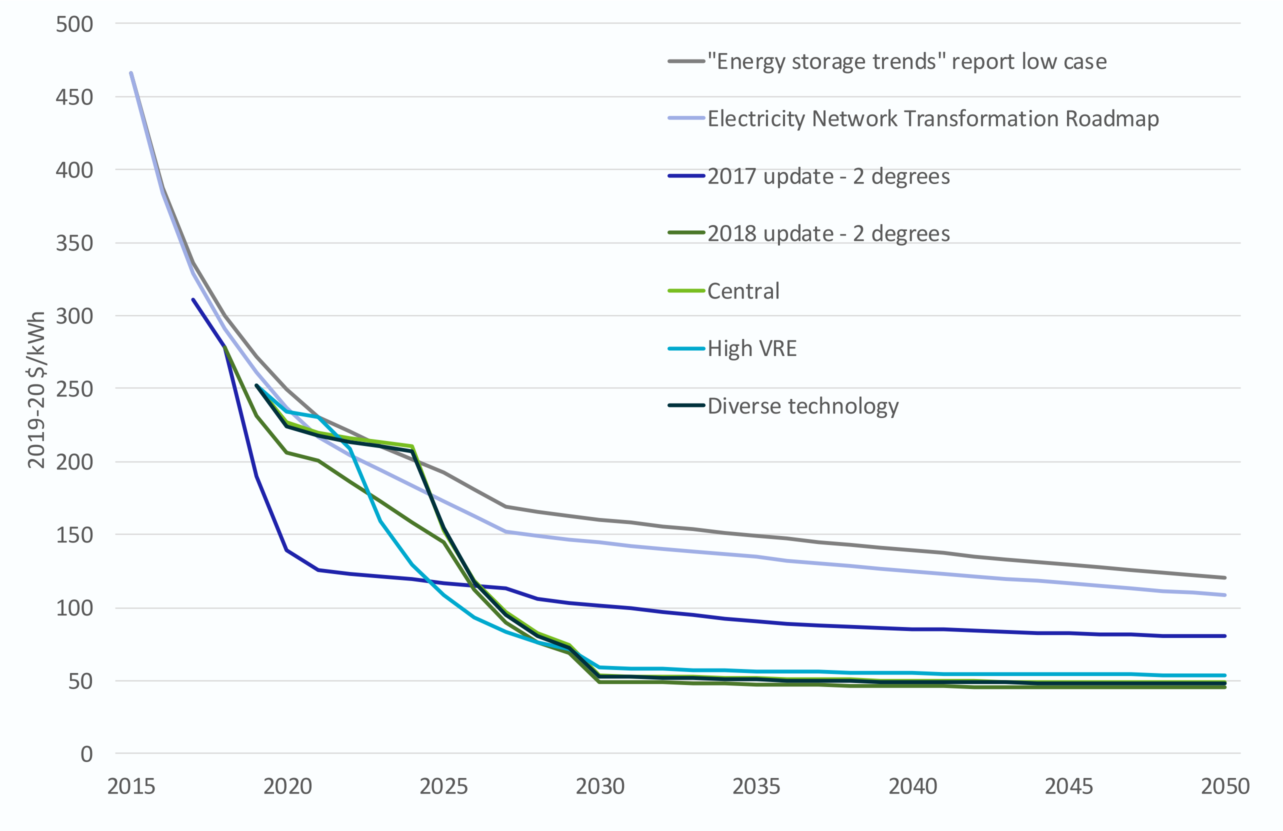


Figure 3-13 Projected capital costs for batteries by scenario compared to previous studies

3.2.13 Other technologies

There are a number of technologies have not been included in cost projection studies on a regular basis (such as pumped hydro storage which was only included from 2018) or have higher uncertainty about their future potential investment prospects (ocean located technologies, biomass with CCS and fuel cells) but remain of interest. In this report, we have added offshore wind and we exclude enhanced geothermal due to its poor prospects.

Central scenario

The project capital costs for the remainder of technologies of interest under the Central scenario are compared with the GenCost 2018 projections in Figure 3-14. Under the Central scenario the projected capital costs for all of this group of technologies is generally higher than was projected under the equivalent 4 degrees scenario in 2018. This reflects the increased competitiveness of renewables such as onshore wind and solar PV which reduces the need for many of these higher cost technologies. Pumped hydro is one technology which likely benefits from the increased competitiveness of wind and solar PV generation which creates demand for system balancing technologies. However, most of the components of pumped hydro are assumed to be mature already and so cost reduction from increased deployment are limited.

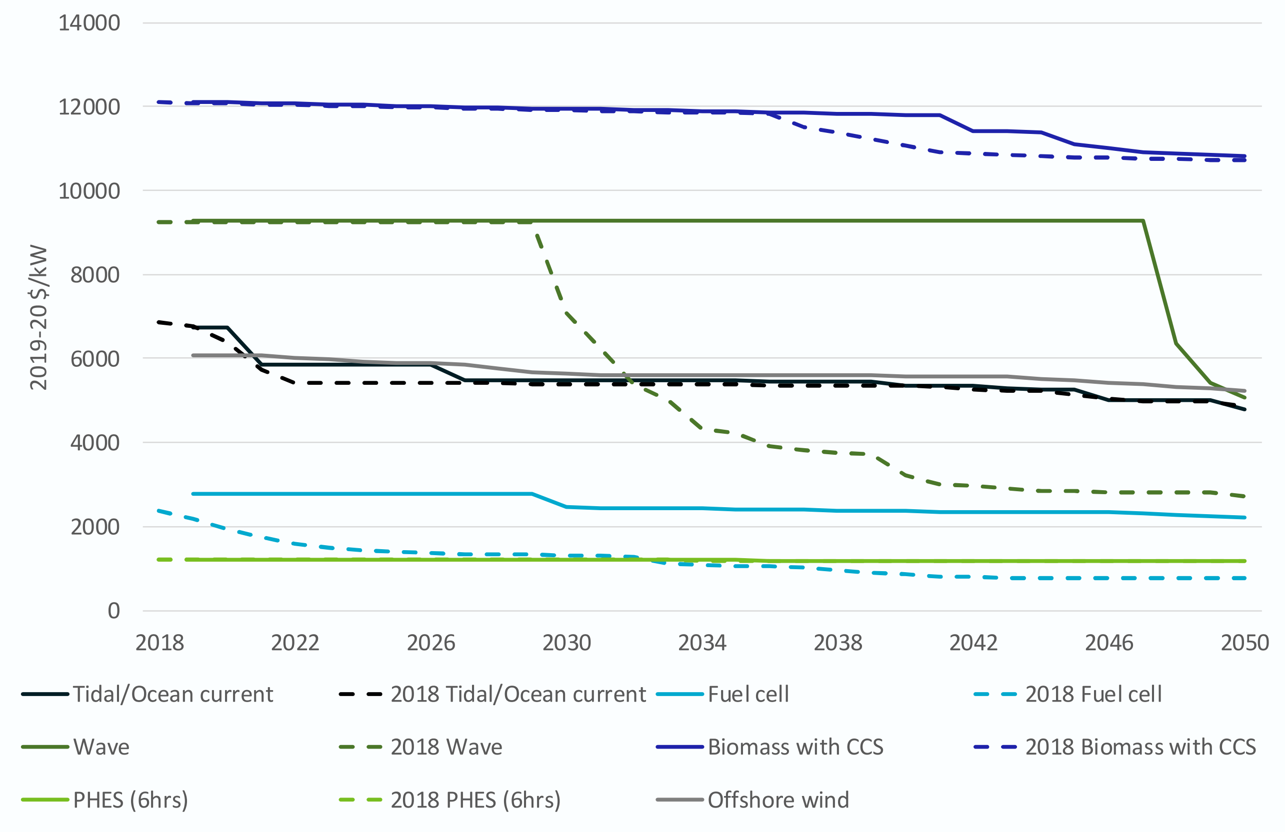


Figure 3-14 Projected technology capital costs under the Central scenario and 2018 4 degrees scenario

High VRE and Diverse technology scenarios

The project capital costs under the High VRE and Diverse technology scenarios are compared with the GenCost 2018 projections in Figure 3-15. Cost reductions for fuel cells, biomass with CCS, wave and tidal/ocean current technologies are all generally less than was projected in 2018 for the equivalent 2 degrees scenario. This mainly due to the inclusion of offshore wind and, to a lesser extent, hydrogen fuelled reciprocating engines[6] in the electricity generation technology set. The new inclusion of these technologies has substantially supplanted the role that these other technologies were projected to play in the 2018 projections. As a result, cost reduction are both delayed and smaller than previously forecasts. Biomass with CCS performs the worst under High VRE. Wave is not required until very late in both scenarios but especially the Diverse technology scenario where variable renewable generation technologies are less dominant.

[6] Hydrogen-fuelled reciprocating engines are not included in these charts because they are considered mature technology (though not commonly used). They are currently estimated at $1526/kW and decline at 0.1% per annum.

Lower cost reciprocating engines are preferred to fuel cells in both scenarios for utilising hydrogen fuel. Tidal/ocean current is classed as a non-variable renewable and as a result achieves the most cost reduction under the Diverse technology scenario where its projected costs are the most consistent with the 2018 2 degrees scenario. As we observed under the Central scenario, pumped hydro costs do not changed significantly owing to the high maturity of its plant components.

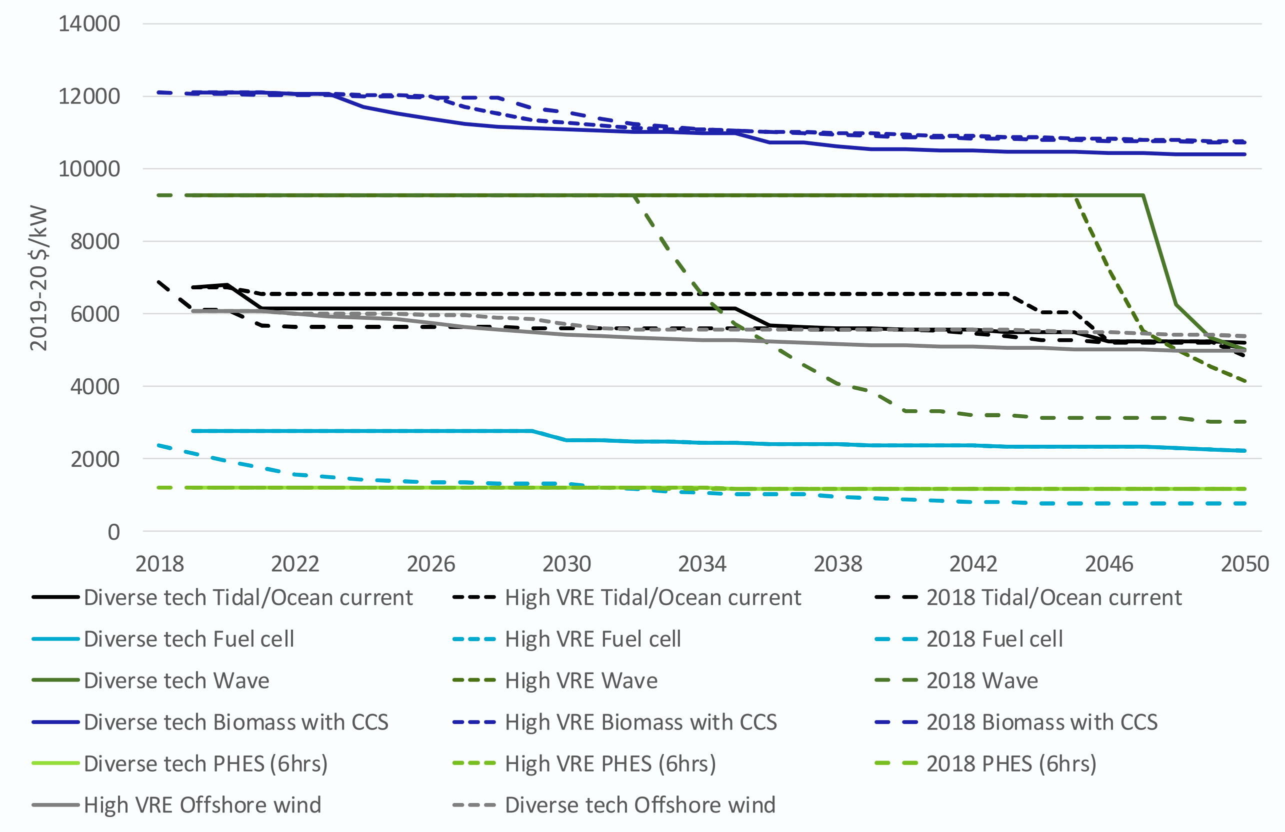


Figure 3-15 Projected technology capital costs under the High VRE, Diverse technology and 2018 2 degrees scenarios

