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Electricity generation technology cost projections

2017-2050

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Executive summary

The continuing importance of electricity futures to the nation and the fast rate of change in costs of some technologies, means that regularly updated electricity generation technology cost projections remain an important public resource. CSIRO's approach to cost projections is based on using the most objective and data driven method available which simultaneously projects both global and local deployment of electricity generation technology and the cost reductions achieved due to the well-known learning by doing effect.

In the past, CSIRO has provided standalone projections or contributed to studies led by other organisations at irregular intervals since 2011, with the last being the *Australian Power Generation Technology Report* in 2015. Those projections are significantly out of date and therefore it is appropriate that CSIRO provide this 2017 update to cost projections.

For this 2017 update, we have improved the regional detail of our Global and Local Learning Model for Electricity (GALLM-E) and have constructed a similar model for transport (GALLM-T) to assist in projecting battery storage costs which, while potentially very important for the electricity sector, are being deployed at a faster rate in the transport sector (making this sector the strongest source of learning and thus cost reductions). We have also updated our assumptions on global renewable resources availability for each region and extended the learning rate for selected technologies which have demonstrated an extended period of higher learning.

The updated projections indicate the trend we have seen in the last few years whereby solar photovoltaics, wind and battery storage technologies reduce their costs at a faster rate than most other technologies continues. Compared to previous projections, these substantial cost reductions in renewables have also begun to impact the cost and adoption of other technologies. For example, in our 4-degrees climate ambition scenario we project very low adoption of carbon capture and storage (CCS) and subsequently very little cost reductions in that technology. In effect, the ongoing cost reductions in renewables has crowded out investment in other technologies.

In the 2-degrees climate ambition scenario the renewable energy resource constraints, together with a stronger carbon price signal, do allow for investment in a wider diversity of electricity generation technologies. Significant adoption and cost reductions in CCS are projected. However, they are less than those that we projected for a similar scenario in the 2015 projections. This is because in either climate ambition scenario, the world deploys a greater share of low cost renewables in response to emission constraints compared to other options.

The capital cost projections are primarily designed to be included in Australian electricity modelling studies as scenario inputs. However, we also provide levelised cost of electricity (LCOE) estimates which are useful for providing a quick indication of what the capital cost projections mean for the future cost of electricity. LCOE estimates have been justifiably criticised for an absence of standardised plant performance and financial assumptions and failing to take into account the additional cost of supporting variable generation technologies to be reliable. These two flaws mean that LCOE comparisons within (i.e. between technologies) and across alternative LCOE projection studies can be meaningless.

To address these issues we provide information about our LCOE calculation assumptions and present a preliminary estimate of the cost of supporting variable renewable generation to be reliable as their share of electricity generation increases. This “extended” LCOE estimate, which includes the additional costs of very high renewable shares, indicates that the LCOE of renewables begins to approach that of CCS and nuclear power (i.e. increasing towards $120/MWh at 90% variable renewable share compared to $30-50/MWh under the conventional LCOE calculation). However, given variable renewable electricity generation shares in most Australian states are low, the cost of supporting renewables also remains low and therefore variable renewables are not expected to face a significant low emission competitor for some considerable time.

1 Introduction

CSIRO has been publishing electricity generation technology cost projections since 2011 which coincided with the development of the Global and Local Learning Model for Electricity (GALLM-E) which is a quantitative modelling framework encapsulating CSIRO's projection methodology (Hayward, et al., 2011) (Hayward & Graham, 2012) (Hayward & Graham, 2013). We will discuss the GALLM-E methodology and changes made for this 2017 update in the next section.

Since 2011, CSIRO has applied GALLM-E in coordination with collaborative cost assessment studies including the 2012 and 2013 *Australian Energy Technology Assessment* (Bureau of Resource and Energy Economics (BREE), 2013) (Bureau of Resource and Energy Economics (BREE), 2012) and the 2015 *Australian Power Generation Technology Report* (CO2CRC, 2015). These all included a stakeholder engagement process, mainly focussed on seeking agreement around the current level of a technology's capital costs but sometimes providing advice on other GALLM-E data assumptions. CSIRO added a battery cost forecast to GALLM-E's capabilities which was published in (Brinsmead, et al., 2015).

The continuing importance of energy futures and the fast rate of change in costs of some technologies, means that the 2015 projections are out of date. Therefore, it is appropriate that CSIRO provide this 2017 update to cost projections. While on this occasion no existing stakeholder engagement process was available, we have sought to include updated current cost data and other inputs from available literature or public announcements.

Because GALLM-E has been described in previous publications we will only provide a brief explanation of the model and focus our methodology discussion on changes and improvements that have since been made. Following that, we provide a discussion and comparison of the updated cost projections to previous work. We conclude with a calculation of the levelised costs of electricity (LCOE), including an estimate of the extended LCOE of variable renewable generation technologies when the cost of supporting technologies is included at different variable renewable electricity generation shares.

2 Updates and changes to GALLM-E

2.1 GALLM-E overview

After considering a broad range of technology cost projection approaches[1] , GALLM-E was chosen primarily because the cost projection methodology does not require as many subjective choices as other approaches. The method is highly data driven and the outputs can be traced through and explained by the assumptions. However, GALLM-E is computationally demanding.

GALLM-E is solved as a mixed integer linear program in which total costs of electricity supply in each region is minimised to meet annual electricity demand over the projection period. The model features endogenous technological learning which means that the electricity technology mix and the cost of electricity generation technologies are solved simultaneously as outputs from the model. Learning occurs at the global and local level. This means that technology costs may fall in a region both because of technology deployment elsewhere in the world or because of local deployment. Each technology is divided into components subject to local learning (e.g. installation costs), global learning (e.g. globally standardised manufactured elements) and no learning at all (e.g. mature parts of plant design).

A key feature of GALLM-E is the technology learning curves, also known as experience curves. Learning curves refer to the observed phenomenon that the costs of new technologies tend to reduce with the cumulative production of the technology (i.e. 'learning by doing'). Also, costs tend to reduce by an approximately constant factor for each doubling of cumulative production. This observation makes it possible to create cost projections based on projections of the future uptake of a technology. Projections are created from a mathematical equation as follows:

$$IC_t = IC_0 \times CC_t^{-b}$$

where IC is the investment cost of a technology at CC cumulative capacity at a given future point in time, t. IC_0 is the investment cost at a given starting period or capacity and b is the learning index. This index is related to the learning rate as follows:

$$LR = 100 - 2^{-b}$$

where LR is the learning rate, represented as a percentage, and which can be interpreted as the percentage reduction in per unit costs resulting from a doubling of cumulative capacity.

Projections of the global and local uptake of a technology needs to be known in order to project changes in costs. However, uptake itself depends on projected costs. To resolve this interdependency, models such as GALLM-E are applied to project cost and uptake simultaneously.

[1] Table 1 in Hayward and Graham (2012) compares approaches

2.1.1 GALLM-T

The learning rate method can be applied to almost any technology where sufficient data is available and recognising this, CSIRO has extended the approach to the transport sector in a model called GALLM-T. The development of GALLM-T was necessary in order to project the costs of battery technologies. While battery storage is becoming increasingly important in the electricity sector, their cost reduction is still driven mostly by learning in the transport sector, specifically through electric vehicle deployment. A second motivation is that CSIRO also conducts a range of transport futures modelling and research and GALLM-T provides a new source of cost data for such projects (Graham & Reedman, 2015) (Reedman & Graham, 2016).

2.2 GALLM-E and GALLM-T interactions to project battery costs

GALLM-T simultaneously solves for the mix of transport fuel supply and alternative engine technologies to meet global transport demand and produces the rate of change in their costs according to the assumed learning rates. In this context we only require the projected deployment of batteries in electric vehicles and to ensure additional electricity demand from vehicle electrification is included in the electricity demand to be met in GALLM-E.

The amount of batteries deployed over time via electric vehicle sales is fed into GALLM-E as an exogenous (fixed) input. GALLM-E is free to choose to deploy additional battery capacity in stationary electricity storage applications depending on each region’s needs (we have not yet considered the potential for “vehicle to grid” which would reduce the need for separate stationary energy battery capacity). Our expectation is that as the cost of solar photovoltaic and wind generation technologies decreases and their deployment increases, it may be cost effective for some regions to deploy battery storage as a means of maintaining requirements for reliability.

The projected cost of batteries is a function of the learning rate applied to the sum of both electricity and transport sector battery capacity deployed. Ideally, we should iterate between GALLM-E and GALLM-T to find an equilibrium level of deployment and costs since costs and deployment in one model will impact the other. However, in practice, we find that electric vehicle deployment saturates in GALLM-T and is not significantly impacted by additional battery deployment and subsequent cost reductions from electricity sector battery applications.

2.3 Extension to a multi-region model

The original version of GALLM-E had three regions (including Australia), which may be sufficient for providing cost projections in Australia but it was unable to capture factors such as renewable resources, trade between regions, energy policies and differences in fuel prices down to a suitable level of granularity. Based on the approach the OECD takes to regional disaggregation, GALLM-E now has 13 regions, some of which are individual countries. Where a region and country overlap, the country has been excluded from that region.

The regions are Africa (AFR), Australia (AUS), China (CHI), Eastern Europe (EUE), Former Soviet Union (FSU), India (IND), Japan (JPN), Latin America (LAM), Middle East (MEA), North America (NAM), OECD Pacific (PAO), Rest of Asia (SEA), and Western Europe (EUW).

GALLM-E now projects the capital cost and uptake of electricity generation technologies in each of these regions. Each region has its own initial installed capacities of electricity generation technologies, capital and operating costs, demand for electricity, fuel prices, energy resources (renewable, fossil fuel and carbon dioxide storage sites), carbon prices and other climate change and energy policies. Electricity trade between EUE, EUW and FSU has been included.

GALLM-T features the same regions as GALLM-E so uptake of technologies can be shared between the models. Each region in GALLM-T has its own initial installed capacity of fuel conversion and new vehicle technologies (battery and fuel cell vehicles), fuel prices, feedstock prices, demand for transport by mode, carbon prices, transport policies such as ethanol blends and other energy policies. Trade in fuels is included between all regions. Trade is assumed to occur by shipping.

2.4 Regional constraints on renewable resources

A key feature of recent developments in technology costs in the last decade has been very large reductions in the cost of solar photovoltaic and wind generation technology. Furthermore, large reductions in the costs of battery storage could mean the share of these low cost variable renewable generation technologies is not as limited as previously thought by reliability constraints.

The lesser influence of both financial and reliability constraints to solar and wind technology adoption means that we must take greater care in ensuring that we understand at what point resource constraints, including other renewables such as solar thermal, geothermal and wave energy may play a role in limiting technology adoption.

While there has for many years been discussion of the potential for new cross-border transmission schemes for accessing high quality renewable resources (e.g. MENA-EU Solar Energy Super Grid; Asia Super Grid), we assume no such schemes are developed during our projection period, due to their great uncertainty. Existing trade via inter-country transmission, such as within the European region, is accounted for.

