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Low Emissions Technology Roadmap

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CSIRO ENERGY

CSIRO Energy is working to ensure economic competitiveness and energy security while enabling the transition to a lower-emissions energy future. We are pioneering energy technologies that create value for industry and households and provide the knowledge to guide us towards a smart, secure energy future. We develop pathways to achieve an enduring legacy from energy resources and the social cohesion to tackle the environmental consequences of the options chosen.

CSIRO FUTURES

CSIRO Futures is the strategic advisory arm of Australia's national science agency. We build on CSIRO's deep research expertise to help clients create sustainable growth and competitive advantage by harnessing science, technology and innovation. We are a trusted advisor to some of Australia's largest companies and government, helping senior decision makers develop evidence-based strategies to address major opportunities and challenges.

Acknowledgements

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We are grateful for the time and input of the stakeholders from industry, government, academia and the CSIRO who were consulted throughout this project. A full list of stakeholders consulted may be found in Appendix E.

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Foreword

Energy lights the way to our future, but like all industries, it is being disrupted by new technology and must reinvent itself. Few new energy technologies have been demonstrated at scale, so a combination of new and existing technologies is needed to ensure our energy security. At CSIRO, we believe science can solve any problem our nation faces. In particular, that industry and environment can and indeed should be partners not competitors.

The reinvention of energy will be largely customer led, so it is appropriate that this Roadmap serves our largest customer – Australia. It is designed to help inform the Australian Government's 2017 climate policy review by providing an independent, science-based analysis of the technology options in the energy sector that can help Australia meet its 2030 emissions reduction target (Paris Agreement, 2015).

This Roadmap is part of a system wide approach to mapping Australia's future markets. It helps us tackle our future challenges before they are upon us – using excellent science. It also provides an assessment of how low emission technologies can create both new growth opportunities but also new challenges for Australian industry. We believe that Australia, with its natural energy resources and manufacturing capabilities, is well-positioned to benefit from the global transition to low-emissions energy. Many of these opportunities are underpinned by Australian science and technology.

But the world is changing rapidly and if we want to capitalise on these opportunities we need to move quickly. This is Australia's 'innovation imperative'. The innovation challenges within the energy sector are indicative of the broader challenge we currently face as a nation. Through our role as Australia's innovation catalyst, and the implementation of Strategy 2020, we are committed to addressing such challenges by progressing world-class science and continuing to work with Australian businesses to develop commercial solutions.

We are doing this in a number of ways. We have made a significant investment in six Future Science Platforms that will underpin innovation and that have the potential to help reinvent and create new industries for Australia. We have also established a new $200 million CSIRO Innovation Fund to invest in the development of early stage technology opportunities from the public research sector. We have also created a national science accelerator, ON, which is bridging the gap between science and solutions.

CSIRO has a formidable track record when it comes to turning world class low emissions technology research into globally-adopted solutions as shown in the case of BuildingIQ and UltraBattery. We recently deployed solar thermal technology in China, and storage for grid stabilisation against renewables in the US.

We have already demonstrated that energy efficiency and smart grid technologies can offer real solutions now. We have also made breakthroughs in energy storage and transport using Hydrogen. Plus, demonstrated cleaner coal, by converting it to a new form of diesel with almost half the emissions. Our Futures team is also working with Australian companies to help them better understand future technology-driven opportunities and develop strategies to harness them.

We look forward to continuing to work with Australian businesses and government to enhance our economic competitiveness and energy security, while enabling the transition to a lower emissions future that will benefit all Australians.

Dr Larry Marshall
Chief Executive
CSIRO

Executive summary

Australia needs an energy sector that addresses the 'energy trilemma' – that is to say it must provide energy security, affordability and environmental sustainability. After a period of relative stability, significant change in the energy sector can be expected in coming years due to the need to reduce greenhouse gas (GHG) emissions, together with the rapid pace of technological development occurring in the sector.

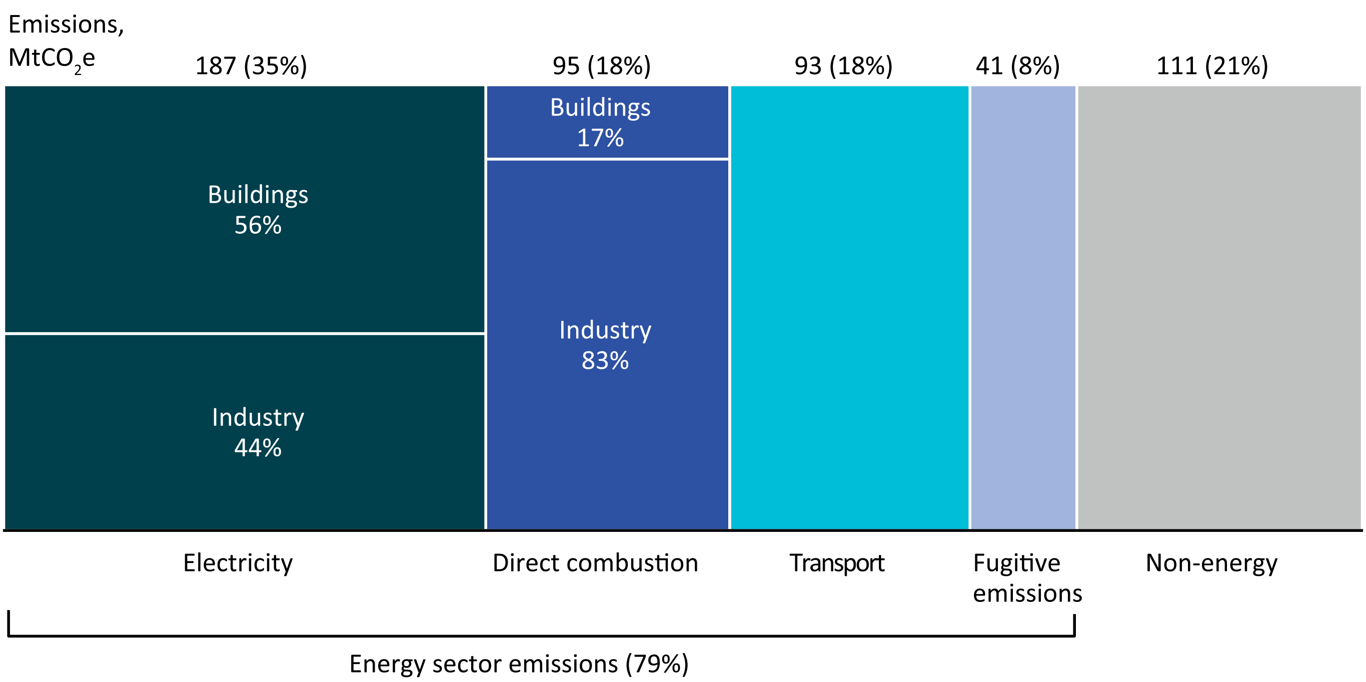
This roadmap seeks to help policy and other decision makers navigate this change by highlighting the key technologies that Australia can draw on as it endeavours to address the energy trilemma. It also identifies the barriers to these technologies and the potential enablers that may be called on to overcome them.

Lastly, the roadmap identifies the key commercial opportunities for industry that low emissions technologies in the energy sector can provide.

Australia's emissions reduction target

On 10 November 2016, Australia ratified the Paris Agreement, committing to achieve a 26-28% reduction in GHG emissions below 2005 levels by 2030. The Paris Agreement also requires signatories to strengthen their abatement efforts over time with the overarching goal of limiting the increase in global average temperature to well below 2°C above pre-industrial levels, with efforts to limit the temperature increase to 1.5°C. The Paris Agreement also recognises that the world will need to achieve zero net emissions in the second half of the century. To achieve this level of decarbonisation, Australia will need to adopt a multi-faceted approach, primarily targeting emissions reduction in the land and energy sectors. The energy sector, which is the focus of this roadmap, will play a key role given it accounts for 79% of Australia's emissions.

BREAKDOWN OF AUSTRALIA'S 2015 EMISSIONS[1]



[1] From (Department of Environment and Energy, 2016). Direct combustion includes emissions from burning coal and gas for industrial and building heat, steam and pressure as well as emissions from combustion of fuel for mobile equipment in mining, manufacturing, construction, agriculture, forestry and fishing. Fugitive emissions includes GHG released during coal mining, and oil and gas production and transport. The split of electricity between buildings and industry is approximated from electricity consumption of commercial and residential as percentage of total thermal electricity in 2014-15 from 2016 Australian Energy Statistics (Office of the Chief Economist, Table F). Split for direct combustion calculated from (Australian Government Department of the Environment and Energy, 2016).

Objectives of the Low Emissions Technology Roadmap

In light of the need for the energy sector to contribute towards Australia's carbon abatement target, to address the energy trilemma more broadly, and to continue to play a central role in growing Australia's prosperity, this roadmap has two key objectives:

1. **The primary objective is to identify the emission reduction technology options within the energy sector that Australia could pursue in order to meet or exceed its 2030 target and achieve deeper decarbonisation post-2030.** The report also considers what actions might be required to achieve rollout of these technologies, while continuing to maintain energy security and affordability.

2. **The secondary objective is to identify the main opportunities presented by low emissions technologies, in terms of economic value and job creation.** The transition to a low emissions economy is often framed in terms of cost; this roadmap seeks to broaden the discussion by also highlighting the opportunities and net benefits that the identified technologies and associated industries can provide.

Approach

In the bottom up analysis, a wide range of technologies were examined, considering criteria such as abatement potential, risk (including technological and commercial readiness), cost (both current and projected), and level of industry support. Based on this analysis, the technologies most likely to play a key role in addressing the energy trilemma were identified, and were further analysed to identify associated barriers, potential enablers and commercial opportunities.

This analysis included wide-ranging consultation with technology experts as well as government and industry stakeholders. Pathways were then constructed to illustrate how these technologies may be combined, and to demonstrate major options available to reduce emissions. Modelling was carried out to demonstrate potential rates of technology deployment, consistent with GHG abatement targets, and to inform how the deployment of low emissions technologies might impact energy costs.

In the context of this roadmap, a pathway is defined as a scenario that explores how a particular set of key technologies can contribute to decarbonisation of the Australian energy sector while maintaining energy security and affordability. Four pathways were developed in order to explore how major shifts in electricity generation and energy use in buildings, industry and transport could impact decarbonisation to 2050.

The key differences between pathways relate to the main options that exist across the different energy subsectors. In buildings, industry and transport, the key options relate to how fast energy productivity improvements take place. Pathways 1 and 4 examine the role that ambitious improvements in energy productivity can play in reducing emissions, while Pathways 2 and 3 assume business as usual (BAU) productivity improvements. 'Ambitious' in this context refers to a rate of improvement at the higher end of what appears to be feasible given the barriers involved, and roughly corresponds to the full opportunity identified in the National Energy Productivity Plan (NEPP), equivalent to a doubling Australia's energy productivity by 2030[2]. BAU roughly corresponds with existing NEPP targets of 40% improvement by 2030, which accelerates energy productivity above what has been achieved historically but does not achieve its full potential.

The other key difference between pathways relates to new build electricity generation technologies. In Pathway 1, given that the focus of the pathway is on energy productivity, new generation is restricted to technologies that have been recently deployed, namely wind, solar PV and gas, with limits placed on deployment of wind and solar PV. Pathway 2 examines the full extent of the role variable renewable energy (VRE) technologies such as wind and solar PV can play, with particular focus on the enabling technologies required to achieve a high share of VRE. Pathway 3 examines the role low emissions, dispatchable technologies can play, namely concentrating solar thermal (CST) with storage, high efficiency low emissions (HELE) fossil fuel technologies with carbon capture and storage (CCS), nuclear and geothermal.

All pathways assume uptake of cost-effective technologies for the abatement of fugitive emissions from coal mining, and oil and gas production. Pathways 3 and 4 also investigate the role hydrogen can play as an energy storage medium across the energy sector.

[2] See www.2xep.org.au

SUMMARY OF PATHWAYS

	1 Pathway 1: Energy productivity plus	2 Pathway 2: Variable renewable energy	3 Pathway 3: Dispatchable power	4 Pathway 4: Unconstrained
Buildings, industry and transport	**Ambitious energy productivity improvements**	**Business as usual energy productivity improvements**		**Ambitious energy productivity improvements**
			Hydrogen for transport and export	
New build electricity generation	**Existing low emissions technologies**: wind, solar PV (45% limit) plus gas	**Cheap, mature, low emissions generation**: mainly wind and solar PV **plus enabling technologies** e.g. batteries pumped hydro	Wind and solar (45% limit) plus **low emissions, dispatchable generation**: • Concentrating solar thermal with storage • High efficiency, low emissions fossil fuels with carbon capture and storage • Nuclear • Geothermal	**All low emissions technologies allowed, with no limit on wind and solar PV**
Fugitive emissions	**Uptake of cost-effective technologies**			

It is important to recognise that the pathways are not intended as deterministic predictions. Rather, they are designed to illustrate some of the plausible combinations of technology options that arise based on assumptions on the rate of technology development and external drivers. They also enable an examination of the associated trade-offs, costs, risks and opportunities and allow comparisons to be made between different choices. No one pathway is recommended as preferable; rather, they are intended to serve as a tool for policy and other decision makers to conceptualise possible futures in the face of considerable uncertainty.

Key findings

I. Australia is well positioned to benefit from innovation in low emissions technologies

1. **Australia has many sources of comparative advantage for low emissions technologies to build on.** While the transition to a low emissions economy is often framed in terms of cost, this transition will also create demand for new products and services both in Australia and in export markets. Australia is endowed with some of the world's best energy resources, has good skills in low emissions technologies, strong institutions and strong trading relationships with key consumers of energy. These advantages leave it well placed to benefit from a domestic and global transition to low emissions energy. Capturing these benefits will require decisions on where to focus effort and long-term commitment to the required actions.

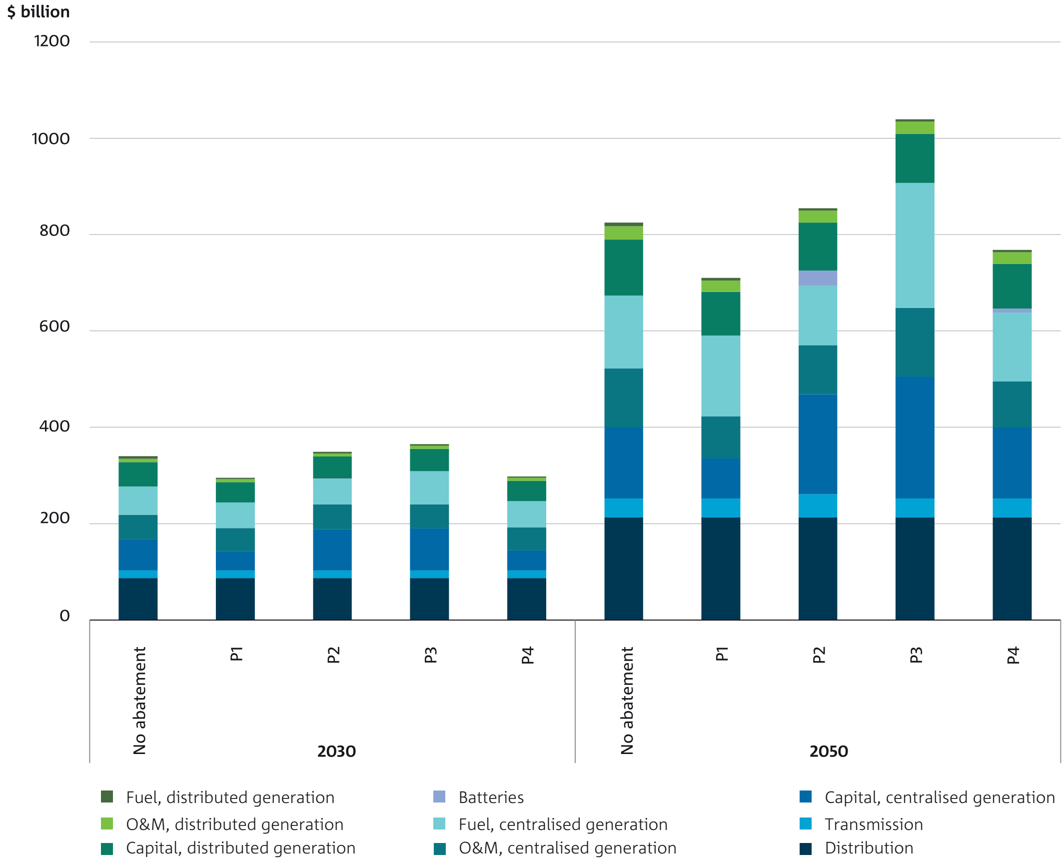
2. **Australia's existing strengths and needs can guide both local technology RDD&D and Australia's role in global efforts.** Australian research, development, demonstration and deployment (RDD&D) of low emissions technologies can be guided by comparative advantage, existing strengths and where there are local problems to solve. While relying on other countries for many technologies, Australia can also play an important role in global uptake of low emissions technologies, by contributing to technology development, helping regional neighbours deploy technologies, demonstrating possibilities to other countries and exporting low emissions commodities and products.

II. Ambitious improvements in energy productivity, enabled by largely mature technologies, can unlock billions of dollars of cost savings

3. **There are largely mature technologies available within the buildings, industry and transport sectors that could enable significant improvements in energy productivity.** While energy productivity is a key focus for industry leaders, opportunities still remain for many companies. For buildings, considerable energy productivity gains could be realised through more extensive adoption of mature technologies such as efficient lighting, heat pumps, improved building envelopes and higher efficiency appliances and equipment. In the industrial sector, gains can be made via higher efficiency equipment (e.g. boilers, trucks, grinders, motors), electrification, fuel switching, improved use of waste heat as well as use of renewable heat (e.g. from biomass or solar thermal). Improvements within transport can be made through incremental improvements in mature technologies, such as higher efficiency internal combustion engines and improved vehicle aerodynamics. Fuel substitution (e.g. advanced biofuels, hydrogen vehicles and particularly electric vehicles) will increasingly deliver abatement, and energy productivity in transport can be further improved through demand reduction (e.g. mode shifting, telecommuting and improved routing in freight).

4. **Ambitious improvements in energy productivity can help minimise energy spend.** Pathways with faster improvements in energy productivity have significantly lower average household electricity, gas and transport costs by 2030 than pathways with slower improvements. In the electricity sector, improving energy productivity reduces the amount of electricity required and consequently the price, given that less new build generation is required. In transport, improved energy productivity primarily lowers cost through lower operating costs for electric vehicles (EVs), compared with internal combustion engine vehicles (after the mid-2020s), and reduced demand for travel (measured in vehicle-km). Potential savings from increased energy productivity represent a $20 billion opportunity to 2030 in buildings (Australian Sustainable Built Environment Council, 2016) and $14 billion of cumulative benefit to 2040 in road transport (Department of Infrastructure and Regional Development, 2016).

ELECTRICITY SUPPLY CHAIN SPEND IS LEAST IN PATHWAYS 1 AND 4, WHICH HAVE AMBITIOUS IMPROVEMENTS IN ENERGY PRODUCTIVITY



III. A range of technologies exist to allow deep decarbonisation of the electricity sector while maintaining security and reliability of supply, as well as providing significant opportunities for Australian industry

5. **A secure and reliable electricity system based on low emissions wind and solar PV could be possible and cost effective, but technical challenges must be addressed.** Maintaining reliability in a system with high wind and solar PV share requires technologies that provide flexibility in matching supply and demand, such as energy storage (e.g. batteries and pumped hydro) and demand response (enabled by smart grid technologies), as well as other approaches such as building excess VRE generation capacity and geographic and technology diversity. Modelling carried out for this roadmap finds that with a mix of battery storage, excess VRE capacity and gas generation, a reliable electricity system delivering 95% abatement in 2050 compared with 2005 levels and VRE share of ~90% is possible at moderate cost (as compared to the no abatement scenario in the figure below).

   In addition to maintaining reliability, it will be critical to ensure system security, via additional enabling technologies such as synthetic inertia from batteries, wind farms and synchronous condensers. These technologies are expected to be low cost compared with total system spend. For instance, for the mainland network operating with high non-synchronous penetration, an initial conservative estimate suggests $7 billion worth of synchronous condensers could provide sufficient inertia and fault current; this is less than 1% of cumulative total system spend to 2050. However, as a priority, these technologies need to be appropriately trialled, tested and demonstrated at scale under a range of operating scenarios. This requires a considered, whole of industry approach.

6. **An alternate scenario for electricity generation sees a transition to low emissions dispatchable generation, with less need for grid transformation.** Deep decarbonisation of the electricity sector could be achieved using a suite of low emissions electricity generation technologies like CST with storage, post carbon capture (PCC) retrofit and/or HELE with CCS, nuclear, and geothermal. These technologies are dispatchable and synchronous[3] and therefore avoid the challenges involved in reaching a high share of wind and solar PV (e.g. intermittency, lack of inertia). These technologies should be considered individually, with the benefits of dispatchability and inertia balanced with the unique cost and risk profiles (technology, commercial, social licence) of each of these technology options and their anticipated development paths.

7. **Gas could contribute to decarbonisation of electricity generation, with energy productivity potentially helping to address supply constraints.** While decarbonisation is supported by a shift away from gas in buildings and parts of industry, gas could play a role as a transition fuel in electricity generation. From an emissions point of view, the duration of this role could be extended if ambitious improvements in energy productivity are realised or if gas generation is combined with CCS. Improved energy efficiency and electrification could reduce gas demand from buildings and industry, helping ease supply constraints for electricity generation. Increased reliance on gas however would further expose the electricity sector to the risk of price increases.

8. **While the existing coal power industries may decline, the transition to low emissions electricity presents significant opportunities for Australian industry**. The move away from existing thermal generation will impact the local economy, particularly in communities reliant on power stations for employment.

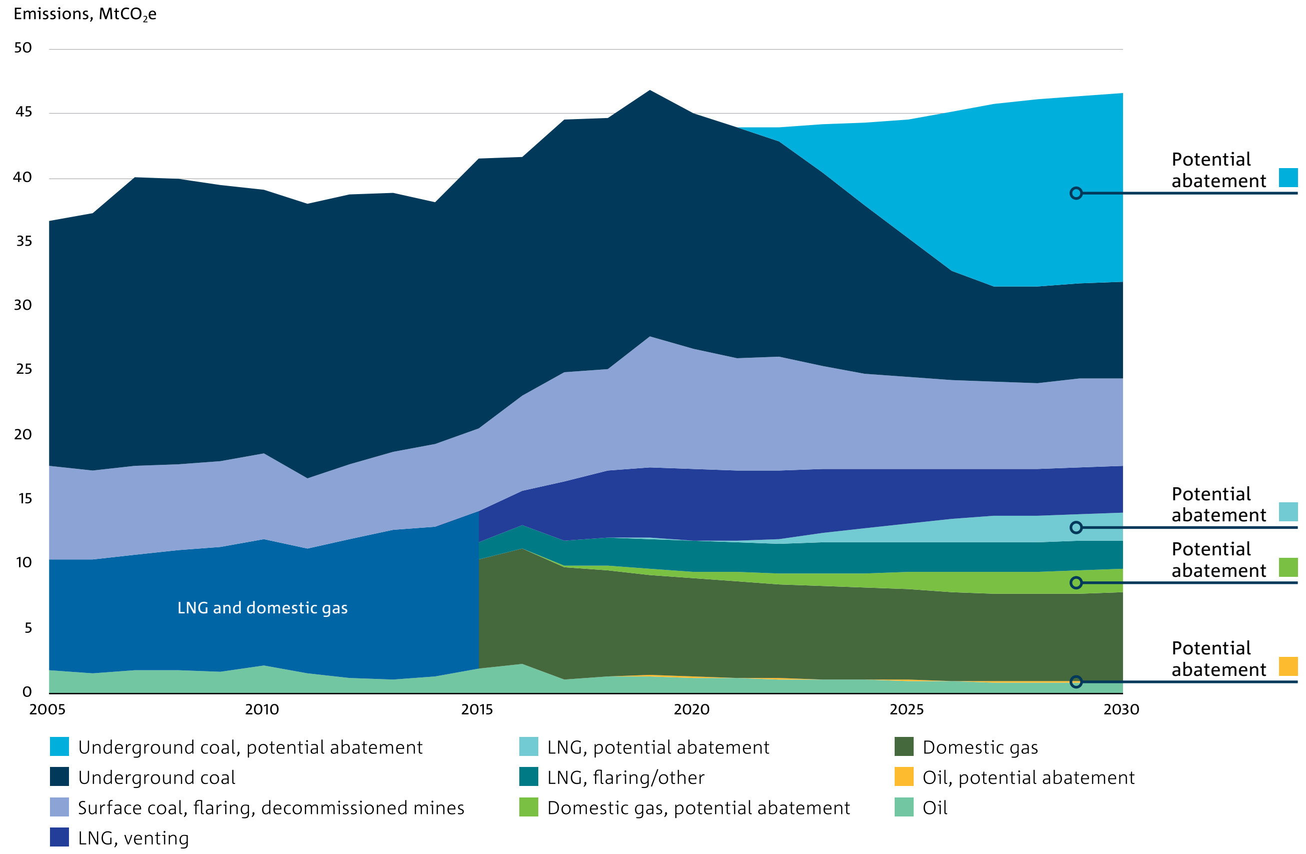
   However, replacing Australia's existing generation fleet with low emissions technologies will create significant opportunities in the electricity sector in construction, installation, operations and maintenance (O&M) which provide a source of employment that could continue for decades.

[3] Dispatchable generation is electricity generation that can be turned on and off when required. Synchronous generation is electricity generation that uses large rotating masses synchronised with the frequency of the alternating current (AC) grid. The rotating masses have high inertia, which helps stabilise the frequency of AC grids.

Large-scale low carbon electricity also presents opportunities for manufacture of specialised components such as heliostats for the domestic market and for export. Further, the transition to decentralised low carbon electricity presents opportunities for innovative Australian companies to develop new products and services such as home energy management systems. Australia's leading position in this transformation means Australian companies are well placed to export such products and services. Export opportunities also exist in energy engineering and consulting services such as renewable energy policy, standards and project development. This could also allow Australia to help regional neighbours achieve low carbon growth.

The magnitude of the impact of a move away from coal could also be reduced though the deployment of HELE coal-fired power generation and CCS in both Australia and its trading partner nations. Additionally, CCS could enable the local production of low emissions hydrogen via gasification of coal. This has the potential to become a key export opportunity for Australia and to help transition communities impacted by a decline in coal-fired generation.

TECHNOLOGIES FOR THE ABATEMENT OF FUGITIVE EMISSIONS COULD ACHIEVE 19 MtCO$_2$e OF ABATEMENT BY 2030[4]

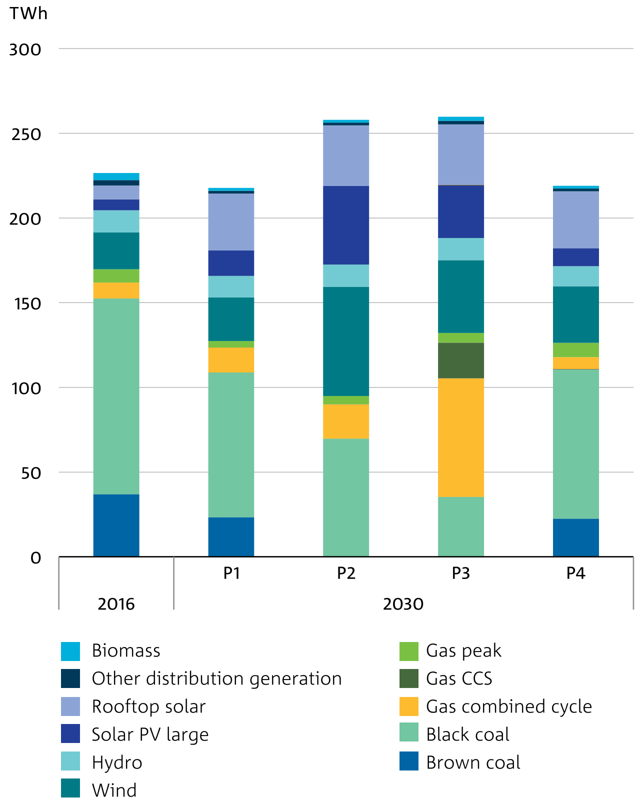


[4] Current and BAU projected emissions are from (Australian Government Department of the Environment and Energy, 2016). Potential abatement is from CSIRO modelling. Assumes BAU gas consumption; domestic gas consumption, and hence fugitive emissions, increases or decreases depending on the pathway.

IV. Fugitive emissions from coal mining, and oil and gas production could be reduced by 40% compared to BAU in 2030

9. **Innovative technologies could allow fugitive emissions from coal mining, and oil and gas production to be reduced by up to 40% compared to BAU in 2030, as well as providing export opportunities.** Technologies currently in development in Australia for the abatement of ventilation air methane (VAM) in underground coal mining could potentially be deployed at scale by 2030, achieving approximately 80% abatement of emissions from this source. These technologies also represent an export opportunity for Australia, especially to China. Fugitive emissions from liquefied natural gas (LNG) production could be reduced by deployment of CCS where economically feasible. Further, abatement of fugitive emissions in oil and gas production and in domestic gas transmission and distribution could be achieved through improved operational practices. Combined, these technologies could decrease fugitive emissions by 19 $MtCO_2e$ in 2030 compared with BAU and contribute 8% of energy sector abatement.