4 Levelised cost of electricity

The levelised cost of electricity (LCOE) is a simple screening tool for quickly determining the relative competitiveness of electricity generation technologies. It is not a substitute for detailed project cashflow analysis or electricity system modelling which are both better suited to representing real electricity generation project operational costs and performance. Furthermore, in the GenCost 2018 report and a supplementary report on calculating the balancing cost of renewables (Graham, 2018), we described a number of issues and concerns in calculating and interpreting levelised cost. These include:

- LCOE does not take account of the additional balancing costs associated with variable renewable electricity generation technologies
- LCOE applies the same discount rate across all technologies even though fossil fuel technologies face a greater risk of being impacted by the introduction of new climate change policies.
- LCOE does not recognise that electricity generation technologies have different roles in the system. In particular, some technologies are operated less frequently, increasing their costs, but are valued for their ability to quickly make their capacity available at peak times.

To address some of these issues, when we present LCOE information we:

- Separate and group peaking technologies, flexible technologies and variable technologies together
- Include additional LCOE data on fossil fuel technologies which includes additional risk premiums or carbon prices on fossil fuel technologies
- Present variable renewable technologies with additional storage costs.

In regard to the issue of including system balancing costs with variable renewable technologies, the inclusion of storage costs at 2 and 6 hours is not ideal. Storage is one of only several different ways of balancing the system and the amount of storage needed will vary by region depending on the variable renewable generation share. However, we will continue to present these LCOE estimates with storage until a more accurate method, currently under development, is available.

The LCOE estimates for the beginning of each decade to 2050 are shown in Figure 4-1 to Figure 4-4. The cost ranges apply the lowest and highest cost outcomes from the capital cost projections presented in the previous section. The additional cost assumptions are listed in Appendix B.

The results indicate that, at 20% capacity factor, gas reciprocating engines are a lower cost peaking technology than gas turbines owing to higher fuel efficiency offsetting slightly higher capital costs. Among the flexible load high emission technology options, if there is no climate policy risk the relative competitiveness of fossil fuel generation is largely a function of what fuel price the project is able to secure with gas being competitive at low gas prices but less competitive at higher prices. If climate policy risks are a concern (either through a carbon price or the risk of a future climate policy being built into the financing rate) then gas is the lower cost option reflecting its lower emission intensity than coal. These fossil fuel technology comparisons remain the same through to 2050 because, as mature technologies, their capital costs are stable. Any changes in relative competitiveness are largely due to fuel prices and climate policy risk.

In the low emission flexible generation technology category, solar thermal with 8 hrs storage and gas or coal with CCS are the lowest cost up to 2030. Gas with CCS has a lower capital cost but higher fuel cost than coal with CCS. The relative prices of fuels (inclusive of any potential future carbon pricing) will ultimately determine which of the CCS technologies are most competitive.

From the early 2030s, under the Diverse technology scenario discussed in the previous section, nuclear SMR capital costs reduce substantially. This development is what underpins the low range of SMR costs in the 2040 LCOE results. If this capital cost reduction pathway is achieved then nuclear SMR is competitive with CCS. The top of the LCOE range remains high because in other scenarios, nuclear SMR capital costs remain high.

In the variable technology category, wind and solar photovoltaic costs are similar in 2020 at around $50/MWh. However, over time solar photovoltaic capital costs fall faster and by 2050 the LCOE cost range is projected to be lower than for wind. When storage is added to solar and wind, this raises their costs to a similar level to that of fossil fuels without a carbon price or risk premium.