Each region’s total supply of renewable generation is therefore limited by the quality of domestic resources. CSIRO sought information from a variety of sources to determine maximum supply (see for example, (Government of India, 2016) (Chandler, et al., 2014). Given that supply is assumed to be fixed, if a region’s electricity demand is rising, the maximum percentage share of renewables falls over time. Figure 2-1 shows the maximum percentage of demand that can be met by four renewable technologies for each region in the year 2050.

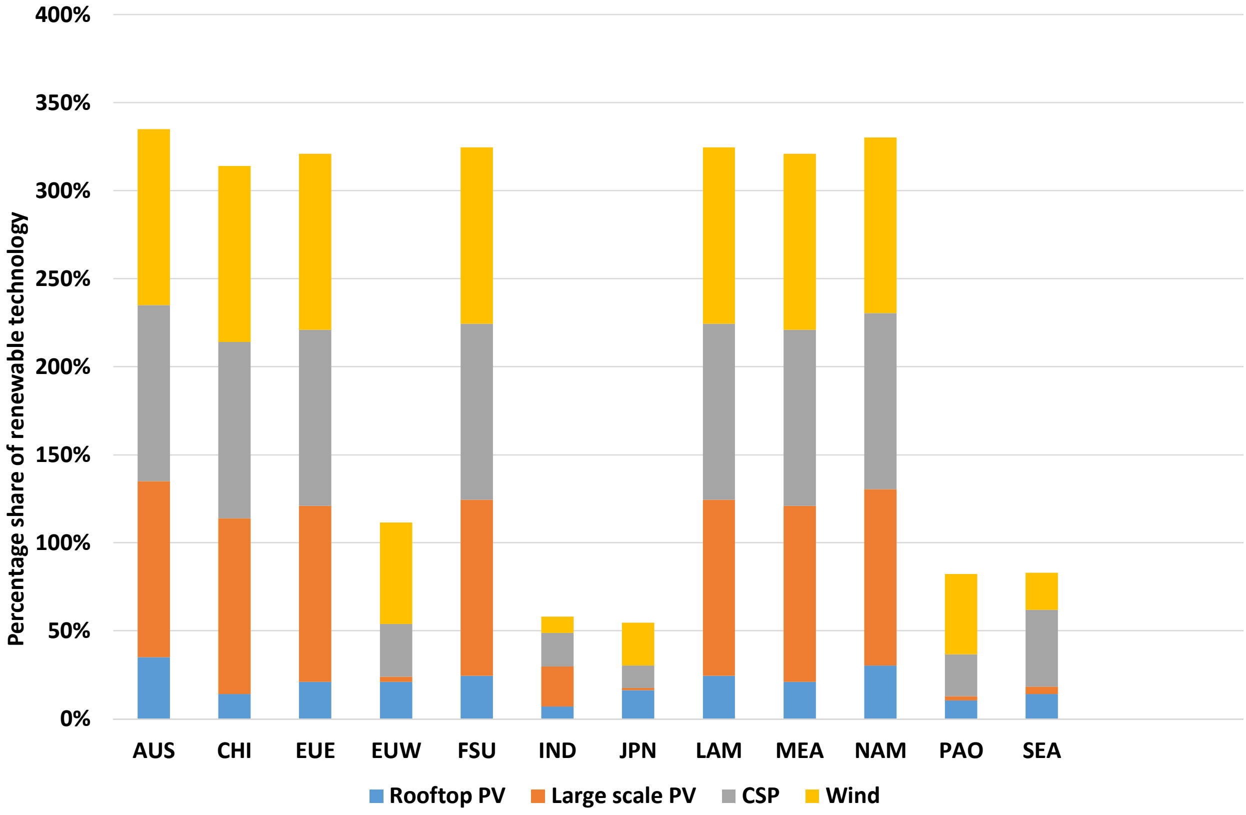

Figure 2-1 – Upper limit on percentage of demand that can be met by various renewable technologies in 2050

Data on this topic will likely change over time. Some particular areas for future review are building integrated solar and offshore wind. The upper limit on rooftop and building integrated solar depends on the form in which solar panels or other yet to be demonstrated solar structural materials take and their ease of incorporation into existing and new structures. Business models for sharing the benefits of solar electricity production across building tenants and owners could also broaden building integrated solar adoption. Free floating offshore wind technologies could open up a wider area of ocean resources if proven cost effective and robust.

2.5 Longer learning period for selected technologies

The learning by doing approach allows technologies to achieve rapid cost reductions at the early stages of their development. However, the requirement that a technology's capacity must double before learning is achieved eventually becomes a major limiting factor on achieving ongoing cost reductions. In contrast, some technologies, due to their modular nature can continue doubling capacity for longer than others, even after gaining a significant share of the market. To limit mature modular technology learning, as a standard assumption, we decrease the rate of learning once the capacity is at significant market share. This approach effectively imposes a soft floor on the cost reduction that can be achieved within the projection period. This approach is supported by the existence of engineering and thermodynamic limits such as on the size or strength of a component, or on the theoretical maximum energy conversion efficiency.

However, we have chosen to modify this approach for two technologies: solar photovoltaic electricity generation and battery storage. These two technologies are selected because they do not appear to have a strongly settled set of underlying material components. While silicon panels are currently the dominant solar photovoltaic technology, there are a number of alternative materials being explored where significant progress is being made in achieving efficient energy conversion and in different systems for installing the solar conversion system (Jacoby, 2016) (Fraunhofer ISE, 2015). This could mean improvements not only in the panel but in the installation and balance of system costs. Similarly, alternative battery chemistries and configurations also continue to be explored with no obvious limit on what might be achieved (Miller, 2017).

Since future science and engineering advances are likely but unknowable in advance, rather than apply the standard approach which implies innovations peter out with growing maturity, the alternative approach we take for these two technologies is to apply their high historically observed learning rate indefinitely. In practice, this means these technologies can achieve steeper cost reduction curves for longer than other technologies.

3 Updated technology cost projections

3.1 Global climate policy scenarios

The assumed level of global ambition to reduce greenhouse gas emissions to address the risk of climate change is a major driver for low emission technology deployment in GALLM-E. In 2015 we assumed two global climate policy ambition scenarios which we called 550ppm and 450ppm and which had corresponding carbon price assumptions.

For this 2017 update, we have expressed the scenarios in terms of expected changes in global average temperature increases above pre-industrial levels of 4-degrees and 2-degrees. This approach was developed as part of an update to the 2015 Australian National Outlook[2]. For each climate ambition scenario, a global carbon price path differentiated by region was constructed from several sources. For the near term (to 2025 for the 4-degree scenario and to 2020 for the 2-degree scenario), regional prices were taken from the International Energy Agency (IEA) where a projected price is provided (IEA, 2016). For countries/regions not covered by the IEA, a zero price is applied unless the country is shown as having a price in (World Bank, Ecofys and Vivid Economics, 2016). It is assumed that international policy cooperation results in a global uniform carbon price in the long term, which is derived from (IPCC, 2014). For the 2-degree global warming scenario this occurs relatively early, from 2020 onwards. For the 4-degree global warming scenario, uniform global pricing does not occur until 2040, and there is furthermore a transition period between 2025 and 2040 where regional prices converge from their near term trajectories to the long term uniform global price – annual prices are constructed assuming a constant percentage growth rate over the 15 year transition period.

In the 2-degree scenario, prices increase at a rate of 6% pa from $20 USD (2015 prices) per tCO_2e, in 2020 reaching $86 in 2045 and $115 in 2050. In the 4-degree scenario, uniform prices start at $40 in 2045, increasing more slowly by 1% pa to only $42 in 2050.

Besides carbon pricing, countries have renewable energy targets, feed-in-tariffs and related policies to encourage emissions reduction and promote renewable technologies. The IEA's three climate change scenarios: 'Current Policies', 'New Policies' and '450ppm' were used to match non-carbon price policies to the 2- and 4-degree scenarios.

3.2 Discussion and comparison of cost projections

For selected low emission technologies, we compare the 2017 4-degrees scenario to the 2015 550ppm scenario cost projections (Figure 3-1 to Figure 3-4) and of the 2017 2-degrees scenario to the 2015 450ppm scenario cost projections (Figure 3-5 to Figure 3-8). We have not included mature technologies in these figures because they are assumed to be no longer subject to costs decreases that depend on cumulative deployment. Rather, a small fixed annual decline for general

[2] http://www.csiro.au/nationaloutlook/

productivity improvements is applied across their cost inputs - an assumption which has not changed compared to previous projections. We have also excluded less prospective technologies such as enhanced geothermal. We make available the underlying cost projection data for all technologies in Appendix A. Note that the costs shown are for Australian deployed technologies. Costs differ in each country due to local learning, particularly on balance of plant (BOP) costs.

Given most assumptions remain similar to the 2015 analysis we expect that most differences in the 2017 cost projections are due to the new carbon price assumptions, the changes to the model described in Section 2 and the subsequent different rates of technology deployment projected by the model.

One theme that emerges from the comparison is that carbon capture and storage (CCS) technologies (brown coal, black coal and gas) do not achieve as much cost reduction by 2050 in the 2017 projections as in the 2015 projections. The lack of a strong carbon price signal in the 4-degrees scenarios means that CCS is not taken up in that scenario and any cost reduction reflects general productivity improvements rather than learning from deployment.

In the 2-degrees scenario, CCS is deployed, however it is deployed later (the mid rather than early 2020s) and to a lower level of capacity than in the 2015 projections. This likely reflects the impact of renewables taking up a greater share of generation owing to their significant cost reductions between 2015 and 2017 that have been incorporated into the projections.

A recurring limitation of GALLM-E's modelling of CCS is that the model is not able to examine retrofit projects. It is possible that some CCS retrofit projects could proceed at lower cost than new build projects and speed up learning for this technology category. This is an opportunity for consideration in the next decade. However, as existing coal plant ages, the window for life extension with CCS will also close because new-build CCS plant, with longer achievable life will be available at lower lifetime cost. The challenge for CCS retrofit plant is that, in the period in which they are lower cost than new build CCS plant, they lack a strong emissions constraint or carbon price incentive to support the investment.

The 2017 cost projections for nuclear power remain very similar to 2015. This reflects two constraints. The first is that many countries choose to limit new or expanded nuclear programs, particularly in developed countries. As a consequence, while nuclear is expanding in some regions these are partially offset by retirements elsewhere. Thus, it is difficult for conventional nuclear power to double capacity and achieve further learning. The second constraint is that the model does not include new designs of nuclear plants or modular nuclear as a distinct technology type. It is possible that these technologies have better prospects.