NEW GENERATION TO 2030 IS MOSTLY ONSHORE WIND AND SOLAR PV ACROSS ALL PATHWAYS



V. The energy sector can achieve a proportional share of the 2030 target and achieve deeper abatement post-2030

10. **New electricity generation to 2030 is likely to comprise mainly wind and solar PV. In each pathway, onshore wind and large-scale and rooftop solar PV are expected to make up the majority of new generation to 2030.** This is due to the low cost, low emissions and commercial maturity of these technologies. An exception is Pathway 3, where gas combined cycle could also form a large part of the mix, combined with CCS towards the end of this period. Less new generation is required to be built in Pathways 1 and 4. These pathways also show slower decreases in coal-fired generation.

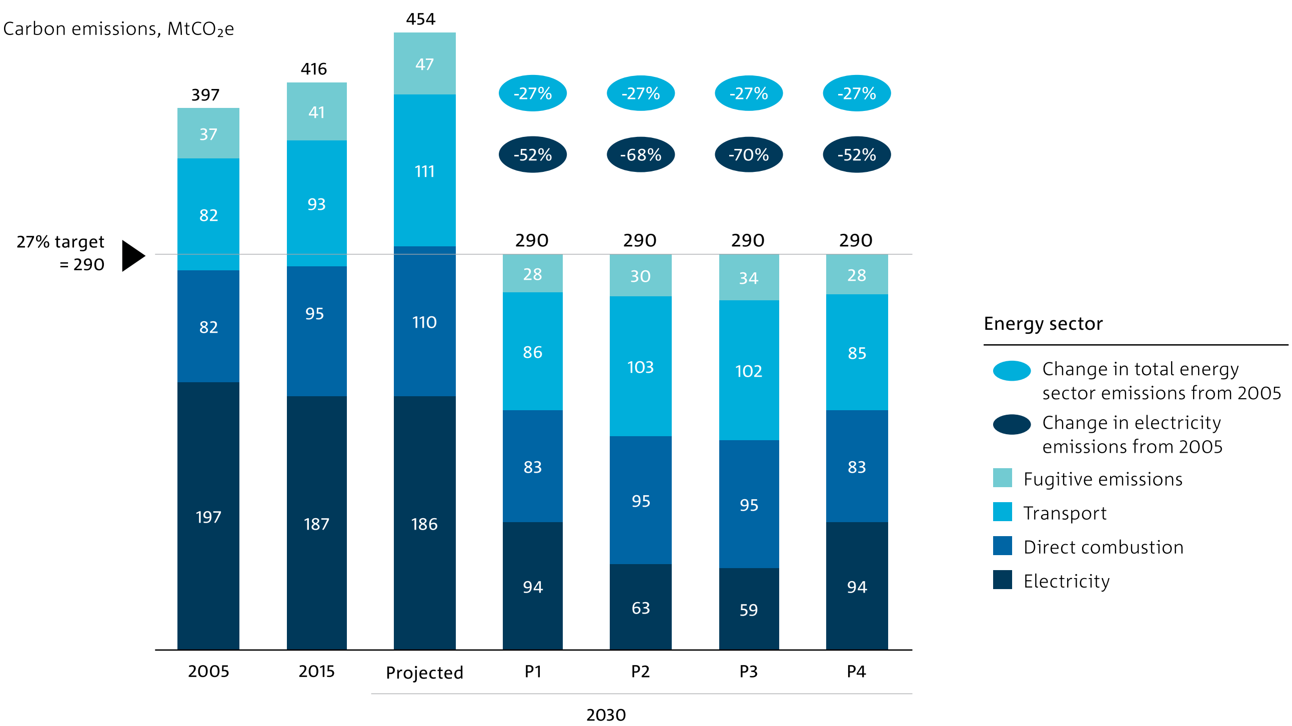
11. **In addition to unlocking billions of dollars of savings, ongoing improvements in energy productivity can prevent increases in emissions in transport and direct combustion to 2030.** As mentioned in Key Finding 4, improving energy productivity can lead to energy cost savings and further decarbonisation.

Even BAU (as opposed to ambitious) energy productivity improvements allow for significant increases in emissions to be avoided. For example, for pathways 2 and 3, despite increasing demand, 2030 transport and direct combustion emissions remain flat as compared with 2015 levels.

For the transport sector, in 2015, road vehicles were responsible for 85% of total transport emissions. Most of the potential abatement in road vehicle emissions to 2030 is likely to stem from improvements in vehicle efficiency, which can offset expected growth in transport demand.

Abatement of direct combustion emissions in buildings and industry can be achieved through energy efficiency improvements, electrification and fuel switching (including direct use of renewables such as CST and bioenergy). An important point to note is that achieving ambitious improvements in energy productivity now, particularly in relation to the deployment of new demand side assets, will help to avoid locking in higher emissions assets that would make subsequent decarbonisation more difficult.

ALL PATHWAYS CAN ACHIEVE THE 2030 TARGET, WITH SLOWER TRANSITION OF THE ELECTRICITY SECTOR POSSIBLE IN PATHWAYS WITH AMBITIOUS IMPROVEMENTS IN ENERGY PRODUCTIVITY (P1 & P4)



12. **Ambitious improvements in energy productivity can allow more time to transition the electricity sector to low emissions generation.** Ambitious increases in energy productivity can allow more time for Australia to transition the electricity sector to low emissions generation and still meet 2030 targets.

There are two reasons for this. Firstly, increasing the rate of energy productivity improvements from BAU to the more ambitious rates (shown in Pathways 1 and 4) would result in up to 35 $MtCO_2e$ of additional abatement (including the effect of reduced gas use on fugitive emissions). Secondly, ambitious energy productivity rates can offset BAU demand growth and increased demand from electrification (as shown in Pathway 1 and 4). These two effects mean that electricity sector emissions can be higher in Pathways 1 and 4 than in Pathways 2 and 3 with the energy sector as a whole still achieving 26-28% abatement compared with 2005 levels by 2030. In Pathways 1 and 4, electricity sector emissions in 2030 could be up to 94 $MtCO_2e$, while in Pathways 2 and 3 they could be up to 59-63 $MtCO_2e$, corresponding to reductions in electricity sector emissions of 52-70% compared with 2005 levels. Less electricity sector abatement could be targeted if faster improvements in energy productivity than assumed in this report prove feasible, or if greater abatement is achieved outside the energy sector.

EACH PATHWAY FACES RISKS; PROGRESSING MULTIPLE PATHWAYS WILL ALLOW OVERALL RISK TO BE MINIMISED

		PATHWAYS			
	Description	1 PATHWAY 1: Energy productivity plus	2 PATHWAY 2: Variable renewable energy (VRE)	3 PATHWAY 3 Dispatchable power	4 PATHWAY 4 Unconstrained
Technology, commercial and market risk	**Technology risk:** Technology needs development to overcome technical challenges or to bring down costs **Commercial risk:** Technology not commercially mature in Aus. hence costs not well understood **Market risk:** Revenue generated over the lifetime of the asset is uncertain		Technological challenge to transform the electricity grid to support VRE at high share with acceptable security and reliability, with uncertain cost of transformation	Market risk with large, long lead time projects given uncertain demand Technology and commercial risk with HELE, CCS, CST, geothermal and nuclear	As per P2
Social licence risk	Technology may face opposition from local community, broader community or specific groups e.g. environmental groups	High reliance on expansion of domestic gas for electricity generation	Social licence risk with wind power	Social licence risk with new build coal, CCS, nuclear and with expansion of domestic gas for electricity generation	Social licence risk with gas and CCS
Stakeholder coordination risk	Deploying the technology depends on coordination or behaviour change of a large number of individuals or groups	Relies on behaviour change by millions of energy users	Transformation of the grid to support high share of VRE requires overcoming regulatory and cultural challenges	Investor coordination typically required for large capital projects	As per P1 and P2

Timeframe in which risk becomes significant

Before 2020 | 2020–2030 | After 2030

13. **Continued uptake of likely low emissions technologies could allow the energy sector to reduce emissions by 55-69% by 2050.** Deep cuts in energy sector emissions by 2050 will be challenging but possible through a combination of deep decarbonisation of electricity generation and sustained, ambitious improvements in energy productivity in buildings, industry and transport. This could allow abatement of almost 70% compared with 2005 levels with the technologies considered in this report, at rates of uptake likely to be feasible. There may be further opportunities to reduce energy sector 2050 emissions if faster deployment proves possible, as well as through deployment of additional, more prospective technologies. Achieving net zero emissions across the economy in the second half of the century however will likely depend on negative emissions (i.e. net removal of GHG from the atmosphere) in land use, land use change and forestry (LULUCF) and/or carbon credits from other countries which is outside the scope of this report.

14. **Progressing multiple pathways would allow Australia to reduce the risks in addressing the energy trilemma.** Each pathway faces a different set of risks, including technology risk, commercial risk, market risk, social licence risk and stakeholder coordination risk. By simultaneously progressing multiple pathways, the overall risk in transitioning to a low carbon energy sector, while maintaining energy security and affordability, can be minimised. Progressing pathways will require enabling actions as described below.

15. **Low emission energy technologies are higher cost and have a number of associated risks that need to be addressed in order to encourage investment from the private sector.** With the exception of regulated networks, Australia's energy sector is designed to be competitive such that new technologies are supplied and purchased by private investors at their own risk. For the most part, investment in new low emission energy technologies comes at a higher cost than continued use of currently deployed higher emissions technologies. Additionally, abatement opportunities, regardless of cost, may face a range of non-financial barriers to investment (including technical, social and stakeholder barriers). Without the right regulatory/policy environment, these risks manifest as barriers to investment and therefore serve as a barrier to adoption of new technologies.

    Examples of present policies and institutions designed to overcome these barriers to investment include the Clean Energy Finance Corporation (CEFC), Australian Renewable Energy Agency (ARENA) and State and Federal Renewable Energy Targets. Existing policies do not yet address all available energy sector abatement opportunities or target each of the types of risks faced. Additional policies will therefore likely be required to ensure a broader range of low emissions technologies are deployed and that investment returns are strong enough (relative to risk) for deployment to proceed at the rate required.

Next steps

Key strategic decisions

The Australian Government will review its climate change policies in 2017 to ensure they are effective in achieving the 2030 target and Paris Agreement commitments. The Low Emissions Technology Roadmap, along with findings from the Finkel Review into the Security and Reliability of the National Electricity Market, will be inputs into that review.

Policy makers face a range of strategic decisions that need to be made now in order to inform policy design, as well as to inform priorities for RDD&D and community engagement. These decisions include:

- Whether policy should be national vs jurisdiction-specific?
- Whether policy to drive uptake of low emissions technologies should be economy-wide vs sector-specific?
- Whether policy should be technology neutral vs technology specific?
- How much should governments rely on private sector co-funding for RDD&D support for specific technologies?
- Whether Australia should develop technology locally vs acting as a 'technology taker'?

There are also specific key questions for policy makers to decide on regarding the future of nuclear power and domestic gas supply.

While action would be required in the short term to maintain optionality regarding low emissions dispatchable electricity generation technologies, there is a further set of strategic decisions that can be made post-2020 on whether to decrease or increase support for each of these technologies.

Section 4.1 of the report discusses the key points that could be considered in making each of these strategic decisions.

Key enabling actions

Policy is the most critical enabler for addressing the key barrier to low emissions technologies, namely the risk to investors of deploying them in favour of their higher emission alternatives. Stakeholder engagement, skills and business models and RDD&D funding are also important.

The key enabling actions are listed below, with additional enablers and further detail provided in the body of the report. The relevant actors in each case vary, with government responsible for policy, but with a combination of government and industry responsible for other actions.

POLICY

Action 1.1 Review targeted rate of improvement in energy productivity ('Ambitious' or 'BAU') and revise policy as needed to support this rate, for instance to overcome market failures such as split incentives, competing priorities and lack of information.

Action 1.2 Implement stable, long term policy to drive uptake of low emissions electricity generation technology consistent with required electricity sector decarbonisation.

Action 1.3 I mplement policy to drive deployment of enabling technologies for VRE.

Action 1.4 Implement policy to incentivise full deployment of cost-effective technologies to reduce fugitive emissions from coal mining, and oil and gas production.

STAKEHOLDER ENGAGEMENT

Action 2.1 Provide supporting data, information as well as training and education to assist in driving uptake of technologies that improve energy productivity in buildings and industry.

Action 2.2 Continue stakeholder engagement for electricity sector transformation, including creating a technical roadmap to transition the grid to support higher shares of distributed generation and large-scale variable renewable generation with continued security and reliability.

Action 2.3 Communicate findings from the demonstration and deployment of key technologies such as utility-scale battery storage, CCS and microgrids with a high share of renewables, to increase stakeholder confidence in these technologies and enable further deployment.

Action 2.4 Accelerate deployment of consumer technologies such as rooftop solar PV, behind the meter batteries and EVs through increased consumer engagement, including by retailers and other consumer-facing technology providers.

Action 2.5 Continue engagement with the community on all technologies with potential social licence barriers e.g. wind, gas, nuclear and CCS.

SKILLS AND BUSINESS MODELS

Action 3.1 Upskill industries to support rollout of new low emissions technologies, particularly in the electricity sector and in industries where new supply chains will require development.

Action 3.2 Develop business models that increase the rollout of low emissions technologies, e.g. by offering mobility as a service using low emissions vehicles, by offering smart systems to increase energy productivity, and by aggregating behind the meter batteries to provide ancillary services.

RESEARCH, DEVELOPMENT, DEMONSTRATION AND DEPLOYMENT

Action 4.1 Review RDD&D program, ensuring efforts are aligned with comparative advantage, existing strengths, local needs, market opportunities and international collaborations.

Action 4.2 Support demonstration and deployment projects aimed at improving energy productivity in buildings, industry and transport, including through energy efficiency, fuel switching, electrification and direct use of renewable energy for heat.

Action 4.3 Continue RDD&D in low emissions energy generation technologies, such as Solar PV, CST and CCS, aimed at bringing down costs and establishing supply chains.

Action 4.4 Undertake a cross-disciplinary program to understand how to transition electricity grids (including remote area power systems and microgrids) to support higher shares of distributed energy resources and variable renewable energy at least cost, while maintaining security and reliability, including detailed system modelling at sub-5 second timescales, grid-scale demonstration projects (e.g. in South Australia) and development of cyber-security architectures and protocols.

Action 4.5 Increase RDD&D in bioenergy and low emissions hydrogen, including bioenergy conversion pathways, development of bioenergy feedstocks and supply chains and development of hydrogen for export.

Action 4.6 Conduct R&D in next generation VAM abatement technologies and carry out commercial scale demonstration projects for VAM abatement technologies.

Due to the uncertainties inherent in technological development, it will be important to review the findings of this roadmap at regular intervals and to adjust enablers accordingly. In terms of policy, these reviews should generally only be minor course corrections. Stable policy is crucial to creating the investment certainty required to drive investment in low emissions technologies.

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Abbreviations

AC	Alternating current
AEMC	Australian Energy Market Commission
AEMO	Australian Energy Market Operator
AER	Australian Energy Regulator
ANU	Australian National University
ANZSIC	Australian and New Zealand Standard Industrial Classification
ARENA	Australian Renewable Energy Agency
BAU	Business as usual
BECCS	Bioenergy with carbon capture and storage
BMS	Battery management system
BoS	Balance of System
BTM	Behind-the-meter
CAES	Compressed air energy storage
CCS	Carbon capture and storage
CEFC	Clean Energy Finance Corporation
CfD	Contract for difference
C	Carbon
CNG	Compressed natural gas
CO	Carbon monoxide
COAG	Council of Australian Governments
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
CRI	Commercial readiness index
CSIRO	Commonwealth Science Industry Research Organisation
CST	Concentrated solar thermal
DC	Direct current
DER	Distributed energy resource
DICE	Direct injection carbon engine
DNI	Direct normal irradiation
ECBM	Enhanced coal bed methane recovery
EE	Energy efficiency
EGS	Enhanced geothermal systems
EITE	Energy intensive trade exposed
ENA	Energy Networks Australia
EOR	Enhanced oil recovery
EP	Energy productivity
EPC	Engineering, procurement and construction
ERF	Emissions Reduction Fund
ESM	Energy sector model
EUA	Environmental upgrade agreements
EV	Electric vehicle
FCAS	Frequency control ancillary services
FCSPS	Frequency Control System Protection Scheme
FCV	Fuel cell vehicle
FFR	Fast Frequency Response
FGD	Flue gas desulphurisation
FiTs	Feed in tariffs
FLNG	Floating liquefied natural gas
FT	Fischer Tropsch
GCCSI	Global carbon capture storage institute
GDP	Gross Domestic Product
GHG	Greenhouse gas
GPG	Gas for power generation
GW	Gigawatt
H2	Hydrogen gas
HELE	High efficiency low emissions
HESC	Hydrogen Energy Supply Chain
HSA	Hot Sedimentary Aquifer
HTF	Heat transfer fluid
HTL	Hydrothermal liquefaction
HVAC	Heating, ventilation and air conditioning
HVDC	High voltage direct current
IAEA	International Atomic Energy Agency
ICE	Internal combustion engine
ICT	Information and communications technology
IEA	International Energy Agency
IGCC	Integrated gasification combined cycle

IP	Intellectual property
LCA	Life-cycle analysis
LCOE	Levelised cost of electricity
LED	Light-emitting diode
LETR	Low Emissions Technology Roadmap
LNG	Liquefied natural gas
LULUCF	Land use, land use change and forestry
MEPS	Minimum Energy Performance Standard
MMV	Measurement, monitoring and verification
MSW	Municipal solid waste
Mt	Megatonnes
$MtCO_2e$	Megatonnes of CO_2 equivalent
Mtpa	Million tonnes per annum
MW	Megawatt
MWh	Megawatt hour
MWt	Megawatt thermal
NGL	Natural gas liquids
NEFR	National Electricity Forecasting Report
NEM	National Electricity Market
NEPP	National Energy Productivity Plan
NFCRC	Nuclear Fuel Cycle Royal Commission
NOx	Mono-nitrogen oxides
NPV	Net Present Value
NSP	Non-synchronous penetration/Network service provider
NTNDP	National Transmission Network Development Plan
O&G	Oil & gas
O&M	Operations & Maintenance
ORE	Ocean Renewable Energy
O_2	Oxygen gas
PCC	Post-combustion capture
Pf	Pulverised fuel
PHES	Pumped hydro energy storage
PHEV	Plug-in hybrid vehicles
PPA	Power purchase agreements
PtG	Power to Gas
PQ	Power quality
PV	Photovoltaic
R&D	Research & development
RAPS	Remote area power systems
RD&D	Research, development, demonstration
RDD&D	Research, development, demonstration and deployment
RET	Renewable Energy Target
RoCoF	Rate of change of frequency
SAPS	Standalone power system
SCADA	Supervisory control and data acquisition system
SCR	Selective catalytic reduction
SRMC	Short-run marginal cost
SME	Small to medium enterprises
SMR	Steam methane reforming/Small modular reactors
SO_2	Sulphur dioxide
SUV	Suburban utility vehicle
SWIS	South-West Interconnected System
Syngas	Synthesis gas
TCO	Total cost of ownership
TEF	Thermochemical energy storage
Totex	Total expenditure
TOU	Time-of-use
TRL	Technology readiness level
UNSW	University of New South Wales
USD	US Dollar
VAM	Ventilation air methane
VRE	Variable renewable energy
WA	Western Australia

1 Introduction

1.1 Australia's emissions reduction target

Australia has committed to reducing emissions by 26-28% below 2005 levels by 2030, and may need to achieve net zero emissions in the second half of the century to meet future international commitments, with the energy sector expected to provide the majority of abatement.

On 10 November 2016, Australia ratified the Paris Agreement, committing to achieve a 26-28% reduction in GHG emissions below 2005 levels by 2030. The Paris Agreement also requires signatories to strengthen their abatement efforts over time, with 2030 targets to be confirmed in 2020, 2035 targets to be submitted by 2025, 2040 targets to be submitted by 2030 and so on.

Under the Paris Agreement, parties have set a goal to limit the increase in global average temperature to well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels. The Paris Agreement also recognises that the world will need to achieve zero net emissions in the second half of the century (United Nations Framework Convention on Climate Change, 2015).

To achieve this level of decarbonisation, Australia will need to adopt a multi-faceted approach primarily comprising reductions in emissions associated with the land and energy sectors. The energy sector accounts for 79% of Australia's emissions, and consists of (Australian Government Department of the Environment and Energy, 2016):

- Electricity generation (35% of total 2015 emissions)
- Direct combustion in buildings and industry[5] (18% of total 2015 emissions)
- Transport (18% of total 2015 emissions)
- Fugitive emissions from coal mining and oil & gas production (8% of total 2015 emissions).

This breakdown is shown in Figure 1. Also shown is the split of building and industry emissions in electricity and direct combustion[6]. Non-energy emissions cover agriculture, LULUCF, industrial (other) and waste.

This roadmap considers the possible pathways to achieving the necessary emissions reductions for the energy sector[7].

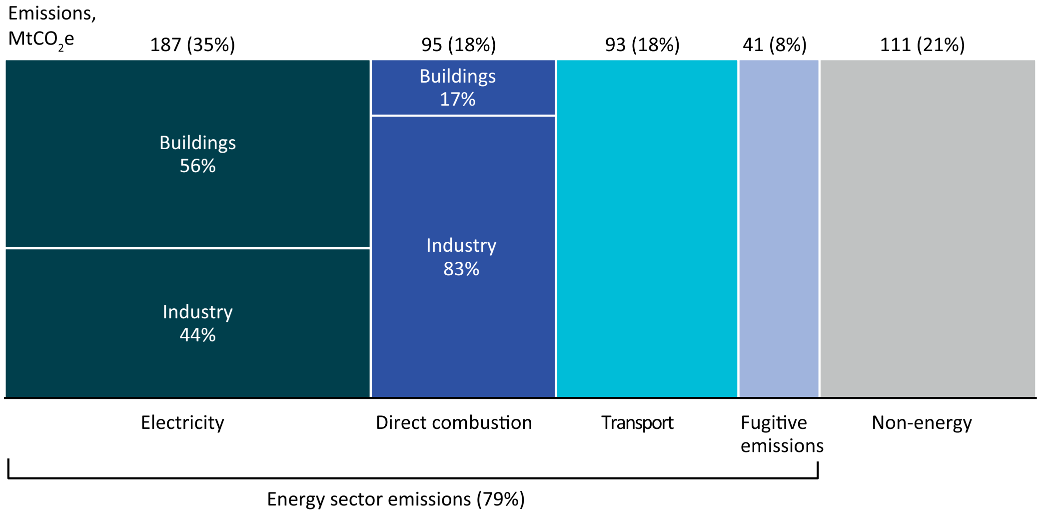

Figure 1. Breakdown of Australia's 2015 emissions

5 Direct combustion includes emissions from burning coal and gas for industrial and building heat, steam and pressure as well as emissions from combustion of fuel for mobile equipment in mining, manufacturing, construction, agriculture, forestry and fishing.

6 Split of electricity between buildings and industry is approximated from electricity consumption of commercial and residential as % of total thermal electricity in 2014-15 from 2016 Australian Energy Statistics (Office of the Chief Economist, Table F). Split for direct combustion approximated from (Australian Government Department of the Environment and Energy, 2016).

7 This roadmap focuses on domestic emissions only (i.e. international aviation and shipping are excluded).

1.2 Objectives

Australia needs a combination of technologies that address the so-called energy trilemma, i.e. providing energy security and affordability while transitioning to a low emissions economy[8]. Development and deployment of these technologies also presents economic opportunities for Australia.

The first two aspects of the energy trilemma have traditionally been prioritised and continue to be crucial. In addition to these aspects and in light of the Paris Agreement, Australia now needs to reduce emissions from its energy supply.

In support of its Paris commitment, the Australian Government announced it would prepare a Low Emissions Technology Roadmap (LETR), with CSIRO undertaking this work on behalf of and in collaboration with the Australian Government. CSIRO was asked to focus on two main objectives:

1. The primary objective of this roadmap is to identify the emission reduction technology options within the energy sector that Australia could pursue in order to meet or exceed its 2030 target and achieve deeper decarbonisation post-2030. The report also considers what actions might be required to achieve rollout of these technologies, while continuing to maintain energy security and affordability.
2. The secondary objective of this roadmap is to identify the main opportunities presented by low emissions technologies, in terms of economic value and job creation. The transition to a low emissions economy is often framed in terms of cost; this roadmap seeks to broaden the discussion by also highlighting the opportunities and benefits that the identified technologies and associated industries can provide.

This roadmap does not make specific policy recommendations, but instead is intended to provide a strong body of evidence to support policy makers and to suggest areas in which policy changes could help enable the development and deployment of low emissions technologies. For example, this roadmap will form one of the key inputs to the Australian Government's 2017 review of climate change policies. Implementation of actions identified in the Roadmap would require partnership between government, industry, the research sector and the broader community.

1.3 Global context and trends

The technologies that are likely to contribute to Australia's decarbonisation and to deliver economic opportunities will be heavily influenced by the global and local trends impacting the energy sector. These trends are driven by technological change, an evolving economy and environmental constraints.

Australia's abatement task will be influenced by major global trends over which Australia has little direct control. As shown in Figure 2, these trends, depending on how they play out, could either assist or hinder development of low emissions technologies.

In addition to these broad trends, the energy sector, and the electricity sector in particular, is undergoing significant structural and technological disruption and change. This is driven in part by the need for decarbonisation, as well as other factors.

- The increasing pace of technological change, falling technology costs and government policy are disrupting the conventional electricity supply chain. For example:
  - Rapidly declining costs of rooftop solar PV and batteries combined with government incentives are causing electricity generation to become increasingly decentralised, with consumers driving the change.
  - The increase in variable renewable generation is causing electricity grid net demand to become more volatile, moving the system from a paradigm of peak and off-peak to one of under and oversupply (with variable timing). This increases the importance of electricity system flexibility, including generation that is easily ramped up or down to match supply and demand.
  - The digital revolution is enabling greater system automation and decentralised decision-making, as well as increasing the vulnerability of the future grid to cyber-attacks. Key emerging technologies including the Internet of Things, big data analytics, artificial intelligence and blockchain offer considerable scope to disrupt the electricity sector.

[8] Energy security is defined as "effective management of primary energy supply from domestic and external sources, reliability of energy infrastructure, and the ability of energy providers to meet current and future demand" (World Energy Council, 2016). In the context of electricity specifically, a secure power system is one that is "able to continue operating within defined technical limits, even in the event of the disconnection of a major power system element such as an interconnector or large generator". A reliable power system is "one in which there is sufficient generation and transmission capacity to meet all grid demand" (Commonwealth of Australia, 2016).

	TRENDS SUPPORTING DEVELOPMENT OF LOW EMISSIONS TECHNOLOGIES	TRENDS UNDERMINING DEVELOPMENT OF LOW EMISSIONS TECHNOLOGIES
Global economy and geopolitics	Global economy shows strong growth	Global economic growth weakens
	International cooperation and trade strengthens	International cooperation and trade weakens
	Oil returns to >$100/barrel, gas rises similarly	Oil and gas remain cheap
Ambition and coordination on decarbonisation	Citizens demand decarbonisation with many consumers adopting low emissions technologies	Citizen concern is focused on other issues
	Countries increase Nationally Determined Contributions to achieve 1.5-2°C goal	Countries deliver on current commitments only
	World increases low emissions RDD&D spend and level of coordination	RDD&D spend remains at current levels and degree of fragmentation
	Widespread and coordinated carbon abatement mechanism emerges	No widespread and coordinated carbon abatement mechanism emerges

Figure 2. Major potential global trends influencing development of low emissions technologies

  - EVs are becoming cheaper, and while almost negligible at present in the Australian market, their share of sales is expected to increase significantly over the next decade. This will disrupt the transport sector and present challenges and opportunities to the electricity sector.
  - CCS is starting to be applied internationally to emissions from coal-fired power stations and could be an important technology to reduce emissions in industrial use.
  - CST has emerged internationally as a commercial, large-scale electricity generation technology.
- Increasing energy prices have started to impact energy use and have begun to incentivise improved energy efficiency. Energy price increases are also driving consumer interest in alternate sources of supply. Rising energy prices have recently been driven largely by electricity network spend and the exposure of the Australian domestic gas market to international prices with the development of the LNG export industry. A continued rise in energy prices is to be expected in a carbon-constrained world, and will provide an ongoing driver for continued energy productivity improvements.
- Countries such as Japan, South Korea, the UK and Germany are actively working to make hydrogen a significant part of their energy systems, as an energy storage medium and fuel source.
- Energy use is increasingly becoming decoupled from economic growth, driven by improvements in energy efficiency, fuel switching and a shift toward less energy intensive industries (Department of Industry and Science, 2015). This is set to continue, with global energy use per dollar of gross domestic product (GDP) expected to decline a further 35-50% from 2015 to 2040 (for the International Energy Agency's Current Policies Scenario[9] and 450 Scenario[10] respectively) (International Energy Agency, 2016, p. 60).

9 This scenario takes into account only those policies for which implementing measures had been formally enacted as of mid-2016 and assumes that these policies continue unchanged. It does not consider the changes implied by the pledges made as part of the Paris Agreement.

10 This scenario assumes measures are introduced that limit the atmospheric concentration of carbon dioxide to around 450 parts per million, consistent with a 50% chance of limiting warming to a 2°C temperature rise in 2100.