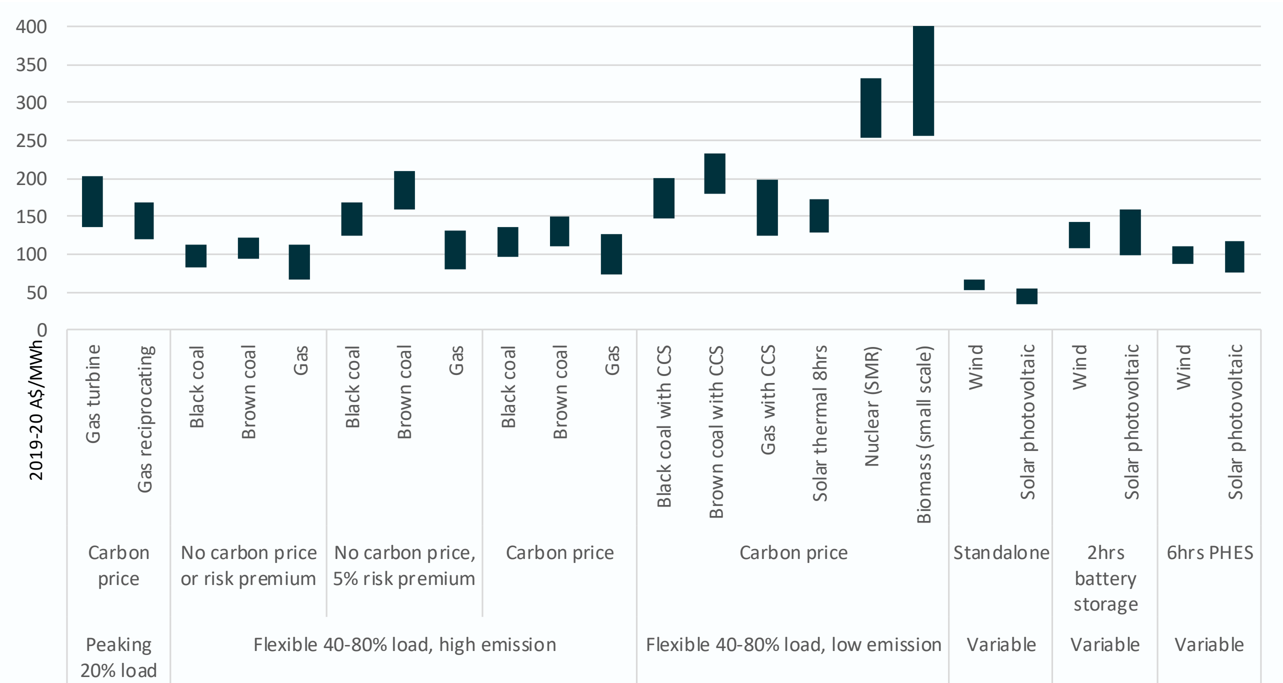


Figure 4-1 Calculated LCOE by technology and category for 2020

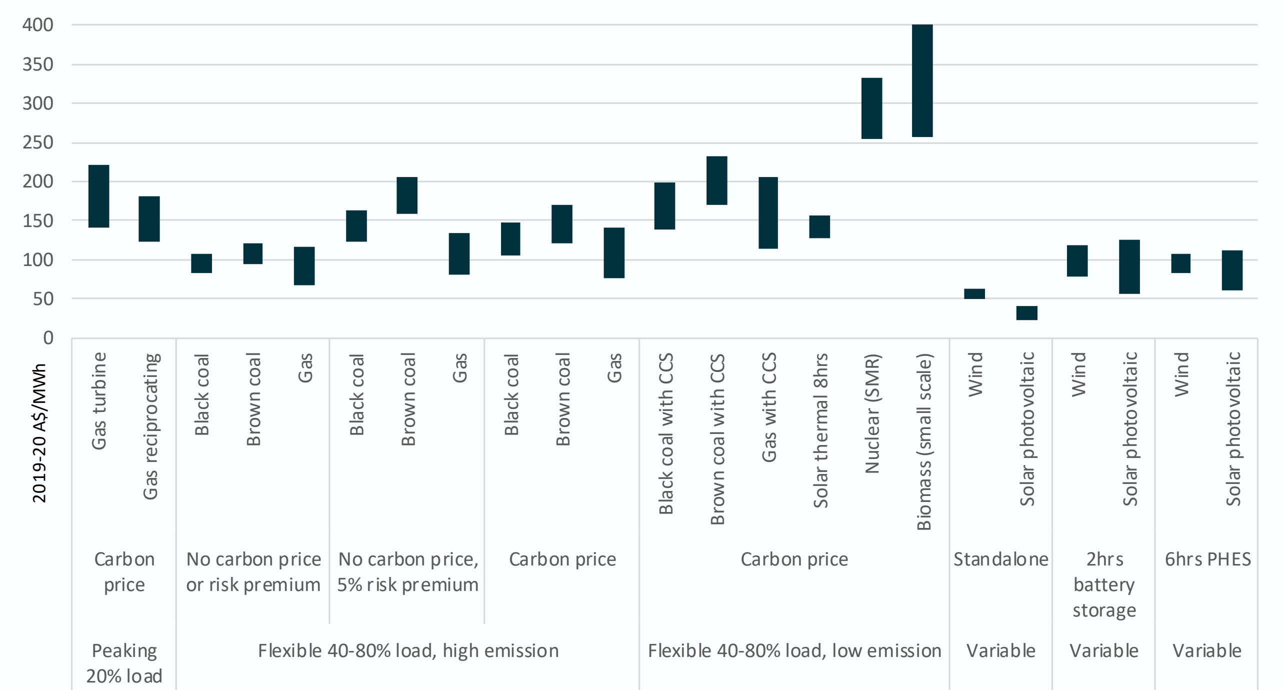


Figure 4-2 Calculated LCOE by technology and category for 2030

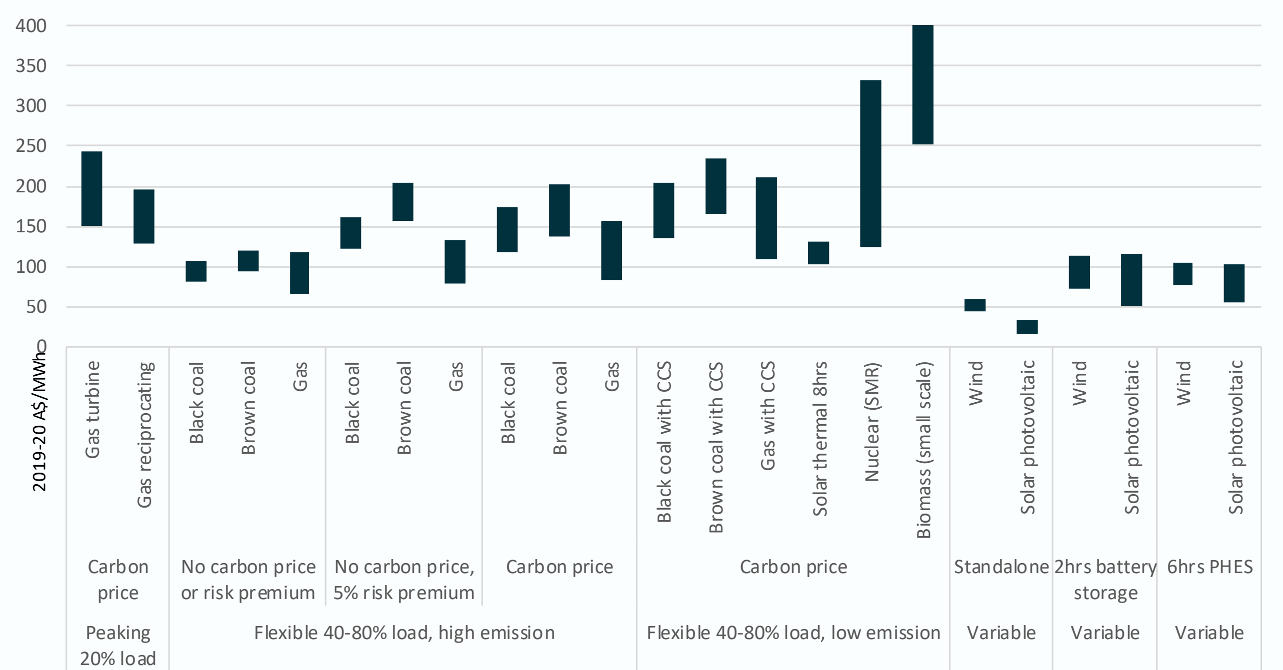


Figure 4-3 Calculated LCOE by technology and category for 2040

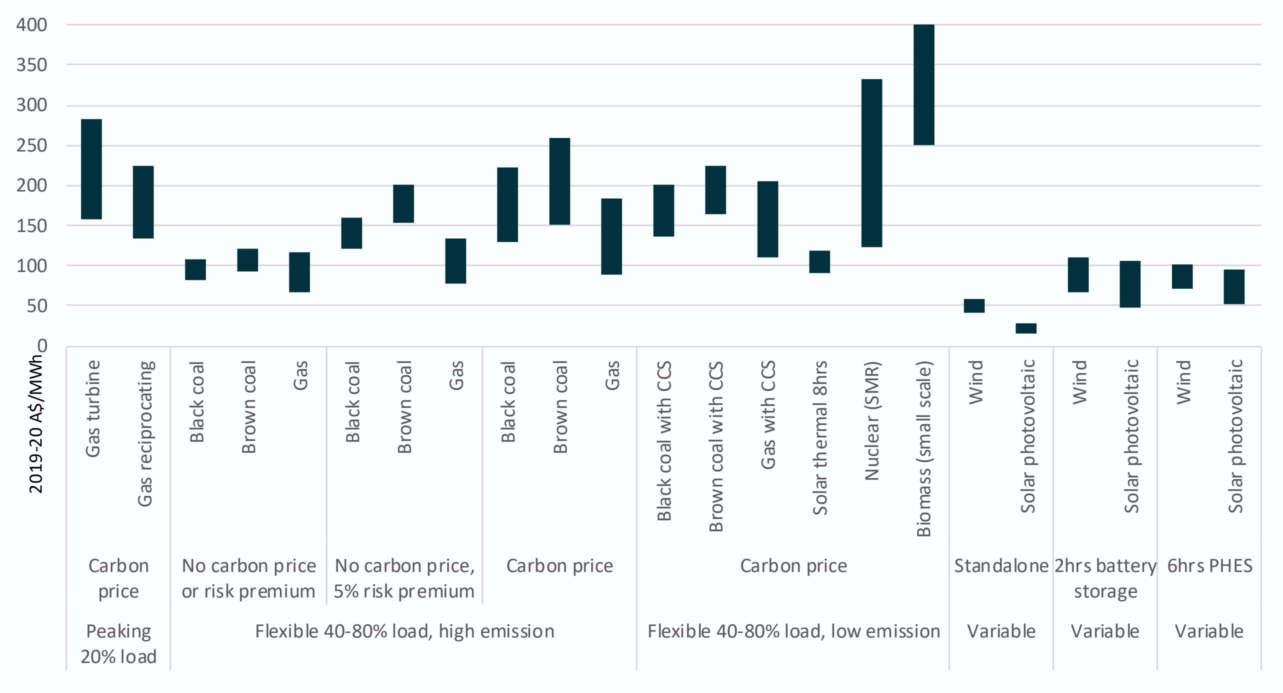


Figure 4-4 Calculated LCOE by technology and category for 2050

Appendix A Capital cost projection with GALLM

A.1 GALLM

The Global and Local Learning Models (GALLMs) for electricity (GALLME) and transport (GALLMT) are described briefly here. More detail can be found in several existing publications (Hayward & Graham, 2017) (Hayward & Graham, 2013) (Hayward, Foster, Graham, & Reedman, 2017).

A.1.1 Endogenous technology learning

Technology cost reductions due to 'learning-by-doing' were first observed in the 1930s for aeroplane construction (Wright, 1936) and have since been observed and measured for a wide range of technologies and processes (McDonald & Schrattenholzer, 2001). Cost reductions due to this phenomenon are normally shown via the equation:

$$IC = IC_0 \times \left(\frac{CC}{CC_0}\right)^{-b},$$

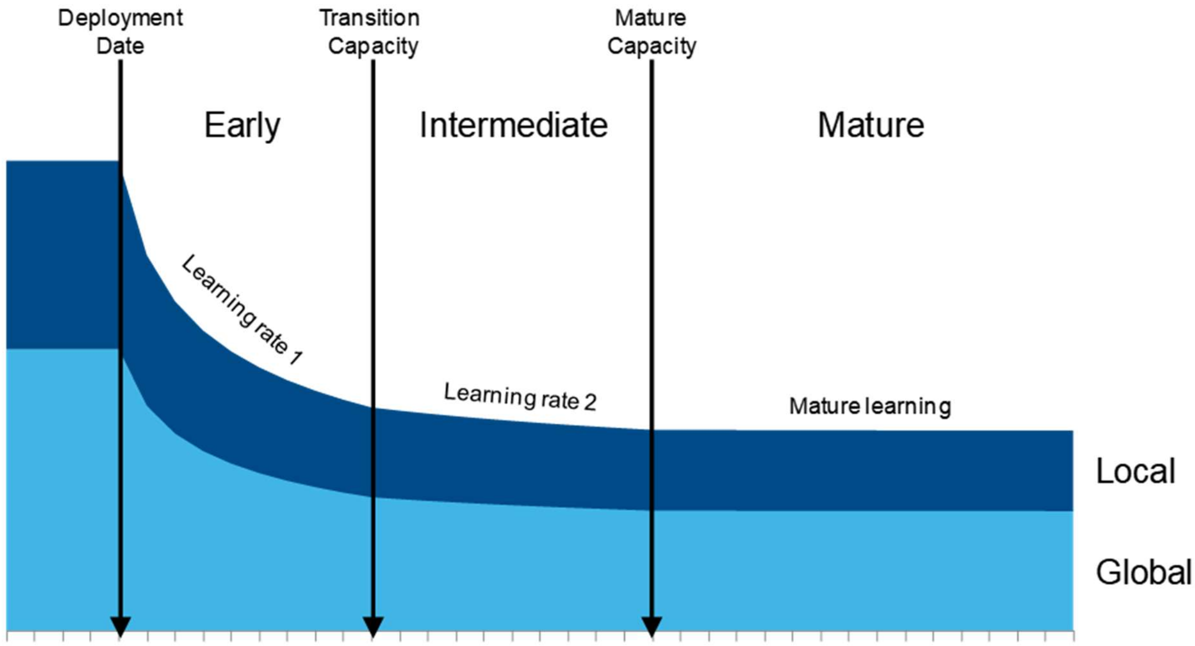
or equivalently $$\log(IC) = \log(IC_0) - b(\log(CC) - \log(CC_0))$$

where IC is the unit investment cost at CC cumulative capacity and IC_0 is the cost of the first unit at CC_0 cumulative capacity. The learning index b satisfies $0 < b < 1$ and it determines the learning rate which is calculated as:

$$LR = 100 \times (1 - 2^{-b})$$

(typically quoted as a percentage ranging from 0 to 50%) and the progress ratio is given by PR=100-LR. All three quantities express a measure of the decline in unit cost with learning or experience. This relationship says that for each doubling in cumulative capacity of a technology, its investment cost will fall by the learning rate (Hayward & Graham, 2013). Learning rates can be measured by examining the change in unit cost with cumulative capacity of a technology over time.

Typically, emerging technologies have a higher learning rate (20–15%), which reduces once the technology has at least a 5% market share and is considered to be at the intermediate stage (to approximately 10%). Once a technology is considered mature, the learning rate tends to be 0–5%. The transition between learning rates based on technology uptake is illustrated in Apx Figure A.1.



Apx Figure A.1 Schematic of changes in the learning rate as a technology progresses through its development stages after commercialisation

However, technologies that do not have a standard unit size and can be used in a variety of applications tend to have a higher learning rate for longer (Wilson, 2012). This is the case for solar photovoltaics and historically for gas turbines.

Technologies are made up of components and different components can be at different levels of maturity and thus have different learning rates. Different parts of a technology can be developed and sold in different markets (global vs. regional/local) which can impact on the cost reductions as each region will have a different level of demand for a technology and this will affect its uptake.

A.1.2 The modelling framework

In order to project the future cost of a technology using experience curves, the future level of cumulative capacity/uptake needs to be known. However, this is dependent on the costs. The GALLMs solve this problem by simultaneously projecting both the cost and uptake of the technologies. The optimisation problem includes constraints such as government policies, demand for electricity or transport, capacity of existing technologies, exogenous costs such as for fossil fuels and limits on resources (e.g. rooftops for solar photovoltaics). The models have been divided into 13 regions and each region has unique assumptions and data for the above listed constraints. The regions have been based on Organisation for Economic Co-operation Development (OECD) regions (with some variation to look more closely at some countries of interest) and are: Africa, Australia, China, Eastern Europe, Western Europe, Former Soviet Union, India, Japan, Latin America, Middle East, North America, OECD Pacific, Rest of Asia and Pacific.

The objective function of the model is to minimise the total system costs while meeting demand and all constraints. The model is solved as a mixed integer linear program. The experience curves are segmented into step functions and the location on the experience curves (i.e. cost vs.

cumulative capacity) is determined at each time step. See (Hayward & Graham, 2013) and (Hayward, Foster, Graham, & Reedman, 2017) for more information. Both models run from the year 2006 to 2100. However, results are only reported from the present day to 2050.