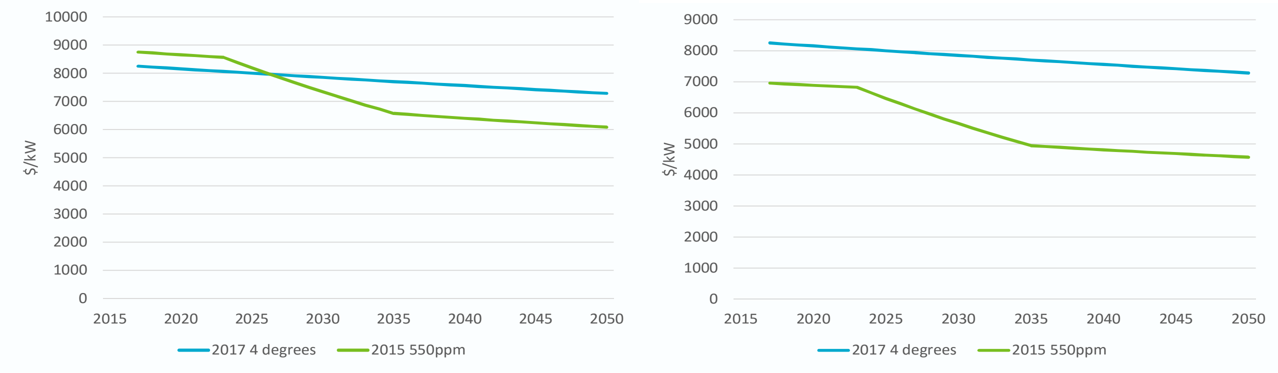

Figure 3-1: Brown coal with CCS (left) and black coal with CCS (right)

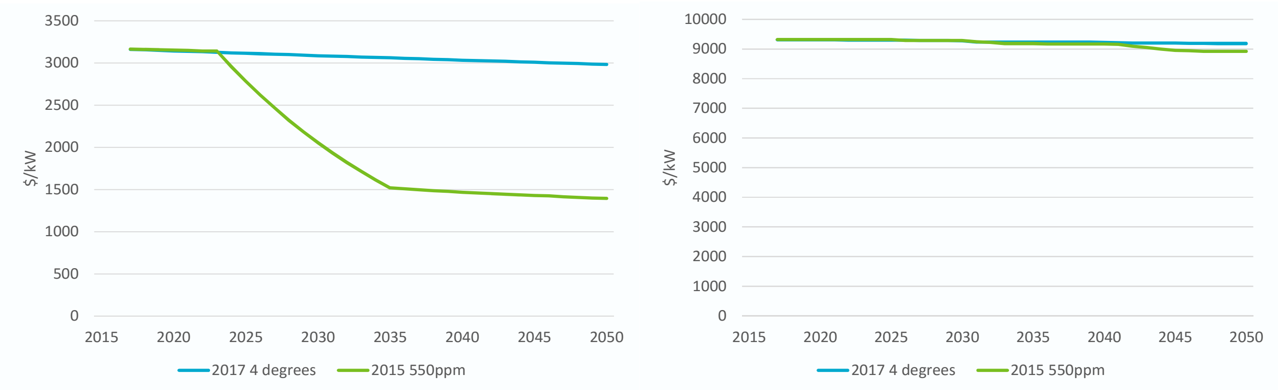

Figure 3-2: Gas with CCS (left) and nuclear (right)

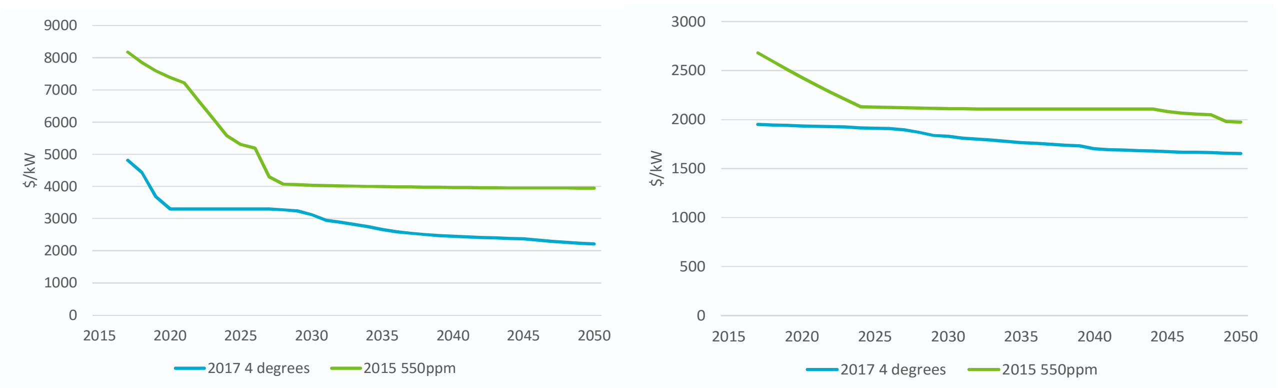

Figure 3-3: Solar thermal with 6 hours storage (left) and wind (right)

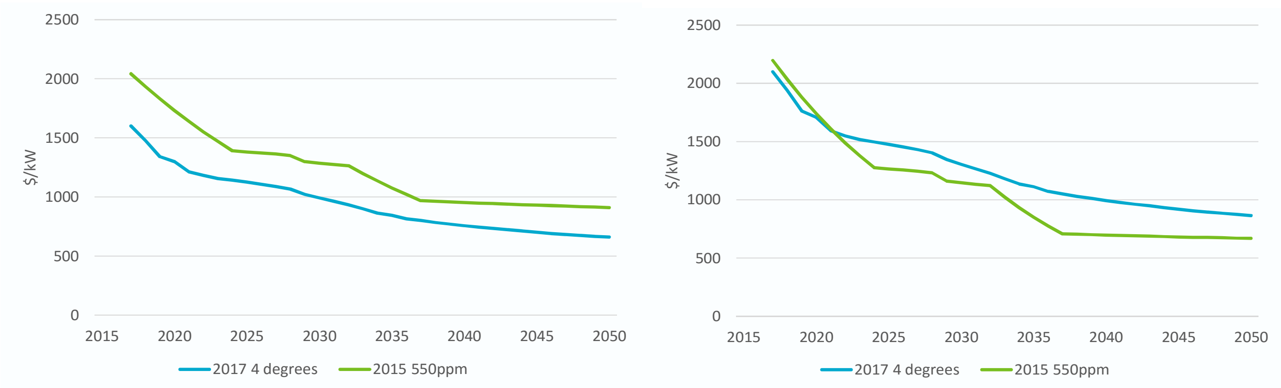

Figure 3-4: Rooftop solar photovoltaics (left) and large scale solar photovoltaics (right)

Comparison of 2017 4-degrees and 2015 550ppm scenario costs, 2017 AUS dollars sent-out basis

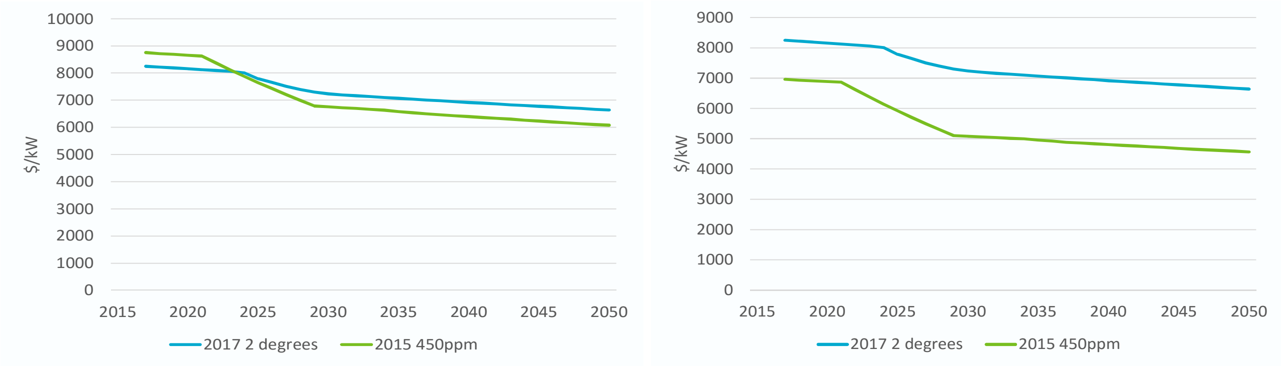

Figure 3-5: Brown coal with CCS (left) and black coal with CCS (right)

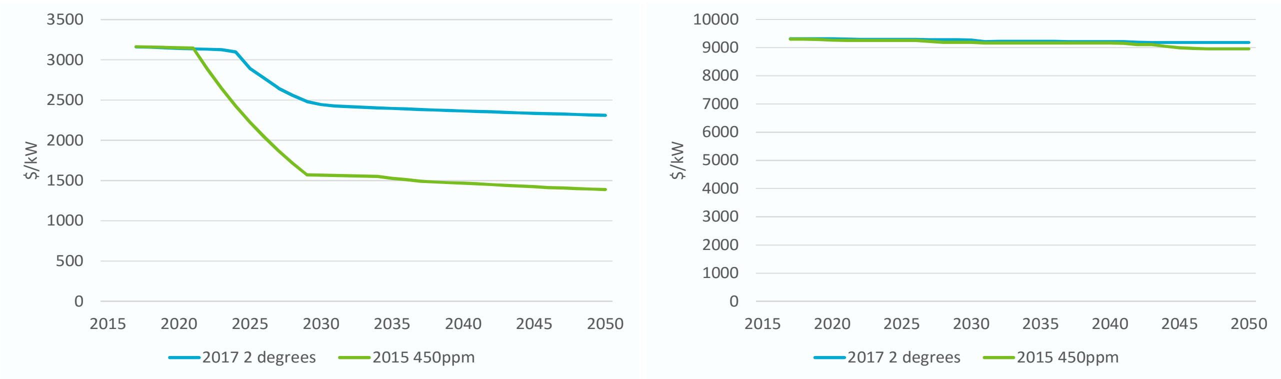

Figure 3-6: Gas with CCS (left) and nuclear (right)

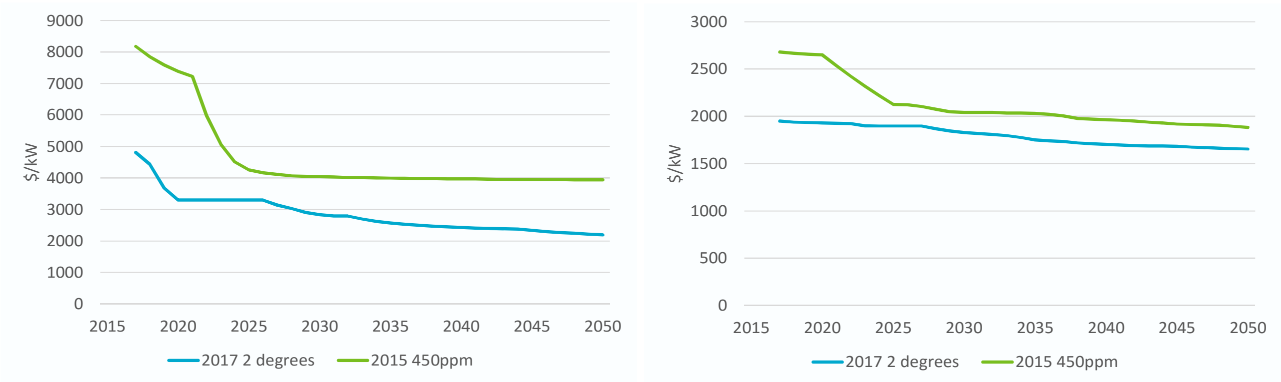

Figure 3-7: Solar thermal with 6 hours storage (left) and wind (right)