- Global demand for energy will be heavily influenced by action to reduce emissions. In the IEA's Current Policies Scenario, global demand is expected to increase by 43% between 2014 and 2040, whereas in its 450 Scenario, in which strong action is taken to limit emissions, global demand is expected to increase by only 9% (International Energy Agency, 2016).
- Accordingly, demand for Australian energy commodities will depend strongly on the degree to which decarbonisation goals are met. In the Current Policies Scenario, global demand for coal and gas increase by 36% and 63% between 2014 and 2040 respectively, while in the 450 Scenario these decrease by 49% and increase by 14% respectively (International Energy Agency, 2016, pp. 165-167, 207).
- Investment patterns and access to capital are changing. The finance community is increasingly pricing carbon risk when evaluating projects and there is growing investor concern regarding the impact of environmental issues on the future value of fossil fuel businesses.
- The energy sector is also affected by trends related to water and food (i.e. the water-energy-food nexus). Growing economic prosperity while protecting Australia's natural assets is possible. However, managing the challenges related to water use, energy and food production will require policies and institutions to manage trade-offs (e.g. between growing biofuels and food) and risks (CSIRO, 2015).

Given the rapid pace of change and uncertainty surrounding the evolution of these national and global trends, this report seeks to provide Australia with a clear roadmap that outlines the options, trade-offs, comparative development pathways and requirements of different emissions reduction technologies and shows how Australia can capture opportunities arising from these trends.

1.4 Structure of the report

The main body of this report provides a high level description of the approach taken in developing the roadmap (Section 2), the key findings (Section 3), and recommended next steps (Section 4). Appendices A-D describe the pathways in further detail, covering the key technologies in each pathway, the uptake of these technologies and associated emissions impact (as informed by modelling), and details of the barriers to uptake, potential enablers and supply chain opportunities for the key technologies related to each pathway. The LETR Technical Report covers the details of the electricity cost modelling carried out for this report and a detailed description of the methodology. The list of stakeholders consulted throughout the report is included in Appendix E.

An accompanying (electronic-only) document, the LETR Technical Report, contains detailed technical assessments for each of the key technologies as well as a description of the overall methodology.

2 Approach

2.1 Bottom up analysis

This roadmap was developed through a detailed evaluation of technologies based on their potential to deliver abatement and economic opportunities for Australia. Barriers to uptake of technologies and potential enablers were identified in consultation with technology experts and industry and government stakeholders, and used to inform modelled rates of technology uptake and abatement delivered.

In developing the roadmap, each of the relevant energy sector technologies was evaluated in an Australian context according to a common set of criteria. These include:

- Abatement potential
- Risk, including technology and commercial readiness, market risk, social licence risk and stakeholder coordination risk
- Cost (current and projected)
- Level of domestic and international support (including current level of investment, policy support, and support from industry stakeholders, such as through R&D funding)

Technology and commercial readiness were evaluated using the Technology Readiness Level (TRL) and Commercial Readiness Index (CRI) scales. See Appendix B of the LETR Technical Report for a description of these metrics.

This evaluation was used to identify the most important technologies, which informed the development of the pathways (see Section 2.2 below). Given the breadth of relevant technologies in the energy sector, the pathways focus on technologies judged most likely to contribute to abatement, factoring in risk, cost and level of support.

The most recent authoritative information available on the status and anticipated development trajectory of each technology was sourced wherever possible. It is noted this information will need to be regularly updated to accurately reflect actual development of the various technologies. However, this is not expected to change the key findings from this report in the near future, and except where noted in Section 4.1, does not warrant delaying the enabling actions described in Section 4.2.

In line with the secondary objective of the roadmap, the supply chains of the prioritised technologies were analysed in order to identify where the key opportunities for Australian industry might exist. Some technologies that were judged less likely to contribute to Australian abatement but were seen as providing commercial opportunities or opportunities for international abatement were also examined. The potential level of deployment of each technology was used to inform the potential size of the associated supply chain opportunity for Australian industry.

The analysis of economic opportunities is intended to identify the most important areas of opportunity, for further investigation. Due to the broad scope of this roadmap, it was not possible to precisely quantify the value provided by each of these opportunities or to quantify the overall economic impact of a shift to a low carbon economy.

For the prioritised technologies, the barriers as well as potential enablers to deployment in Australia were identified. While the roadmap does not make specific policy recommendations, it does identify areas in which policy changes could help overcome barriers. Due to the uncertainty as to which technologies will ultimately prove lowest cost and most operationally effective, enablers have been specified in a technology neutral way where possible. For example where changes to policy are identified as being required to drive uptake of low emissions electricity generation, this enabler has been identified as applying to all relevant technologies (rather than a subset, such as renewables). In some instances however, enablers are technology specific. For example, applying concentrated solar thermal technology to industrial heat applications will require research & development (R&D) focused on this specific technology.

This roadmap was developed with extensive consultation with technology experts and stakeholders from industry, government and non-government organisations (see Appendix E for further details).

The key technologies are summarised in Table 1 and are described further in Appendices A-D. Further detail can be found in the accompanying LETR Technical Report.

TABLE 1. KEY LOW EMISSIONS TECHNOLOGIES

CATEGORY	SUB-CATEGORY	TECHNOLOGIES
Energy productivity	Buildings sector technologies	Technologies supporting energy and emissions reductions in buildings such as light-emitting diode (LED) lighting, high efficiency heating, ventilation and air conditioning (HVAC), sensors and controls, high efficiency appliances, building envelope improvements and electrification
	Industry sector technologies	Technologies enabling improvements in process heating, materials handling, compression equipment and other industrial equipment such as efficient motors and pumps, fuel switching from coal to gas and from gas/petroleum to electricity, direct use of renewable heat e.g. solar thermal and biomass
	Transport sector technologies	Technologies supporting fuel substitution (e.g. EVs, hydrogen fuel cell vehicles, biofuels), improved vehicle efficiency and demand reduction including via mode shifting
Low carbon electricity	Variable renewable energy (VRE)	Rooftop solar PV, large-scale solar PV, onshore wind, wave energy
	Enabling technologies for VRE	
	- Energy storage	Energy storage technologies such as batteries and (PHES)
	- Smart grid technologies	Technologies to enable greater uptake of VRE and distributed energy resources (e.g. rooftop solar PV, behind the meter batteries and electric vehicles) such as smart appliances, smart inverters, control platforms, smart meters, telemetry and sensors, system models, demand forecasting, generation forecasting and cyber-security solutions
	- Conventional power equipment	Reactive power control technologies such as synchronous condensers, transmission and distribution lines
	- Microgrids, RAPS, SAPS	Integration of renewables and enablers of renewables in off-grid systems such as remote area power systems (RAPS), standalone power systems (SAPS) and microgrids
	Biomass	Conversion of biomass to electricity via direct combustion, combustion of biogas produced by anaerobic digestion or biomass gasification
	CST	Concentrated solar thermal power with integrated thermal storage
	HELE	High efficiency, low emissions coal and gas power including supercritical pulverised coal, integrated gasification combined cycle (IGCC), gas turbines and reciprocating combustion engines
	CCS	Capture, transport and storage of CO_2 into underground rock and reservoir formations. Also includes technologies supporting utilisation of CO_2
	Nuclear	Fission and fusion reactors
	Geothermal	Electricity generation using heat obtained through deep drilling in hot sedimentary aquifers (HSA) and enhanced geothermal systems (EGS)
Other	Hydrogen	Hydrogen production (e.g. thermochemical, electrochemical), storage & transport (e.g. using liquefaction) and consumption (fuel cells, turbines)
	Fugitives	Technologies supporting reductions in fugitive emissions in coal and oil and gas production e.g. ventilation air methane abatement technologies, CCS for vented CO_2 in LNG

2.2 Pathways analysis

In the context of this roadmap, a pathway is defined as a scenario that explores how a particular set of key technologies can contribute to decarbonisation of the Australian energy sector while maintaining energy security and affordability. Four pathways were developed, in order to explore how major shifts in electricity generation and energy use in buildings, industry and transport could impact decarbonisation to 2050.

The prioritised technologies were grouped into four pathways, which were used as scenarios to show how these technologies might be deployed and how they might contribute to both short and long term decarbonisation (see Figure 3).

Pathway 1: Energy productivity plus is a scenario that considers the impact of ambitious energy productivity improvements in meeting Australia's 2030 target and achieving deeper decarbonisation beyond that. 'Ambitious' in this context refers to a rate of improvement at the higher end of what appears to be feasible given the barriers involved, and roughly corresponds to the full opportunity identified in the NEPP, equivalent to a doubling of Australia's energy productivity by 2030[11]. BAU roughly corresponds with existing NEPP targets of 40% improvement by 2030[12], which accelerates energy productivity above what has been achieved historically but does not achieve its full potential.

Pathway 1 focuses on actions to reduce emissions from energy consumption at the point of use (demand side). This pathway places strong emphasis on the potential for abatement in buildings, industry and transport sectors. New build electricity generation in this pathway is assumed to continue to come from the types of low emissions sources already currently deployed, i.e. mainly onshore wind, solar PV and gas[13]. A 45% limit was placed on wind and solar PV share[14], since addressing the challenges of reaching higher wind and solar PV shares is the focus of Pathway 2.

Pathway 2: Variable renewable energy is a scenario that assumes BAU improvements in energy productivity and relies largely on uptake of mature, low cost, VRE technologies, namely onshore wind and solar PV. Bioenergy also plays a limited role in distributed applications. However, in contrast to the other pathways, deployment of VRE remains the primary source of electricity generation in order to achieve deeper decarbonisation by 2050. The focus of the pathway then is on understanding the key enabling technologies and other means that are required for the network to accommodate high VRE share.

Pathway 3: Dispatchable power is a scenario that also assumes BAU improvements in energy productivity, but which places a limit on the uptake of VRE. Instead it relies largely on currently less mature forms of low emissions generation to achieve decarbonisation post-2030. These generation technologies have similar characteristics to conventional thermal generation – they are dispatchable and synchronous, and provide inertia and fault current to the network. The electricity grid therefore does not require the same degree of modification required in Pathway 2. The key generation technologies are CST with storage, fossil fuel generation (HELE if new build) with CCS, nuclear and geothermal power. A shift towards a hydrogen economy (largely export focused) was also considered in this pathway due to its connection with other Pathway 3 technologies such as CST, HELE and CCS[15].

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11 See http://www.2xep.org.au/

12 The National Energy Productivity Plan (NEPP) aims to improve energy productivity (defined in the NEPP as economic output (GDP) per unit of primary energy) by 40 per cent to 2030, equivalent to 402 PJ of final energy savings. Although a detailed comparison between modelling for this report and the NEPP is outside the scope of this report, the level of abatement modelled in this report for Pathways 2 and 3 is broadly in line with the NEPP target.

Furthermore, it is recognised that there is potential to achieve greater energy savings – up to 761 PJ – by implementing all identified cost effective energy efficiency activities (Australian Government, 2015, p. 13). Again, while a detailed comparison was out of scope, the level of abatement modelled for Pathways 1 and 4 is broadly aligned with the greater energy savings thought to be available. While the current suite of NEPP measures is intended to go some way to capturing the available savings, the 2016 NEPP Annual Report highlights the challenges in achieving abatement from activities in industrial sectors and heavy vehicles particularly. This underscores the importance of continued focus on energy productivity. Furthermore, in order to achieve the greater potential identified, additional or accelerated policy measures are required.

13 Note that gas counts as a low emissions power generation source in this roadmap since it was found to be compatible with Australia's decarbonisation target, although with limits to use which grow tighter with time.

14 In this report, share is defined as the proportion of energy (TWh) provided by a generation source, unless otherwise specified.

15 Industrial emissions (i.e. non-energy related emissions produced by industrial process e.g. cement manufacture) are out of scope for this roadmap, but since abatement of these emissions may rely on CCS, they have been considered in the context of drivers for deployment of this technology.

	1 PATHWAY 1: Energy productivity plus	2 PATHWAY 2: Variable renewable energy (VRE)	3 PATHWAY 3 Dispatchable power	4 PATHWAY 4 Unconstrained
Buildings, industry and transport	**Ambitious energy productivity improvements**	**Business as usual energy productivity improvements**		**Ambitious energy productivity improvements**
			Hydrogen for transport and export	
New build electricity generation	**Existing low emissions technologies:** wind, solar PV (45% limit) plus gas	**Cheap, mature, low emissions generation:** mainly wind and solar PV **plus enabling technologies** e.g. batteries pumped hydro	Wind and solar (45% limit) plus **low emissions, dispatchable generation**: • Concentrating solar thermal with storage • High efficiency, low emissions fossil fuels with carbon capture and storage • Nuclear • Geothermal	**All low emissions technologies allowed, with no limit on wind and solar PV**
Fugitive emissions	**Uptake of cost- effective technologies**			

Figure 3. Low Emissions Technology Roadmap pathways

BOX 1 | Key terms

Energy productivity: The amount of useful output, such as economic value or distance travelled, achieved per unit of input energy. Improving energy productivity reduces emissions when the amount of energy used is reduced, or when energy from a lower emissions source is used.

Synchronous generation: Electricity generation using large, rotating masses synchronised with the frequency of the alternating current (AC) grid. These generators are usually powered by steam turbines, or running water in the case of hydro. The rotating masses have high rotational inertia, which helps stabilise the frequency of AC grids.

Dispatchable generation: Electricity generation that can be turned on when required.

VRE: Electricity generation that is non-dispatchable due to the variable and uncontrollable nature of its primary energy source (e.g. sunlight and wind). It is also non-synchronous, and currently in Australia doesn't provide inertia to stabilise the grid.

Pathway 4: Unconstrained is a scenario that assumes that all the key technology options are available to achieve emissions reductions, i.e. ambitious improvements in energy productivity as per Pathway 1, no limits to deployment of VRE as per Pathway 2 and no limits to the dispatchable power generation technologies covered in Pathway 3. This pathway assumes the key risks associated with Pathways 1-3 are overcome, and that the lowest cost options deliver the abatement task.

All pathways assume deployment of cost-effective technologies to reduce fugitive emissions from coal mining and oil & gas production, as well as some degree of the following:

- Electrification of industrial and building heat
- Uptake of solar thermal and biomass heating in industry
- Fuel switching from coal to gas in industry
- Uptake of EVs
- Some fuel switching to gas in transport
- Uptake of biofuels, particularly in aviation.

<table>
<tr><th colspan="2"></th><th colspan="4">PATHWAYS</th></tr>
<tr><th colspan="2">Pillars of decarbonisation</th><th>1
PATHWAY 1: Energy productivity plus</th><th>2
PATHWAY 2: Variable renewable energy (VRE)</th><th>3
PATHWAY 3 Dispatchable power</th><th>4
PATHWAY 4 Unconstrained</th></tr>
<tr><td colspan="2">Energy efficiency</td><td>• Full potential of EP captured through a range of demand-side technologies</td><td colspan="2">• BAU progress</td><td>• Full potential of EP captured through a range of demand-side technologies</td></tr>
<tr><td rowspan="2">Low carbon electricity</td><td>New build generation</td><td>• Wind and solar PV (capped at 45%)
• Gas combined cycle</td><td>• Wind and solar PV (no cap)
• Gas combined cycle</td><td>As per P1, plus:
• CST
• HELE + CCS
• Nuclear
• Geothermal</td><td>• All allowed (no cap on wind and solar PV)</td></tr>
<tr><td>Enablers</td><td>• n/a</td><td>• Storage (batteries, PHES)
• Smart grid technologies
• Conventional power equipm.
• Remote area power systems (RAPS) and microgrids</td><td>• n/a</td><td>• As per P2</td></tr>
<tr><td colspan="2" rowspan="5">Electrification and fuel switching</td><td colspan="4">• Electrification of industrial and building heat (when emissions intensity of grid allows emissions reduction)
• Electric vehicles (EVs) and electrification of mobile equipment in mining (switch to conveyors)</td></tr>
<tr><td colspan="4">• Solar thermal heat
• Biomass heat</td></tr>
<tr><td colspan="4">• Switch from coal to gas in industrial heat</td></tr>
<tr><td colspan="2">• Switch to gas in freight</td><td colspan="2">• Hydrogen economy e.g. solar fuels, export of hydrogen, FCVs</td></tr>
<tr><td colspan="4">• Next-generation biofuels</td></tr>
</table>

Figure 4. Key technologies in each pathway[17]

The key technologies in each pathway are shown in Figure 4, categorised according to the four pillars of decarbonisation described by ClimateWorks Australia and Australian National University (ANU) (ClimateWorks Australia, 2014):

1. **Energy efficiency,** using less energy to achieve a given outcome[16]
2. **Low carbon electricity**, from renewable sources, nuclear power or from fossil fuel generation with CCS
3. **Electrification and fuel switching** from fossil fuels to bioenergy and other renewable sources, and from coal and oil to gas
4. **Other** or non-energy emissions, including process improvements and CCS in industry. For the scope of this roadmap, this category covers fugitive emissions from coal mining and oil & gas production.

16 Energy efficiency (EE) is one way of improving energy productivity, by reducing the amount of energy required at the point of use. Energy productivity extends beyond just energy efficiency, as energy productivity can also be improved by other changes at the point of use (e.g. electrification).

17 EP – energy productivity; BAU – business as usual; PV – photovoltaic; CST – concentrated solar thermal; HELE – high efficiency low emissions fossil fuel generation; CCS – carbon capture and storage; PHES – pumped hydro energy storage; EV – electric vehicle; FCV – fuel cell vehicle; LNG – liquefied natural gas. Conventional power equipment includes technologies such as synchronous condensers, transmission & distribution and protection systems. Note, new biomass generation was also included in the modelling for each pathway, but due to costs relative to other technologies did not form a significant part of the generation mix. Similarly, wave energy was also included in the modelling for Pathway 2, but not deployed due to higher costs relative to wind and solar PV.

It is important to recognise that the pathways are not intended as deterministic predictions. Rather, they are designed to illustrate some of the plausible combinations of technology options that arise based on assumptions on the rate of technology development and external drivers. They also enable an examination of the associated trade-offs, costs, risks and opportunities and are intended to serve as a tool for policy and other decision makers to conceptualise possible futures in the face of considerable uncertainty.

Which pathway Australia will eventually take (which may be one of the pathways described, some combination of these pathways or a distinct pathway) will depend on how global and national priorities are set and investment decisions are made. Development of the pathways will also depend on global trends, particularly in relation to the development of specific technologies, as shown in Figure 5.

No order of importance or priority should be implied from the order in which the pathways are listed. Also, this report does not recommend any one pathway. Rather, it recognises that each pathway has trade-offs in risk, cost and opportunities, and that consequently there is value in maintaining optionality. While maintaining optionality has costs, given the importance of decarbonising the energy sector, there is value in incurring some degree of cost, with the appropriate level to be determined by policy makers as well as the broader Australian community. Options should be kept open as long as it makes sense to do so, taking into account the cost of each and the risks associated with other options. This is discussed further in Section 3.14. The enabling actions described later in Section 4.2 can be thought of as actions that can be taken to maintain optionality.

Each pathway can maintain energy security and affordability, providing certain challenges are successfully addressed. The relative costs of the pathways (focused on electricity and transport where the modelling tools allow calculation of costs) are discussed in Sections 3.4 and further in Appendix A of the LETR Technical Report.

The deployment of the technologies and the associated abatement in each pathway was modelled through a combination of approaches. For buildings, industry (covering electricity demand and direct combustion), transport and fugitive emissions, potential rates of technology deployment were informed by historical improvements in energy productivity, as well as input from industry stakeholders. In the transport sector, rates of deployment were also informed by CSIRO's Energy Sector Model (ESM), which deploys technologies based on least cost. For the electricity generation sector, technology deployment was also modelled using ESM, subject to an emissions constraint, which for 2030 was determined by the rate of decarbonisation of the other energy sectors and by the assumption that the energy sector delivers 26-28% abatement compared with 2005 levels (see Table 2). Note that less abatement from the electricity sector would be required if the energy sector delivers less than 26-28% abatement, which could be possible if non-energy sectors deliver more than 26-28% abatement, or if carbon credits from other countries are used[18].

Abatement in direct combustion, transport, fugitive emissions and demand reduction in electricity were first determined, and then used to inform the remaining abatement delivered by the electricity subsector to meet an overall energy sector abatement target. This approach was

1 **PATHWAY 1:** Energy productivity plus	2 **PATHWAY 2:** Variable renewable energy (VRE)	3 **PATHWAY 3** Dispatchable power and hydrogen	4 **PATHWAY 4** Unconstrained
• Global implementation of strong policy measures to improve energy efficiency e.g. more regulation on minimum standards for equipment, buildings, infrastructure and minimum performance improvement rates on EE for industrial companies	• Continued reductions in cost of batteries, solar PV & wind • Development of enabling technologies	• Strong global effort in CCS • Successful deployment of small modular nuclear reactors • Continued cost reductions of CST • Continued push towards hydrogen economy	• As per other pathways

Figure 5. Global trends that would support each pathway

[18] See Section 3.13 for a discussion on the potential role of carbon credits from other countries in Australia's decarbonisation.

taken for two main reasons. Firstly, abatement in the non-electricity energy subsectors largely involves opportunities with positive net present value, and which should therefore be pursued to the full extent possible, subject to addressing other barriers such as availability of capital, competing priorities and lack of skills or awareness of opportunities. Secondly, the electricity generation subsector has a wide range of technologies available to achieve zero or near-zero emissions than in other areas of the energy sector. For instance, technologies such as solar PV, wind, CST, nuclear and fossil fuel generation with CCS allow electricity generation with zero or close to zero emissions.

For 2050, the same approach for calculating electricity demand and direct combustion, transport and fugitive emissions was taken as for 2030. For the electricity generation sector however, since there is currently no 2050 target for Australia, a different approach was required. In determining this approach, it was recognised that:

1. There is a need for economy-wide net zero emissions in the second half of the century (see Section 1.1).
2. Deep decarbonisation of direct combustion, transport and fugitive emissions may either prove costly or rely on a switch to low emissions electricity (using technologies such as heat pumps and electric vehicles).
3. The electricity sector has a range of potential zero or low emissions technologies available to it.

It was therefore decided that a figure of close to 100% was an appropriate level of decarbonisation to assume for the electricity sector in each pathway. For Pathway 1, a value of 75% was chosen, since with the specified mix of new-build electricity generation technologies in this pathway it becomes significantly more expensive to surpass this level, due to the relatively high cost of electricity generation from biomass. For Pathways 2 to 4, a number of different levels of abatement between 75 and 95% were examined. It was found that it was feasible to achieve up to 95% abatement without significantly higher costs than 75% abatement, and therefore for Pathways 2 to 4, a value of 95% was chosen. Choosing a value of 95% rather than 100% means it is possible to explore the full range of technology options – CCS is not zero emissions and therefore would not be possible in a zero emissions electricity sector. A value of 95% also leaves open the possibility of using some gas to support VRE, reducing the cost and complexity of Pathway 2.

Note also that assuming strong abatement in 2050 avoids the deployment of technologies in the short term that would be 'locked in' and make longer-term decarbonisation more costly, such as fossil fuel generation without CCS.

Based on the lack of a specified overall 2050 target, the different pathways achieve varying levels of 2050 abatement.

Modelled rates of deployment of the various technologies are based on the assumption that the key barriers for each technology are overcome and based on assumptions about the evolution of costs for electricity generation and transport technologies. The level of adoption of individual technologies will ultimately depend on a combination of policy settings and levels of sustained investment in their development, demonstration and deployment. It is also likely to depend on how successful technologies are at delivering anticipated improvements in cost reduction, operability and emissions reduction.

Based on electricity sector modelling, certain technologies were found to have relatively little scope for (further) deployment in Australia, namely ocean renewable energy (ORE), offshore wind and biomass for electricity generation[19], due mainly to expected costs compared to alternatives or due to limited resource supply.

[19] Of the different ORE technologies, wave energy is the most promising for Australia; other forms such as tidal energy have a more limited resource (CSIRO, 2012). Electricity sector modelling carried out for this report indicates that wave energy and offshore wind are unlikely to be competitive in Australia and are unlikely to be needed in Australia at scale, given the large available solar and onshore wind resources (see e.g. (AEMO, 2013)). This is not necessarily true for other countries that don't share Australia's world class solar and onshore wind resources as well as large amount of land per capita. Biomass for electricity generation was found to be uncompetitive at scale with other forms of generation. Furthermore, available biomass is more likely to be required for decarbonisation of other sectors (e.g. transport, particularly aviation) that have fewer abatement options than the electricity sector.

TABLE 2. CHANGE IN EMISSIONS RELATIVE TO 2005 IN EACH PATHWAY

	2030				2050			
	P1	P2	P3	P4	P1	P2	P3	P4
Electricity	Back calculated, to meet overall energy sector target				-75%	-95%	-95%	-95%
Direct combustion, transport and fugitive emissions	Based on bottom up modelling, positive net present value and moderate cost opportunities and taking into account pathways' levels of ambition in energy productivity							
Total energy	-27%	-27%	-27%	-27%	CALCULATED BASED ON ABATEMENT IN SUBSECTORS			

3 Key findings

I. Australia is well positioned to benefit from innovation in low emissions technologies

KEY FINDING 1: Australia has many sources of comparative advantage for low emissions technologies to build on

While the transition to a low emissions economy is often framed in terms of cost, this transition will also create demand for new products and services in Australia and in export markets. Australia is endowed with some of the world's best energy resources, has good skills in low emissions technologies, reputable institutions and established trading relationships with key consumers of energy. These advantages leave it well placed to benefit from a domestic and global transition to low emissions energy. Capturing these benefits will require decisions to be made about where to focus effort and long-term commitments to the required actions.

Commercial opportunities related to low emissions technologies exist where Australia has, or can build a comparative advantage in areas with large potential markets (either domestic or export). Opportunities exist through increasing energy productivity and in products, services, commodities, and licencing of intellectual property (IP).

Australia has many existing sources of comparative advantage relevant to building commercial opportunities in low emissions technologies (see Table 3). It is endowed with some of the world's best renewable resources, particularly when compared with the size of the population and the land area available, as well as strong skills and research capability in low emissions technologies. Australia also has developed social, market and government institutions which provide foundations for reorienting the economy towards low emissions technologies. Additionally, it has well established trading relationships with Asia, which is the region with the largest net imports of energy globally (International Energy Agency, 2015).

To build on these existing advantages, Australia could seek to add value to its natural resources, for instance by processing raw materials (e.g. lithium) for use in batteries and other low emissions technologies. Australia could also continue to build on its existing research capabilities, while continuing to build its international collaboration in research and improving the transfer of research to industry, including in international supply chains. Additional support could be provided to help Australian small to medium enterprises (SMEs) grow into globally competitive enterprises, in particular by helping them integrate into global value chains. In manufacturing, Australia could focus on specific value chain elements, rather than necessarily trying to specialise on entire products (Withers, 2015). Australia could also seek to strengthen its existing institutions, particularly by updating its market structures and regulatory regimes to better support the trial, demonstration and uptake of low emissions technologies[20].

Given the range of areas in which Australia could benefit from low emissions technologies, decisions on where to focus effort will likely be required. To fully deliver the potential benefits, development of and commitment to a long term strategy would also be required to maximise Australia's comparative advantage in different products and services.

[20] This topic is discussed further for the electricity sector in Energy Networks Australia and CSIRO's Electricity Network Transformation Roadmap (Energy Networks Australia and CSIRO, 2016).

TABLE 3. AUSTRALIA'S CURRENT AND POTENTIAL FUTURE SOURCES OF COMPARATIVE ADVANTAGE IN LOW EMISSIONS TECHNOLOGIES

EXISTING SOURCES OF COMPARATIVE ADVANTAGE		HOW TO LEVERAGE AND BUILD ON STRENGTHS
Natural resources and geography	• World-class renewable energy resources (solar, wind, wave) • Abundance of other natural resources e.g., minerals (incl. lithium, uranium), gas, geological storage reserves, forestry, agricultural land • Large land area for deploying renewable generation • Proximity to Asia (large and growing energy importer)	• Add value to basic resources e.g. materials for batteries • Transition existing industries and develop new ones based on clean energy resources e.g. export of low emissions hydrogen to Asia
Human capital and skills	• Strength in basic research in key low emissions technologies e.g. smart grid, grid integration of renewables, solar PV, batteries, CST, VAM abatement technologies, CCS • Strength in education and skills, particularly in technical skills (Withers, 2015) • Strong resources and services sectors • World-leading capabilities in off-grid renewables • Strong systems thinking and ability to integrate technologies and design systems e.g. National Electricity Market (NEM), water trading • Strength in high-value, low-volume manufacturing, with a strong focus on the design, R&D and innovation side of the production process (Withers, 2015)	• Continue to build knowledge, research capability and skills, recognising these as key to sustainable comparative advantage; increase government support for R&D • Improve translation of research to industry, including to international supply chains (e.g. developing CST components for deployment in international projects) • Improve international collaboration in research • Export services to Asia-Pacific in off-grid renewables • Focus on advanced manufacturing • Specialise at the pre-production end of the value chain to take advantage of our high-cost, highly-skilled labour (Withers, 2015) • Specialise in specific value chain elements rather than whole industries e.g. heliostats and receivers for CST, rather than the whole system • Help grow small, innovative companies that are commercialising low emissions technologies
Society, governance and infrastructure	• Strong trading relationships with Asia • Robust systems of government, law and culture (Withers, 2015) • Strength in public policy 'building blocks' for low-carbon transition, such as design of regulatory frameworks, emissions and electricity data generation, and funding models for low-carbon investment • Energy markets relatively deregulated by global standards • Strong financial sector, with large superannuation funds • High share of distributed renewables • Population of 'early adopter' consumers • Geographically large grid	• Further develop businesses links into global supply chains, particularly in Asia • Strengthen and adapt markets and regulatory regimes given changes caused by new technologies • Influence the agenda for global standards and regulations • Continue to share knowledge of market structures, regulatory regimes and models for low-carbon investment with developing countries in Asia-Pacific and elsewhere • Leverage financial institutions to help drive the transition to a low emissions future • Build on Australia's role as a 'testbed' for new technologies, encouraging domestic and international companies to invest and build new businesses in Australia

KEY FINDING 2: Australia's existing strengths and needs can guide both local technology RDD&D and Australia's role in global efforts

Australian RDD&D in low emissions technologies can be guided by comparative advantage, existing strengths and where there are local problems to solve. While relying on other countries for many technologies, Australia can also play an important role in global uptake of low emissions technologies, by contributing to technology development, helping regional neighbours deploy technologies, demonstrating possibilities to other countries and exporting low emissions commodities and products.