A.1.3 Technologies and learning rates

GALLME projects the future cost and installed capacity of 31 different electricity generation and energy storage technologies. Where appropriate, these have been split into their components and there are 48 different components. Components have been shared between technologies; for example there are two carbon capture and storage (CCS) components – CCS technology and CCS construction – which are shared among all CCS plant technologies. The technologies are listed in Apx Table A.1 showing the relationship between generation technologies and their components and the assumed learning rates under the central scenario (learning is on a global (G) basis, local (L) to the region, or no learning (-) is associated).

Apx Table A.1 Assumed technology learning rates under the Central and High VRE scenarios

Technology	Component	LR 1 (%)	LR 2 (%)	References
Coal, pf	-	-	-	
Coal, IGCC	G	-	2	(International Energy Agency, 2008; Neij, 2008)
Coal/Gas/Biomass with CCS	G	10	5	(EPRI Palo Alto CA & Commonwealth of Australia, 2010; Rubin et al., 2007)
	L	20	10	As above + (Grübler et al., 1999; Hayward & Graham, 2013; Schrattenholzer & McDonald, 2001)
Gas peaking plant	-	-	-	
Gas combined cycle	-	-	-	
Nuclear	G	-	3	(International Energy Agency, 2008)
SMR	G	20	10	(Grübler et al., 1999; Hayward & Graham, 2013; Schrattenholzer & McDonald, 2001)
Diesel/oil-based generation	-	-	-	
Reciprocating engines	-	-	-	
Hydro	-	-	-	
Biomass	G	-	5	(International Energy Agency, 2008; Neij, 2008)
Concentrating solar thermal	G	14.6	7	(Hayward & Graham, 2013)
Photovoltaics	G	20 then 35	10	(Fraunhofer ISE, 2015; Hayward & Graham, 2013; Wilson, 2012)

	L	-	17.5	As above
Onshore wind	G	-	4.3	(Hayward & Graham, 2013)
	L	-	11.3	As above
Offshore wind	G	-	3	(Samadi, 2018) (van der Zwaan, Rivera-Tinoco, Lensink, & van den Oosterkamp, 2012) (Voormolen, Junginger, Sark, & M, 2016)
Wave	G	-	9	(Hayward & Graham, 2013)
CHP	-	-	-	
Conventional geothermal	G	-	8	(Hayward & Graham, 2013)
	L	20	20	(Grübler et al., 1999; Hayward & Graham, 2013; Schrattenholzer & McDonald, 2001)
Fuel cells	G	-	20	(Neij, 2008; Schoots, Kramer, & van der Zwaan, 2010)
Utility scale energy storage – Li-ion	G	-	15	(Brinsmead, Graham, Hayward, Ratnam, & Reedman, 2015)
	L	-	7.5	
Utility scale energy storage – flow batteries	G	-	15	(Brinsmead et al., 2015)
	L	-	7.5	
Pumped hydro	G	-		
	L	-	20	(Grübler et al., 1999; Schrattenholzer & McDonald, 2001)

Pf=pulverised fuel, IGCC=integrated gasification combined cycle, CHP=combined heat and power, SMR=small modular reactor
Solar photovoltaics is listed as one technology with global and local components in Apx Table A.1 however there are three separate PV plant technologies in GALLME:
Rooftop PV includes solar photovoltaic modules and the local learning component is the balance of plant (BOP).
Large scale PV also include modules and BOP. However, a discount of 25% is given to the BOP to take into account economies of scale in building a large scale versus rooftop PV plant.
PV with storage has all of the components including batteries.
Inverters are not given a learning rate instead they are given a constant cost reduction, which is based on historical data.
Li-ion batteries are a component that is used in both PV with storage and utility scale Li-ion battery energy storage.
Geothermal BOP includes the power generation and is a component shared among both types of geothermal plant in Apx Table A.1. Installation BOP is a component of utility scale battery storage that is shared between both types of utility scale battery storage.
Shared technology components mean that when one of the technologies that uses that component is installed, the costs decrease not just for that technology but for all technologies that use that component.

The LR for PV BOP and li-ion batteries was adjusted for the Diverse technology scenario. Instead of continuing with a LR of 17.5% indefinitely, it was reduced to 10% for both technologies.

We have changed the technologies included in GALLME since the 2018 GenCost report. Given there no longer appear to be any developments in Enhanced Geothermal Systems (EGS), which experienced technical difficulties and high costs, we have decided to remove this technology. Conventional geothermal is still included as there are geothermal plants operating globally.

Offshore wind is a new technology in GALLME. Offshore wind has been included as a separate technology as it has been installed globally for several years and has quite distinct costs and capacity factors from onshore wind. It has its own learning rate of 3%, based on findings in the literature (Samadi, 2018) (Voormolen, Junginger, Sark, & M, 2016) (van der Zwaan, Rivera-Tinoco, Lensink, & van den Oosterkamp, 2012). While this limits the potential for capital cost reductions, offshore wind farms have seen significant increases in capacity factor as larger turbines are used, which reduce the LCOE (IRENA, 2019). We have included an exogenous increase up to the year 2050 of 6% in lower resource regions, and 7% in higher resource regions, up to a maximum of 55%, in capacity factor.

Two types of reciprocating engines have now been included in GALLME. The first type uses diesel as a fuel and the second, more expensive type uses hydrogen as fuel. They are considered to be mature technologies and therefore do not have a learning rate. They can be used as peaking plant or as 'baseload' plant in the model.

A.1.4 Mature technologies and the "basket of costs"

There are three main drivers of mature technology costs: imported materials and equipment, domestic materials and equipment, and labour. The indices of these drivers over the last 20 years (ABS data) combined with the split in capital cost of mature technologies between imported equipment, domestic equipment and labour (Bureau of Resource and Energy Economics (BREE), 2012) was used to calculate an average rate of change in technology costs: - 0.01%. This value has been applied as an annual capital cost reduction factor to mature technologies and to operating and maintenance costs.

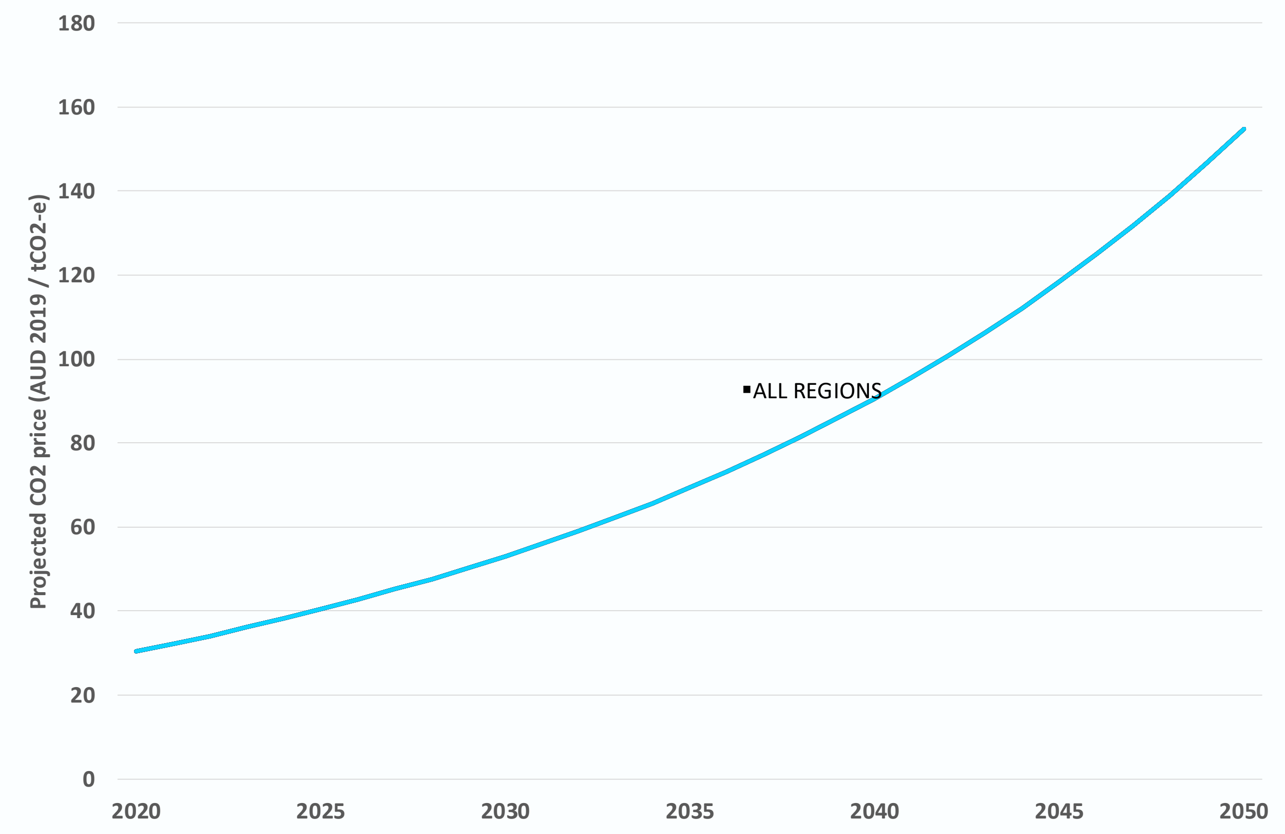
A.2 GALLME assumptions

A.2.1 Government policies

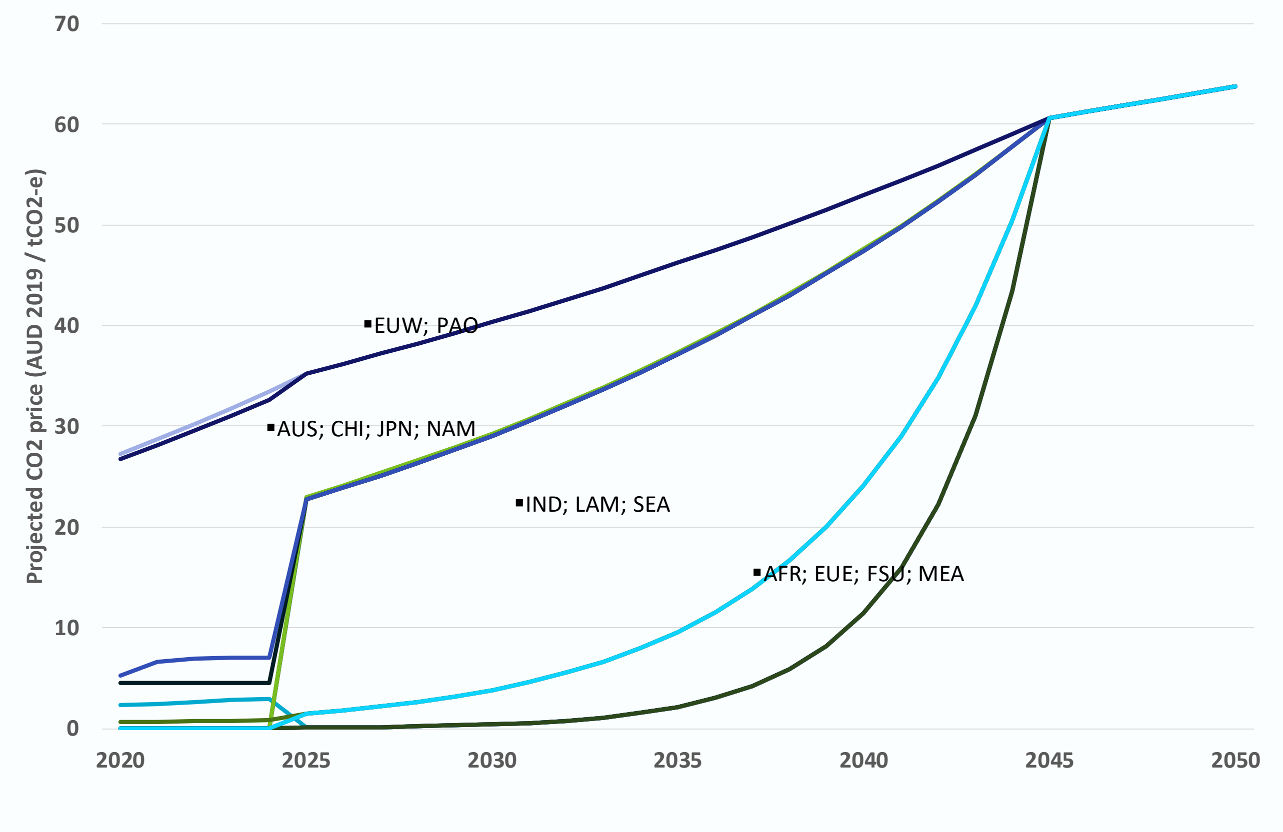
GALLME contains government policies which act as incentives for technologies to reduce costs or limits their uptake. The key assumption about government policy that has an impact on results is a carbon price. The carbon prices are based on those of Clarke et al. (2014).