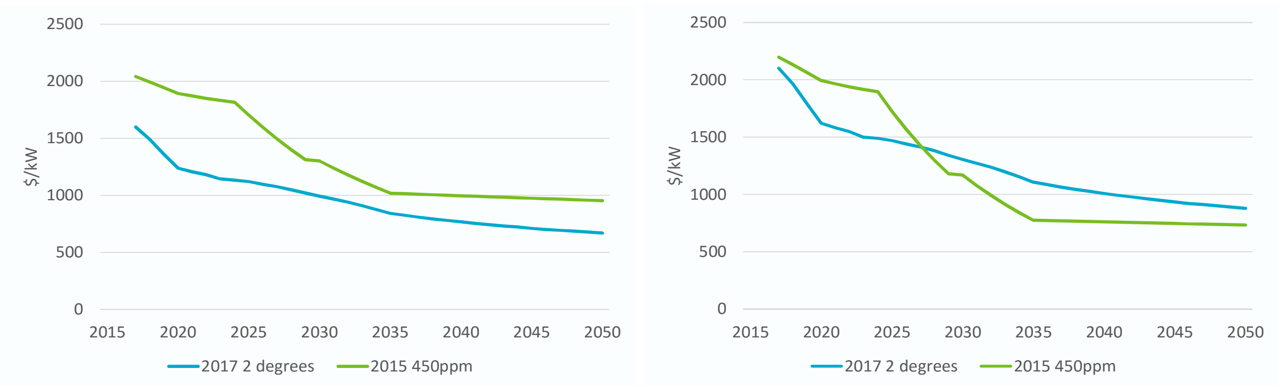

Figure 3-8: Rooftop solar photovoltaics (left) and large scale solar photovoltaics (right)

Comparison of 2017 2-degrees and 2015 450ppm scenario costs, 2017 AUS dollars sent-out basis

In terms of renewable technologies, wind rooftop solar PV and solar thermal have decreased faster than expected (in 2015) in both 2017 climate ambition scenarios. Large scale solar PV has also improved, however, it remains more aligned with the previous 2015 cost in the long term. By 2050, under either scenario the 2017 cost projection for wind and rooftop PV are lower than that projected in 2015. For wind this reflects greater adoption owing to lower near term costs and more generous assumptions about regional resource constraints. For rooftop solar PV, the recent cost estimate reductions have also improved the longer term outlook, together with our new assumption that learning for both the panel and balance of system can continue at faster rates for longer. Large scale PV does not achieve as great a cost reduction, and is in fact less than that projected in either of the 2015 scenarios. This is not due to lack of learning on the panels but the revised assumption that the balance of system in large scale plants are not as fertile for innovation as rooftop or building integrated systems.

The projected costs for solar thermal technology have changed mainly due to information being available from the first commercial plant that is due for completion in South Australia in 2020. This follows anecdotal evidence that projects in other regions of the world are also achieving lower costs. Up to 2025, cost reductions and deployment are projected to stall briefly as other technologies are prioritised. Cost reductions resume at a steady rate to 2050 leading to almost half the cost level as that projected in both of the 2015 scenario projections.

3.3 Technology deployment by region

The projected share of electricity generation by technology in key world regions is shown in Figure 3-9 for the 4-degree scenario. Europe is a combination of GALLM-E regions EUW and EUE and Asia includes CHI, IND, JPN, PAO and SEA. “Solar” refers to both photovoltaic and thermal systems. Brown and black coal are aggregated into “Coal”.

All regions see a large drop in coal-fired electricity generation and an increase in solar between 2030 and 2050 however the shares of other technologies are more variable. This is due to saturation of available renewable resources which means that the maximum share reduces as demand increases. For instance, North America sees a reduction in the share of wind generation but an increase in other renewables, which includes geothermal and ocean energy. Asia has an increase in both wind and other renewables between 2030 and 2050 and Europe sees a large increase in wind and solar but a drop in the share of other renewables.

The projected share of electricity generation by technology for the 2-degree scenario is shown in Figure 3-10. Under the 2-degrees scenario there is also a large reduction in black and brown coal generation that is somewhat offset by CCS. CCS technologies generate some electricity in all regions in 2030, and make a large contribution in Asia in particular by 2050. The solar shares are very similar to the 4-degree scenario however there is some variation across scenarios in wind and other renewable shares. This means that the uptake of solar is not impacted by the level of the carbon price but other renewable technologies are. Demand for electricity, which can also impact the shares of different technologies, is lower under the 2-degree scenario. The higher carbon price means that in 2030 North America has more gas-fired than coal-fired generation.

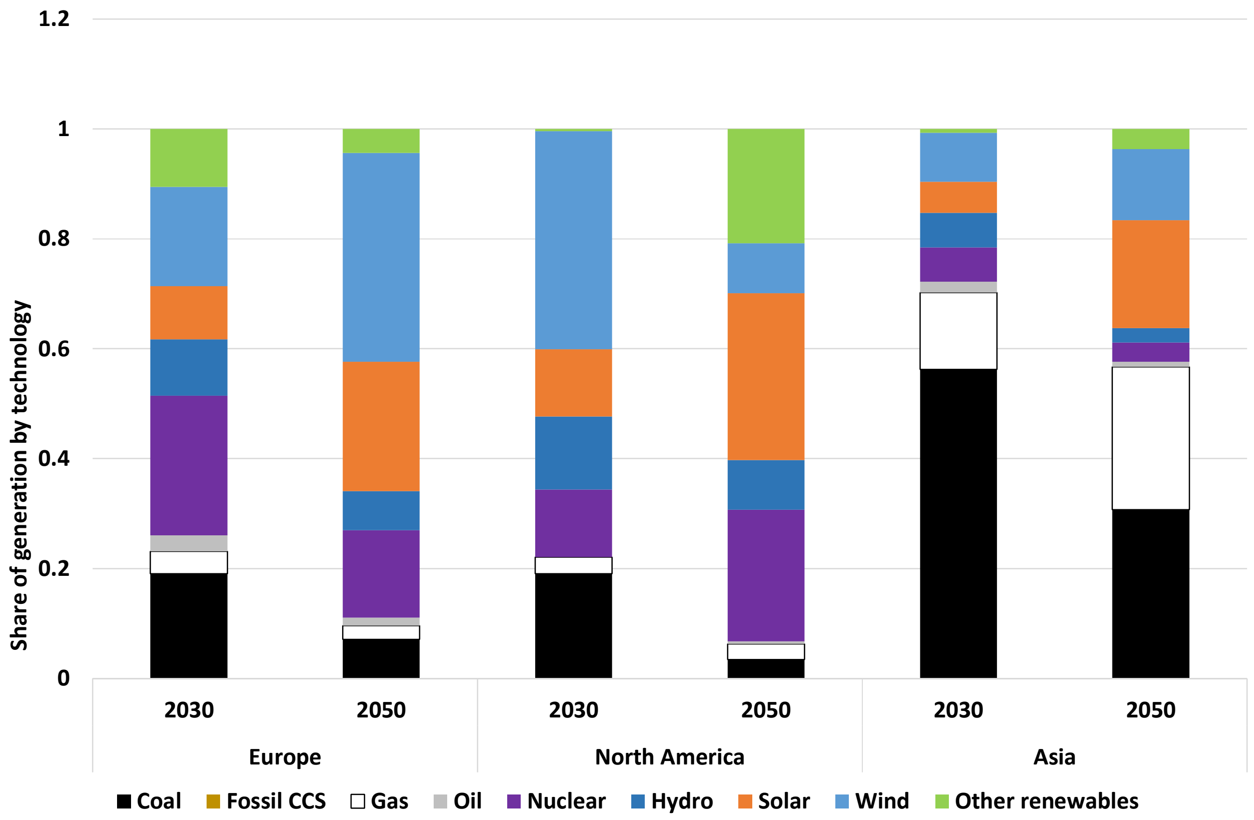

Figure 3-9 – Projected share of generation by broad technology category under the 4-degree scenario for selected regions for the years 2030 and 2050

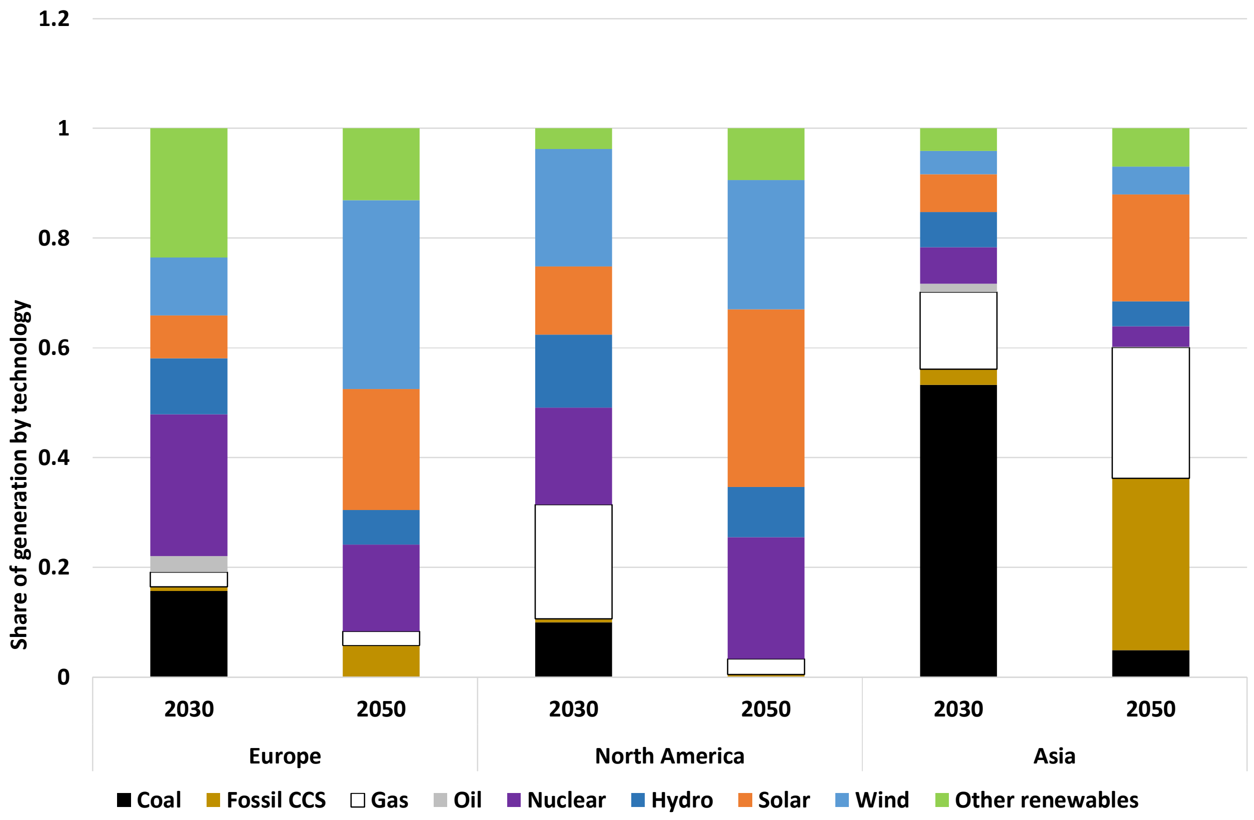

Figure 3-10 – Projected share of generation by broad technology category under the 2-degree scenario for selected regions for the years 2030 and 2050