Given limited budgets and due to the fact that most global RDD&D spend will occur internationally, Australia should focus domestic spend on areas that can make the greatest impact. In addition to building on areas of comparative advantage and existing strengths, Australian RDD&D of low emissions technologies should be guided by where there are local problems to solve, e.g.:

- Driving down the cost of technologies in Australia
- Developing/adapting technology for local conditions[21]
- Overcoming local barriers e.g. financing

Global decarbonisation and market opportunities should also guide Australia's focus. Based on these local and global needs, Figure 6 shows where Australia could develop technology locally versus acting as a 'technology taker'.

Figure 6 also shows how Australia can continue to contribute to other countries' decarbonisation. This is primarily through:

- Contributing to development of low emissions technology, such as through Australia's work in improving silicon PV efficiencies
- Helping regional neighbours deploy low emissions technologies such as VRE, HELE and CCS (with mutual benefits in accelerating learnings), including through assistance in developing policies and standards
- Demonstrating successful uptake of low emissions technologies e.g. showing how to achieve grid stability with high VRE share
- Exporting low emissions commodities and products, e.g. uranium, LNG[22], low emissions hydrogen, minerals for batteries and components for CST

By contributing to the global development of low emissions technology, there is room for Australia to improve its collaboration and coordination with other countries to ensure collective efforts and funds are optimally allocated and to achieve best return on investment (Bell, 2014). This should however be balanced against the potential benefits of separate groups working independently to solve a given problem, and the transactions costs that can apply to large, international collaborations.

Australia can benefit from closely monitoring international developments in technology, including via participation in international working groups, and communicating relevant insights to stakeholders in government and industry, so that efforts and priorities in Australia are informed by the latest global developments. For example, Australia is improving its capabilities in nuclear energy by increasing its participation in the research and development of Generation IV reactors. This has led to recent membership in the 'Generation IV International Forum'.

21 For example by addressing issues related to the integration of VRE.

22 Can be regarded as 'low emissions' when displacing coal.

Potential decarbonisation impact

Large | Medium | Small

		Develop locally ↔ Tech. taker	COMMENTS	OPPORTUNITIES TO HELP OTHER COUNTRIES DECARBONISE
Energy efficiency			Implement mature global technologies (some domestic also)	Develop policies to accelerate EE in industry and export via consulting services
Low emissions electricity	Wind & solar PV		Import solar PV modules and wind turbines but contribute to global R&D programs	Continue to contribute IP to global supply chains
	Wave		Develop technology for international deployment	Deploy wave in other countries
	Enabling tech for VRE		Bring global technologies into integrated systems; develop niche solutions e.g. software	Demonstrate grid stability with high penetration of VRE; Deploy VRE in RAPS in other countries
	Storage		Import most battery technology with some local development	Export lithium and other key materials
	CST		Demonstrate local technology but potentially import for large scale deployment	Contribute to global R&D programs; develop components for global supply chains
	Geothermal		Learn how to make enhanced geothermal viable in Australia	Potential transfer of technology to other countries with suitable geology
	CCS		Import capture technologies; contribute to global R&D; develop storage locally	Develop capture & utilisation tech.; demonstrate CCS; assist regional neighbours implement CCS
	HELE		Import technologies in general if required; some local development e.g. DICE	Export skills and assistance to emerging markets
	Nuclear		Contribute to global R&D; import technologies if nuclear is required	Supply uranium and contribute to global R&D
Electrification and fuel switching	Bioenergy		Develop local biomass supply chains and biofuel production; may rely on some imported IP	Export technologies developed in Australia
	Hydrogen		Develop local hydrogen production using mix of local and imported IP	Export low emissions hydrogen to Asia
	EVs		Import EVs; retrofit heavy vehicles; develop local charging infrastructure	Export lithium and other key materials
Other	Fugitives		Deploy locally developed ventilation air methane abatement technologies; implement CCS in LNG	Export technology for ventilation air methane (VAM) abatement in underground coal mines

Figure 6. Global coordination in RDD&D of low emissions technologies

II. Ambitious improvements in energy productivity, enabled by largely mature technologies, can unlock billions of dollars of cost savings

KEY FINDING 3: There are largely mature technologies available within the buildings, industry and transport sectors that could enable significant improvements in energy productivity

The buildings, industry and transport sectors have access to a large range of highly efficient technologies that can deliver significant improvements in energy productivity compared with existing technologies. While energy productivity is a key focus for many industry leaders, opportunities still remain for a significant proportion of companies.

For buildings, considerable energy productivity gains could be realised through the adoption of mature technologies such as efficient lighting (e.g. LEDs), heat pumps, improved building envelopes and higher efficiency appliances and equipment. Further, implementation of sensors and controls (e.g. smart meters and home energy management systems) are important in improving the efficiency of buildings.

Within industry, significant energy productivity gains may be achieved via the application of improved process heating. This could involve use of higher efficiency equipment, electrification and fuel switching, ambient or waste heat utilisation and renewable heat sources such as solar, geothermal or bioenergy. In the mining sector, significant increases in energy productivity may be achieved through improved materials handling equipment and comminution processes (i.e. crushing and grinding). Other more efficient general equipment such as electric motors and variable speed and frequency drives, can also be effective in increasing energy productivity.

In oil & gas production, particularly in LNG plants, emissions reductions can be realised through more efficient 'aero-derivative' gas turbines and electric motors to drive liquefaction processes. Floating LNG plants are also important given they can utilise the high pressure gas feeds directly from the gas reservoir and lower general gas compression requirements.

Improvements within transport can be made through incremental improvements in mature technologies, such as higher efficiency internal combustion engines and improved vehicle aerodynamics. Fuel substitution, i.e. replacing crude oil derived fuels with other energy sources such as hydrogen, biofuels and particularly electricity, as well as with compressed and liquefied natural gas, can increasingly deliver abatement. Energy productivity in transport can be further improved through demand reduction, i.e. reducing the total number of vehicle-kilometres travelled, for instance through mode shifting, telecommuting and improved routing in freight.

KEY FINDING 4: Ambitious improvements in energy productivity can help minimise energy spend

Pathways with faster improvements in energy productivity have significantly lower average household electricity, gas and transport costs by 2030 than pathways with slower improvements. In the electricity sector, higher energy productivity reduces the amount of electricity required and consequently the price, given that less new build generation is required to be built. In transport, improved energy productivity primarily lowers cost through reduced operating costs for EVs compared with internal combustion engine vehicles (after the mid-2020s) and reduced demand for travel (measured in vehicle-km). Potential savings represent a $20 billion opportunity to 2030 in buildings (Australian Sustainable Built Environment Council, 2016) and $14 billion of cumulative benefit to 2040 in road transport (Commonwealth of Australia, 2016).

Ambitious improvements in energy productivity can help minimise household energy costs. The average residential customer stationary energy (electricity plus gas) bill for each pathway (including additional capital spend for higher efficiency appliances) is shown in Figure 8. For comparison, the average bill under a 'no abatement' scenario[23] is also shown. While these costs are only indicative of an average consumer, points to note include:

- The pathways with greatest energy productivity have the lowest bills; bills in Pathways 1 and 4 are lower than in Pathways 2 and 3 and remain lower than the no abatement scenario to 2030, with bills similar between Pathway 1 and the no abatement scenario to 2050.
- Bills are lower in Pathways 1 and 4 due to lower retail prices and lower electricity demand. Retail prices are lower in these pathways since, due to faster improvements in energy productivity in transport and direct combustion, less abatement is required from the electricity sector to meet the 2030 target.

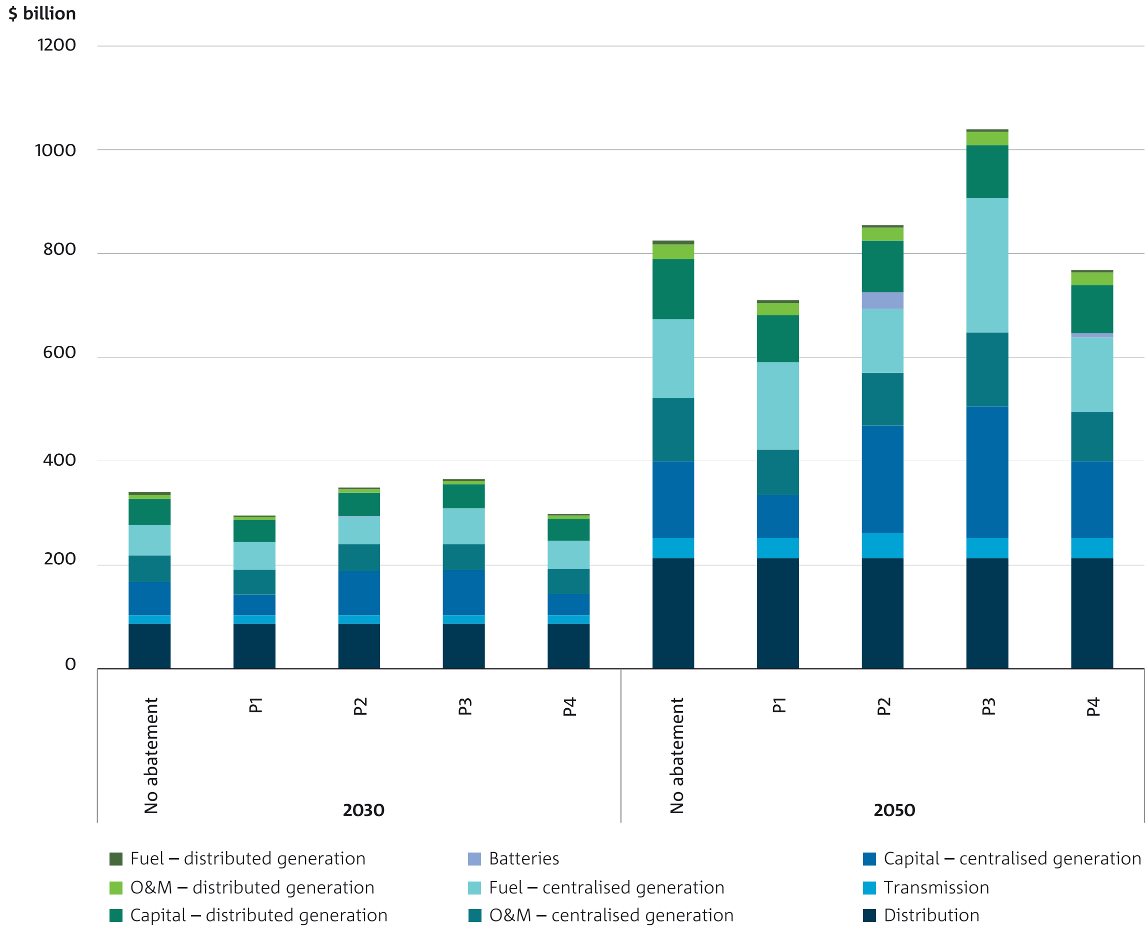

Figure 7. Electricity supply chain spend is least in Pathways 1 and 4, which have ambitious improvements in energy productivity

[23] Note that the 'no abatement' scenario is a counterfactual, rather than a realistic scenario, given Australia's commitment to reduce emissions. Even in the absence of explicit policy, investors expect some form of abatement policy, making a 'no abatement' scenario unrealistic, although useful as a hypothetical scenario to show the impact of abatement on energy costs.

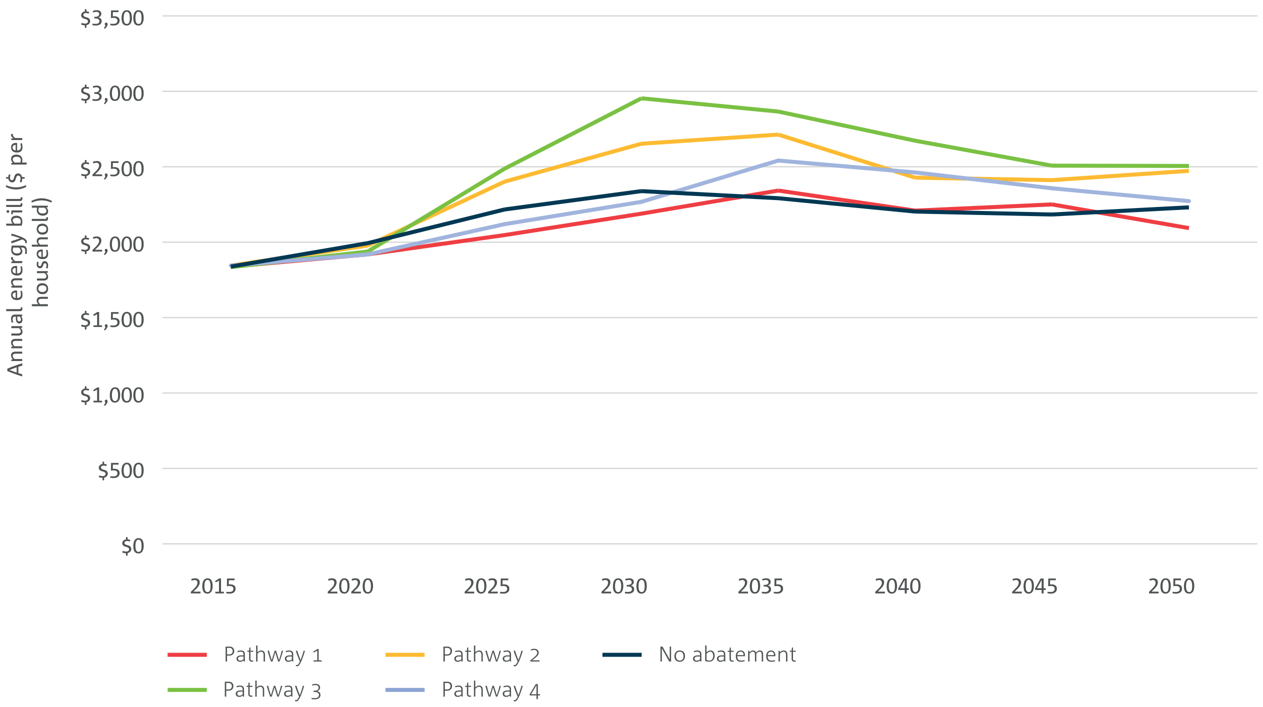

Figure 8. Comparison of annual energy bill (electricity + gas) across pathways ($ per household) including capital costs for high efficiency equipment in Pathways 1 and 4

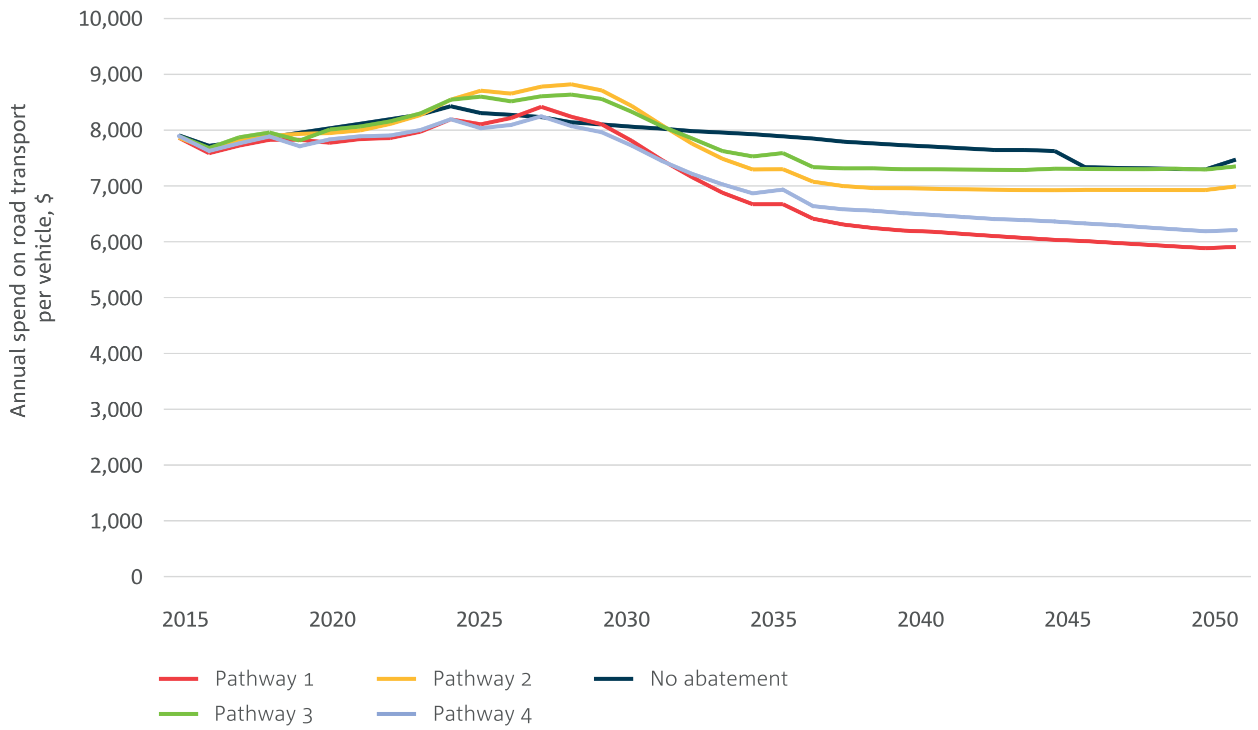

Figure 9. Average annual spend on passenger road transport per vehicle[24]

[24] Spend includes amortised cost of vehicle, fuel and all on-road costs including registration, insurance, maintenance etc.

Together with faster improvements in energy efficiency in electricity use in Pathways 1 and 4, this means less expenditure for new generation assets is required, reducing the wholesale price. (See Appendix A of LETR Technical Report for further details).

- Total bills converge to similar levels in the long term.

Average bills are shown for customers without rooftop solar PV. For customers with rooftop solar PV, similar price dynamics would be observed between pathways, albeit with lower absolute price differences due to the lower proportion of electricity sourced from the grid.

Transport costs are also lower in pathways with higher energy productivity. The average annual spend on passenger road transport is shown in Figure 9.

Key points to note regarding transport spend include:

- Across pathways, cost increases in the short term, driven by higher fuel costs and uptake of initially more expensive EVs, but decrease from the late 2020s as EVs start to have a lower total cost of ownership than internal combustion engine ICE vehicles and begin to reach a significant share of the fleet.
- Pathways 1 and 4 have lower total spend than Pathways 2 and 3 due mainly to lower demand (i.e. fewer kilometres travelled). On a per kilometre basis, fuel savings in Pathways 1 and 4 are balanced by higher capital cost of vehicles, resulting in close to zero net impact on travel cost per kilometre.
- Spend in Pathway 3 is higher than in Pathway 2 and spend in Pathway 4 is higher than in Pathway 1 due to the higher share of fuel cell vehicles (FCVs) in these pathways, and the fact that FCVs are expected to continue to have a higher total cost of ownership.
- Annual costs overall appear higher than what may be intuitively expected – this is due to the assumption that vehicles have a 7 year lifetime[25].
- Costs exclude road infrastructure; this is not expected to vary significantly between pathways.
- From around 2030 onwards, annual costs in all pathways are lower than the no abatement scenario reflecting greater uptake of EVs.

Increased energy productivity, achieved through the implementation of high efficiency and electric technologies, represents a $20 billion opportunity in net present value to 2030 in the building sector alone (Australian Sustainable Built Environment Council, 2016). In the road transport sector, increasing vehicle efficiency to levels that are broadly comparable to European and US targets by 2025 would result in a net cumulative benefit of nearly $14 billion to 2040, mostly from fuel cost savings (Commonwealth of Australia, 2016). More broadly, doubling Australia's energy productivity to 2030 could result in increased GDP by up to 2.8%, equivalent to a gain of $59.5 billion (A2SE, 2014).

Further to these benefits, EVs will have the benefit of localising the fuel supply (i.e. electricity) as compared with ICEs that rely on petrol/diesel derived from mostly imported crude oil. By 2030 in Pathway 1, EV uptake could lead to 6.76 TWh of additional electricity demand and the displacement of 11,000 barrels of oil equivalent per day[26]. The transition to EVs powered by low emissions electricity has the additional benefits of reducing costs for consumers (as noted above, once costs of EVs drop below those of ICE vehicles) and improving air quality.

Fuel-switching to bioenergy for stationary energy and transport offers further economic opportunities. Biomass cultivation provides an opportunity for Australian farmers to derive income from agricultural residues and underutilised land. Widespread uptake could also lead to the development of a local, low emissions fuel industry, and provide a range of job opportunities relating to construction and operation of bio-refineries, particularly in regional areas. An example of a company developing this kind of opportunity is Licella, which has developed a process to convert waste biomass into bio-crude oil which can be further refined in a conventional refinery. The technology has been successfully commercialised at pilot scale and the company has recently reached a final investment decision on its first commercial scale plant (Licella, 2017).

[25] CSIRO assumption approximating ownership period of new vehicles.

[26] This calculation is based on CSIRO modelling undertaken for Pathway 1 and a conversion factor of 1.68 TWh per million barrels of oil equivalent as derived from (BP Approximate conversion factors: Statisitical review of world energy). It was also assumed that barrels of oil were used entirely for petrol.

TABLE 4. SUMMARY OF OPPORTUNITIES FROM ENERGY PRODUCTIVITY IN BUILDINGS, INDUSTRY AND TRANSPORT

OPPORTUNITY	OPPORTUNITY TYPE AND DESCRIPTION	DIFFICULTY	DESCRIPTION
Increased productivity from high efficiency and electric technologies in buildings, industry and transport	Domestic productivity - buildings: (~$20b net-present value (NPV) to 2030) • Energy cost savings associated with energy efficiency and fuel switching opportunities • Other potential benefits such as increased comfort and improved staff productivity Domestic productivity transport: (~$14b NPV to 2040): • Increased productivity as a result of high efficiency and electric vehicles Domestic productivity economy wide (~$59.5b to 2030)	High	• Mature technologies available. Likely to require regulatory change or incentives to stimulate uptake
EV charging infrastructure	Domestic products & services • Opportunities to build and operate commercial charging stations, distribute home charging technology and home integration systems	Low	• Largely organic growth within industry as demand for EVs increases
EV localised fuel supply	Domestic productivity: • Localisation of fuel as a result of higher use of EVs (i.e. 6.74 TWh additional annual capacity displacing 11,000 barrels per day)	Low	• Automatic outcome from uptake of EVs
Commercialisation of high temperature solar thermal technology	Domestic & export products: • Opportunity to develop and implement technology to avoid/reduce energy consumption in high-temperature and fossil fuel-intensive alumina production using direct solar radiation	Medium	• Requires further RD&D and commercialisation support
Energy management and energy efficiency products and services	Domestic /export products and services: • Development and commercialisation of smart systems, including products and service offerings • Opportunity areas include building management systems, smarts in mining, 'Uber for freight', carpooling	High	• Requires further RD&D and commercialisation support • New types of services may have higher investment risk or face regulatory barriers, so need the right market conditions
Biomass cultivation, engineering, procurement and construction (EPC) and operations and maintenance (O&M) for bio-refineries, biofuel production	Domestic products & services, export products: • Farmers to derive new revenue streams from waste residues or otherwise underutilised land • Development of a local, low emissions fuel industry EPC and O&M job opportunities for bio-refineries, particularly in regional areas	Medium	• RD&D required to continue developing industry. Policy support also needed to ensure demand for biofuels

III. A range of technologies exist to allow deep decarbonisation of the electricity sector while maintaining security and reliability of supply, as well as providing significant opportunities for Australian industry

KEY FINDING 5: A secure and reliable electricity system based on low emissions wind and solar PV could be possible and cost effective, but technical challenges must be addressed

Maintaining reliability in a system with high wind and solar PV share will require technologies that provide flexibility in matching supply and demand, such as energy storage (e.g. batteries and PHES) and demand response (enabled by smart grid technologies), as well as other approaches such as building excess VRE generation capacity and geographic and technology diversity. Modelling carried out for this report finds that with a mix of battery storage, excess VRE capacity and gas generation, a reliable electricity system delivering 95% abatement in 2050 compared with 2005 levels and VRE share of ~90% is possible at moderate cost (as compared to the no abatement scenario shown in Figure 7 above), with storage being required from the mid to late 2020s for Pathway 2. Additional enabling technologies to provide system security will be required, such as synthetic inertia from wind farms and batteries and synchronous condensers. These technologies will likely be required from the early 2020s across the NEM and are expected to be low cost compared with total system spend.

Several recent studies have looked at how a 100% renewable electricity system might be achieved in Australia, and have concluded that such an outcome is feasible (Wright & Hearps, 2010) (AEMO, 2013) (Teske, Dominish, Ison, & Maras, 2016) (Riesz, Elliston, Vithayasrichareon, & MacGill, 2016). These studies typically model a mix of renewables, including VRE such as wind and solar PV as well as dispatchable, synchronous sources like CST with storage, geothermal and biogas.

In Pathway 2, this report builds on that work by examining the feasibility and cost of an electricity supply based mainly on wind and solar PV. The rationale for considering such a system is that wind (onshore specifically) and solar PV are more mature and low cost than other forms of low emissions generation, with further rapid cost reductions expected. Furthermore, the batteries that could be used to support such a system have also been rapidly declining in cost, with a growing recognition emerging of the important role they can play. Another point of difference to previous studies is that rather than requiring that the electricity system be 100% renewable, Pathway 2 focuses on emissions, and (as with Pathways 3 and 4) assumes 95% abatement in 2050 (see discussion in Section 2.2). This opens up the possibility of supporting VRE generation with non-renewable gas generation, which offers a technologically and commercially mature and low-cost alternative to dispatchable renewables.

There are two key metrics to consider in a standalone AC electricity grid powered by a large amount of VRE – the average and the instantaneous share of power provided by VRE. The average share (usually just referred to as 'VRE share' in this report) relates to the total amount of energy provided by VRE over a specified period. It is also the metric that determines emissions. The variability and non-dispatchability of VRE makes achieving high VRE share challenging without enabling technologies. The instantaneous share, which is equivalent to the 'non-synchronous penetration (NSP)' [27], relates to how much of the power delivered at a particular moment is from VRE. The instantaneous VRE share and NSP are important for system security, because with the current design of the grid and associated markets, synchronous generation is needed for important services such as frequency stabilisation. Since the VRE share is the average of the instantaneous VRE share over a specified period, the maximum instantaneous VRE share is higher in a given system than the average VRE share.

To date, some small grids have been able to achieve high VRE share and high NSP. The King Island electricity system, developed by Hydro Tasmania, serves a population of 1,200 people, with 50-60% of annual energy generated from renewable sources, and runs with 100% VRE generation (i.e. a NSP of 100%) for periods of up to 60 hours (Piekutowski, 2016). Achieving the same is more challenging in larger grids. The Irish grid is the most advanced in this respect – in 2015, Ireland was able to provide 23% of demand with wind power while operating to an NSP limit of 50% (Vayu Energy, 2015). This limit was put in place to ensure system security and Ireland is currently working on technical solutions to progressively to increase the limit to 75% by 2020 (Eirgrid Group, 2016).

[27] Neglecting other sources of non-synchronous supply, such as batteries and high voltage DC (HVDC) lines.

MAINTAINING GRID RELIABILITY

There are several potential technological solutions for managing the variability and non-dispatchability of VRE. Half-hourly modelling carried out for this report (see Section B.3.2 for details) shows that VRE share of up to 40-50% is possible without requiring any enabling technologies for supply-demand matching, other than dispatchable generation, to manage wind and solar PV variability. Beyond this point, other approaches to provide system flexibility[28] are needed. The main potential approaches are energy storage (including batteries and PHES), demand response (enabled by smart grid technologies), greater interconnection between regions, and building excess VRE capacity (so there is more VRE capacity than required at certain times, with some energy from VRE being curtailed).

The modelling for the NEM for Pathway 2 carried out for this roadmap assumes a mix of battery storage, excess VRE capacity and gas generation, and finds that a reliable[29] system with 95% abatement in 2050 and VRE share of ~90% is possible at moderate cost compared with the other pathways (noting also the need to maintain security, as described below). Battery storage allows excess energy to be stored when the supply from renewables exceeds demand.

Figure 10 illustrates how batteries can support VRE, showing three consecutive days of relatively high battery use in NSW in 2046 in Pathway 2, with most energy provided by wind and solar PV. The black line shows demand as a function of time. The coloured areas between the x-axis and the black line represent power provided by generators and batteries. Values below the x-axis represent charging of the batteries, which tends to occur in the middle of the day, when there is excess solar energy available. Values above the black line represent curtailed power (i.e. the power not needed, either to meet demand or to recharge the batteries[30]). At night, most of the power is delivered from the batteries and wind in this example, with some power also gas peaking plants.