The carbon price trajectory under the High VRE and Diverse technology scenario has been designed to produce CO_2 emissions from electricity generation at the same level as those of the IEA Sustainable Development Scenario (SDS). This limits the increase in global temperatures to 1.8°C (IEA, 2018). It is a modification of the 2-degrees scenario carbon price trajectory used in GenCost 2018 where, in order to match the emissions from the SDS scenario, the carbon price trajectory has been increased 1.7 times after the year 2025. This carbon price trajectory is higher than what the IEA use in their modelling, however, the IEA have greater regional and country granularity and are better able to include individual country emissions reduction policies, which is not possible in GALLME due to our regional aggregation. This means the IEA model reduces emissions through a greater variety of levers and not just a high carbon price. We do include some of these regional policies, such as renewable energy targets and mandated construction of particular renewable technologies in countries like China.

The Central scenario uses the 4-degrees carbon price trajectory from GenCost 2018. The High VRE and Diverse technology carbon price trajectories are shown in and the Central scenario carbon price trajectory is shown in are designed and are shown in Apx Figure A.2and Apx Figure A.3 respectively.



Apx Figure A.2 Projected carbon price trajectory under the High VRE and Diverse technology scenarios



Apx Figure A.3 Projected carbon price trajectory under the Central scenario

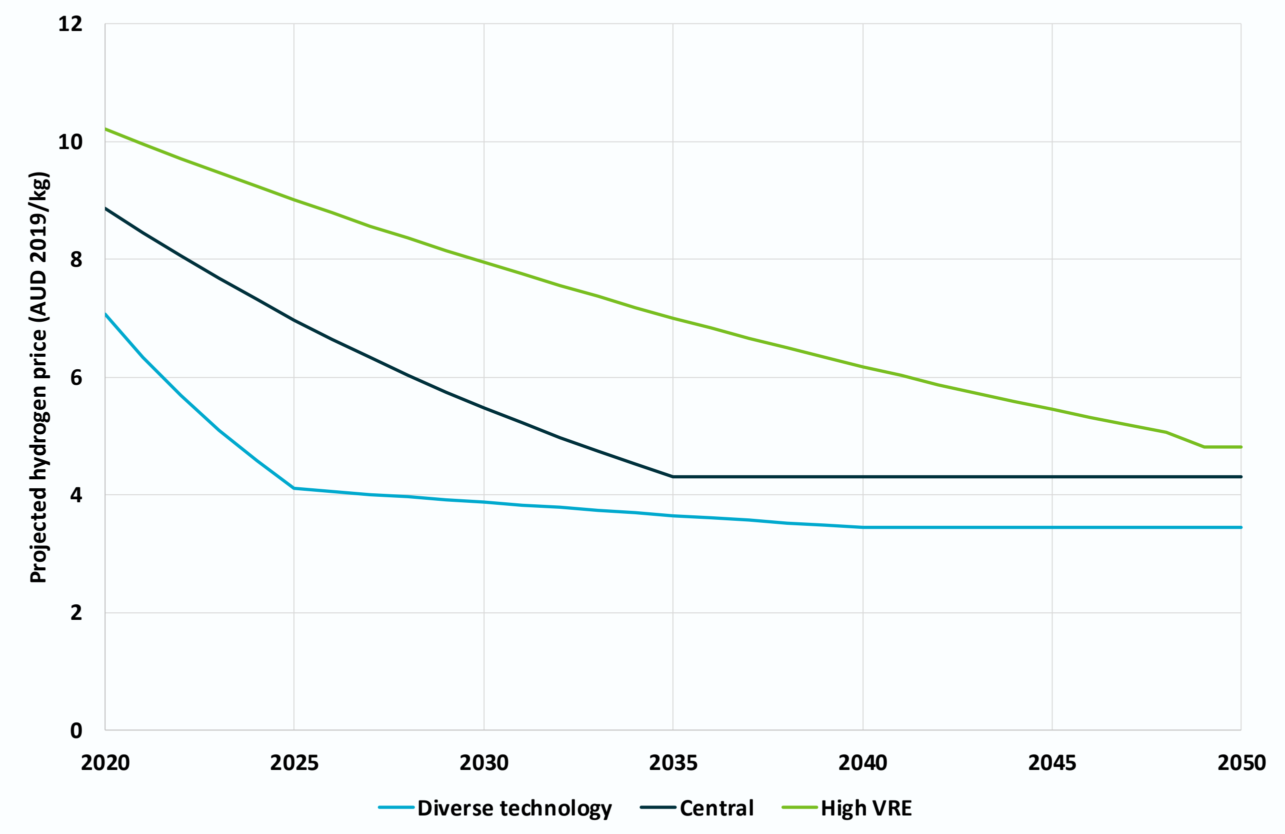
A.2.2 Resource constraints

Constraints around the availability of suitable sites for renewable energy farms, available rooftop space for rooftop PV and sites for storage of CO_2 generated from using CCS have been included in GALLME as a constraint on the amount of electricity that can be generated from these technologies (Government of India, 2016) (Edmonds, et al., 2013). See (Hayward & Graham, 2017) for more information. In the High VRE scenario the resource constraint on renewables was removed. In the Diverse technology scenario variable renewables were limited to 50% of generation below the year 2060, however, this did not limit all renewables i.e. all forms of biomass-fuelled and hydrogen-fuelled generation, hydro and geothermal.

A.2.3 Exogenous data assumptions

GALLME obtains demand for electricity and international fossil fuel prices from (IEA, 2018). However, in the High VRE scenario demand for electricity was sourced from (Brinsmead, et al., 2019). Australian fossil fuel prices are from GHD (2018). Power plant technology operating and maintenance (O&M) costs, plant efficiencies and fossil fuel emission factors were obtained from (IEA, 2016) (IEA, 2015), capacity factors from (IRENA, 2015) (IEA, 2015) (CO2CRC, 2015) and historical technology installed capacities from (IEA , 2008) (Gas Turbine World, 2009) (Gas Turbine World, 2010) (Gas Turbine World, 2011) (Gas Turbine World, 2012) (Gas Turbine World, 2013) (UN, 2015) (UN, 2015) (US Energy Information Administration, 2017) (US Energy Information Administration, 2017) (GWEC) (IEA) (IEA, 2016) (World Nuclear Association, 2017) (Schmidt, Hawkes, Gambhir, & Staffell, 2017) (Cavanagh, et al., 2015).

Hydrogen price trajectories vary between the scenarios as shown in Apx Figure A.4**Error! Reference source not found.**. The prices are based on the variability in the base and best cases calculated for the CSIRO National Hydrogen Roadmap and include hydrogen production and liquefaction (Bruce, et al., 2018).

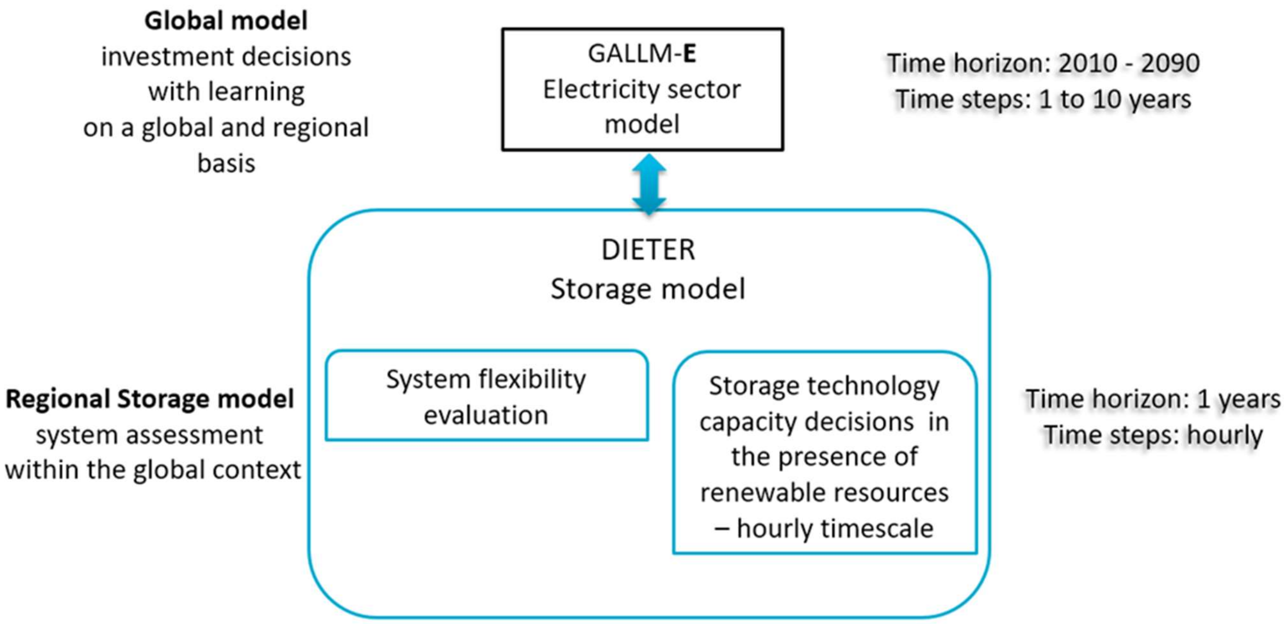


Apx Figure A.4 Projected hydrogen price trajectories by scenario

A.2.4 Variable Renewables and Energy Storage

The Dispatch and Investment Evaluation Tool with Endogenous Renewables (DIETER) is an open source model which has been designed to model the cost of electricity generation systems with high shares of variable renewables (PV, onshore and offshore wind and ocean renewables) and energy storage (http://www.diw.de/dieter). DIETER contains hourly renewable resource and load data for one calendar year, and because of this granularity, it is better able to optimise variable renewable and storage combinations than GALLME in any one year.