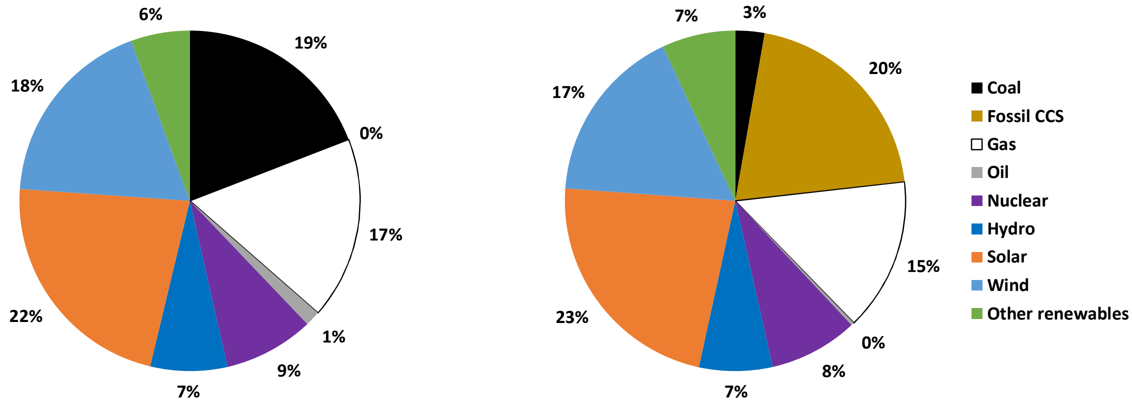

Figure 3-11 – Projected 2050 global share of generation by technology category under the 4-degree (left figure) and 2-degree (right figure) scenarios.

The projected global shares by generation technology type in the year 2050 under each scenario are shown in Figure 3-11. The clear differentiating factor between scenarios is the quantity of coal generation and CCS; CCS essentially replaces coal's share of generation under the 2-degree scenario. The renewable share increases slightly from 53% to 54%. The increase is limited because of a number of factors. The first is that, while carbon prices have increased in the 2-degree scenario, in some regions renewable generation has already reached the assumed resource limits in the 4-degree scenario, particularly in the Asian region. The second is that in the 2-degree scenario, because CCS is deployed, CCS capital costs are significantly lower (around half their level in the 4-degree scenario) and it is therefore more competitive with renewables. The third factor is that, given the global scale of the GALLM-E model the information applied to determine the costs of supporting the reliability of variable renewable generation are conservative compared to more detailed national level electricity modelling[3]. Our expectation is that the CCS share remains highly uncertain and will change over time as our understanding of the cost of supporting the reliability of variable renewable generation in each region improves.

As a source of comparison, the IEA (2017) *World Energy Outlook* projects the share of CCS in global electricity generation to be less than 1% by 2040 in its 'New Policies' scenarios and 6% by 2040 in its 'Sustainable Development' scenario. Those two scenarios are most similar to the 4-degree and 2-degree scenarios respectively. Aligning the projection date at 2040, the global shares for CCS in our 4-degree and 2-degrees scenarios are less than 1% and 10% respectively.

The total amount (in GJ) of fossil fuels consumed is slightly higher under the 2-degree scenario by 2050 owing to the reduced fuel efficiency of CCS plants on an electricity sent-out basis. However, note that CCS is applied to a mix of coal and gas plant types and therefore this still represents a reduction in coal-fired electricity, losing market share to gas with CCS. A 90% carbon dioxide capture rate has been assumed in GALLM-E.

[3] The analysis in Section 4 shows calculations for Australia of the cost of making variable renewables reliable based on detailed simulations of different levels of variable renewable electricity generation share in each major state region. Ideally this analysis should be repeated with country/region specific variable renewable generation profiles but was beyond the current scope of work.

3.4 Battery storage cost projections

As discussed, this update included changes in our modelling approach in regard to battery storage cost projections by including transport sector projections. These transport projections, which include adoption of electric vehicles, are a significant driver for deployment and subsequent cost reductions in battery storage which can be taken up by the electricity sector. A second change was to allow batteries to experience a high rate of learning for a longer period than in our previous projections.

As a result of these two changes in method and/or assumptions the updated battery cost projections were calculated and are shown in Figure 3-12. For comparison, the figure shows two previous CSIRO cost projections. Our first projection was provided in an energy storage trends report commissioned by the Australian Energy Market Commission (Brinsmead, et al., 2015). This earlier projection provided both a low and high cost case. However, the low cost case has been more often used in our subsequent work as battery costs continued to fall rapidly following publication of the report. This low cost case projection was slightly amended for the Electricity Network Transformation Roadmap to include a 20% lower long term end point for use in scenarios with 100% renewable shares which would include greater battery adoption and therefore greater learning.

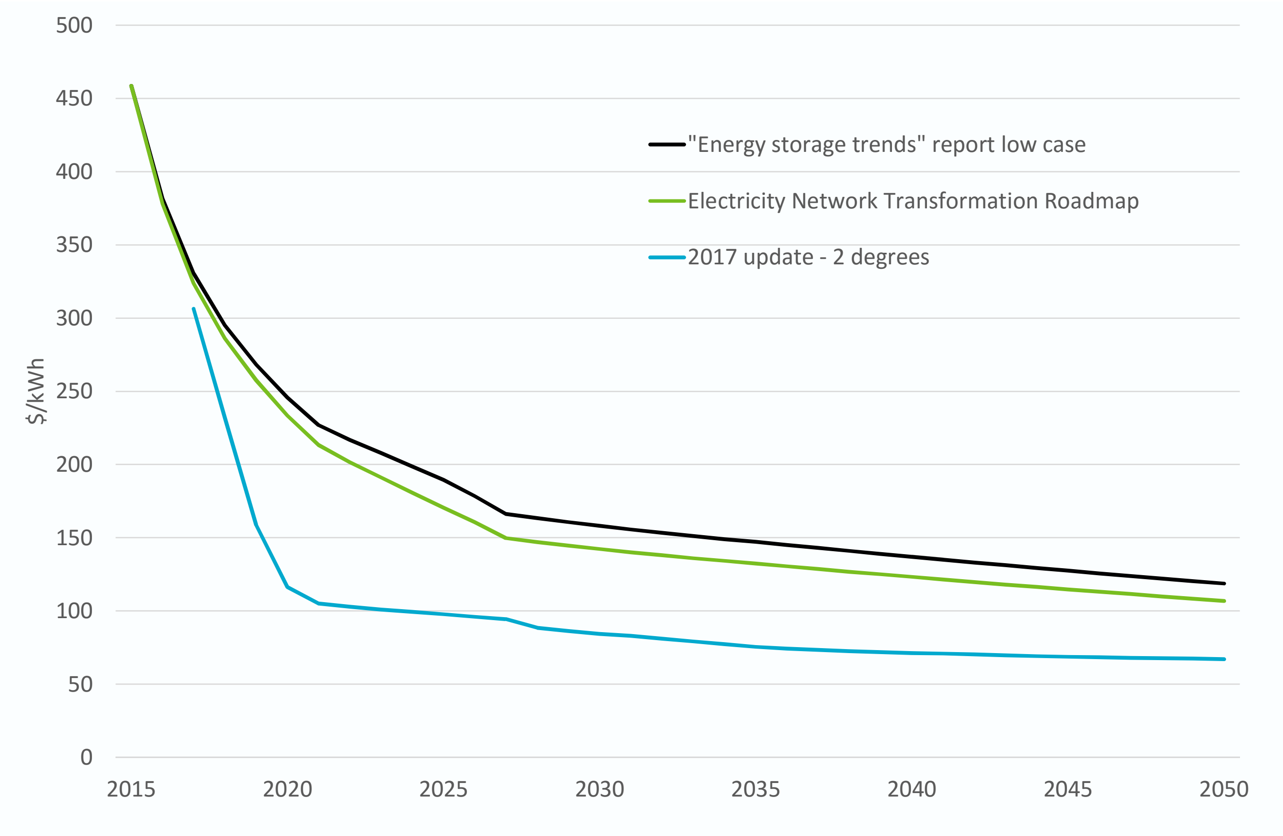

Figure 3-12: Comparison of battery only cost projections: 2017 update and previous projections, 2017 AUS dollars

We provide separate cost projections for the battery only and the balance of system costs. The 2017 updated battery only cost projection recognises that costs have continued to fall since 2015 and may continue to do so at a similar rate through to 2020 after which we project the rate of decline to moderate. The level of costs projected in 2050 is around half that of the earlier 2015 low cost projections.

In utility scale deployments, the balance of plant costs are very significant. We project that balance of plant costs will almost halve over the projection period from around $520/kWh to $270/kWh in 2050 (in real 2017 dollars) based on learning rates from (Schmidt, et al., 2017). There is a significant uncertainty range around balance of system costs which is difficult to define as they are context dependent. Utility scale battery storage projects have the potential to reduce costs by co-locating with wind and solar photovoltaic plant. The degree to which that integration is planned and that resources can be shared will see cost outcomes achieved at the lower end of the range.

3.5 Trends in cost projections

Since the turn of the 21st century the global technology market has undergone a series of marked trends. These include:

- Initially low gas turbine costs reflecting delayed orders following the Asian financial crisis of the late 1990s which impacted economic growth and power station building plans.
- Rising prices for coal and wind plants. This reflected strong global economic growth, particularly in China, that motivated strong power station building programs as well as a widely held preference for these two mature technologies. There was also a simultaneous increase in power station raw material costs (such as prices for steel). The preference for coal plant reflected high oil and gas prices. The preference for wind plant was due to many countries seeking to demonstrate adoption of low emission technologies with wind being by far the lowest cost large scale technology.
- Rising prices for solar photovoltaic plant during a period in which there was a temporary shortage of silicon supply.