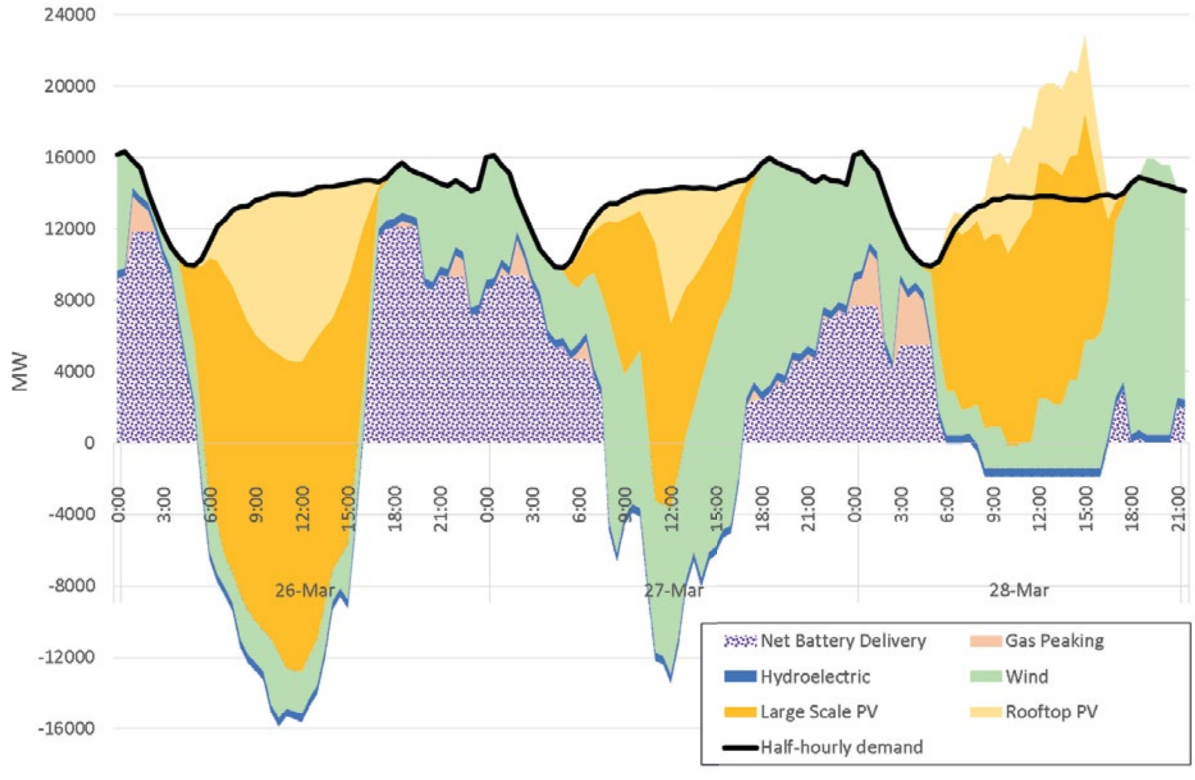

Figure 10. Example time series of electricity supply and demand in Pathway 2 showing role of battery storage; NSW, 2046, MW, 3 example days

28 Flexibility is the ability to increase, decrease or shift in time supply and/or demand such that supply equals demand at all times.

29 The modelled system is able to reliably match supply and demand for a period of poor weather conditions (i.e. low wind and sun) significantly worse than the worse period observed between 2003 and 2011; See Appendix B of the LETR Technical Report for details.

30 While solar PV is shown apparently being curtailed, this is just due to the order in which each generation type is shown in the chart – the curtailed power could be from wind or solar PV.

Figure 11 shows how much battery power is needed relative to the installed VRE capacity, against VRE share (see Figure 39 in Section B.3.2 for a similar chart for battery energy capacity). Batteries are only needed above VRE share of 40-50%, which occurs in the mid to late 2020s in Pathway 2, and around a decade later in the other pathways (see Figure 40 in Section B.3.2). To permit 90% renewables penetration, around 0.75 GW (2.6 GWh) of battery capacity is sufficient to support each 1 GW of VRE capacity; this provides around 10 hours of storage at average load.

Building additional renewable generation capacity beyond the amount at which renewable generation must be sometimes curtailed, rather than installing additional battery storage, allows for a lower system cost. The amount of additional renewable generation capacity required to minimise total system costs results in effective capacity factors for wind and large-scale solar PV decreasing by 83% and 62% of their average values at low penetration respectively.

Gas generation (or some other form of flexible dispatchable generation) is a crucial part of the mix to provide sufficient dispatchable capacity to run the system when there are extended periods of low wind and sun, without the need for a much more costly deployment of batteries. Provided sufficient battery storage capacity is available, dispatchable generation capacity equivalent to only average (not peak) demand would be sufficient to satisfy demand, even for extended periods of time with no other generation available. This is because the battery storage could be used to store energy at the times of lower than average demand in order to top up effective supply capacity at times of peak demand. Gas capacity equivalent to 55-67% (depending on state[31]) of peak demand is sufficient to provide enough dispatchable capacity to ensure a reliable system under the worst weather conditions modelled.

The cumulative total expenditure to 2050 in Pathway 2 is approximately $855 billion. This is only 4% more than the no abatement scenario and is 18% less than in Pathway 3, in which VRE share is limited to 45% and the remaining power is supplied by synchronous, dispatchable low carbon sources. This total includes an additional $9 billion of transmission spend which is estimated to be required to connect additional VRE (see Appendix B of the LETR Technical Report). The cumulative spend on battery storage to 2050 in Pathway 2 is only $32 billion, 4% of total cumulative system spend, and could potentially be further reduced if off-river pumped hydro energy storage proves viable and cost-effective at scale.

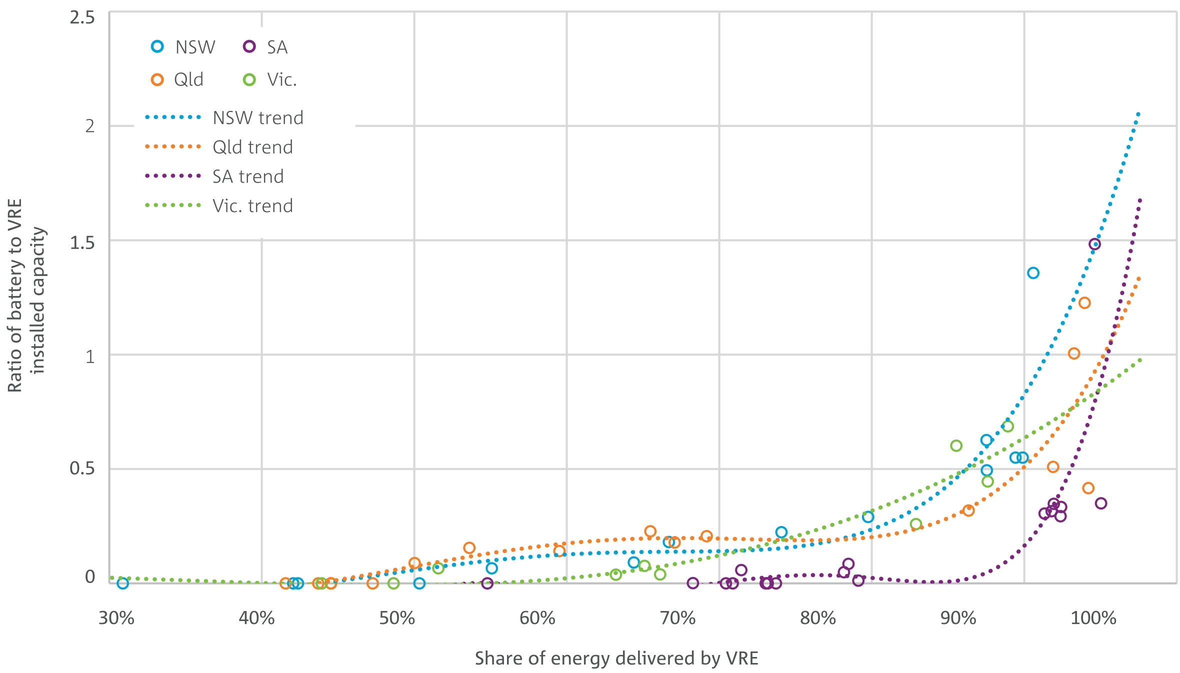

Figure 11. Ratio of battery and VRE generation capacity (GW) required to achieve energy balancing for modelled shares of energy (GWh) delivered by VRE

31 For the mainland NEM; Dispatchable capacity in Tasmania is provided by hydro with no need for gas.

The cost of a high VRE share system could be further reduced using cheaper sources of flexibility, with demand response likely to be the best candidate, since it relies on making better use of assets that are already deployed for other purposes, and hence avoids large incremental capital expenditure[32]. This could involve contractual load shedding as well as managing the charging times of EVs.

A summary of the total cumulative expenditure and breakdown of each component in Pathway 2 is shown in Table 5.

TABLE 5. SUMMARY OF CUMULATIVE EXPENDITURE FOR PATHWAY 2

COMPONENT	CUMULATIVE EXPENDITURE ($ BILLION)	PROPORTION OF OVERALL COST
Capital (centralised generation)	208	24%
O&M (centralised generation)	102	12%
Fuel - (centralised generation)	123	14%
Batteries	32	4%
Capital (Decentralised generation)	100	12%
O&M (Decentralised generation)	25	3%
Fuel (Decentralised generation)	4	1%
Distribution	213	25%
Transmission	48	6%
Total	**854**	

MAINTAINING GRID SECURITY

Achieving the high VRE share implied by Pathway 2 will also require solving the technical challenges related to high NSP in order to maintain system security. Well before 90% share is achieved, the system NSP will approach levels at which technical solutions will be needed to ensure the grid frequency is stable and that there is sufficient system strength. Figure 12 shows the annual maximum instantaneous share of VRE in each state of the NEM for the modelling carried out for Pathway 2. This is roughly equivalent to the maximum NSP (the difference being it does not include power from HVDC links or batteries). Across the NEM, the maximum instantaneous VRE share reaches levels at which enabling technologies will be required as early as the early 2020s. Given that all pathways have similar VRE penetration to around 2024 (see Figure 40 in Section B.3.2), this result also applies for Pathways 2-4.

Several technologies for managing high NSP exist or are in development, such as synchronous condensers and synthetic inertia from batteries or wind farms. The cost of deploying these technologies is expected to be relatively low – for the mainland NEM operating with high NSP, an initial conservative estimate suggests $7 billion worth of synchronous condensers could provide sufficient inertia and fault current; this is less than 1% of cumulative total system spend to 2050 (see Appendix A of the LETR Technical Report). Other solutions involving retired synchronous generators converted to synchronous condensers or synthetic inertia from batteries or wind farms may prove more cost effective. More work is required to understand how best to operate a system with high NSP, including required regulatory and market design changes.

[32] Deployment of smart grid technologies will be required to enable some forms of demand response, but the cost is likely to be moderate compared to system cost (see Appendix A of the LETR Technical Report).

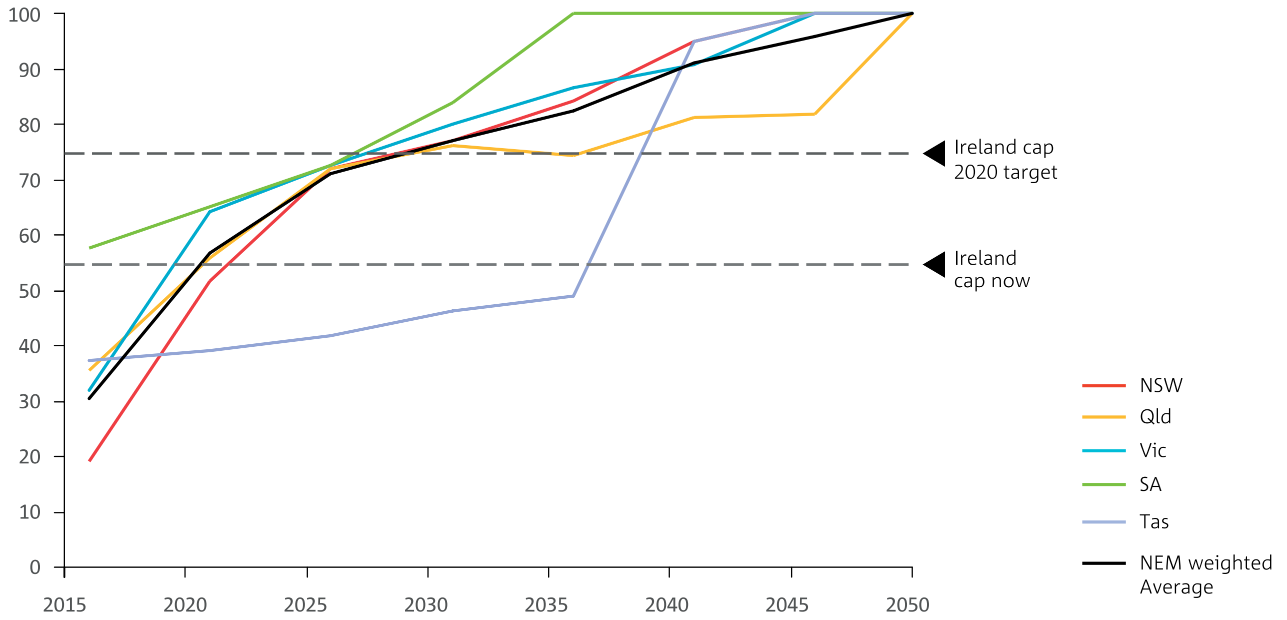

Figure 12. Maximum instantaneous share of VRE in Pathway 2, percent

KEY FINDING 6: An alternate scenario for electricity generation sees a transition to low emissions dispatchable generation, with less need for grid transformation

Deep decarbonisation of the electricity sector could be achieved using a suite of low emissions electricity generation technologies like CST with storage, PCC retrofit and/or HELE with CCS, nuclear, and geothermal. These technologies are dispatchable and synchronous and therefore avoid the challenges involved in reaching high share of wind and solar PV. These technologies should be considered individually, with the benefits of dispatchability and inertia balanced with the unique cost and risk profiles (technology, commercial, social licence) of each of these technology options and their anticipated development paths.

The relevant low emissions dispatchable technologies are:

- **CST with storage:** CST operates by concentrating sunlight onto a receiver containing a heat transfer fluid (HTF), which is used to create steam to drive a turbine. The dispatchable nature of the technology stems from relatively cheap thermal storage, which can be drawn upon to provide heat to power the turbine when required. Typically anywhere from 3-14 hours of energy storage can be achieved (i.e. the plant can continue to run up to 14 hours at a specified load from the point at which there is no sunlight).
- **HELE:** HELE technologies, such as supercritical, ultra-supercritical and IGCC coal-fired power generation and direct injection carbon engines (DICE), operate by combusting fossil fuels at higher efficiencies than coal-fired technologies currently deployed in Australia. Consequently, they require less fuel per unit of electricity generated, reducing emissions by 11-53%[33] compared with existing coal-fired generation, or by approximately 3-10% compared to the average emissions intensity of the NEM[34]. CCS is required with these technologies to achieve deep decarbonisation.
- **CCS**: CCS involves the capture, transport and storage of CO_2. The technology may be applied to both new build HELE or retrofitted to current coal or gas generation in order to significantly reduce emissions. Depending on the specific technology applied, typically 90-100% of the CO_2 may be captured. CCS increases the cost of electricity from fossil fuel generation, due to the additional equipment and operational cost involved, and because it requires a significant amount of power to run, reducing the available output from the generator.

33 Range calculated by comparing emissions intensities of supercritical, ultra-supercritical and IGCC plants (740-793 kg CO_2/MWh sent out) (CO2CRC, 2015) against lowest and highest emissions intensity coal fired-power stations in Australia currently (891 kg CO_2e/MWh sent out at Millmerran Power Station to 1558 kg CO_2e/MWh sent out at Hazelwood) (AEMO, 2016).

34 Based on average indirect (scope 2) emissions intensity (i.e. at point of use) of the NEM, which is 820 kg CO_2/MWh (Department of the Environment and Energy, 2016). Weighted average NEM generator emissions intensity (kg CO_2/MWh sent out) is lower than this, due to losses in the transmissions and distribution networks. Hence, the range specified for the difference in emissions intensity of HELE coal-fired generation technologies (3-10%) is an overestimate. Other grids in Australia (SWIS, NWIS and DKIS) have lower emissions intensities than HELE coal-fired generation (560-720 kg CO_2/MWh) (Department of the Environment and Energy, 2016).

- **Nuclear**: Currently, all nuclear power plants rely on nuclear fission (splitting of atoms into smaller atoms and subatomic particles and releasing energy) in order to generate heat to power a turbine. New designs feature improved safety and reduced waste and proliferation risk. Further, small modular reactors will potentially allow deployment of smaller increments of capacity than is possible with current large reactors.

- **Geothermal**: Geothermal energy is derived from heat contained inside the earth. Australia's potential geothermal resources for electricity generation are mainly HSA and EGS ('or hot rocks') (Huddlestone-Holmes & Russell, 2012). Heat is accessed via deep drilling into different subsurface formations (1-3.5 km for HSA and 4-6 km for EGS) and may then be used to power a steam turbine.

While generally not yet commercial in Australia, many of these technologies are being deployed overseas (e.g. Boundary Dam CCS in Canada, CST in Chile – refer to Box 9 in Section C.4.2). Australia is playing an active role in global RDD&D programs for most of these technologies. Further, Australia's vast natural resources (e.g. sunlight, coal, gas, uranium) and well-established coal and oil & gas industries means that it would be well placed to adopt these technologies by upskilling the current workforce and transitioning existing supporting infrastructure (e.g. drill rigs currently used for gas exploration could be made available for CO_2 energy storage site appraisal in CCS).

A possible scenario for the deployment of Pathway 3 technologies is shown in Figure 13. Modelling indicates that each of the technologies discussed could have a role in the generation mix. While coal-based HELE with CCS does not appear in this particular scenario, it could be deployed in a high gas price scenario (as shown in 'Sensitivity 1' in Section C.3.1).

In the scenario shown in Figure 13, gas is initially the primary source of new generation other than VRE. As the required abatement increases, new build gas is combined with CCS.

Note that this scenario is dependent on factors that include:

- Gas price increases and supply constraints
- Obtaining social licence for deployment of nuclear generation and new build coal
- The successful demonstration and deployment of geothermal generation.

The impact of these factors is explored in the Pathway 3 sensitivities discussed in Appendix C.

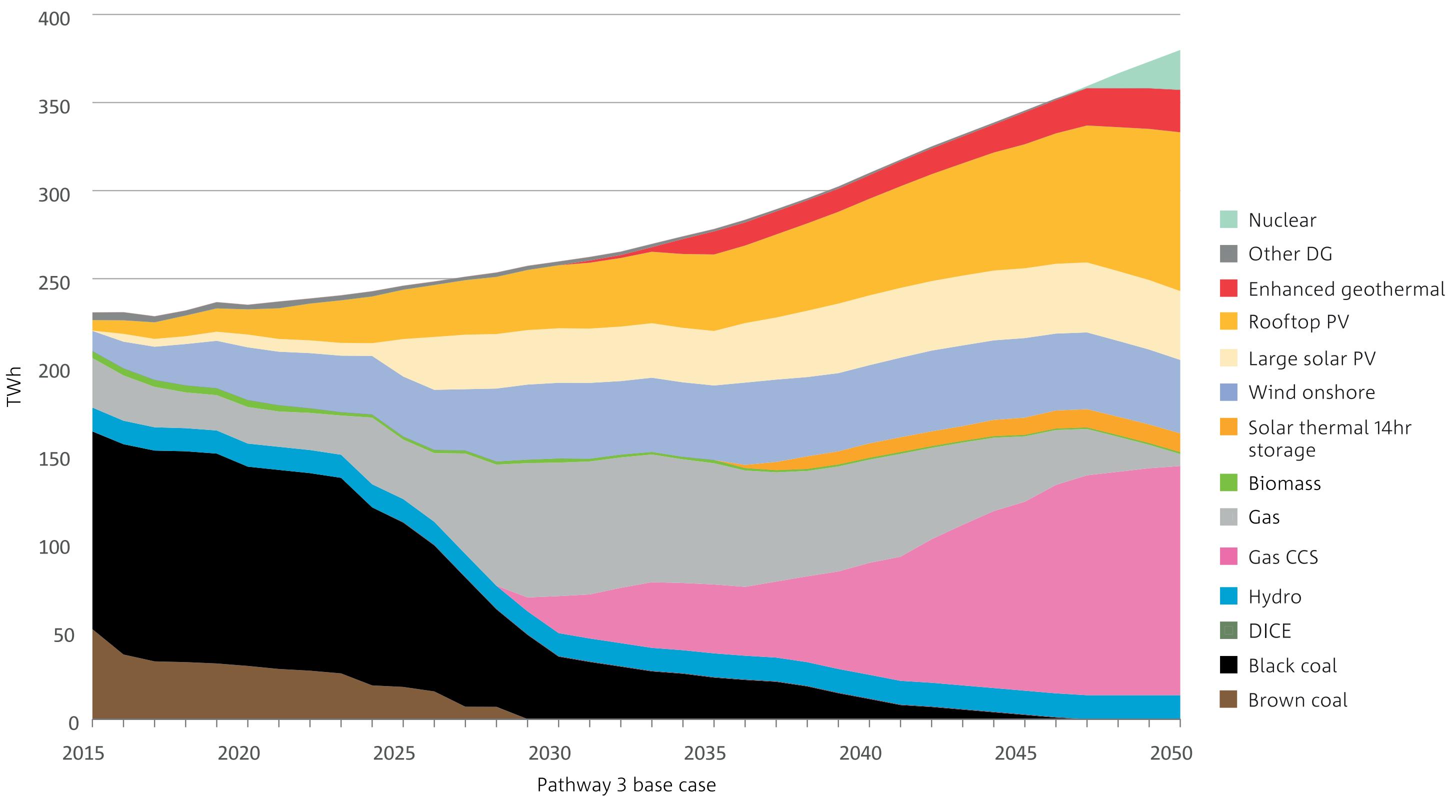

Figure 13. Possible electricity generation scenario for Pathway 3

KEY FINDING 7: Gas could contribute to decarbonisation of electricity generation, with energy productivity potentially helping address supply constraints

While decarbonisation is supported by a shift away from gas in buildings and parts of industry, gas could play a role as a transition fuel in electricity generation, and from an emissions point of view, the duration of this role could be extended if ambitious improvements in energy productivity are realised or if gas generation is combined with CCS. Improved energy efficiency and electrification could reduce gas demand from buildings and industry, helping ease supply constraints for electricity generation. Increased reliance on gas however would further expose the electricity sector to the risk of price increases.

Gas can continue to play a role in a decarbonising energy sector. In this sector, gas for power generation (GPG) can be used to support VRE via peaking plants, which form a flexible source of supply to complement variable renewable generation[35]. Closed cycle gas turbines can be used for baseload generation with lower emissions intensity than coal (373 kg CO_2/MWh for gas vs 792 kg CO_2/MWh for supercritical pulverised black coal (CO2CRC, 2015)). When combined with CCS, gas emissions can be further reduced by a factor of ~10.

In Pathway 2, GPG could act as a cost effective complement to battery storage. Battery costs scale with energy storage capacity, and costs could become prohibitive if sufficient battery storage were required to support VRE through all weather conditions (such as a wet windless week in winter, when both solar and wind generation are low). A more cost effective solution is to deploy sufficient battery storage to support VRE through most weather conditions, with gas as an additional supply. With gas used in this way, the total emissions created are relatively small. While gas has a higher fuel cost than coal, the lower capital cost of gas turbines make them more cost effective for this type of low utilisation case.

In buildings and industry, decarbonisation can be supported by decreasing gas consumption through improved energy efficiency, electrification and the use of solar thermal and bioenergy for heat. In industry, a shift away from coal to gas for direct heat reduces emissions, but deeper decarbonisation will require a shift away from gas also.

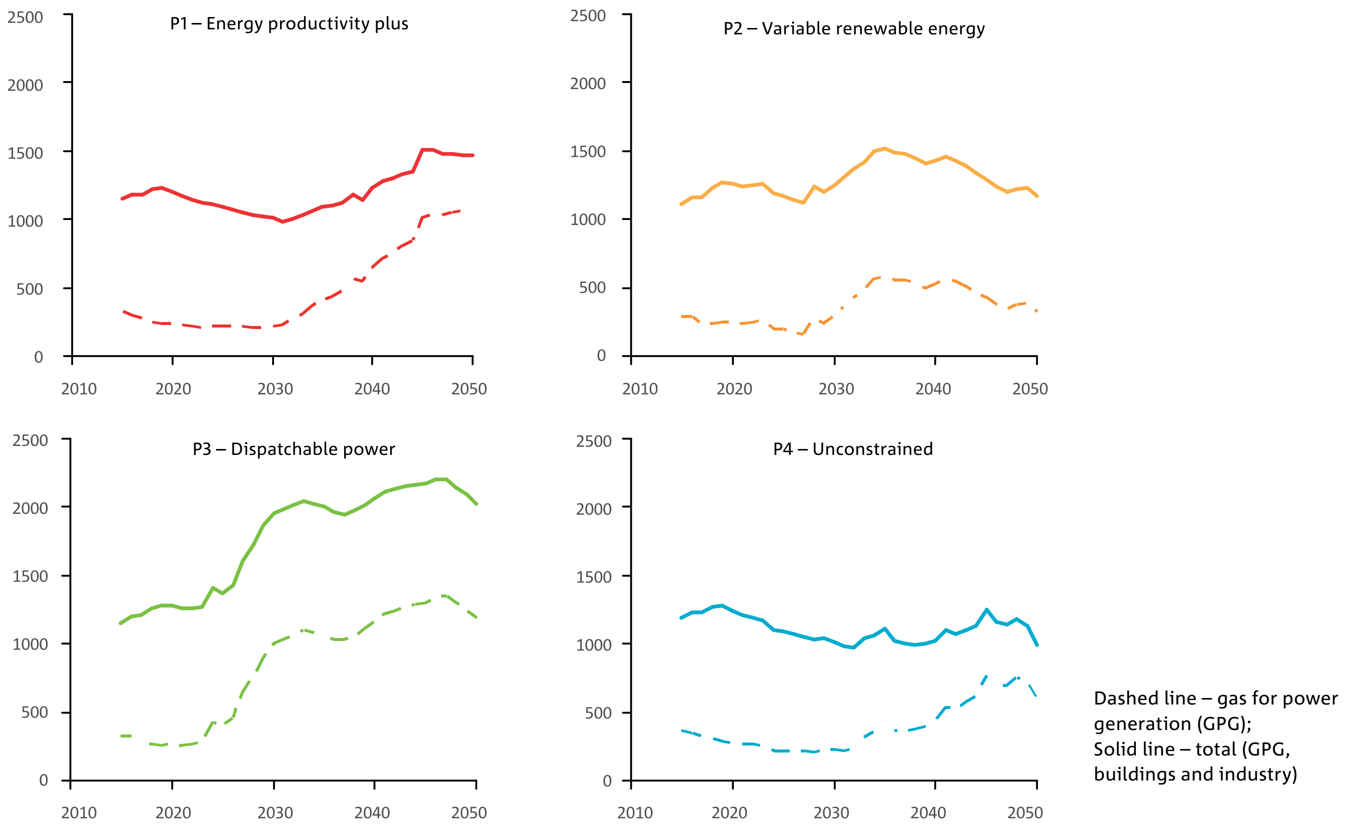

Figure 14. Gas consumption by pathway, PJ

[35] Direct injection carbon engines (DICE) could potentially also play this role. As a modular technology it can be rapidly ramped (see the HELE section in the LETR Technical Report).

Gas consumption in each pathway is shown in Figure 14[36]. Total consumption remains relatively flat in Pathways 1, 2 and 4. In Pathways 1 and 4, an increase in gas for power generation is offset by a decrease in gas in buildings and industry, driven by ambitious improvements in energy productivity. In Pathway 2, total gas consumption for power generation and for buildings and industry remains relatively flat overall, although GPG increases between 2030 and 2050, as gas helps support VRE. In Pathway 3, gas consumption grows strongly, driven by GPG[37].

An increase in domestic gas consumption would have an impact on fugitive emissions from exploration, production, transmission and distribution. Fugitive emissions in 2030 are expected to be 6 $MtCO_2e$ higher in Pathway 3 than in Pathway 1 due to the increased domestic gas consumption in this pathway.

The large increase in gas consumption in Pathway 3 could be challenged by supply constraints due to social licence issues, with moratoria under consideration in several states and a ban in place in Victoria. Increased demand without a concurrent increase in supply could also put upward pressure on prices, impacting price sensitive domestic users such as trade-exposed manufacturers. Improved energy productivity can help mitigate such price increases. It should be noted however that since the development of Australia's gas export industry, domestic gas prices are impacted by international prices, in addition to the domestic supply-demand balance. Therefore, an increased reliance on gas exposes energy users to potential price volatility.

An alternative to increasing fossil gas supply is to use excess renewable energy to produce gas. This is known as power to gas (PtG)[38] and produces zero net emissions when the gas is used. This is being investigated in Europe as a way of using gas as a long term storage medium for renewable energy. Given Australia's excellent renewable resources which are less seasonally variable than in Europe, there is less of a driver for this technology in Australia, with battery storage likely to prove sufficient for most storage requirements although with gas also playing a role (see Section 3.5).[39]

KEY FINDING 8: The transition to low carbon electricity presents significant opportunities for Australian industry

A move away from existing thermal generation will impact the local economy, particularly in communities reliant on power stations for employment. However, replacing Australia's existing generation fleet with low emissions technologies will create significant opportunities in the electricity sector in construction, installation and O&M, which provides a source of employment that could continue for decades.

Large-scale low carbon electricity also presents opportunities for the manufacture of specialised components such as heliostats for the domestic market and for export. Further, the transition to decentralised low carbon electricity presents opportunities for innovative Australian companies to develop new products and services such as home energy management systems. Australia's leading position in this transformation means Australian companies are well placed to export such products and services. Export opportunities also exist in energy services such as renewable energy policy, standards and project development. This could also allow Australia to help regional neighbours achieve low carbon growth.