DIETER has been used in this study to determine the new capacity of variable renewables and storage technologies in the years that DIETER is solved and this data has then been included back in GALLME to update the cumulative capacity and thus the capital cost of these technologies. A schematic of the interaction between GALLME and DIETER is shown in Apx Figure A.5.



Apx Figure A.5 Schematic diagram of GALLM and DIETER modelling framework

The model interactions are as follows:

1. GALLME is solved without DIETER to calculate cost and uptake of all technologies
2. GALLME cost data, installed capacity of non-variable renewable technologies and upper and lower bounds on demand for electricity satisfied by variable renewables are used as inputs into DIETER
3. DIETER is solved for each region in 5-yearly intervals, beginning in 2025.
4. The new installed capacity of variable renewables and storage is included in GALLME and GALLME is solved.

Appendix B Data tables

The following tables provide data behind some of the figures presented in this document.

Apx Table B.1 Current and projected generation technology capital costs under the Central scenario

	Black coal	Black coal with CCS	Brown coal	Brown coal with CCS	Gas combined cycle	Gas peak	Gas with CCS	Gas reciprocating	Hydrogen reciprocating	Biomass (small scale)	Biomass with CCS (large scale)	Large scale solar PV	Rooftop solar panels	Solar thermal (8 hrs)	Wind	Offshore wind	Wave	Nuclear (SMR)	Tidal/ocean current	Fuel cell	Battery storage (2 hrs)	Battery storage BOP	Integrated solar and battery (2 hrs)	PHES (6 hr)
	$/kW	$/kW	$/kW	$/kW	$/kW	$/kW	$/kW	$/kW	$/kW	$/kW	$/kW	$/kW	$/kW	$/kW	$/kW	$/kW	$/kW	$/kW	$/kW	$/kW	$/kWh	$/kWh	$/kW	$/kW
2019	3314	6116	5115	9387	1696	1277	4251	1282	1526	12834	12109	1463	1352	6670	1908	6070	9280	16304	6745	2784	252	660	3003	1221
2020	3308	6109	5106	9375	1696	1277	4249	1281	1524	12834	12094	1284	1193	6572	1895	6088	9280	16304	6745	2782	227	613	2667	1219
2021	3303	6102	5098	9364	1693	1275	4246	1279	1521	12826	12079	1227	1139	6572	1881	6067	9280	16304	5854	2780	220	593	2537	1218
2022	3298	6095	5090	9352	1690	1273	4244	1277	1519	12815	12064	1125	1049	6572	1872	6011	9280	16304	5854	2778	216	581	2362	1216
2023	3293	6088	5082	9341	1688	1271	4241	1275	1516	12815	12049	1096	1022	6572	1869	5966	9280	16304	5854	2777	214	572	2289	1214
2024	3287	6081	5074	9329	1685	1269	4238	1273	1514	12815	12035	1071	998	6572	1866	5918	9280	16304	5854	2775	210	563	2223	1213
2025	3282	6074	5066	9318	1682	1267	4236	1271	1511	12815	12020	943	886	6572	1863	5872	9280	16304	5854	2775	153	473	1895	1211
2026	3277	6067	5058	9306	1680	1265	4233	1269	1509	12815	12005	909	854	6572	1856	5872	9280	16304	5854	2774	119	421	1746	1209
2027	3272	6060	5049	9294	1677	1263	4231	1267	1507	12815	11990	885	831	6536	1850	5850	9280	16304	5485	2773	97	389	1644	1208
2028	3266	6053	5041	9283	1674	1261	4228	1265	1504	12815	11975	864	811	6455	1818	5758	9280	16304	5485	2773	83	367	1563	1206
2029	3261	6046	5033	9272	1672	1259	4226	1263	1502	12815	11960	837	786	6187	1815	5675	9280	16304	5485	2773	74	354	1492	1204
2030	3256	6039	5025	9260	1669	1257	4223	1261	1499	12815	11946	810	761	5937	1813	5642	9280	16304	5485	2458	54	322	1392	1203
2031	3251	6033	5017	9249	1666	1255	4221	1259	1497	12813	11931	785	738	5813	1810	5604	9280	16304	5485	2448	53	321	1345	1201
2032	3245	6026	5009	9237	1664	1253	4218	1257	1495	12813	11916	773	726	5772	1785	5604	9280	16304	5485	2439	53	319	1325	1200
2033	3240	6019	5001	9226	1661	1251	4216	1255	1492	12813	11901	761	713	5725	1781	5604	9280	16304	5485	2428	52	318	1304	1198
2034	3235	6012	4993	9215	1658	1249	4213	1253	1490	12813	11887	746	698	5665	1759	5604	9280	16304	5484	2419	52	317	1281	1196
2035	3230	6005	4985	9203	1656	1247	4211	1251	1487	12813	11872	722	676	5558	1755	5604	9280	16304	5484	2409	52	315	1246	1195
2036	3225	5998	4977	9192	1653	1245	4208	1249	1485	12813	11857	707	662	5341	1733	5604	9280	16304	5460	2399	51	314	1223	1193
2037	3220	5992	4969	9181	1650	1243	4206	1247	1483	12813	11843	703	658	5191	1730	5604	9280	16304	5460	2388	51	313	1215	1191
2038	3214	5985	4961	9169	1648	1241	4203	1245	1480	12813	11828	687	643	5082	1719	5604	9280	16304	5460	2378	51	312	1191	1190
2039	3209	5978	4953	9158	1645	1239	4201	1243	1478	12813	11814	680	636	4999	1717	5604	9280	16304	5460	2368	50	311	1180	1188
2040	3204	5971	4945	9147	1642	1237	4198	1241	1476	12813	11799	654	613	4933	1710	5583	9280	16304	5359	2359	50	309	1144	1186
2041	3199	5964	4937	9135	1640	1235	4196	1239	1473	12813	11785	649	608	4880	1703	5581	9280	16304	5359	2355	50	309	1136	1185
2042	3194	5732	4930	8849	1637	1233	3849	1237	1471	12813	11415	638	597	4837	1697	5563	9280	16304	5359	2351	50	308	1118	1183
2043	3189	5724	4922	8836	1635	1231	3845	1235	1469	12813	11398	621	582	4801	1695	5560	9280	16304	5291	2347	50	307	1095	1182
2044	3184	5717	4914	8824	1632	1229	3842	1233	1466	12813	11383	604	567	4770	1693	5498	9280	16304	5273	2343	49	307	1071	1180
2045	3179	5529	4906	8593	1629	1227	3564	1231	1464	12813	11084	588	552	4743	1691	5466	9280	16304	5273	2340	49	306	1047	1178
2046	3173	5476	4898	8525	1627	1225	3491	1229	1461	12813	10997	573	539	4705	1683	5420	9280	16304	5008	2337	49	306	1026	1177
2047	3168	5419	4890	8452	1624	1223	3412	1227	1459	12813	10904	560	527	4623	1680	5377	9280	16304	5005	2318	49	305	1007	1175
2048	3163	5403	4882	8429	1622	1221	3394	1225	1457	12813	10873	554	521	4550	1676	5322	6367	16304	5005	2280	49	304	998	1174
2049	3158	5388	4875	8409	1619	1219	3380	1223	1454	12813	10847	547	514	4486	1673	5279	5418	16304	5005	2239	49	303	987	1172
2050	3153	5364	4867	8376	1616	1217	3352	1221	1452	12813	10805	543	510	4429	1660	5220	5074	16304	4773	2204	49	303	981	1170

Apx Table B.2 Current and projected generation technology capital costs under the High VRE scenario

	Black coal	Black coal with CCS	Brown coal	Brown coal with CCS	Gas combined cycle	Gas turbine	Gas with CCS	Gas reciprocating	Hydrogen reciprocating	Biomass (small scale)	Biomass with CCS (large scale)	Large scale solar PV	Rooftop solar panels	Solar thermal (8 hrs)	Wind	Offshore wind	Wave	Nuclear (SMR)	Tidal/ocean current	Fuel cell	Battery storage (2 hrs)	Battery storage BOP	Integrated solar and battery (2 hrs)	PHES (6 hr)
	$/kW	$/kW	$/kW	$/kW	$/kW	$/kW	$/kW	$/kW	$/kW	$/kW	$/kW	$/kW	$/kW	$/kW	$/kW	$/kW	$/kW	$/kW	$/kW	$/kW	$/kWh	$/kWh	$/kW	$/kW
2019	3314	6116	5115	9387	1696	1277	4251	1282	1526	12834	12109	1463	1352	6670	1908	6070	9280	16304	6745	2784	252	660	3003	1221
2020	3308	6109	5106	9375	1696	1277	4249	1281	1524	12737	12094	1171	1136	5984	1897	6088	9280	16304	6745	2782	234	635	2569	1219
2021	3303	6102	5098	9364	1693	1275	4246	1279	1521	12728	12079	1116	1083	5984	1888	6067	9280	16304	6557	2780	230	628	2442	1218
2022	3298	6095	5090	9352	1690	1273	4244	1277	1519	12718	12064	1069	1039	5984	1877	5991	9280	16304	6557	2778	209	620	2307	1216
2023	3293	6088	5082	9341	1688	1271	4241	1275	1516	12718	12049	954	933	5984	1867	5944	9280	16304	6557	2777	159	588	2021	1214
2024	3287	6081	5074	9329	1685	1269	4238	1273	1514	12718	12035	878	863	5984	1859	5896	9280	16304	6557	2776	129	551	1808	1213
2025	3282	6074	5066	9318	1682	1267	4236	1271	1511	12718	12020	849	836	5984	1851	5850	9280	16304	6557	2775	108	527	1687	1211
2026	3277	6067	5058	9306	1680	1265	4233	1269	1509	12718	12005	822	811	5984	1845	5736	9280	16304	6557	2775	94	512	1589	1209
2027	3272	5872	5049	9065	1677	1263	3944	1267	1507	12718	11693	800	788	5984	1839	5645	9280	16304	6557	2774	83	501	1511	1208
2028	3266	5752	5041	8916	1674	1261	3770	1265	1504	12718	11501	780	768	5984	1834	5577	9280	16304	6557	2774	76	495	1448	1206
2029	3261	5656	5033	8795	1672	1259	3631	1263	1502	12718	11346	755	743	5984	1827	5500	9280	16304	6557	2773	72	491	1386	1204
2030	3256	5611	5025	8737	1669	1257	3570	1261	1499	12718	11270	740	729	5984	1819	5427	9280	16304	6557	2527	59	478	1317	1203
2031	3251	5553	5017	8663	1666	1255	3490	1259	1497	12718	11175	721	709	5984	1811	5377	9280	16304	6557	2507	58	478	1275	1201
2032	3245	5519	5009	8619	1664	1253	3446	1257	1495	12718	11118	712	700	5969	1804	5341	9280	16304	6557	2490	58	478	1260	1200
2033	3240	5506	5001	8599	1661	1251	3434	1255	1492	12718	11093	705	691	5937	1798	5313	9280	16304	6557	2472	57	477	1246	1198
2034	3235	5495	4993	8584	1658	1249	3426	1253	1490	12716	11073	696	682	5876	1792	5292	9280	16304	6557	2457	57	477	1231	1196
2035	3230	5486	4985	8570	1656	1247	3420	1251	1487	12714	11055	649	638	5704	1758	5274	9280	16304	6557	2440	57	476	1166	1195
2036	3225	5467	4977	8543	1653	1245	3399	1249	1485	12714	11021	642	630	5343	1750	5247	9280	16304	6557	2426	56	476	1154	1193
2037	3220	5460	4969	8532	1650	1243	3396	1247	1483	12703	11006	600	591	5179	1743	5207	9280	16304	6557	2408	56	476	1096	1191
2038	3214	5448	4961	8514	1648	1241	3386	1245	1480	12651	10983	597	588	5060	1737	5173	9280	16304	6557	2395	56	476	1090	1190
2039	3209	5441	4953	8502	1645	1239	3382	1243	1478	12535	10967	563	556	4839	1733	5144	9280	16304	6557	2380	55	475	1043	1188
2040	3204	5428	4945	8483	1642	1237	3370	1241	1476	12457	10943	555	548	4694	1727	5118	9280	16304	6557	2369	55	475	1031	1186
2041	3199	5414	4937	8463	1640	1235	3357	1239	1473	12373	10917	549	542	4592	1713	5096	9280	16304	6557	2363	55	475	1021	1185
2042	3194	5400	4930	8443	1637	1233	3343	1237	1471	12373	10891	542	535	4516	1705	5077	9280	16304	6557	2358	55	475	1010	1183
2043	3189	5392	4922	8431	1635	1231	3339	1235	1469	12373	10875	536	529	4457	1692	5060	9280	16304	6557	2353	55	475	1001	1182
2044	3184	5383	4914	8416	1632	1229	3333	1233	1466	12373	10857	524	517	4411	1684	5045	9280	16304	6021	2349	54	475	983	1180
2045	3179	5375	4906	8404	1629	1227	3330	1231	1464	12373	10842	520	513	4373	1680	5031	9280	16304	6021	2345	54	474	976	1178
2046	3173	5361	4898	8385	1627	1225	3316	1229	1461	12373	10816	509	503	4342	1672	5019	7240	16304	5245	2341	54	474	960	1177
2047	3168	5353	4890	8371	1624	1223	3311	1227	1459	12373	10799	504	498	4316	1668	5007	5520	16304	5245	2336	54	474	952	1175
2048	3163	5344	4882	8357	1622	1221	3305	1225	1457	12373	10781	499	492	4267	1661	4997	5035	16304	5245	2311	54	474	944	1174
2049	3158	5335	4875	8344	1619	1219	3299	1223	1454	12373	10763	494	488	4188	1657	4988	4566	16304	5245	2263	54	474	936	1172
2050	3153	5325	4867	8329	1616	1217	3292	1221	1452	12373	10744	481	475	4119	1650	4980	4146	16304	4859	2224	54	474	917	1170