Following after these trends, the most recent and dominant trend has been the very rapid fall in solar photovoltaic and wind technology costs and at the same time a stagnation or increase in the (projected and actual) costs of alternative low emission technologies such as carbon capture and storage (CCS) and nuclear.

The previous decade's rising trend in prices in part explains why, even in 2011, some projections to 2030 still had not anticipated the coming fall in wind and solar photovoltaic technology costs (Figure 3-13). The greatest change in projected costs has been in solar photovoltaics with the outlook for costs halving twice over several studies as data is updated to reflect more current cost data and historical learning rates adjusted.

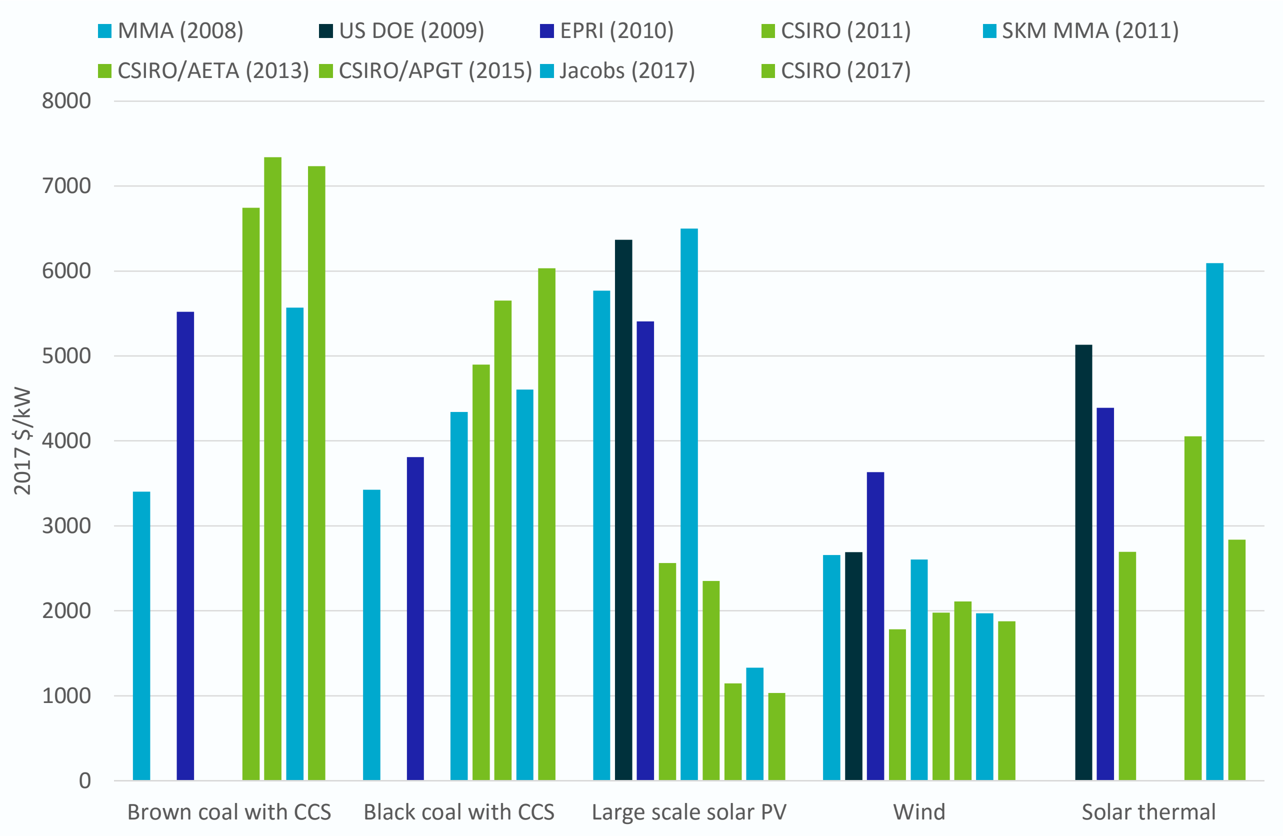

Figure 3-13: Previous CSIRO and other publicly available electricity generation technology cost projections for 2030

Notes: All CSIRO projections are shown in green with earliest starting on the left where available. The 2015 APGT was written by EPRI with cost projections provided by CSIRO. Similarly, AETA was written by the Bureau of Resources and Energy Economics and consultants. MMA, SKM MMA and Jacobs represent a reasonably continuous projections team with changes to their trading name. Consequently their projections are all shown in blue with earliest projections starting on the left where available.

The projected cost for CCS has increased by around 50% to 100% across the projections. This is largely due to slow progress in demonstrating commercial scale CCS plant, due to the high minimum scale and hence high cost of each demonstration. Earlier cost projections had also anticipated faster and stronger action to address climate change, including carbon prices high enough to fund CCS projects. Instead, in most countries, high carbon prices have not emerged as yet and policy support has been strongest for renewable electricity generation plant through renewable energy targets, feed in tariffs and other policy mechanisms.

Projections developed across the period 2008 to 2017 for solar thermal costs in 2030 have been varied. Early expectations in 2011 that solar thermal may achieve similar cost reductions to that achieved by solar photovoltaics were moderated by 2015. This reflected a concern that solar thermal has experienced a crowding out of investment, as costs reductions already achieved by wind and solar photovoltaics snow-balled, soaking up available investment funds. However, recent costs demonstrated by current projects has restored some confidence. In the long term, as the share of renewable electricity generation increases in the future and concerns about the variability of wind and solar photovoltaics begin to be priced in the market through various policies or market mechanisms, solar thermal will be better positioned to attract a greater share of investment.

4 Levelised costs of electricity

CSIRO uses projected capital costs of electricity generation technologies directly in its modelling rather than deriving the levelised costs of electricity (LCOE) to determine the implications of those capital costs. However, LCOE is useful for non-technical audiences to make simple comparisons and projections of the future costs of electricity supply. Even so, the simple comparisons which are made using LCOE are becoming less useful, as we see the cost of variable renewable electricity generation technologies fall and their share of generation rise. Variable electricity generation includes generation from solar photovoltaics and wind power which delivers energy as variable climate weather conditions make the solar and wind resources available. When the share of variable electricity generation is low it can rely on the flexibility of other generation capacity to support system reliability by providing more power when variable supply falls. However, at sufficiently high shares of variable electricity generation, the power system requires additional supporting technologies, such as storage or peaking plant, creating additional costs.

Below we provide the conventional LCOE estimates which ignore the differences in variable generation and only compare the cost of energy delivered, excluding any need for auxiliary technology to support reliability. Next we provide an alternative estimate which extends the conventional approach by adding the costs of supporting technologies.

4.1 Conventional levelised cost of electricity estimates

Even without the relatively new complication of needing to make a distinction between variable versus flexible generation, a major ongoing concern with conventional LCOE estimates is that, even with a consistent set of capital cost estimates, LCOE calculations include a variety of other data assumptions for which there is no consistent standard, calculation method or data source. This means comparing LCOEs between studies can be meaningless. While we cannot ensure consistency with other studies, to assist with comparison we report our key assumptions in Table 4-1. Note that we use a weighted average real cost of capital of 7% across all technologies consistent with Australian government guidelines[4].

The LCOE estimates are shown in Figure 4-1 for the years 2030 and 2050 for selected low emission technologies. The estimates are provided as a range. The range considers the differences in capital costs between the 2- and 4-degrees climate ambition scenarios and the high and low ranges for the other key assumptions included in Table 4-1. Note that governments may choose to impose additional costs on nuclear power plants to fund development and operation of centralised facilities for storage of spent fuel – these costs have not been included. Also, solar thermal includes 6 hours storage.

[4] https://www.pmc.gov.au/sites/default/files/publications/cosst-benefit-analysis.docx

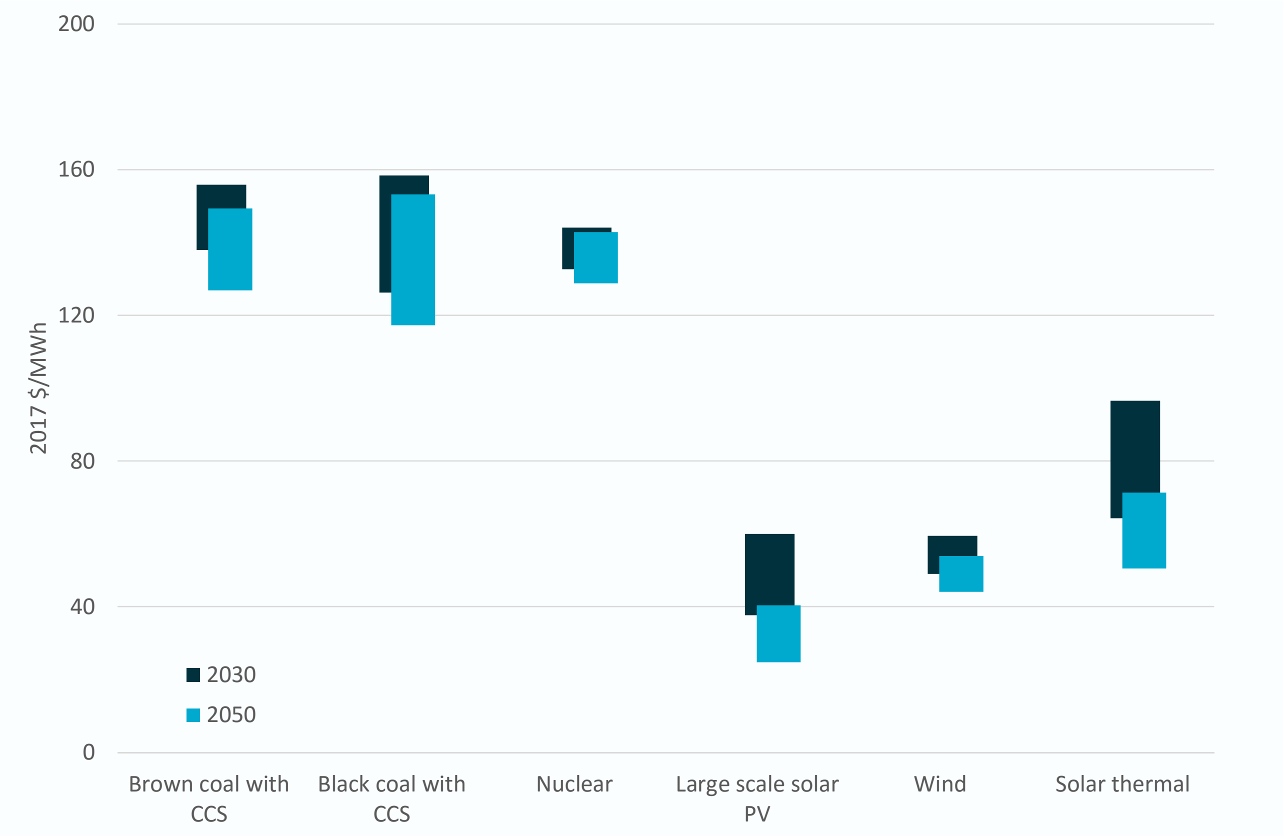

Figure 4-1: Conventional LCOE estimates for selected technologies

Table 4-1: High and low values for key LCOE assumptions

	Capacity factor (%)		O&M 2050 ($/MWh)		Fuel 2050 ($/MWh)	
	Low	High	Low	High	Low	High
Brown coal with CCS	85	85	17	21	15	25
Black coal with CCS	85	85	14	17	25	49
Nuclear	85	85	12	15	11	22
Large scale solar PV	19	32	5	6	0	0
Wind	35	42	6	7	0	0
Solar thermal	40	55	12	17	0	0

4.2 Extended levelised cost of electricity estimates

The inherent problem with any attempt to take into account the cost of supporting the reliability of variable electricity generation technologies is that the cost is context dependent. The contexts that influence the supporting costs include:

- The type and capacity of existing flexible generation or demand management that can be accessed
- The shape of the demand profile that needs to be met
- The share of variable renewable electricity
- The mix and diversity of variable renewable electricity
- The type of storage technology available (for example, pumped hydro requires a specific topography that needs to be available in the region being examined)
- The supply reliability standards that must be met.