The magnitude of the impact from a move away from coal could also be reduced though the deployment of HELE coal-fired power generation and CCS in both Australia and its trading partner nations. CCS could enable the local production of low emissions hydrogen via gasification of coal. This has the potential to become a key export opportunity for Australia and to help transition communities impacted by a decline in coal-fired generation.

36 Gas used for transport is negligible compared with buildings, industry and electricity and is not shown.

37 Note, this growth is moderated in the sensitivity cases, in which a higher gas prices is assumed.

38 In PtG, electricity from VRE is used to produce hydrogen via electrolysis. This hydrogen is then combined with carbon dioxide to synthesise methane (via methanation) which can be added to the gas distribution network. See for instance http://www.storeandgo.info/ and http://www.erig.eu/ .

39 Gas produced via PtG or other low emissions means is also likely to cost significantly more than fossil gas production methods. Analysis carried out for this roadmap indicates other means of hydrogen production are likely to be more cost effective in Australia than electrolysis (see the hydrogen section in the LETR Technical Report). Making gas via methanation using hydrogen produced from brown coal with CCS (the cheapest low emissions hydrogen production method) is estimated to cost $29/GJ in 2030, significantly more than the high case gas price assumed in this roadmap ($12.7/GJ in 2030).

Impact

A shift away from coal-fired generation in Australia will cause job losses in the coal-fired generation sector and more broadly in affected communities. For instance, closures of brown coal-fired generators in the Latrobe Valley could impact 1400 jobs directly and a further 1771 jobs indirectly (Committee for Gippsland, 2016). Accelerated closures of coal-fired generation compared with a no abatement scenario is expected in all pathways, although with variations in degree and timing.

A long term global shift away from coal-fired generation will also likely present a challenge to Australia's thermal coal export industry. With global demand for coal in 2040 predicted to be 49% less than today, in a scenario in which the world follows an energy pathway consistent with a 50% chance of limiting warming to 2°C, Australia's thermal coal exports could be greatly affected. Trade of coking coal however, is expected to remain at 80% of current levels in this scenario, meaning a considerable level of export-oriented mining activity could be sustained in Australia, even while meeting the 2°C warming target (International Energy Agency, 2016).

By way of indication of the level of impact that might be expected from a reduction in coal production, modelling by Victoria University's Centre of Policy Studies found a moratorium on new coal mines and coal mine expansions in Australia, which would see Queensland and NSW coal production decline to close to zero by 2050 (similar to the declines in domestic coal-fired generation expected in the pathways examined in this roadmap), would result in a 0.6% difference to 2040 GDP, a maximum difference in employment of 0.04% and a 1% reduction in the value of exports[40] (Denniss, Adams, Campbell, & Grudnoff, 2016).

Further, closures of coal-fired generators could have impacts to the wider Australian community through unexpected electricity price rises and reduced grid stability if sufficient new low emissions generation, enabling technologies and reductions in energy demand through improved energy efficiency are not deployed sufficiently early. The risk of such impacts can be reduced by increasing investor confidence in the policy framework for reducing electricity emissions. If the policy framework for emissions reduction in electricity is clear and stable, investors can forward plan new assets to replace closing coal plants. This also allows for new employment opportunities in low emissions generation to be created and for retraining to occur in a timely manner.

Impact mitigation – Opportunities within the electricity sector

Outside of a few countries in Asia where the manufacturing of renewable energy technologies is concentrated, the bulk of job opportunities associated with low emissions generation are in construction, installation, O&M (IRENA, 2015). Replacing Australia's existing generation fleet with low emissions technologies will create large job opportunities in these areas. A 2016 report from the Climate Council and EY found that a scenario in which renewable energy provides 50% of electricity generated in 2030, with new build generation consisting of large-scale and rooftop solar PV and wind, will result in thousands of net additional electricity sector jobs in Australia. (Ernst & Young and the Climate Council of Australia, 2016).

Around 55% of the net additional jobs are in construction/installation, with the remainder in O&M. Most of the construction jobs are for rooftop solar, will be located in population centres, and will represent an ongoing source of employment. For wind and large-scale solar, construction jobs will likely involve a mix of continuous employment for skilled labour moving from site to site as well as local unskilled and semi-skilled labour for individual construction projects. Large-scale wind and solar projects will provide ongoing employment opportunities in rural and regional areas. Similar opportunities exist in construction and O&M of other low emissions technologies, such as CST (both for electricity and industrial heat) and CCS. Opportunities also exist in incorporating renewables in standalone power systems in Australia and building modularised components for these systems. Note however that a net positive jobs impact won't necessarily apply in communities subject to coal-fired generator closures and it will be important to manage this transition to reduce the impact on the individuals and communities involved.

There are also a number of Australian companies developing niche solutions relating to EPC and O&M that could be exported overseas as well as servicing the local market. Bladepile is an example of such a company, and has developed a novel structural pile for deployment in local solar farms (see Box 7 in Section C.5). Another example is Heliostat SA, which builds heliostats for international CST projects (see Box 11 in Section C.5) using innovative Australian technology, enabling the company to diversify out of providing parts to the auto industry.

40 Compared with a reference case in which there is no moratorium and coal production continues to grow at around 0.8% CAGR.

While presenting a challenge, transformation of Australia's electricity sector also provides an opportunity to modernise the system and ensure it continues to provide secure, reliable and accessible power for the decades to come.

Transitioning Australia's grid to a more decentralised model with high penetrations of distributed energy resources (DERs) such as solar PV, batteries, EVs and smart appliances also creates a range of diverse opportunities for innovative products and services. These include home energy management systems, energy trading platforms and cyber-security solutions. Australia's leading position in this transition also creates opportunities to export technologies and services in this area. An example of this type of opportunity is provided by Evergen, which provides home energy systems, capitalising on leading Australian research and a clear market opportunity in distributed energy (see Box 8 Section B.5).

These types of opportunities could also be built on by offering assessment and installation of high-efficiency appliances and building services at the time of installation of rooftop solar PV systems, batteries and EV chargers. Undertaking an energy efficiency assessment at the same time as a solar PV installation offers a range of benefits. For instance, identifying opportunities to reduce energy demand could allow for the solar PV system and battery sizes to be reduced, lowering the amount of investment required.

Clean energy transitions require strong regulatory environments and the deployment of a range of energy services that differ greatly from traditional energy system models. Australia has a significant comparative advantage across the range of energy services, especially in South East Asia and the Pacific, and could help developing countries achieve low-carbon growth. Australia's capabilities include economic and financial management, renewable energy policy and planning, software for measurement and modelling of resources, standards and certification and remote area power solutions, including feasibility, design, construction and commissioning. An example of a company pursuing these types of opportunities is Carnegie Clean Energy, a wave energy technology developer which has recently diversified into microgrid development through the acquisition of Energy Made Clean.

Impacts to coal-fired generation could also be reduced by avoiding plant closures through CCS retrofit. This would require a clear and stable emission reduction policy so that investors could be confident there was a sufficient time window for a retrofitted coal plant to operate (and recover the cost of the retrofit). It would also require some effort on the part of investors to gain the social licence needed to extend the life of existing coal plant.

In Pathway 1, brown coal generation continues until the mid-2040s and black coal until after 2050. In Pathway 3, while brown-coal fired generation is phased out by the late 2020s and black coal-fired generation declines by 70-80% by 2030 compared with current values, the emergence of CCS (either as retrofit to existing power stations or with new build) may allow for the continuation of coal-fired power in Australia, albeit at a reduced level (see Section 3.6).

A summary of the key opportunities in the electricity sector is presented in Table 6 below.

TABLE 6. SUMMARY OF KEY OPPORTUNITIES IN THE ELECTRICITY SECTOR

OPPORTUNITY	OPPORTUNITY TYPE AND DESCRIPTION	DIFFICULTY	DESCRIPTION
EPC & O&M for VRE	Domestic services: • Job creation from widespread adoption of solar (large-scale and rooftop) and wind	Low	• Mature technology and industry. Some investment may be required to ensure industry grows at the required rate
Battery distribution, installation and operation	Domestic services: • Expanding local market for large-scale and behind-the-meter (BTM) batteries	Low	• Mature technology • Organic industry growth
EPC, O&M and modularised components for RAPS, SAPS and microgrids	Domestic/export products & services: • Opportunity to design, procure and operate RAPS, SAPS and microgrids using integrated renewables and storage • Opportunity to export modularised components and services	Medium	• Further RD&D investment required before RAPS, SAPS and microgrids using integrated renewables and batteries are widely accepted
Thin-film solar manufacturing	Domestic/export products: • Opportunity to manufacture thin-film solar panels for local use and export	Medium	• Requires further RD&D support
Software and marketing new services for smart grid technologies	Domestic/export services: • Opportunity to develop and market software supporting smart grid technologies both locally and overseas	Medium	• Requires further RD&D support • New types of services which may have higher investment risk and so need the right commercial/regulatory framework
Managing distribution network	Domestic services: • Operating a platform to enable market participants to trade energy and services to optimise system operation	High	• Market/regulatory reform required
Export of CST components (e.g. heliostats, receivers)	Domestic/export products: • Opportunity to continue to commercialise Australian IP and manufacture CST components (e.g. heliostats) for local use and export to key economies such as India and China	Medium	• Further support required to continue to commercialise IP, manufacture locally and export
EPC and O&M for CCS (including servicing sites in south east Asia)	Domestic/export services: • Opportunity to procure and operate local end-to-end CCS network as well as manage storage projects in S.E. Asia	High	• Further RD&D investment required • Potential social licence barriers • Relies on policy drivers in target markets

Impact mitigation – Energy productivity

Impacts to the coal-fired electricity generation sector in Australia, and to associated communities, could be delayed through ambitious improvements in energy productivity – coal generation is phased out later in Pathways 1 and 4 than in Pathways 2 and 3 (not including continued coal fired generation with CCS in one of the Pathway 3 sensitivities – see Section B.3.1). See Section 3.12 for further discussion on why ambitious improvements in energy productivity allow more time to transition the electricity sector.

Impact mitigation – commodities

Impacts to the coal mining sector could also be reduced through strong global action to implement HELE generation with CCS, which would allow Australia to export a greater proportion of its coal reserves than a scenario in which these technologies are not deployed, and would allow more time to transition communities that depend on extraction of these resources[41].

Impacts to affected communities can be further reduced through a transition plan covering new jobs, skills, technology, infrastructure and industries (Committee for Gippsland, 2016). One new industry of particular relevance for communities currently dependent on coal production is the production of low emissions hydrogen. Hydrogen can be produced via the gasification of coal, and can be low emissions if CCS is used. A multi-billion dollar hydrogen or ammonia export market from low emissions Australian facilities could be created if Japan and South Korea successfully transition to hydrogen economies[42].

For exports to Japan alone, the opportunity could be worth ˜$1-4 billion annually by 2030 (see Section C.5). Australia is well positioned to capitalise on this opportunity due to its existing trading relationships with Japan and South Korea, and its excellent resources for producing low emissions hydrogen, such as brown coal in the Latrobe Valley, which is located near to potential CCS storage resources. Low emissions hydrogen could also be produced by electrolysis using low emissions electricity. Australia also has a comparative advantage for this production method due to its excellent solar resources, although this method is expected to be more costly than gasification of brown coal with CCS (see the hydrogen section of the LETR Technical Report).

A global clean energy transition will also create opportunities in mining and minerals processing for key resources used in batteries and other technologies, such as lithium, magnesium, cobalt, nickel, lead, zinc and graphite. Australia has the world's fourth largest lithium reserves[43], and is currently the leading producer (U.S. Geological Survey, 2016) and is therefore well positioned to benefit from growth in the global battery market, which is likely to remain heavily reliant on lithium for the foreseeable future. Australia currently produces 13 Mtpa of lithium, worth around $40 million at current prices. Lithium prices have grown at 10% p.a. over the last decade (Metalary, 2016), and are predicted to continue growing at 8.9% p.a. through 2019 (Freedonia Group, 2016). Furthermore, the global market for storage is expected to reach 1000 GW in the next 20 years (D'Aprile, Newman, & Pinner, 2016), which is likely to drive an exponential increase in the demand for lithium. Additional value from minerals used for clean energy technologies could be captured if processing is carried out locally.

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41 This will not provide an indefinite life to Australia's thermal coal industry however; a 2015 study published in Nature found that uptake of CCS allowed 7% of Australia's coal reserves to be used by 2050 in a scenario in which warming is limited to 2°C, compared with 5% in the same scenario but excluding CCS (McGlade, 2015). This contrasts with 20% of reserves being used by 2050 at current production rates.

42 As countries that rely heavily on imported energy, a shift towards hydrogen makes sense for Japan and South Korea for diversifying and reducing emissions from their energy imports. Given that hydrogen is produced using gas, coal or renewable energy, which are all primary energy sources that Australia has large supplies of, the same drivers for shifting towards a hydrogen economy do not apply for Australia, and hydrogen mainly represents an export opportunity for Australia. This is discussed further in Appendix C.

43 Based on current prices, Australia's lithium reserves are valued at ~USD 11 billion.

TABLE 7. SUMMARY OF KEY OPPORTUNITIES IN COMMODITIES

OPPORTUNITY	OPPORTUNITY TYPE AND DESCRIPTION	DIFFICULTY	DESCRIPTION
Hydrogen production for export	• Export commodities & local services: • Opportunity to develop large-scale low emissions hydrogen production for export to Asia, using coal/CCS or dedicated renewables ($1-4 billion annually for Japan alone) • EPC and O&M requirements for large-scale hydrogen production facilities and supporting infrastructure	High	• Requires significant RDD&D support to establish commercial industry
Extraction and processing of coal and gas	Export commodities: • Deployment of HELE and CCS globally may allow for continued export of coal/gas overseas despite global limits on carbon emissions	Medium	• Existing mature industry • Uncertainty over future global demand for coal/gas • Potential social licence barriers
Mining of raw materials for clean technologies (e.g. lithium, silica)	Local and export products: • Expanding local industry, driven by growth in global demand	Low	• Mature industry • Organic industry growth
Receipt and storage of nuclear waste	Export services: • Opportunity to establish infrastructure supporting receipt and storage of radioactive waste from overseas	High	• Significant investment required to develop infrastructure • Social licence barriers

IV. Fugitive emissions from coal mining and oil & gas production could be reduced by 40% compared to BAU in 2030

KEY FINDING 9: Innovative technologies could allow fugitive emissions from coal mining and oil & gas production to be reduced by up to 40% compared to BAU in 2030, as well as providing export opportunities

Technologies currently in development in Australia for the abatement of ventilation air methane in underground coal mining could potentially be deployed at scale by 2030, achieving approximately 80% abatement of emissions from this source. These technologies also represent an export opportunity for Australia, especially to China. Fugitive emissions from LNG production could be reduced by deployment of CCS where economically feasible. Further abatement of fugitive emissions in oil & gas production and in domestic gas distribution and transmission could be achieved through improved operational practices. Combined, technologies for the abatement of fugitive emissions could decrease emissions by 19 $MtCO_2e$ in 2030 compared with BAU and contribute 8% of energy sector abatement.

Fugitive emissions accounted for 41 $MtCO_2e$ in 2015, with 50% of emissions coming from underground coal mining, 20% of emission from domestic gas, 16% of emissions from open cut and abandoned coal mines, 9% of emissions from LNG and most of the remainder from flaring in oil production. Fugitive emissions from LNG are expected to grow to 18% of total fugitive emissions over the next few years (Australian Government Department of the Environment and Energy, 2016).

The largest opportunity for abatement exists in reducing emissions from underground coal mines. Fugitive emissions in underground coal mining result primarily from the release of methane during the mining process. High volumes of ventilation air are required to keep the concentrations of methane low enough to avoid the risk of explosions. This low concentration methane is referred to as VAM. Commercial technologies for VAM abatement exist, as well as more efficient technologies at the demonstration stage. With sufficient focus on RDD&D, technologies for VAM abatement could feasibly be rolled out to all underground coal mines in Australia as early as 2027, and achieve an estimated 80% reduction in VAM emissions, equivalent to a 15 $MtCO_2e$ reduction vs BAU in 2030.

The key opportunity for abatement of fugitive emissions in LNG is CCS of vented CO_2. CCS requires a pure stream of CO_2, the expertise to safely inject the CO_2 underground and access to a suitable geological storage reserve. LNG operations typically involve the first two of these elements, with the third depending on the specific project. In some cases, lack of a suitable nearby storage reserve may make CCS cost prohibitive. An example of geological storage of vented CO_2 is provided by the Gorgon project in Western Australia (WA), which is set to start injecting 3.4-4 million tonnes per annum of CO_2 in 2017, making it the world's largest CCS project (Global CCS Institute, 2016). In addition to the Gorgon project, it is estimated that 33% of vented CO_2 from LNG could be cost-effectively reinjected underground, potentially reducing fugitive emissions by 1.3 $MtCO_2e$ in 2030.

For domestic gas, most fugitive emissions result from venting and flaring methane, as well as leaks from transmission, distribution and storage. Venting and flaring can be reduced by process improvements, enabled by technological solutions such as advanced process control. Leaks can be reduced through improved maintenance and planning processes (ClimateWorks Australia, 2014). Emissions can also occur during exploration and production of domestic and export gas. Abatement of these emissions is primarily an operational issue, requiring improved maintenance to reduce leaks. Abatement through these measures could achieve an estimated 1.8 $MtCO_2e$ in abatement in 2030.

Domestic gas fugitive emissions could be expected to decrease with declining residential, commercial and industrial gas use. Conversely, more fugitive emissions can be expected if more gas is used for electricity generation, as is the case in some of the scenarios modelled in this report.

Development of technologies for the abatement of fugitive emissions from ventilation air methane represents a potential opportunity for licencing IP, in particular to China, which accounts for 45% of global VAM emissions. There may also be opportunities to offer consulting services overseas for the abatement of fugitive emissions from oil & gas production, in particular for CCS of vented CO_2 from LNG production. These opportunities depend on regulatory drivers creating a demand for such technologies in overseas markets.

Technologies for the abatement of fugitive emissions are discussed further in Appendix A and in the fugitive emissions section of the LETR Technical Report.

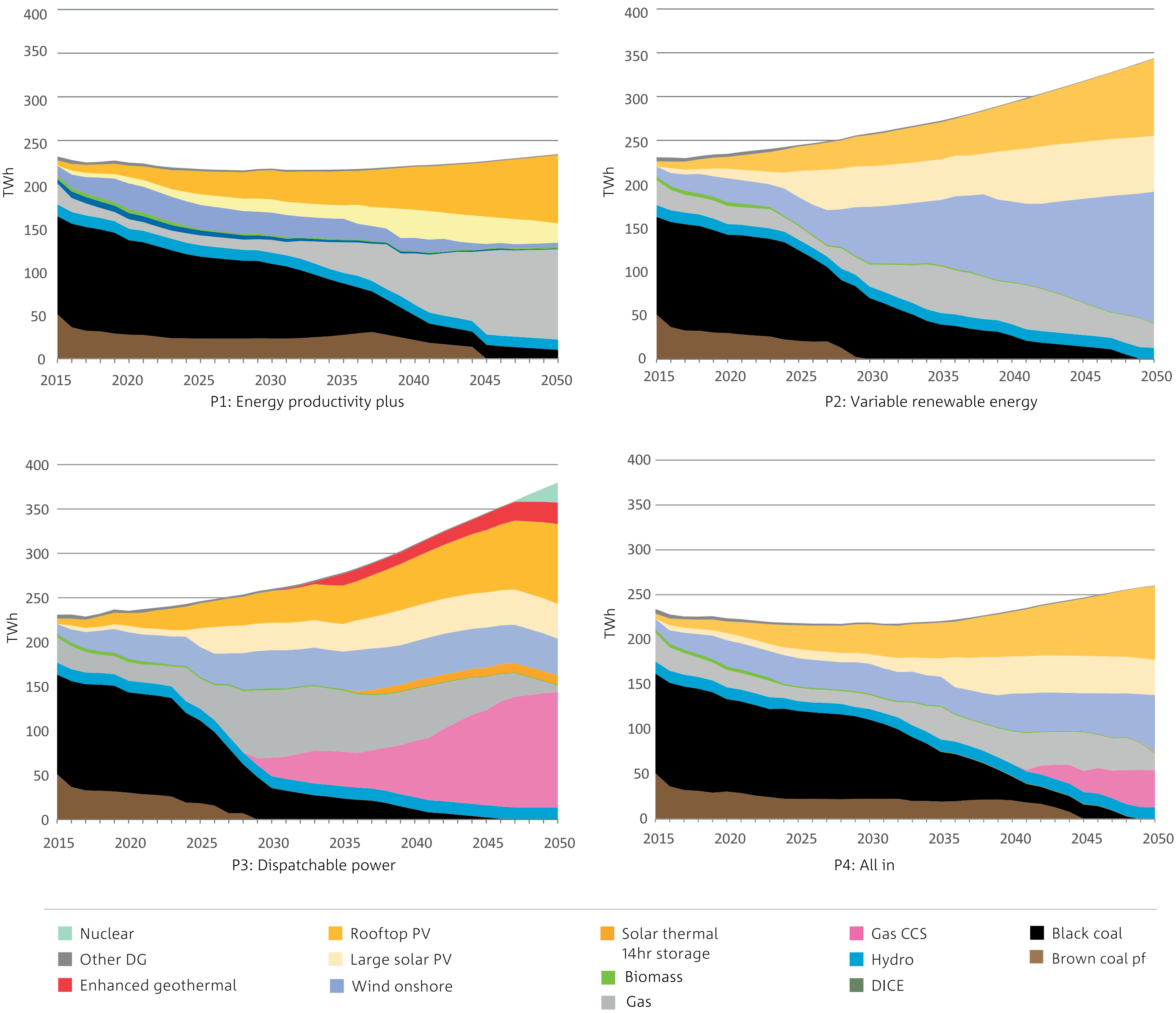

Figure 15. Electricity generation mix to 2050 under each pathway [44]

[44] DG – distributed generation.

V. The energy sector can achieve a proportional share of the 2030 target and achieve deeper abatement post-2030

KEY FINDING 10: New electricity generation to 2030 is likely to comprise mainly wind and solar PV

In each pathway, onshore wind and large-scale and rooftop solar PV are expected to make up the majority of new generation to 2030, due to the low cost, low emissions and commercial maturity of these technologies. An exception is Pathway 3, where gas combined cycle could also form a large part of the mix, combined with CCS towards the end of this period. Less new generation is required in Pathways 1 and 4; these pathways also show slower decreases in coal-fired generation.

The expected electricity generation mix to 2050 under each pathway is shown in Figure 15.

Due to emissions constraints imposed on the electricity sector (straight line declines in emissions from 2015 values to the 2030 values shown in Figure 18), any new generation in this period must be low emissions. This excludes coal-fired generation without CCS. New generation therefore mainly comprises low cost, low emissions technologies, namely solar PV (large-scale and rooftop) and onshore wind. Gas-fired generation is sufficiently low emissions to form part of the electricity mix, although nearing 2030, any new gas generation requires CCS to meet the emissions constraints. Gas with CCS is the most cost-effective low emissions form of baseload generation, and hence is seen entering the mix in Pathway 3, before coal with CCS (including retrofit to existing generators) or other forms of generation such as CST with storage, nuclear and geothermal. These forms of generation could all potentially enter after 2030. In a high gas price sensitivity case, the modelling predicts less gas-fired generation in Pathway 3, with instead CST with storage and geothermal entering the generation mix towards the end of the 2020s (see Pathway 3 chapter).

Pathways 2 and 3 see a phasing out of brown coal generation by 2030 (other low carbon uses for brown coal could continue indefinitely), as well as steep declines in black coal during the 2020s. In Pathways 1 and 4, coal-fired generation is more gradually phased out over time.

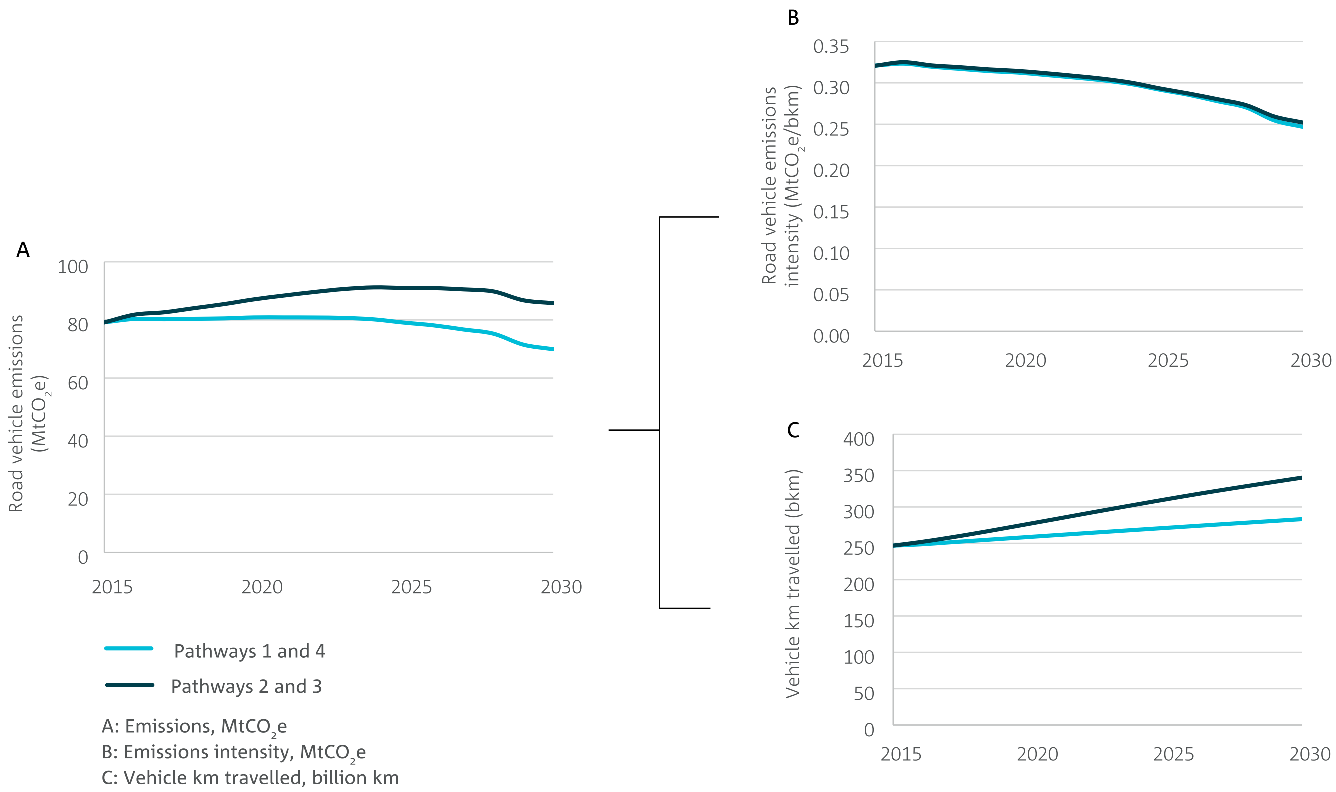

Figure 16. Road transport modelling results

KEY FINDING 11: In addition to unlocking billions of dollars of savings, ongoing improvements in energy productivity can prevent increases in emissions in transport and direct combustion to 2030

Improving energy productivity in transport and direct combustion is key to achieving abatement of emissions from these sources, with significant progress possible in a 2030 timeframe. Achieving ambitious improvements in energy productivity now, particularly in relation to the deployment of new assets, will help to avoid locking in higher emissions assets that would make subsequent decarbonisation more difficult.

In Pathways 2 and 3, BAU energy productivity improvements allow large increases in emissions to be avoided, with transport and direct combustion emissions increasing by 10% and remaining flat respectively compared with 2015 levels, despite significant increases in demand. In Pathways 1 and 4, which have ambitious improvements in energy productivity, 2030 emissions from transport and direct combustion decline from 2015 levels by ~8% and 13% respectively. Total 2030 transport and direct combustion emissions are 29 $MtCO_2e$ lower in these pathways than in Pathways 2 and 3 (see Figure 18).

In transport, road vehicles contribute the majority of emissions, comprising 85% of 2015 transport emissions. Most of the potential abatement in road vehicle emissions to 2030 comes from improvements in vehicle efficiency (particularly from EVs), which offsets an expected growth in transport demand (see Figure 16). The lower emissions in Pathways 1 and 4 result mainly from lower demand for private road vehicle transport in these pathways, driven by a continuing trend away from vehicle ownership and higher levels of mode shifting to public transport and non-motorised transport like walking, cycling or telecommuting.

EV adoption is expected to begin to make an important contribution to reducing average road vehicle emissions intensity by 2030. EVs are already lower emissions when charged from today's grid than equivalent internal ICEs[45]. As the grid decarbonises further, the emissions advantage of EVs will further increase, even with ambitious improvements to ICE efficiency (see EVs section in the LETR Technical Report).