Apx Table B.3 Current and projected generation technology capital costs under the Diverse technology scenario

	Black coal	Black coal with CCS	Brown coal	Brown coal with CCS	Gas combined cycle	Gas turbine	Gas with CCS	Gas reciprocating	Hydrogen reciprocating	Biomass (small scale)	Biomass with CCS (large scale)	Large scale solar PV	Rooftop solar panels	Solar thermal (8 hrs)	Wind	Offshore wind	Wave	Nuclear (SMR)	Tidal/ocean current	Fuel cell	Battery storage (2 hrs)	Battery storage BOP	Integrated solar and battery (2 hrs)	PHES (6 hr)
	$/kW	$/kW	$/kW	$/kW	$/kW	$/kW	$/kW	$/kW	$/kW	$/kW	$/kW	$/kW	$/kW	$/kW	$/kW	$/kW	$/kW	$/kW	$/kW	$/kW	$/kWh	$/kWh	$/kW	$/kW
2019	3314	6116	5115	9387	1696	1277	4251	1282	1526	12834	12109	1463	1352	6670	1908	6070	9280	16304	6745	2784	252	660	3003	1221
2020	3308	6109	5106	9375	1696	1277	4249	1281	1524	12834	12094	1295	1270	6273	1884	6088	9280	16304	6797	2782	225	613	2750	1219
2021	3303	6102	5098	9364	1693	1275	4246	1279	1521	12826	12079	1231	1208	6250	1870	6067	9280	16304	6137	2780	218	593	2608	1218
2022	3298	6095	5090	9352	1690	1273	4244	1277	1519	12815	12064	1188	1167	6199	1859	6017	9280	16304	6137	2778	214	581	2507	1216
2023	3293	6088	5082	9341	1688	1271	4241	1275	1516	12815	12049	1152	1132	6055	1853	6017	9280	16304	6137	2777	211	572	2418	1214
2024	3287	5863	5074	9063	1685	1269	3906	1273	1514	12815	11691	1131	1110	5869	1847	6017	9280	16304	6137	2776	207	563	2313	1213
2025	3282	5748	5066	8919	1682	1267	3738	1271	1511	12815	11505	1106	1086	5625	1843	6015	9280	16304	6137	2775	155	473	2174	1211
2026	3277	5654	5058	8802	1680	1265	3604	1269	1509	12815	11354	1082	1063	5470	1840	5958	9280	16304	6137	2775	118	421	2051	1209
2027	3272	5585	5049	8715	1677	1263	3507	1267	1507	12815	11242	1068	1048	5372	1837	5958	9280	16304	6137	2774	95	389	1963	1208
2028	3266	5543	5041	8660	1674	1261	3451	1265	1504	12815	11172	1051	1031	5304	1834	5880	9280	16304	6137	2774	81	367	1890	1206
2029	3261	5506	5033	8612	1672	1259	3402	1263	1502	12815	11109	1036	1016	5176	1832	5853	9280	16304	6137	2773	73	354	1836	1204
2030	3256	5487	5025	8585	1669	1257	3381	1261	1499	12811	11075	1021	1000	5048	1829	5705	9280	16304	6137	2527	53	322	1755	1203
2031	3251	5466	5017	8557	1666	1255	3358	1259	1497	12800	11039	1007	986	4948	1826	5607	9280	16304	6137	2507	52	321	1722	1201
2032	3245	5454	5009	8539	1664	1253	3347	1257	1495	12736	11015	1002	980	4868	1824	5559	9280	7624	6137	2490	52	319	1711	1200
2033	3240	5447	5001	8528	1661	1251	3344	1255	1492	12607	11001	995	971	4803	1821	5559	9280	7569	6137	2472	51	318	1697	1198
2034	3235	5440	4993	8516	1658	1249	3341	1253	1490	12467	10985	985	961	4748	1819	5559	9280	7544	6137	2457	51	317	1680	1196
2035	3230	5432	4985	8504	1656	1247	3338	1251	1487	12218	10969	979	954	4702	1814	5559	9280	7526	6137	2440	51	315	1668	1195
2036	3225	5277	4977	8312	1653	1245	3110	1249	1485	12155	10722	968	943	4662	1810	5559	9280	7203	5689	2426	50	314	1649	1193
2037	3220	5269	4969	8299	1650	1243	3105	1247	1483	12155	10705	962	937	4628	1805	5559	9280	7203	5621	2408	50	313	1639	1191
2038	3214	5203	4961	8215	1648	1241	3013	1245	1480	12150	10598	934	910	4599	1801	5559	9280	7146	5617	2395	50	312	1597	1190
2039	3209	5172	4953	8174	1645	1239	2972	1243	1478	12150	10544	930	905	4572	1797	5559	9280	7146	5617	2380	49	311	1588	1188
2040	3204	5163	4945	8161	1642	1237	2968	1241	1476	12144	10527	913	889	4549	1793	5559	9280	7145	5565	2369	49	309	1562	1186
2041	3199	5154	4937	8146	1640	1235	2961	1239	1473	12144	10508	900	876	4529	1781	5559	9280	7145	5565	2363	49	309	1542	1185
2042	3194	5146	4930	8134	1637	1233	2957	1237	1471	12124	10492	888	864	4510	1778	5559	9280	7145	5565	2358	49	308	1523	1183
2043	3189	5139	4922	8122	1635	1231	2954	1235	1469	12124	10477	878	854	4442	1764	5559	9280	7145	5501	2353	49	307	1507	1182
2044	3184	5132	4914	8111	1632	1229	2952	1233	1466	12099	10463	867	844	4380	1758	5529	9280	7145	5484	2349	49	307	1491	1180
2045	3179	5126	4906	8100	1629	1227	2949	1231	1464	12055	10448	858	835	4324	1755	5511	9280	7145	5484	2345	48	306	1476	1178
2046	3173	5119	4898	8089	1627	1225	2947	1229	1461	12055	10434	849	826	4273	1751	5485	9280	7145	5247	2341	48	306	1462	1177
2047	3168	5112	4890	8077	1624	1223	2944	1227	1459	12054	10420	846	823	4227	1745	5453	9280	7145	5247	2336	48	305	1456	1175
2048	3163	5106	4882	8066	1622	1221	2942	1225	1457	12048	10405	842	819	4184	1740	5434	6255	7145	5247	2309	48	304	1450	1174
2049	3158	5099	4875	8055	1619	1219	2939	1223	1454	12033	10391	836	813	4145	1735	5406	5333	7145	5247	2261	48	303	1440	1172
2050	3153	5092	4867	8043	1616	1217	2936	1221	1452	12030	10376	833	810	4109	1732	5381	5035	7145	5212	2222	48	303	1435	1170

Apx Table B.4 Storage cost data by source

Source	Storage type	Unit	Amount
CSIRO 2017	Battery (2hrs)	$/kW	1535
		$/kWh	767
GHD 2018	Battery (1hr)	$/kW	1294
		$/kWh	1294
Aurecon 2019	Battery (1hr)	$/kW	1228
		$/kWh	1228
	Battery (2hrs)	$/kW	1824
		$/kWh	912
	Battery (4hrs)	$/kW	2612
		$/kWh	653
	Battery (8hrs)	$/kW	4592
		$/kWh	574
Entura 2018	PHES (6hrs)	$/kW	1506
		$/kWh	251
	PHES (48hrs)	$/kW	2794
		$/kWh	58