Each state in Australia has its own unique contexts now and in the future. As such, it is a significant task to calculate an extended LCOE for variable generation which includes reliability supporting costs for every current and likely future context.

While such a task is beyond this report's scope, we were able to draw on previous modelling analysis by CSIRO which focussed on scenarios where the share of variable renewable generation was required to increase over time to 100% or slightly less by 2050 (Campey, et al., 2017b) (Campey, et al., 2017a) (Brinsmead, et al., 2017)[5]. Under such circumstances, the analysis examined each state of Australia and found that the requirement for any supporting technology below 40% variable renewable generation share was nil. However, at this share there is a loss of capacity factor due to transmission congestion which should be taken into account.

Above 40% renewable share, the modelling found the requirement for supporting technologies increased at a low to moderate rate depending on each states' quality of renewable resources and its contribution to the national renewable share. Up to a renewables share of 60%, the modelling tended to favour the strategy of building a combination of a small quantity of batteries and deploying a greater capacity of diverse renewables which does result in greater "spilling" of energy. However, the increasing losses to the capacity factor does not significantly increase the total cost of generation because, over time, the cost of capital has also fallen to offset this effect. As batteries also reduce in cost and the renewable share rises above 60%, the ratio of batteries to renewable capacity increases. Also, to cover periods of extended low variable renewable output, the modelling found that adding further batteries alone was not cost effective. Instead we needed to replace a proportion of retiring flexible plant with gas peaking plant which has low capital costs and is highly suited to the task of filling in infrequent gaps in supply for relatively extended periods.

[5] Results are reported across several studies but the specific modelling equations are reported in Campey et al. (2017)a

By the time we reach 90% variable renewable generation in 2050 the following points indicate the ratios of supporting technologies that were deployed and other requirements:

- Around 8 hours battery storage or 0.75kW of battery storage per kW of variable renewable capacity
- Around 0.4kW of dispatchable (flexible) capacity (e.g. gas open cycle) per kW variable renewable capacity
- Synchronous condensers directly proportional to battery capacity
- A 17% and 39% relative loss in capacity factor of wind and solar photovoltaics respectively.

The recommended ratios of storage to renewables are based on cost minimisation and are hence specific to battery storage. These ratios would change with the different costs and performance characteristics of other forms of storage such as pumped hydro and solar thermal storage which have been explored in other high renewable share studies. Our focus on battery storage reflected the availability of reliable cost and performance data.

The modelling tended to favour a fairly even energy generation mix of wind and solar photovoltaic to provide diversity, which reduces the capacity required of other supporting technologies. However, this diversity factor makes it complicated to calculate a unique “extended LCOE for wind” or “extended LCOE for solar photovoltaics”. Given the apparent importance of the two technologies working together to create diversity and reducing support costs, it is more appropriate to calculate an extended LCOE for a combined wind and solar field.

This is the approach that has been taken in Figure 4-2. It shows the extended LCOE for a combined wind and solar photovoltaic field for a scenario where the national share of those technologies increases to 90% by 2050. Given some states, particularly South Australia, are already at 40% or more, some battery storage was required before the nation reached 40% on average across all states in 2030.

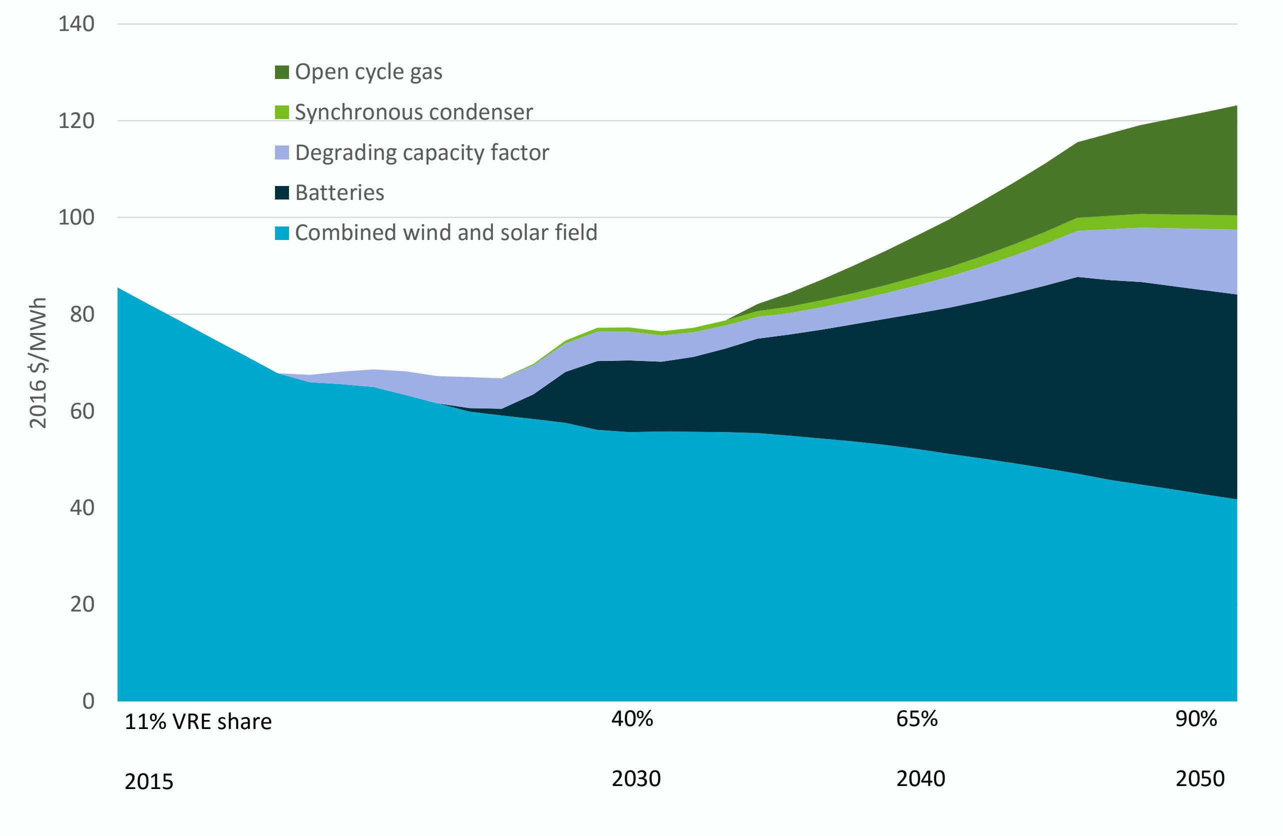

Figure 4-2: Extended LCOE for combined wind and solar field for a scenario with increasing variable generation share

The projected extended LCOE uses the combination of technologies that were estimated to be least cost in previous CSIRO analysis. However, that analysis was not comprehensive. Due to scope limitations previous modelling did not include pumped hydro and neither the use of or extensions to state interconnectors. Inclusion of these alternative technologies could reduce the overall cost of supporting the reliability of variable renewables. Future work will also need to examine the cost of systems with high solar thermal share which have not been modelled to the same extent as wind and solar photovoltaics.

With the caveat that more analysis will be required to narrow down the extended LCOE of high shares of variable renewables, it is interesting to see that, once the cost of supporting technologies is included in high renewable share electricity system (>80%), the LCOE becomes similar to that of nuclear and CCS technologies. However, the cost disadvantage for CCS and nuclear in the short term remains. That is, the first gigawatt of capacity for those technologies will result in electricity generation costs of more than $120/MWh. However, the first gigawatt of variable renewable generation, in states where the share is below 40%, results in around half that cost as it can rely on existing flexible generation capacity.

Appendix A Projection data tables

A.1 Guide to data tables

Data tables are provided for electricity generation and battery storage capital cost projections that are shown in Figure 3-1 to Figure 3-8. The technology data here set is slightly larger than that presented in the main body of the report, which focussed on the most prospective options for Australia and also excluded mature technologies whose costs are not likely to make significant further changes. GALLM considers an even larger set of technologies, such as combined heat and power plant and conventional geothermal, which are important outside of Australia. These are not reported here due to their lack of relevance for Australia and corresponding difficulty in finding an initial starting point for an Australian specific development cost.

Apx Table A.1 and Apx Table A.2 show the projections for the 4-degrees and 2-degrees climate ambition scenarios respectively. The following points provide further information on the table column titles:

- Rooftop solar panels includes the whole system fully installed
- CCS – carbon dioxide capture and storage
- HELE – high efficiency, low emission plant. This is based on an ultra-super critical steam plant
- BOP – balance of plant
- The battery storage cost is for the batteries only and is applicable to large or small scale installations. However, the balance of plant is for a large scale plant co-located with a variable renewable electricity generation field. The battery costs are based on a lithium-ion battery chemistry.
- The biomass plant is a pulverised fuel steam plant
- Nuclear power refers to conventional reactor designs.
- Solar thermal without storage is not considered because it is less cost effective (on a cost of unit energy output basis) than including storage.