Abatement in direct combustion relies mainly on a combination of energy efficiency improvements, electrification and fuel switching (including direct use of renewables such as CST and bioenergy). In Pathways

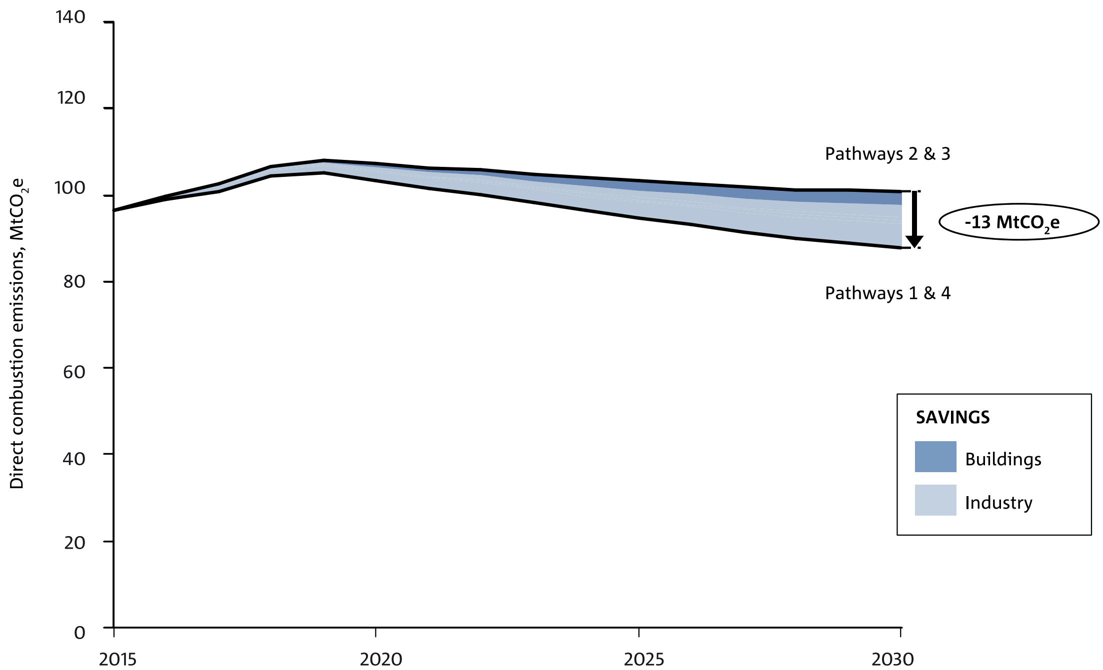

Figure 17. Direct combustion emissions 2015-2030 ($MtCO_2e$)showing emissions for Pathways 2 & 3, Pathways 1 & 4 and relative savings in buildings and industry sectors.

[45] An exception to this is in Victoria, where the higher emissions intensity of the grid resulting from brown coal fired electricity generation means that EVs currently have higher emissions than equivalent ICEs. With the grid decarbonisation assumed in this roadmap, EVs are expected to have lower emissions than ICEs in Victoria from the mid-2020s (see the EVs section of the LETR Technical Report for further details).

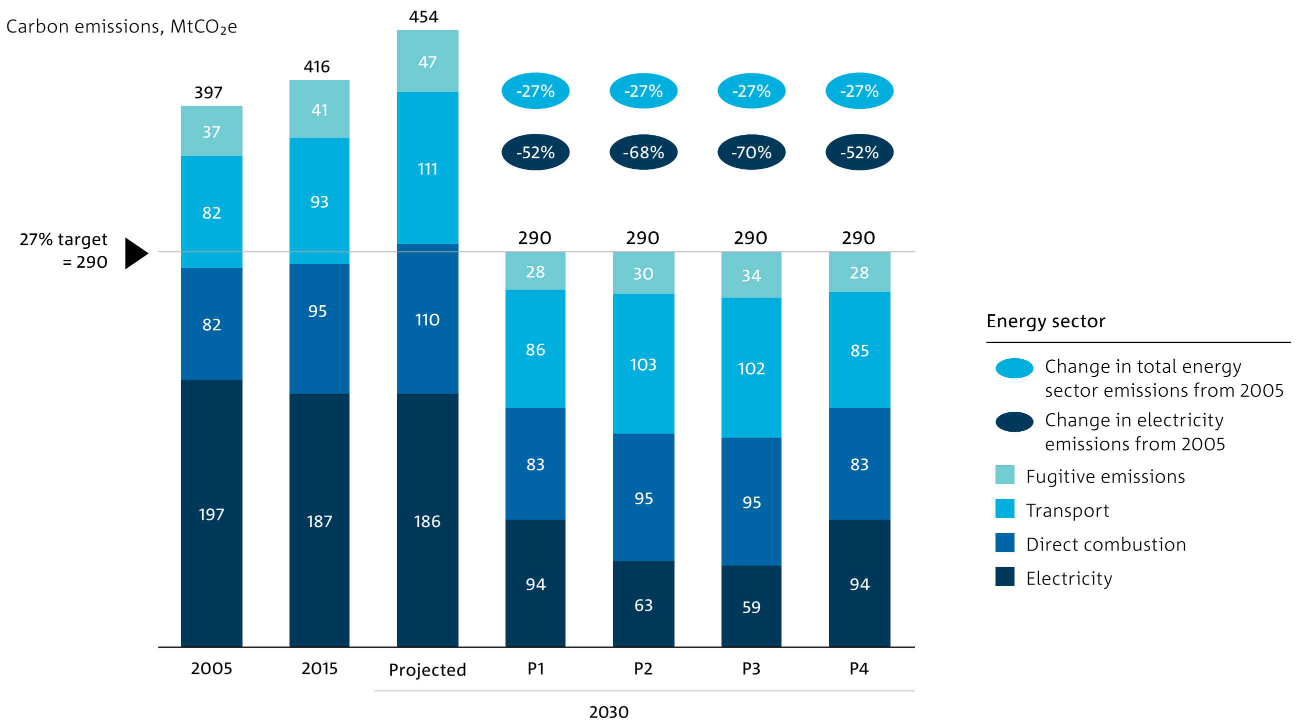

Figure 18. 2030 abatement achieved by each pathway[46]

2 and 3, which rely on BAU improvements in energy productivity, there is a slight increase in direct combustion emissions from 2015 to 2030 (Figure 17). Ambitious improvement in energy productivity in Pathways 1 and 4 result in an incremental 13 $MtCO_2e$ of abatement in 2030.

Emissions savings in industry accounts for nearly three quarters of this additional abatement in 2030. This reduces direct combustion emissions from industry by 7% compared to 2015 levels, with the rate of improvement limited by the current replacement rate of equipment. In the case of electrification, abatement also depends on decarbonisation of the electricity supply; for some processes a switch from gas-fired heat to electricity only results in emissions abatement from around 2040 based on the uptake of low emissions electricity generation assumed in this roadmap (see Appendix B of the LETR Technical Report).

The buildings sector can contribute a quarter of total direct combustion abatement in 2030 in Pathways 1 and 4, with emissions from this source decreasing 17% compared to 2015 levels, achieved through cost-effective energy efficiency and fuel switching.

An important point to note is that achieving ambitious improvements in energy productivity now, particularly in relation to the deployment of new demand side assets, will help to avoid locking in higher emissions assets that would make subsequent decarbonisation more difficult.

[46] Due to rounding, some totals may not correspond with the sum of the separate figures. The 2030 target of 290 $MtCO_2e$ is based on energy sector abatement proportional to Australia's total abatement target of 26-28% compared to 2005 levels, with the mid-point value of 27% chosen to calculate a specific target. 2005, 2015 and projected 2030 numbers from (Australian Government Department of the Environment and Energy, 2016). Projected numbers assume current policy.

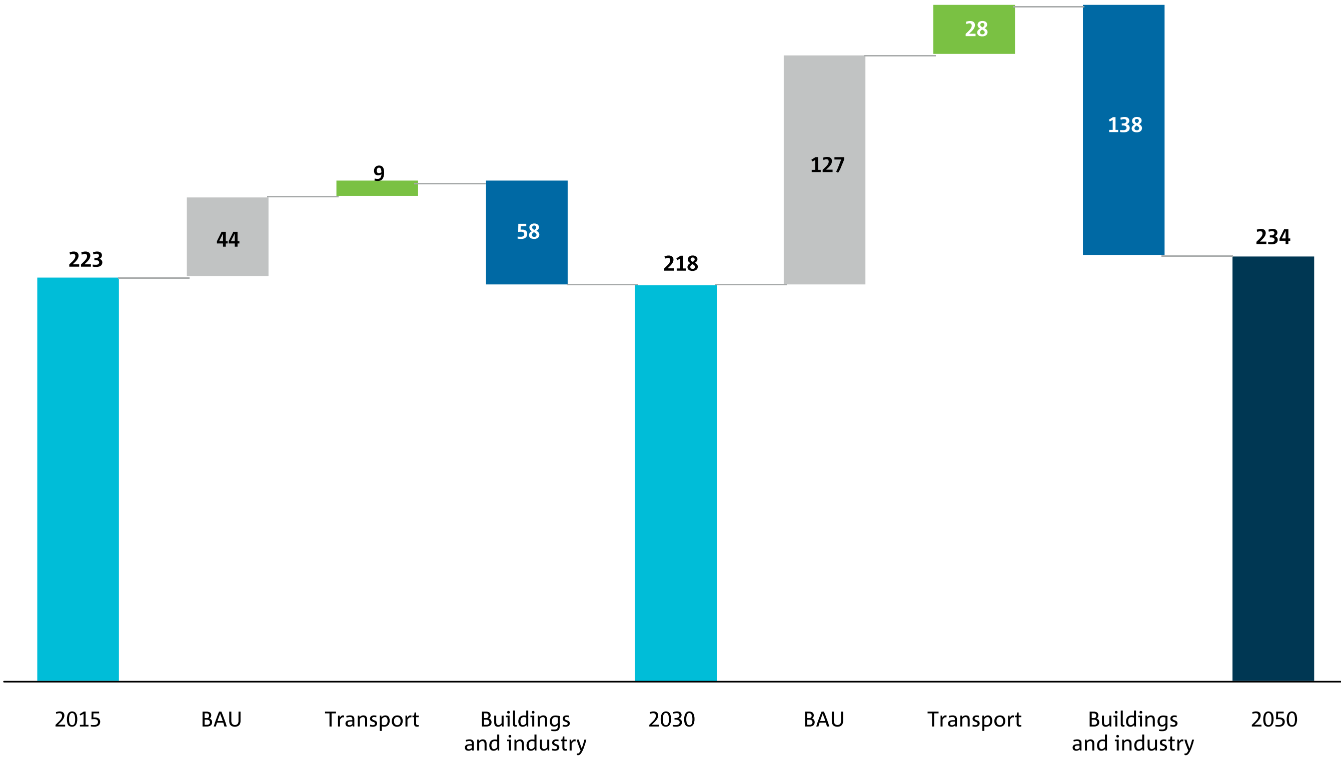

Figure 19. Changes in national electricity demand (TWh) between 2015, 2030 and 2050 in Pathway 1 showing contributions of BAU growth, increase from transport[47] electrification and net effects of electrification and energy efficiency in buildings and industry[48]

KEY FINDING 12: Ambitious improvements in energy productivity can allow more time to transition the electricity sector to low emissions generation

In addition to the benefits ambitious increases in energy productivity provide to energy users in buildings, industry and transport, such increases can also allow more time to transition the electricity sector to low emissions generation. This is due to less abatement being required from the electricity sector to meet the 2030 target, and to flat electricity demand resulting from energy productivity improvements.

The expected breakdown of 2030 energy sector emissions for each pathway is shown in Figure 18.

Depending on the pathway, electricity emissions decline by between 52% and 70% by 2030 from 2005 values. The required abatement is less in Pathways 1 and 4, in which there is faster improvement in energy productivity across the energy sector. This underscores the important role ambitious energy productivity can play in contributing to decarbonisation and reducing the abatement requirement of the electricity sector.

This analysis assumes the energy sector delivers a proportional share of the 2030 target. The required abatement of electricity and other energy emissions would be reduced if non-energy emissions are able to deliver greater abatement. This could be achieved

[47] To arrive at these figures, BAU electricity consumption was taken from AEMO, without energy efficiency and solar PV assumptions. This served as the baseline upon which the new assumptions of contributions from transport electrification and buildings and industry were applied.

for instance if the magnitude of negative emissions from LULUCF could be significantly increased from their 2015 value of -4 $MtCO_2e$, which is expected to possible in a strong abatement scenario (which reaches close to net zero emissions by 2050) (CSIRO, 2015).

Aside from reducing the amount of abatement required from the electricity sector, increased energy productivity also has the effect of reducing electricity demand, making the task of decarbonising the electricity sector less costly, since less new generation capacity is required. Figure 19 shows that in Pathway 1, electricity demand can stay relatively flat, with energy efficiency offsetting increases from BAU growth and electrification.

KEY FINDING 13: Continued uptake of likely low emissions technologies could allow the energy sector to reduce emissions by 55-69% by 2050

Deep cuts in energy sector emissions by 2050 will be challenging but possible through a combination of deep decarbonisation of electricity generation and sustained, ambitious improvements in energy productivity in buildings, industry and transport. This could allow abatement of almost 70% compared to 2005 levels with the technologies considered in this report, at rates of uptake likely to be feasible. There may be further opportunities to reduce energy sector 2050 emissions if faster deployment proves possible, as well as through deployment of additional, more prospective technologies. Achieving net zero emissions in the second half of the century however will likely depend on negative emissions (i.e. net removal of GHG from the atmosphere) in LULUCF and/or carbon credits from other countries.

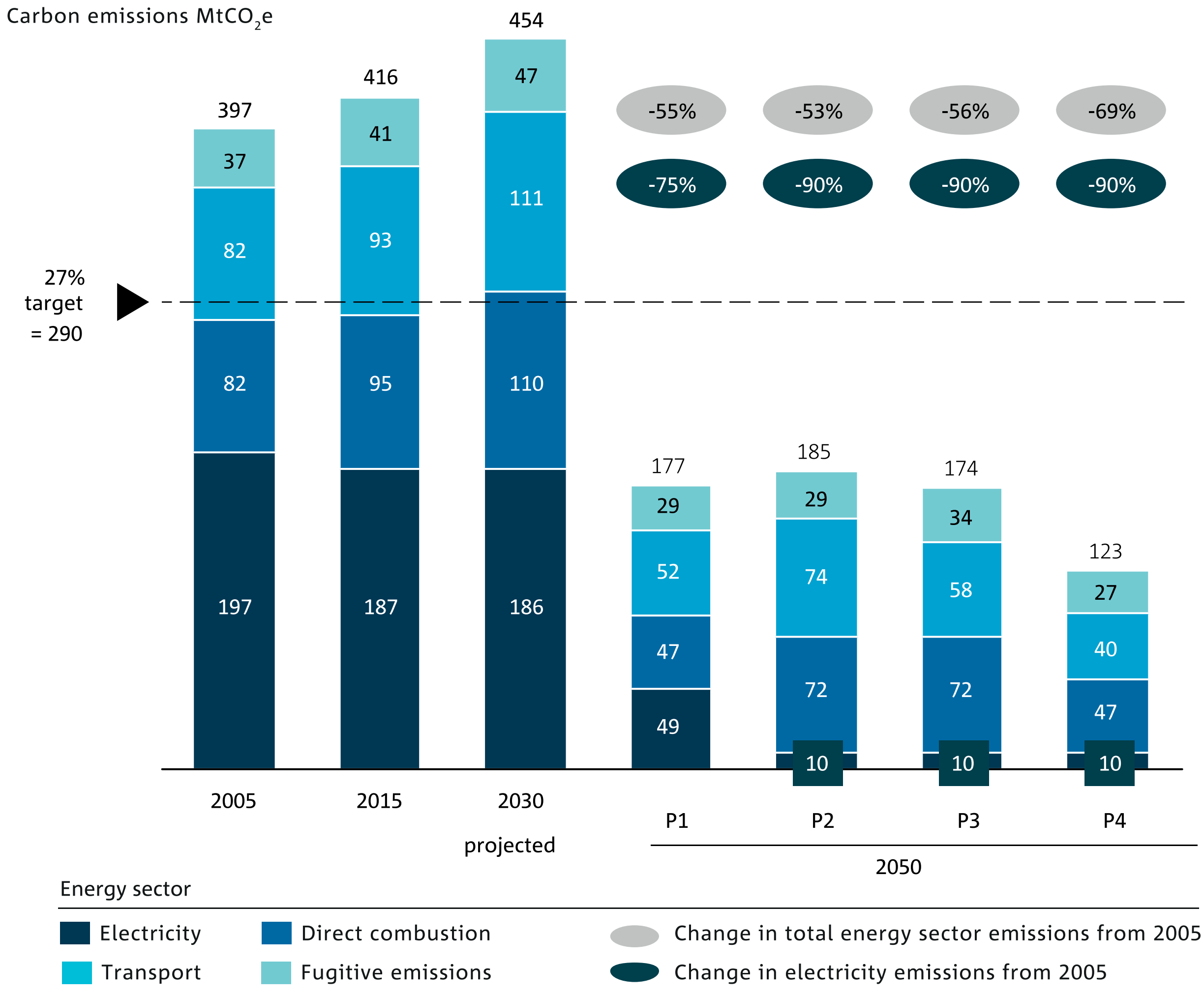

Figure 20. 2050 abatement achieved by each pathway

While Australia does not have a target for 2050, according to the Paris Agreement the world needs to achieve zero net emissions in the second half of the century. It will therefore be important for Australia to achieve deep reductions in emissions by 2050.

To achieve deep decarbonisation, it is expected the electricity sector will need to achieve close to complete decarbonisation by 2050 as part of Australia's overall abatement. This is due limitations in potential decarbonisation in other sectors (or a reliance on electrification and a low emissions electricity sector), and to the electricity sector having the greatest optionality for zero or low emissions technologies (see Section 2.2 for further discussion; as discussed in that section, values of 75% and 95% were chosen as levels of abatement to model for Pathways 1 and 2-4 respectively). In addition to VRE and gas, new types of low carbon dispatchable generation could play a role in the post-2030 period, such as HELE fossil fuel generation with CCS, geothermal, CST with storage and nuclear power. While low emissions dispatchable generation technologies exist, deploying them will present considerable challenges, which are discussed further in Section 3.14.

The biggest contributor to long term decarbonisation of the transport sector is likely to be electric and hydrogen vehicles. Road transport is set for further unpredictable disruption from autonomous vehicles and shared mobility that could significantly decrease vehicle transport demand and drive uptake of efficient and zero emission vehicles. Given expected increases in demand for air travel, aviation emissions are expected to experience significant growth under BAU. Biofuels are likely to be the key contributor to long term decarbonisation of this sector, along with improvements in aircraft efficiency. Although targeted at international aviation emissions, the recent International Civil Aviation Organization goal of carbon neutral growth for the aviation sector from 2020 will drive the development of domestic biofuel infrastructure.

Deeper decarbonisation of the buildings and industrial sectors will rely on continued rollout of energy efficiency, fuel-switching and electrification as well as greater uptake of solar thermal heating and bioenergy (e.g. biomass heating). CCS could potentially contribute to a reduction in industrial direct combustion emissions.

With the assumed uptake of technologies, 2050 energy sector-wide emissions are between 53% and 69% lower than 2005 levels (see Figure 20). Given expected economic growth driving higher activity levels in transport and direct combustion, even with improvements in energy productivity significantly faster than BAU in Pathways 1 and 4, 87-99 MtCO_2e of emissions are still expected in these sectors in 2050.

If Australia does require deeper energy sector abatement than that shown in Figure 20, this could be achieved in several ways:

- The energy sector could reach deeper abatement through a more complete transition to the low or zero emissions technologies considered in this roadmap. The main opportunities for greater abatement are:
  - Greater electrification or switching to renewable heat within direct combustion
  - Greater uptake of low emissions technologies in transport, including:
- Greater shift of light vehicle transport to EVs, low emissions hydrogen or biofuels (up to additional ~35 MtCO_2e of abatement in 2050 in Pathway 1)
- Greater uptake of biofuels in aviation (up to additional ~11 MtCO_2e of abatement in 2050)
- Electrification of diesel rail (up to additional ~3 MtCO_2e of abatement in 2050)
  - Full decarbonisation of the electricity sector (up to an additional 10-49 MtCO_2e of abatement in 2050 depending on the pathway). Note, this is assumed in the Electricity Network Transformation Roadmap (Energy Networks Australia and CSIRO, 2016).
  - Bioenergy with CCS (BECCS) could be used for electricity generation or heating. Assuming all of Australia's estimated ~1000 PJ/year[48] of potential biomass was used for BECCS, this could provide around a third of Australia's current electricity demand and create 84 MtCO_2e[49] of negative emissions. However this is likely to be expensive ($210-260/MWh in 2030) (as shown in Appendix B of the LETR Technical Report).
- Additional energy sector technologies to those considered in this report could be developed and deployed. More prospective technologies with the potential to make a significant impact include:
  - Substantial material efficiency through a 'circular economy' involving recycling, extreme durability and advanced alloy design to reduce the energy and resource demand for the primary creation of energy and emissions-intensive materials such as steel and

48 See (ClimateWorks Australia, 2014, pp. 62-64).

49 Calculation based on emissions factor of 93.6 Kg CO_2/GJ using lignocellulosic biomass (Farine, 2012) and a 90% CO_2 capture rate for CCS.

cement. Advanced material manufacturing may include the widespread use of novel manufacturing techniques such as additive manufacturing.

  - Additional technologies to reduce emissions from industry could include process intensification and advanced materials (to improve chemical and heat resistance or mechanical performance). Additional sector-specific technologies also exist to reduce emissions from chemicals, steel, cement and paper manufacturing (Breakthrough Energy, 2017).
  - Other more prospective demand reduction or mode-shifting technologies include virtual reality collaboration systems or alternate high speed ground transport systems, such as the Hyperloop (to be trialled in Dubai), to reduce air transport demand.

- A shift in the sectoral makeup of the economy could reduce emissions intensity or a reduction in coal or oil & gas production compared with assumed levels would reduce fugitive emissions from these sectors.
- Other parts of the economy outside the energy sector could contribute more than their share. For example, while outside the scope of this roadmap, LULUCF could provide up to 40% of Australia's 2050 abatement (CSIRO, 2015).
- Australia could buy carbon credits from other countries. There are however concerns about the credibility and effectiveness of such credits. For instance, forests that provide credits may be cut down later. This is possible to mitigate to some degree with proper certification endorsed by environmental groups whose reputations rely on ensuring robust schemes. A second issue with buying credits is that it is not possible for all countries to do this – for there to be credits available, some countries need to be providing them. It is not clear that there are necessarily cheaper options for abatement outside Australia. Also, a high demand for international credits would drive up their cost.

Due to limitations of foreseeable technologies in achieving decarbonisation at reasonable cost in some parts of the energy sector, full decarbonisation of the sector is unlikely (outside of electricity). Therefore achieving net zero emissions economy-wide will likely require negative emissions elsewhere in the economy or carbon credits from other countries.

KEY FINDING 14: Progressing multiple pathways would allow Australia to reduce the risks in addressing the energy trilemma

Each pathway faces a different set of risks, including technology risk, commercial risk, market risk, social licence risk and stakeholder coordination risk. By simultaneously progressing multiple pathways, the overall risk in transitioning to a low carbon energy sector, while maintaining energy security and affordability, can be minimised.

Pathway 1 relies on rapid improvements in energy productivity which poses stakeholder coordination risks, given the significant action from residential, commercial and industrial end users this pathway would require. In the longer term it also relies heavily on expanding gas-fired electricity generation, which presents price/supply risks and social licence risks given current constraints on onshore gas exploration.

In **Pathway 2** the key risks are associated with achieving very high VRE share. While there are no fundamental physical limits to the share of electricity that could be provided by VRE, the variability and low inertia and fault current of these technologies means significant technical, regulatory and cultural challenges must be addressed to achieve high VRE while maintaining electricity security and reliability. It should be noted that the enabling technology solutions required are yet to be robustly stress-tested at scale and the cost of these technologies and of the required transformation is unproven. In addition to these risks, wind power also faces social licence risk due to opposition from some residents located close to wind farm developments (Hall, 2014). Note that reaching the 45% VRE shares assumed in Pathways 1 and 3 will also involve addressing the challenge of maintaining stable electricity grids with high instantaneous VRE share.

Pathway 3 avoids the key risks of Pathways 1 and 2 by relying on dispatchable, low carbon generation. These technologies present other risks however. Each of the key Pathway 3 generation technologies (HELE, CCS, CST, geothermal and nuclear) require relatively large capital investments with long lead times compared with the key technologies in Pathways 1 and 2, which creates market risk in an environment of uncertain electricity demand.

Large capital projects may also require participation by a number of investors to avoid excessive concentration of risk for any one investor[50], increasing project complexity. HELE, CCS, CST, geothermal and nuclear also represent sectors of investment that are new in Australia. New sectors are difficult to establish, requiring development of new skills (including in the investment community), developing supply chains and often developing new regulations. Government support would likely be required to underwrite the associated commercial risk. HELE, CCS, geothermal and nuclear have additional risks as described below:

- **HELE:** These technologies are at varying stages of technological and commercial readiness, and consequently have technology and commercial risk, to varying degrees. New build HELE technologies may also face social licence risk (Jeanneret, Muriuki, & Ashworth, 2014). While lower emissions than older fossil fuel generation technologies, HELE technologies would require CCS in order to be sufficiently low emissions to form part of Australia's future electricity generation mix, and are therefore exposed to the same risks facing CCS.
- **CCS:** The main risk associated with CCS is commercial risk due to a lack of demonstrated integrated, end-to-end CCS projects in Australia. Social licence risk applies but existing demonstration projects indicate this risk is manageable with appropriate community engagement (Ashworth, et al., 2013). Market risk also applies for CCS dedicated to gas powered generation. The high short-run marginal cost of gas generation means that developers of GPG projects would face the risk of cheaper forms of generation entering the market and displacing them from dispatch.
- **Geothermal:** Geothermal power (i.e. HSA and ESG) presents technology risk. With current technology, it is not possible to reliably and economically locate geothermal resources with sufficient heat and permeability for cost effective power generation (ARENA, 2014).
- **Nuclear:** As discussed above, large capital investments, such as those required for large nuclear reactors, present market risk. Small modular reactors (SMRs) provide a potential means of reducing this risk by reducing the size of individual projects, and may also have a lower capital cost per MW. However, SMRs have not yet been commercially demonstrated and hence pose technology and commercial risk. Nuclear power also presents social licence risk; significant community engagement would be required to build a nuclear power generation industry in Australia (Nuclear Fuel Cycle Royal Commission, Government of South Australia, 2016).

Similar to Pathway 1, certain sensitivity cases of Pathway 3 rely on expanding gas-fired electricity generation, presenting price/supply risks and social licence risks given current restrictions on onshore gas exploration and production.

Pathway 4 has the same risk of Pathway 1 of relying on rapid improvements in energy productivity. It also has the risk of Pathway 2 associated with reliance on a high share of VRE. It also has the risks of Pathway 3 associated with gas generation with CCS. The risks associated with VRE and gas with CCS are delayed however due to the faster improvements in energy productivity in this pathway.

50 For example, Australia's LNG projects, which range from $1.5 billion to over $50 billion in capital investments typically involve 2-6 large investors (APPEA, 2017).

The risk associated with each pathway are summarised in Figure 21.

There is inherent uncertainty associated with each of the risks described above. Given this uncertainty, and the importance of achieving an energy sector that has acceptable security, affordability and reduced GHG emissions, it would be imprudent to follow only one pathway. When faced with uncertainty, there is value in having options, such that the least cost and most effective options can emerge, and this can be achieved by progressing each of the pathways in parallel.

Maintaining options and progressing each pathway involves activities such as funding RDD&D, redesigning markets, developing regulation and engaging in public debate, each of which involves costs. While there is still uncertainty as to the best pathway for Australia's energy sector, it is worth incurring a certain level of cost to maintain optionality. As more information becomes available on each pathway, and risks of certain pathways decrease, points will be reached at which it no longer makes sense to keep certain options open. This could be the case for instance if further work confirms at a high level of confidence that the grid can be transitioned to 90% VRE with acceptable security and reliability at lower cost than using dispatchable generation. An important consideration for policy makers will be how much public money to invest to keep options open, and when to close off certain options. Where possible, lower cost actions to maintain optionality should be preferred, with large items of expenditure deferred as long as possible. For example to support CCS, lower cost actions to maintain optionality include confirming priority basins, developing legal frameworks and tracking technology/international project progress, while higher cost actions include carrying out pre-competitive exploration and appraisal of priority basins and carrying out medium to large-scale demonstration projects.

		PATHWAYS			
	Description	1 PATHWAY 1: Energy productivity plus	2 PATHWAY 2: Variable renewable energy (VRE)	3 PATHWAY 3 Dispatchable power	4 PATHWAY 4 Unconstrained
Technology, commercial and market risk	**Technology risk:** Technology needs development to overcome technical challenges or to bring down costs **Commercial risk:** Technology not commercially mature in Aus. hence costs not well understood **Market risk:** Revenue generated over the lifetime of the asset is uncertain		Technological challenge to transform the electricity grid to support VRE at high share with acceptable security and reliability, with uncertain cost of transformation	Market risk with large, long lead time projects given uncertain demand Technology and commercial risk with HELE, CCS, CST, geothermal and nuclear	As per P2
Social licence risk	Technology may face opposition from local community, broader community or specific groups e.g. environmental groups	High reliance on expansion of domestic gas for electricity generation	Social licence risk with wind power	Social licence risk with new build coal, CCS, nuclear and with expansion of domestic gas for electricity generation	Social licence risk with gas and CCS
Stakeholder coordination risk	Deploying the technology depends on coordination or behaviour change of a large number of individuals or groups	Relies on behaviour change by millions of energy users	Transformation of the grid to support high share of VRE requires overcoming regulatory and cultural challenges	Investor coordination typically required for large capital projects	As per P1 and P2

Timeframe in which risk becomes significant

Before 2020 | 2020–2030 | After 2030

Figure 21. Key risks in each pathway

KEY FINDING 15: Low emission energy technologies are higher cost and have a number of associated risks that need to be addressed to encourage private investment

With the exception of regulated networks, Australia's energy sector is designed to be competitive such that new technologies are supplied and purchased by private investors at their own risk. For the most part, investment in new low emission energy technologies comes at a higher cost than continued use of currently deployed higher emissions technologies. Additionally, abatement opportunities, regardless of cost, may face a range of non-financial barriers to investment (including technical, social and stakeholder barriers). Without the right regulatory/policy environment, these risks manifest as barriers to investment and therefore serve as a barrier to adoption of new technologies.