Apx Table B.5 Data assumptions for LCOE calculations

	Constant						**Low assumption**					**High assumption**				
	Economic life	Construction time	Efficiency	O&M fixed	O&M variable	CO_2 storage	Capital	Fuel	Capacity factor	Emission factor	Carbon price	Capital	Fuel	Capacity factor	Emission factor	Carbon price
	Years	Years		$/kW	$/MWh	$/MWh	$/kW	$/GJ		$ktCO_2e$/PJ	$/$tCO_2e$	$/kW	$/GJ		$ktCO_2e$/PJ	$/$tCO_2e$
2020																
Gas with CCS	25	1.8	41%	17.9	12.6	1.9	4249	5.8	80%	6.4	16.9	4249	11.3	60%	19.9	28.7
Gas combined cycle	25	1.3	51%	10.9	3.7	0.0	1696	5.8	80%	52.1	16.9	1696	11.3	60%	65.6	28.7
Gas turbine	25	0.7	36%	12.6	4.1	0.0	1277	5.8	20%	53.1	16.9	1277	11.3	20%	66.6	28.7
Gas reciprocating	25	0.5	50%	4.2	7.6	0.0	1281	5.8	20%	53.5	16.9	1281	11.3	20%	67.0	28.7
Black coal with CCS	25	4.0	30%	77.1	9.5	4.1	6109	2.8	80%	8.5	16.9	6109	4.1	60%	15.4	28.7
Black coal	25	4.0	40%	53.2	4.2	0.0	3308	2.8	80%	88.0	16.9	3308	4.1	60%	88.0	28.7
Brown coal with CCS	25	4.0	21%	101.6	11.6	4.7	9375	0.6	80%	5.8	16.9	9375	0.7	60%	5.8	28.7
Brown coal	25	4.0	32%	69.0	5.3	0.0	5106	0.6	80%	85.0	16.9	5106	0.7	60%	85.0	28.7
Biomass (small scale)	25	2.0	23%	131.6	8.4	0.0	12737	0.5	60%	0.0	16.9	12834	2.0	40%	0.0	28.7
Nuclear (SMR)	60	5.0	45%	200.0	20.0	0.0	16304	0.0	80%	0.0	16.9	16304	0.0	60%	0.0	28.7
Large scale solar PV	30	0.4	100%	17.0	0.0	0.0	1171	0.0	32%	0.0	16.9	1284	0.0	22%	0.0	28.7
Solar thermal (8hrs)	25	1.0	100%	142.5	5.4	0.0	5984	0.0	52%	0.0	16.9	6572	0.0	42%	0.0	28.7
Wind	20	1.0	100%	21.9	2.7	0.0	1897	0.0	44%	0.0	16.9	1895	0.0	35%	0.0	28.7
2030																
Gas with CCS	25	1.8	41%	17.9	12.6	1.9	3381	5.8	80%	6.4	27.5	4223	11.8	60%	19.9	50.1
Gas combined cycle	25	1.3	51%	10.9	3.7	0.0	1669	5.8	80%	52.1	27.5	1669	11.8	60%	65.6	50.1
Gas turbine	25	0.7	36%	12.6	4.1	0.0	1257	5.8	20%	53.1	27.5	1257	11.8	20%	66.6	50.1
Gas reciprocating	25	0.5	50%	4.2	7.6	0.0	1261	5.8	20%	53.5	27.5	1261	11.8	20%	67.0	50.1
Black coal with CCS	25	4.0	30%	77.1	9.5	4.1	5487	2.9	80%	8.5	27.5	6039	3.8	60%	15.4	50.1
Black coal	25	4.0	40%	53.2	4.2	0.0	3256	2.9	80%	88.0	27.5	3256	3.8	60%	88.0	50.1
Brown coal with CCS	25	4.0	21%	101.6	11.6	4.7	8585	0.7	80%	5.8	27.5	9260	0.7	60%	5.8	50.1
Brown coal	25	4.0	32%	69.0	5.3	0.0	5025	0.7	80%	85.0	27.5	5025	0.7	60%	85.0	50.1
Biomass (small scale)	25	2.0	23%	131.6	8.4	0.0	12718	0.5	60%	0.0	27.5	12815	2.0	40%	0.0	50.1
Nuclear (SMR)	60	5.0	45%	200.0	20.0	0.0	16304	0.0	80%	0.0	27.5	16304	0.0	60%	0.0	50.1
Large scale solar PV	30	0.4	100%	17.0	0.0	0.0	740	0.0	32%	0.0	27.5	810	0.0	19%	0.0	50.1
Solar thermal (8hrs)	25	1.0	100%	142.5	5.4	0.0	5984	0.0	52%	0.0	27.5	5937	0.0	42%	0.0	50.1
Wind	20	1.0	100%	21.9	2.7	0.0	1819	0.0	46%	0.0	27.5	1813	0.0	35%	0.0	50.1

2040																
Gas with CCS	25	1.8	41%	17.9	12.6	1.9	2968	5.8	80%	6.4	44.9	4198	11.8	60%	19.9	85.7
Gas combined cycle	25	1.3	51%	10.9	3.7	0.0	1642	5.8	80%	52.1	44.9	1642	11.8	60%	65.6	85.7
Gas turbine	25	0.7	36%	12.6	4.1	0.0	1237	5.8	20%	53.1	44.9	1237	11.8	20%	66.6	85.7
Gas reciprocating	25	0.5	50%	4.2	7.6	0.0	1241	5.8	20%	53.5	44.9	1241	11.8	20%	67.0	85.7
Black coal with CCS	25	4.0	30%	77.1	9.5	4.1	5163	2.9	80%	8.5	44.9	5971	3.8	60%	15.4	85.7
Black coal	25	4.0	40%	53.2	4.2	0.0	3204	2.9	80%	88.0	44.9	3204	3.8	60%	88.0	85.7
Brown coal with CCS	25	4.0	21%	101.6	11.6	4.7	8161	0.7	80%	5.8	44.9	9147	0.7	60%	5.8	85.7
Brown coal	25	4.0	32%	69.0	5.3	0.0	4945	0.7	80%	85.0	44.9	4945	0.7	60%	85.0	85.7
Biomass (small scale)	25	2.0	23%	131.6	8.4	0.0	12457	0.5	60%	0.0	44.9	12813	2.0	40%	0.0	85.7
Nuclear (SMR)	60	5.0	45%	200.0	20.0	0.0	7145	0.0	80%	0.0	44.9	16304	0.0	60%	0.0	85.7
Large scale solar PV	30	0.4	100%	17.0	0.0	0.0	555	0.0	32%	0.0	44.9	654	0.0	19%	0.0	85.7
Solar thermal (8hrs)	25	1.0	100%	142.5	5.4	0.0	4694	0.0	52%	0.0	44.9	4933	0.0	42%	0.0	85.7
Wind	20	1.0	100%	21.9	2.7	0.0	1727	0.0	48%	0.0	44.9	1710	0.0	35%	0.0	85.7
2050																
Gas with CCS	25	1.8	41%	17.9	12.6	1.9	2936	5.8	80%	6.4	60.3	3352	11.8	60%	19.9	146.3
Gas combined cycle	25	1.3	51%	10.9	3.7	0.0	1616	5.8	80%	52.1	60.3	1616	11.8	60%	65.6	146.3
Gas turbine	25	0.7	36%	12.6	4.1	0.0	1217	5.8	20%	53.1	60.3	1217	11.8	20%	66.6	146.3
Gas reciprocating	25	0.5	50%	4.2	7.6	0.0	1221	5.8	20%	53.5	60.3	1221	11.8	20%	67.0	146.3
Black coal with CCS	25	4.0	30%	77.1	9.5	4.1	5092	2.9	80%	8.5	60.3	5364	3.8	60%	15.4	146.3
Black coal	25	4.0	40%	53.2	4.2	0.0	3153	2.9	80%	88.0	60.3	3153	3.8	60%	88.0	146.3
Brown coal with CCS	25	4.0	21%	101.6	11.6	4.7	8043	0.7	80%	5.8	60.3	8376	0.7	60%	5.8	146.3
Brown coal	25	4.0	32%	69.0	5.3	0.0	4867	0.7	80%	85.0	60.3	4867	0.7	60%	85.0	146.3
Biomass (small scale)	25	2.0	23%	131.6	8.4	0.0	12373	0.5	60%	0.0	60.3	12813	2.0	40%	0.0	146.3
Nuclear (SMR)	60	5.0	45%	200.0	20.0	0.0	7145	0.0	80%	0.0	60.3	16304	0.0	60%	0.0	146.3
Large scale solar PV	30	0.4	100%	17.0	0.0	0.0	481	0.0	32%	0.0	60.3	543	0.0	19%	0.0	146.3
Solar thermal (8hrs)	25	1.0	100%	142.5	5.4	0.0	4119	0.0	52%	0.0	60.3	4429	0.0	42%	0.0	146.3
Wind	20	1.0	100%	21.9	2.7	0.0	1650	0.0	50%	0.0	60.3	1660	0.0	35%	0.0	146.3

Notes: Wind is onshore. Large-scale solar PV is single axis tracking. Emission factors include fugitive emissions associated with the fuel. The low emission factor is from the lowest state average and the high from the highest emission state.

Apx Table B.6 Electricity generation technology LCOE projections data, 2019-20 $/MWh

Category	Assumption	Technology	2020		2030		2040		2050	
			Low	High	Low	High	Low	High	Low	High
Peaking 20% load	Carbon price	Gas turbine	137	203	142	221	150	244	157	284
		Gas reciprocating	120	167	123	180	129	196	134	224
Flexible 40-80% load, high emission	No carbon price or risk premium	Black coal	83	112	83	109	82	107	82	107
		Brown coal	95	123	94	122	94	121	94	121
		Gas	67	114	67	117	67	117	67	117
	No carbon price, 5% risk premium	Black coal	125	168	124	164	122	162	121	160
		Brown coal	160	209	158	206	156	204	154	201
		Gas	81	132	80	135	79	134	79	133
	Carbon price	Black coal	96	135	104	148	117	175	129	222
		Brown coal	111	151	121	170	137	203	150	260
		Gas	73	127	77	141	83	157	88	184
Flexible 40-80% load, low emission	Carbon price	Black coal with CCS	148	200	140	199	136	204	137	202
		Brown coal with CCS	181	233	170	233	166	235	165	225
		Gas with CCS	125	197	114	205	109	211	109	206
		Solar thermal 8hrs	129	173	129	157	103	132	91	119
		Nuclear (SMR)	254	333	254	333	124	333	124	333
		Biomass (small scale)	256	402	256	402	251	402	250	402
Variable	Standalone	Wind	53	66	49	63	45	60	41	58
		Solar photovoltaic	35	56	22	41	17	33	15	28
Variable	2hrs battery storage	Wind	109	144	78	119	72	114	67	109
		Solar photovoltaic	98	160	57	126	50	117	47	106
Variable	6hrs PHES	Wind	88	112	82	108	76	104	71	102
		Solar photovoltaic	75	118	61	112	55	102	52	95

Shortened forms

Abbreviation	Meaning
ABS	Australian Bureau of Statistics
AEMC	Australian Energy Market Commission
AEMO	Australian Energy Market Operator
APGT	Australian Power Generation Technology report
BOP	Balance of plant
BREE	Bureau of Resource and Energy Economics
CCS	Carbon capture and storage
CHP	Combined heat and power
CO_2	Carbon dioxide
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CSP	Concentrated solar power
DIETER	Dispatch and investment evaluation tool with endogenous renewables
EPRI	Electric Power Research Institute
GALLME	Global and Local Learning Model Electricity
GALLMs	Global and Local Learning Models
GALLMT	Global and Local Learning Model Transport
GWYr	Gigawatt Years
hrs	Hours
IEA	International Energy Agency
IGCC	Integrated gasification combined cycle
kW	Kilowatt

kWh	Kilowatt hour
LCOE	Levelised Cost of Electricity
Li-ion	Lithium-ion
LR	Learning Rate
MW	Megawatt
MWh	Megawatt hour
O&M	Operations and Maintenance
OECD	Organisation for Economic Cooperation and Development
pf	Pulverised fuel
PHES	Pumped hydro energy storage
PV	Photovoltaic
SDS	Sustainable Development Scenario
SMR	Small modular reactor
VRE	Variable Renewable Energy

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