Apx Table A.1: Projections data table for 4-degrees climate ambition scenario, 2017 Australian dollars sent-out

	Black coal	Black coal HELE	Black coal with CCS	Brown coal	Brown coal HELE	Brown coal with CCS	Gas combined cycle	Gas peak	Gas with CCS	Biomass	Biomass with CCS	Large scale solar PV	Rooftop solar panels	Solar thermal (6 hrs)	Wind	Wave	Enhanced geothermal	Nuclear	Battery storage	Battery storage BOP
	$/kW	$/kW	$/kW	$/kW	$/kW	$/kW	$/kW	$/kW	$/kW	$/kW	$/kW	$/kW	$/kW	$/kW	$/kW	$/kW	$/kW	$/kW	$/kWh	$/kWh
2017	3074	3312	7000	3510	4140	8250	1501	1025	3161	3784	8456	2100	1600	4815	1950	7157	14475	9313	306	518
2018	3059	3312	6975	3492	4140	8218	1501	1020	3155	3779	8424	1961	1491	4434	1940	7157	14615	9313	232	508
2019	3044	3312	6950	3475	4140	8187	1501	1015	3149	3771	8391	1750	1332	3678	1936	7157	14704	9313	159	498
2020	3028	3312	6926	3457	4140	8155	1501	1009	3143	3758	8359	1553	1190	3299	1930	7157	14836	9313	116	488
2021	3013	3312	6901	3440	4140	8124	1500	1004	3137	3756	8327	1486	1138	3299	1927	7157	14916	9307	105	478
2022	2998	3312	6877	3423	4140	8093	1500	999	3132	3753	8295	1425	1093	3299	1924	7157	15023	9297	103	469
2023	2983	3312	6853	3406	4140	8062	1500	994	3126	3753	8264	1368	1051	3299	1920	7157	15131	9297	101	459
2024	2968	3312	6829	3389	4140	8031	1500	989	3120	3753	8232	1319	1015	3299	1917	7157	15131	9297	98	450
2025	2953	3312	6805	3372	4140	8001	1499	984	3115	3753	8201	1276	984	3299	1891	7157	15131	9297	96	441
2026	2939	3312	6781	3355	4140	7970	1499	980	3109	3753	8170	1233	952	3299	1882	7157	15131	9296	94	433
2027	2924	3312	6757	3338	4140	7940	1499	975	3103	3753	8139	1192	921	3293	1867	7157	15131	9292	92	424
2028	2909	3312	6734	3322	4140	7910	1498	970	3098	3753	8108	1146	885	3273	1856	6078	15131	9292	90	416
2029	2895	3312	6710	3305	4140	7880	1497	965	3092	3753	8077	1095	848	3240	1809	5010	15131	9290	88	407
2030	2880	3312	6687	3288	4140	7850	1496	960	3087	3753	8046	1046	811	3124	1801	4298	15131	9288	85	399
2031	2866	3312	6664	3272	4140	7820	1495	955	3081	3753	8016	1004	779	2953	1784	3923	15131	9244	83	391
2032	2852	3312	6640	3256	4140	7791	1494	951	3076	3753	7986	975	757	2893	1772	3387	15125	9239	82	383
2033	2837	3312	6617	3239	4140	7762	1493	946	3071	3753	7956	938	728	2822	1762	3083	15117	9238	80	376
2034	2823	3312	6594	3223	4140	7732	1492	941	3065	3753	7926	898	697	2753	1756	2939	15098	9237	78	368
2035	2809	3310	6572	3207	4140	7703	1491	936	3060	3753	7896	853	664	2661	1751	2611	15073	9237	76	361
2036	2795	3310	6549	3191	4140	7674	1491	932	3054	3753	7866	834	650	2595	1745	2484	15046	9237	74	354
2037	2781	3310	6526	3175	4140	7645	1490	927	3049	3753	7837	816	636	2545	1740	2413	15044	9237	73	347
2038	2767	3310	6504	3159	4140	7617	1488	922	3044	3753	7807	800	623	2507	1736	2375	15031	9237	73	340
2039	2753	3310	6482	3143	4140	7588	1487	918	3039	3753	7778	784	611	2476	1731	2308	15009	9237	72	333
2040	2739	3310	6459	3128	3969	7560	1485	913	3033	3753	7749	770	600	2450	1722	2224	14942	9235	71	327
2041	2726	3310	6437	3112	3788	7532	1484	909	3028	3753	7720	756	589	2429	1693	2168	14272	9216	71	320
2042	2712	3310	6415	3096	3788	7504	1483	904	3023	3753	7691	744	580	2412	1690	2168	14270	9204	70	314
2043	2699	3310	6393	3081	3788	7476	1482	900	3018	3753	7662	732	571	2397	1688	2168	14270	9194	70	307
2044	2685	3310	6372	3066	3788	7448	1481	895	3013	3753	7634	721	563	2383	1680	2168	14270	9192	69	301
2045	2672	3310	6350	3050	3788	7420	1479	891	3008	3753	7606	709	553	2372	1672	2166	14270	9191	69	295
2046	2658	3310	6328	3035	3788	7393	1478	886	3002	3753	7577	699	545	2331	1663	2163	14216	9190	68	290
2047	2645	3310	6307	3020	3788	7365	1477	882	2997	3753	7549	692	540	2295	1659	2156	14141	9190	68	284
2048	2632	3310	6286	3005	3672	7338	1475	877	2992	3753	7521	684	534	2262	1654	2145	14099	9190	68	278
2049	2619	3310	6264	2990	3574	7311	1473	873	2987	3753	7493	677	528	2233	1651	2133	14051	9189	67	273
2050	2606	3310	6243	2975	3494	7284	1472	869	2982	3753	7466	668	521	2207	1648	2109	14011	9182	67	267

Apx Table A.2: Projections data table for 2-degrees climate ambition scenario, 2017 Australian dollars sent-out

	Black coal super critical	Black coal HELE	Black coal with CCS	Brown coal super critical	Brown coal HELE	Brown coal with CCS	Gas combined cycle	Gas peak	Gas with CCS	Biomass	Biomass with CCS	Large scale solar PV	Rooftop solar panels	Solar thermal (6 hrs)	Wind	Wave	Enhanced geothermal	Nuclear	Battery storage	Battery storage BOP
	$/kW	$/kW	$/kW	$/kW	$/kW	$/kW	$/kW	$/kW	$/kW	$/kW	$/kW	$/kW	$/kW	$/kW	$/kW	$/kW	$/kW	$/kW	$/kWh	$/kWh
2017	3074	3312	7000	3510	4140	8250	1501	1025	3161	3784	8456	2100	1600	4815	1950	7157	14475	9313	306	518
2018	3059	3268	6975	3492	3988	8218	1501	1020	3155	3779	8424	1952	1484	4434	1945	6297	14534	9313	232	508
2019	3044	3264	6950	3475	3967	8187	1501	1015	3149	3771	8391	1733	1321	3678	1940	5437	14678	9311	159	498
2020	3028	3249	6926	3457	3953	8155	1501	1009	3143	3758	8359	1635	1248	3299	1934	4578	14810	9311	116	488
2021	3013	3234	6901	3440	3944	8124	1500	1004	3137	3756	8327	1492	1143	3299	1925	3718	14916	9307	105	478
2022	2998	3234	6877	3423	3944	8093	1500	999	3132	3753	8295	1421	1091	3299	1921	3249	15016	9296	103	469
2023	2983	3234	6853	3406	3944	8062	1500	994	3126	3753	8264	1363	1048	3299	1909	3022	15106	9296	101	459
2024	2968	3234	6631	3389	3944	7846	1500	989	2927	3753	8042	1317	1013	3299	1901	2939	15078	9296	99	450
2025	2953	3234	6538	3372	3944	7751	1499	984	2854	3753	7944	1270	980	3299	1900	2779	15059	9296	98	441
2026	2939	3234	6385	3355	3944	7598	1499	980	2722	3753	7788	1229	949	3296	1899	2564	14661	9295	96	433
2027	2924	3234	6246	3338	3944	7460	1498	975	2603	3753	7646	1184	914	3137	1899	2431	14562	9289	94	424
2028	2909	3234	6139	3322	3944	7351	1497	970	2516	3753	7535	1148	887	3032	1899	2342	14509	9289	89	416
2029	2895	3234	6072	3305	3944	7281	1496	965	2468	3753	7462	1082	838	2905	1899	2277	14480	9282	86	407
2030	2880	3234	6033	3288	3944	7236	1496	960	2447	3753	7417	1034	802	2836	1876	2228	14455	9259	84	399
2031	2866	3234	5995	3272	3944	7192	1495	955	2427	3753	7372	990	769	2794	1853	2190	14434	9215	83	391
2032	2852	3234	5968	3256	3944	7159	1494	951	2418	3753	7338	954	741	2790	1837	2168	14430	9214	81	383
2033	2837	3234	5943	3239	3944	7128	1493	946	2411	3752	7306	913	710	2693	1825	2168	14426	9214	79	376
2034	2823	3234	5919	3223	3944	7097	1492	941	2404	3752	7275	870	678	2623	1815	2168	14387	9214	77	368
2035	2809	3234	5895	3207	3944	7067	1491	936	2398	3752	7244	851	662	2570	1796	2167	14282	9214	76	361
2036	2795	3234	5871	3191	3944	7037	1491	932	2391	3752	7213	816	637	2528	1766	2167	14227	9214	74	354
2037	2781	3234	5847	3175	3944	7007	1490	927	2384	3752	7182	798	623	2495	1755	2162	14155	9214	73	347
2038	2767	3234	5822	3159	3944	6977	1489	922	2377	3752	7151	782	610	2468	1745	2149	14118	9214	73	340
2039	2753	3234	5799	3143	3944	6947	1487	918	2371	3752	7120	766	598	2445	1736	2125	14086	9214	72	333
2040	2739	3234	5776	3128	3944	6918	1486	913	2365	3752	7091	752	587	2426	1728	2118	14003	9214	71	327
2041	2726	3234	5753	3112	3944	6889	1485	909	2359	3752	7061	738	576	2410	1711	2106	13938	9213	71	320
2042	2712	3234	5730	3096	3944	6860	1483	904	2353	3752	7032	725	567	2396	1707	2096	13938	9192	70	314
2043	2699	3234	5708	3081	3944	6832	1482	900	2347	3752	7002	715	558	2383	1704	2090	13938	9188	70	307
2044	2685	3234	5686	3066	3944	6804	1481	895	2342	3752	6974	703	550	2372	1702	2079	13937	9185	69	301
2045	2672	3234	5664	3050	3944	6776	1480	891	2336	3752	6945	692	541	2334	1700	2071	13933	9185	69	295
2046	2658	3234	5642	3035	3944	6748	1479	886	2331	3752	6916	682	533	2299	1696	2058	13926	9185	68	290
2047	2645	3234	5620	3020	3944	6720	1477	882	2326	3752	6888	674	527	2267	1691	2052	13926	9185	68	284
2048	2632	3234	5599	3005	3944	6693	1476	877	2320	3752	6860	666	521	2239	1685	2052	13926	9184	68	278
2049	2619	3234	5577	2990	3944	6665	1476	873	2315	3752	6832	658	515	2213	1679	2052	13891	9184	67	273
2050	2606	3234	5556	2975	3944	6638	1476	869	2310	3752	6804	652	510	2190	1675	2052	13890	9184	67	267

5 References

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