Examples of present policies and institutions designed to overcome these barriers to investment include the Clean Energy Finance Corporation (CEFC), Australian Renewable Energy Agency (ARENA) and State and Federal Renewable Energy Targets. Existing policies do not yet address all available energy sector abatement opportunities or target each of the types of risks faced. Additional policies will therefore likely be required to ensure a broader range of low emissions technologies are deployed and that investment returns are strong enough (relative to risk) for deployment to proceed at the rate required.

The key barriers to low emissions technologies are discussed further in the following sections.

COST/TECHNICAL BARRIERS

At present, low emissions technologies cost more in general than existing higher emissions alternatives (neglecting costs of externalities). In the case of electricity generation, while new build low emissions technologies can be less expensive than new build fossil fuel alternatives, they are typically more expensive than existing coal- and gas-fired generation, which in the current over-supplied electricity market have low short-run marginal costs.

Even when the total cost of ownership might be lower for low emissions technologies[51], as is the case with most of the technologies related to energy productivity, the upfront capital cost can still prove a barrier to uptake if capital is limited and a particular investment is not the highest return use of that capital. There may also be a search cost to choose an appropriate technology.

While ongoing cost reductions are expected for most low emissions technologies[52], policy support to overcome market failures will also be key in driving uptake.

Many of the technologies expected to deliver abatement by 2030 are technologically and commercially mature, without fundamental technical barriers preventing adoption (e.g. low emissions buildings technologies and even technologies such as CCS using conventional gas storage). For many of these technologies, technological improvements are expected to play a key role in bringing down costs. Conversely, significant technical barriers must be overcome for some of the key technologies discussed in this report to be deployed at scale. For example:

- Reaching high VRE share while maintaining system reliability and security will require overcoming technical grid integration challenges.
- Deploying smart grid technologies will require overcoming the technical challenges associated with integrating these technologies with existing grid infrastructure, orchestrating associated resources to optimise system operation as well as addressing the cyber-security challenges associated with a distributed, intelligent system.
- Deploying geothermal electricity generation will require technological breakthroughs in locating suitable heat resources with sufficient permeability.
- Deploying new VAM abatement technologies in underground mines will require scaling up technologies currently at the demonstration stage.

Costs may also pose a barrier where there are split incentives. For example, split incentives within a company apply when a line area consumes energy, but bills are paid by the corporate headquarters. In this scenario, line areas don't have to account for the cost of the energy consumed, but are also potentially unable to access funds for energy productivity improvements.

51 I.e the net present value (NPV) is positive compared with alternatives.

52 Costs of low emissions technologies tend to fall in with the level of deployment both in Australia and globally. Therefore the competitiveness of low emissions technologies will be in part driven by the actions taken by other countries to reduce their level of emissions.

REGULATION/MARKET OPPORTUNITY BARRIERS

Another key barrier to low emissions technologies is a lack of sufficiently large and low-risk revenue opportunities. This is often related to a lack of suitable policy or regulatory drivers. In the electricity sector, where there is an oversupplied market and existing generation technologies have low short-run marginal costs, clear and stable policy is required to drive uptake of low emissions generation, in particular by supporting long term market contracts. Existing policy, particularly the Renewable Energy Target (RET) (and past feed in tariffs), has helped encourage the deployment of large-scale VRE and rooftop solar PV. At current settings however, this policy will be inadequate to drive sufficient uptake of these technologies to reach the 2030 abatement target[53]. Also, existing electricity sector policy does not incentivise rollout of other low emissions technologies such as CCS. Existing policy also lacks a mechanism to encourage investors to factor in the relative emissions intensity of generation when deciding which plant to retire (e.g. brown vs black coal).

The deployment of some technology enablers of VRE, such as storage, is limited by existing market structures that don't allow revenue to be derived from the full range of services (e.g. fast frequency response, inertia) provided by these technologies because existing technologies tend to deliver these services as a relatively free by-product. In the case of some technologies, such as nuclear generation, existing legislation actively prevents uptake.

STAKEHOLDER ACCEPTANCE BARRIERS

While low emissions technologies are generally widely supported, some technologies (e.g. wind and solar PV) are generally preferred against others such as unconventional gas, nuclear and CCS (Jeanneret, Muriuki, & Ashworth, 2014). As a consequence, these less-preferred technologies may face opposition from some segments of the community.

Industry stakeholder acceptance can also prove a barrier in some cases. In the building and industry sectors, energy efficient technologies may not be adopted due to competing priorities, such as:

- Consumers valuing equipment and appliances in buildings based on factors other than energy productivity (e.g. screen resolution in televisions).
- Energy may be a small percentage of overall cost and management may be focused on other concerns (e.g. throughput).

SKILLS/OTHER BARRIERS

Deployment of certain technologies may be impeded by the absence of a local industry and a lack of required skills. For complex sets of technologies such as the enabling technologies for VRE, smart grid technologies and microgrids, a lack of skills related to these technologies among network operators and project developers may act as a barrier.

A lack of skills and information within businesses can act as a barrier to uptake of technologies to improve energy productivity. For instance, in industry, senior management are often not aware of the energy productivity improvement opportunities that are obvious to line areas or to shop floor machine operators, and so the opportunities are not funded.

Existing business models may also prove to be a barrier to capturing new value streams from innovative low emissions technologies such as batteries, with changes required to how companies do business with each other, such as new contractual arrangements.

The key barriers to uptake of low emissions technologies are summarised in Figure 22. Barriers are classified according to how significant they are in preventing uptake of the respective technologies in line with the most rapid uptake assumed in the various pathways. Further detail on these barriers can be found Appendices A-C.

[53] Government projections based on current policies calculate 2030 total energy sector emissions to be 14% higher than 2005 levels, and electricity sector emissions to be 5% lower. Note these projections include the federal RET (including ACT's RET) and Emissions Reduction Fund (safeguard and purchasing) but exclude policies that are still undergoing development including proposed RETs in Queensland, Victoria and South Australia and the National Energy Productivity Plan (NEPP) (Australian Government Department of the Environment and Energy, 2016). Current uncertainty in the RET post-2020 as well as the fact that support from the RET ends in 2030 (shorter than typical asset life) is currently creating a lack of demand for long term market contracts.

More significant | Significant | Less significant

		Cost/technical	Regulation/market opportunity	Stakeholder acceptance	Skills/other
Energy productivity	Transport	Increased upfront cost		Real/perceived risk and amenability of public transport and cycling	
	Industry and buildings	Payback times, transaction cost, availability of capital; split incentives	Fragmented opportunities; market distortions	Competing priorities e.g., throughput focus; lack of awareness	Lack of internal skills and capability
Low emissions electricity	Large-scale VRE	Higher cost relative to existing coal	Oversupplied electricity market; low demand for large-scale PPAs	Lack of experience with high levels of VRE; public resistance to wind farms	Limited EPC experience for large-scale solar; coordination with NSPs
	Rooftop solar PV	Upfront expense for low income households	Lack of market signals for value provided; split incentives		
	Wave	High cost relative to wind and solar PV	Oversupplied electricity market; low demand for large-scale PPAs	Stakeholder acceptance untested	
	Enabling tech for VRE	Technically challenging to redesign grid for high penetration of VRE	Limits to market drivers to deploy enabling technologies	Utility unfamiliarity with technical enablers	Limited experience with enabling technologies
	Storage	Current high cost of battery storage; uncertain cost of off-river PHES	Owners of storage unable to derive revenue from all sources of value	Utility resistance to deploying storage until multiple demonstrations exist	Limited skills in optimising storage and related business models
	Smart grid technologies	Integration of technologies into systems is required	Lack of financial drivers/ markets; lack of technical standards	Lack of awareness of benefits	Lack of granular, accessible system data
	RAPS and microgrids	Cost of bespoke projects	Regulatory barriers to disconnection from main grid	Concerns about reliability of supply	Lack of experience of project developers
	CST	High cost	Oversupplied electricity market; low demand for large-scale PPAs	Lack of awareness of value provided by CST relative to PV	Limited local supply chains
	Geothermal	High cost (incl. network); high project development risk		Stakeholder acceptance untested	
	CCS	High cost; high cost/high risk appraisal; uncertainty over storage	Lack of economic drivers, regulatory regimes and commercial models	Concern over continued use of fossil fuels, safety and long term stability	Lack of experience integrating full-scale project
	HELE	Only sufficiently low emissions if paired with CCS; availability of gas	Oversupplied electricity market; low demand for large-scale PPAs	Community opposition to new build fossil generation	
	Nuclear	High cost; cost/technical challenge of waste disposal	Oversupplied elec. market; low PPA demand; not allowed by legislation	Significant community opposition	Lack of skills related to nuclear generation
Electrification and fuel switching	Bioenergy	Cost of fuel and bio-refineries, different biomass characteristics	Price volatility, policies preference VRE and conventional biofuels	Perceived competition with food, other enviro concerns (e.g. water)	
	Hydrogen	Cost of hydrogen production, fuel cells, FCVs and infrastructure	Lack of standards regulating overall use	Safety concerns; perception of difficulty of transformation req'd	Limited local supply chains with experience in large-scale production
	EVs	Cost of vehicles and infrastructure; charging impact on network		Lack of familiarity; perceived drawbacks e.g. range, charging time	Lack of skills in automobile industry (e.g. mechanics)
Other	Fugitives	Technologies add cost to operations; technologies require scale-up	Lack of/potentially insufficient economic drivers for deployment	Competing priorities	

Figure 22. Key current barriers to uptake of low emissions technologies

4 Next steps

4.1 Key strategic decisions

Policy makers face a range of strategic decisions to inform policy design, RDD&D priorities and community engagement. There are a further set of strategic decisions that can be made post-2020 to deprioritise or further pursue certain technologies.

In developing policy to support the development and deployment of low emissions technologies, policy makers face a number of important strategic decisions that need to be made now. These are shown in Table 8, along with points to consider when making these decisions.

TABLE 8. KEY STRATEGIC DECISIONS AND ASSOCIATED POINTS TO CONSIDER

KEY STRATEGIC DECISIONS	CONSIDERATIONS
Where should policy be **national vs jurisdiction-specific?**	**Nationally-consistent** policy can reduce transaction costs and allows assets to be deployed in the most geographically favourable locations. **Jurisdiction-specific** policy may better suit the needs of residents of those jurisdictions and require less change to existing legislation and regulations. It also allows different approaches to be trialled in different jurisdictions.
Where should policy to drive uptake of low emissions technologies **be economy-wide vs sector-specific?** E.g., • How much should the energy sector contribute to the 2030 target and should this be driven by specific policy? • What should be the contribution to decarbonisation from the electricity sector and from energy productivity by 2030?	**Economy-wide** mechanisms allow abatement to be achieved in the most cost-effective areas and allow the respective contributions from different sectors to evolve as the relative cost of abatement changes between sectors. **Sector-specific** policy allows sector-specific barriers to be addressed and can ensure all parts of the economy contribute. Also allows support for abatement that is higher cost in the short term, but which has the potential to deliver longer term cost reductions and significant abatement (e.g. renewable energy for process heat).
Where should policy be **technology neutral vs technology specific?**	**Technology neutrality** allows markets to determine over time the lowest cost and most operationally effective solutions without policy makers needing to know this in advance. Allows for the greatest range of possible solutions to be deployed, which may lead to lower cost abatement for consumers. Technology specificity allows governments to support technologies through RDD&D that could provide better/cheaper long term solutions but are too risky for private investors to support (or to support without government assistance). It can also help maintain optionality by progressing a suite of technologies that de-risks Australia's overall decarbonisation. It also allows technology-specific barriers to be addressed.
Where RDD&D support for a specific technology is decided on, how much should governments rely on private sector co-funding?	**Too little government funding** may prevent a promising technology from reaching commercial maturity. **Too much government funding** may waste taxpayer money on a technology that lacks sufficient industry support required for ultimate deployment. May also transfer investment risk for those best placed to bear it to taxpayers. May also introduce distortions into energy markets.
Where should Australia **develop technology locally vs acting as a 'technology taker'?**	**Developing technology locally** allows solving local problems, contributing to global decarbonisation based on Australia's comparative advantages and capture of commercial opportunities. It also builds local skills that may be required for deployment, may result in the development of cheaper/better technologies than those developed overseas, and may allow for faster deployment of technologies. **Acting as a 'technology taker'** lowers cost and risk by allowing Australia to deploy technologies proven elsewhere.

Examples of areas where policy makers need to decide on the value of specific technology options to inform the development of associated enablers include the following:

- To have the option of deploying nuclear power around 2030, Australia would need to start a process of consultation and debate now (Nuclear Fuel Cycle Royal Commission, Government of South Australia, 2016). There is a decision to be made as to whether the value of this option (i.e. de-risking Australia's abatement) warrants the time and expense required to have this national discussion in a rigorous, informed and consultative manner, or whether this action should be deferred until later.
- The Council of Australian Governments (COAG) Energy Council is currently working to increase the domestic supply of gas via its Gas Supply Strategy. With gas demand varying significantly between pathways, there is a decision to be made as to the level of supply targeted, and consequently what enablers will be needed.

There are also strategic decisions to be made as to when certain technology options should be closed off or more heavily pursued, based on certain trigger points. This is particularly the case for the technologies involved in dispatchable, low emissions electricity generation, which are likely to be higher cost than alternate technologies (see Appendix A of the LETR Technical Report) and for which several technology alternatives exist.

The key trigger points for closing off dispatchable technology options (e.g. by discontinuing RDD&D funding) are:

- If alternate electricity sector abatement options prove sufficiently likely to be preferable[54] e.g.,
  - If sufficient energy productivity improvements are made and can be continued.
  - If the cost and technical challenges in supporting very high shares of VRE with high security and reliability prove sufficiently low.
  - If other dispatchable technologies prove to be preferable e.g. if CST with storage rapidly decreases in cost, this could act as a trigger to discontinue RD&D of geothermal.
- If certain dispatchable technology options appear infeasible e.g.,
  - If current research into enhanced geothermal in Australia indicates that cost/technical barriers are insurmountable.
  - If public debate on nuclear indicates high levels of opposition.

Conversely, the key trigger points for increasing focus on dispatchable technologies (e.g. by commencing higher cost actions to achieve CCS readiness such as storage resource characterisation) are:

- If fundamental barriers are encountered to alternate options, e.g., sufficient gains in energy productivity are not realised, or barriers to VRE share are encountered.
- If large improvements in the cost of dispatchable technologies are realised e.g. CCS costs drop below the cost of new build VRE (including integration costs).

It is likely that any of the trigger points discussed above would occur post-2020, and hence this set of strategic decisions can be deferred until then. This could potentially be informed by a detailed, quantitative, options analysis, to help value the options and determine appropriate levels of expenditure to keep options open.

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54 Note that for CCS, given its potential role in Australia outside the electricity sector (for reducing emissions from direct combustion, LNG and hydrogen production and other industrial processes) and given the global importance of CCS for achieving emissions abatement and supporting Australia's fossil fuel exports, trigger points for discontinuing or increasing RD&D on CCS would also need to consider these factors.

4.2 Key enabling actions

Policy is the most critical enabler for addressing the key barrier to low emissions technologies, namely the risk to investors of deploying them in favour of their higher emission alternatives. Stakeholder engagement, skills and business models and RDD&D funding are also key.

The key enabling actions are listed below, with additional enablers and further detail provided in the Sections 4.2.1-4.2.4 and Appendices A-C. The relevant actors in each case vary, with government responsible for policy, but with a combination of government and industry in general responsible for other actions. The timeframe for the enabling actions is in general the period to 2020, with policy required sooner. It will be important to review the findings of this roadmap at regular intervals as technologies are developed and deployed and to adjust enablers accordingly. In terms of policy, these reviews should generally only be minor course corrections. Stable policy is crucial to creating the investment certainty required to drive investment in low emissions technologies.

POLICY

Action 1.1 Review targeted rate of improvement in energy productivity ('Ambitious' or 'BAU') and revise policy as needed to support this rate, for instance to overcome market failures such as split incentives, competing priorities and lack of information.

Action 1.2 Implement stable, long term policy to drive uptake of low emissions electricity generation technology consistent with required electricity sector decarbonisation.

Action 1.3 Implement policy to drive deployment of enabling technologies for VRE.

Action 1.4 Implement policy to incentivise full deployment of cost-effective technologies to reduce fugitive emissions from coal mining and oil & gas production.

Policy (including regulation, market rules and incentives) is key to creating the market demand and investment certainty required for the uptake of low emissions technologies, and for overcoming market failures preventing uptake. Stable and predictable policy will also be key to supporting industry and job creation (IRENA, 2015).

This report does not recommend specific policy settings but rather seeks to identify areas where policy could be used to support technology uptake to reduce emissions.

The right supporting policy is required in two main areas. First, achieving improvement in energy productivity in buildings, industry and transport through increased uptake of lower emissions technologies will require policy support to overcome market and firm-level failures such as split incentives, competing priorities and lack of information. This could take the form of energy and emissions standards, targeted incentives and market reform (such as developing financial instruments to help tenants and owners co-finance energy efficiency, or pricing externalities). This is likely to be incremental to the existing measures in the NEPP (see Box 3 in Section A.4.2)

The second main area in which policy measures are required to address market barriers is in the electricity sector, where stable, long term policy is required to drive uptake of low emissions electricity generation technology to 2030 and beyond. This will be required to enable investors in new, low emissions generation to achieve acceptable returns with sufficiently low market risk. Market reform may also be required to allow providers of dispatchable supply to achieve sufficient returns in the electricity market[55]. Market reform may also be necessary as system optimisation becomes dependent on coordination of regulated electricity markets and contestable wholesale markets, with tariff reform also playing an important role. Market reform or other policy drivers will also be required to drive uptake of enabling technologies for VRE, by allowing these enablers to capture the full value of services provided to the grid (e.g. fast frequency response,

[55] Stakeholder workshops indicated consideration should be given to increasing the market price cap or creating dispatchable capacity markets (rather than energy only markets).

inertia and voltage control), and by enabling all technology owners to participate, including consumers with behind-the-meter batteries. Regulation could also be used to drive provisions of services to the grid. For instance, wind farm developers could be required to ensure wind farms are able to provide fast frequency response, as is the case in Quebec, Ontario and Brazil (DGA Consulting, 2016). Given the uncertainty in which technologies will be most cost effective in helping to provide grid security and reliability, there is a strong argument for ensuring the policies developed for this purpose are technology neutral.

Another area where policy measures may be required is in fugitive emissions from coal mining and oil & gas production. Technologies to reduce these emissions (e.g. VAM abatement technologies in underground coal mines) typically impose a net cost on operations, and hence require policy to drive uptake. The Emissions Reduction Fund (ERF) has recently been revised to include VAM abatement technologies, but it is not yet clear whether this will drive uptake to the full extent of the cost-effective technical potential.

STAKEHOLDER ENGAGEMENT

Action 2.1 Provide supporting data, information, training and education to drive uptake of technologies that improve energy productivity in buildings and industry.

Action 2.2 Continue stakeholder engagement for electricity sector transformation, including creating a technical roadmap to transition the grid to support higher shares of distributed generation and large-scale variable renewable generation with continued security and reliability.

Action 2.3 Communicate findings from the demonstration and deployment of key technologies such as utility-scale battery storage, CCS and microgrids with high renewables share, to increase stakeholder confidence in these technologies and enable further deployment.

Action 2.4 Accelerate deployment of consumer technologies such as rooftop solar PV, behind the meter batteries and EVs through increased consumer engagement, including by retailers and other consumer-facing technology providers.

Action 2.5 Continue engagement with the community on all technologies with potential social licence barriers e.g. wind, gas, nuclear and CCS.

Stakeholder engagement is important in five key areas.

- Providing supporting data, information, training and education will be important for driving uptake of technologies that improve energy productivity in buildings and industry, where adoption is hindered by a lack of awareness of the cost savings opportunities and how to capture them.
- In the electricity sector, industry stakeholder engagement will be key to the transformation required to unlock the savings enabled by greater adoption of distributed energy resources (DERs) such as rooftop solar PV and behind-the-meter batteries. It will also be important in supporting a higher share of VRE. This process has commenced with industry activities such as Australian Energy Market Operator's Future Power System Security Program and the Electricity Network Transformation Roadmap led by Energy Networks Australia (ENA) and CSIRO, and will need to be continued and extended, for instance by developing a technical roadmap for supporting increased VRE share while maintaining system security. There is also a need for a review of consumer protection frameworks addressing issues such as accreditation of suppliers and minimum standards for information provided to consumers when they are offered new technologies (Consumer Action Law Centre, 2016).

- Communicating findings from the demonstration and deployment of key technologies such as utility-scale battery storage, off-river PHES, CCS and microgrids and RAPS with high renewables share will also be required to increase stakeholder confidence in these technologies and enable widespread deployment.
- For consumer technologies such as rooftop solar PV, behind-the-meter batteries and EVs, adoption can be accelerated through increased consumer engagement. This implies retailers and other consumer-facing technology providers will need to play a key role. Tariff reform, such as the introduction of more cost-reflective tariffs, can also help drive certain consumer technologies, such as behind-the-meter batteries and related demand side services.
- It will be important to engage with the community on all technologies with potential social licence barriers e.g. wind, gas, nuclear and CCS.

SKILLS AND BUSINESS MODELS

Action 3.1 Upskill industries to support rollout of new low emissions technologies, particularly in the electricity sector and in industries where new supply chains will require development.

Action 3.2 Develop business models that increase rollout of low emissions technologies, e.g. by offering mobility as a service using low emissions vehicles, by offering smart systems to increase energy productivity, and by aggregating behind the meter batteries to provide ancillary services.

Industry upskilling (with specific technical skills) will be important in supporting the rollout of low emissions technologies. This is particularly the case for the electricity sector, where the existing industry will need to rapidly upskill in order to transition to new types of technologies such as grid-scale batteries and smart grid technologies. Upskilling will also be required where new supply chains need to be established for new technologies such as CST and next-generation biofuels.

The private sector has a key role to play in increasing uptake of low emissions technologies through the development of new business models. For instance in the transport sector, new business models based on offering mobility as a service have the potential to reduce demand and accelerate the uptake of more efficient vehicles.

In the electricity sector, new types of power purchase agreements (PPAs) and other commercial models such as contracts for difference (CFDs) could increase the demand for low emissions generation. New business models could accelerate the rollout of smart grid technologies and also overcome the split incentives between landlords and tenants to increase the uptake of rooftop solar PV. New commercial models can also help support the deployment of enabling technologies for VRE, for instance by aggregating behind-the-meter batteries to allow them to provide dispatchable capacity, fast frequency response or continuous frequency stabilisation. The growing need for orchestration of energy flows across the electricity system will also necessitate the introduction of new system operation and coordination capabilities.

New business models can be encouraged by supporting entrepreneurship more broadly, whether this is through supporting startups and growing Australia's startup ecosystem (for example by developing entrepreneurship programs at schools and universities, improving access to capital and increasing university/industry collaboration) (StartupAUS, 2016) (Jobs for NSW, 2016), or through existing companies such as electricity retailers taking an entrepreneurial approach to developing new products and services.

Key potential enablers of low emissions technologies are shown in further detail in Figure 23 (excluding enablers related to RDD&D funding, which are shown in Figure 24). The enablers are prioritised (high, medium and low) in relation to the importance of the relevant technology in achieving decarbonisation and whether the enabler is time critical in supporting deployment. The priority classifications are intended to help guide investment of time and money, particularly where there is limited capacity to implement all enablers for each of the technologies. Some enablers are classified as applying post-2020, due to expected timeframes for deployment of certain technologies.

		Policy		Stakeholder engagement		Skills/business models	
Energy productivity	Transport	Policy support e.g. vehicles emissions standards, targeted incentives		Improved cycling routes and end-of-use facilities		New business models based on mobility, car sharing etc	
	Industry and buildings	Nat'l plan & policy frameworks e.g min. standards, incentives, market reform, financing instruments		Supporting data, information, training and education measures; Energy audits; Focus public debate on total energy spend rather than price		Business models to help energy users improve EP and transition to low carbon electricity	
Low emissions electricity	Large-scale VRE	Stable long-term policy to drive uptake of low emissions genera-tion; Market/regulatory reform to better incentivise provision of capacity	Incentives supporting network cost sharing	Design technical roadmap for electricity sector (including research) for transition to high % VRE	Communicate revenue benefits of VRE for landowners	Leasing models for low-income owners; commercial models overcoming split incentives	Business models to drive demand for low carbon electricity e.g. - long term PPAs offered by govts and business (e.g. with demand aggregated between multiple businesses) via reverse auctions; - CFD, PPA with firm price in short term transitioning to market risk
	Rooftop solar PV				Inform benefits of rooftop PV	Develop business models for commercial owners to sell electricity to tenants or third parties	
	Wave				Communicate international commercial opportunities		
	Enabling tech for VRE		Introduce regs/markets to drive provision of services e.g. fast FCAS, inertia, voltage control; Harmonise enforce-ment of technical standards; improve access to data		Collaboration between NSPs & DER service providers	Workforce upskilling in enabling technologies	
	Storage			Show benefits of batteries via demonstration projects; Demonstrate off-river PHES		Workforce upskilling in batteries; innovate business models to capture value	
	Smart grid technologies			Industry-wide process to design the future operating model for the grid		Develop new business models to enable value capture from smart grid technologies	
	RAPS and microgrids		Regulatory reform	Share learnings from demonstration projects; foster connections between project developers and supply chain partners			
	CST			Communicate benefits of dispatchability		Progress development of local supply chains, particularly during build of early projects	
	Geothermal						
	CCS		Consistent reg. regime; ensure utilisation included in policy	As part of climate change strategy, reinforce importance of CCS in achieving abatement		Adapt learnings from international projects including potential commercial models	
	HELE			Demonstrate CCS as enabler for near zero emissions HELE			
	Nuclear		Legislative reform enabling nuclear electricity generation	National debate on nuclear, including role in potentially lowering cost or risk of C abatement		Develop local industry skill base	
Electrification and fuel switching	Bioeneregy	Implement internationally consistent, stable policies that favour 'drop-in' fuels		Communicate availability of waste feedstock; Develop clear national life-cycle assessment tools		Develop supply chains	
	Hydrogen	Implement policy to drive FCV uptake in heavy vehicles; Implement necessary standards		Communicate global technological progress and safety testing		Encourage upskilling from oil & gas industry; coordinate deployment between stakeholders	
	EVs	Policy support e.g. targets, targeted incentives, emissions standards on new vehicles		Communicate improvements in driving ranges and recharging		Encourage new ownership models; review incentives for managed charging	
Other	Fugitives	Policy incentivising abatement of vented methane from LNG & potentially VAM from coal					

High priority | Medium priority | Low priority | Dashed boxes: post-2020

Figure 23. Key potential enablers of low emissions technologies (excluding RDD&D funding)

RDD&D FUNDING

Action 4.1 Review RDD&D program, ensuring efforts are aligned with comparative advantage, existing strengths, local needs, market opportunities and international collaborations.

Action 4.2 Support demonstration and deployment projects aimed at improving energy productivity in buildings, industry and transport, including through energy efficiency, fuel switching, electrification and direct use of renewable energy for heat.

Action 4.3 Continue RDD&D in low emissions energy generation technologies, such as solar PV, CST and CCS, aimed at bringing down costs and establishing supply chains.

Action 4.4 Undertake a cross-disciplinary program to understand how to transition electricity grids (including remote area power systems and microgrids) to support higher shares of distributed energy resources and variable renewable energy at least cost, while maintaining security and reliability, including detailed system modelling at sub-5 second timescales, grid-scale demonstration projects (e.g. in South Australia) and development of cyber-security architectures and protocols.

Action 4.5 Increase RDD&D in bioenergy and low emissions hydrogen, including bioenergy conversion pathways, development of bioenergy feedstocks and supply chains and development of hydrogen for export.

Action 4.6 Conduct R&D in next generation ventilation air methane (VAM) abatement technologies and carry out commercial scale demonstration projects for VAM abatement technologies.

RDD&D funding to support Australia's decarbonisation fits into several categories:

- **Key for Australian abatement:** Funding that is key for abatement in all pathways, such as enabling technologies for VRE, solar thermal and bioenergy for industrial heat and VAM abatement technologies
- **For optionality:** Funding of technologies that are key for maintaining optionality, such as CST, HELE and CCS for electricity generation
- **Targeted bets:** Funding of higher risk technologies where small 'targeted bets' may have potentially large payoff, such as geothermal energy or airborne wind

An additional category, '**Primarily commercial/global**' applies where RDD&D funding is less likely to have a large impact on Australia's decarbonisation, but may enable more material decarbonisation at a global scale as well as allowing capture of commercial opportunities in domestic and export markets. Key technologies where this applies are solar PV, batteries, and niche technologies within CST and hydrogen supply chains.

Figure 24 shows recommended funding to support decarbonisation grouped into these categories, as well as according to where it is required in the innovation pipeline:

- R&D funding is required mainly to reduce the costs of technologies, improve performance and to adapt technologies to local conditions. It also has the advantage of maintaining a local skill base, which may be required for subsequent industry development (e.g. funding nuclear R&D helps Australia maintain optionality for developing nuclear generation). It is also important for developing more prospective technologies for longer term decarbonisation, such as improved processes for producing energy intensive materials.
- Demonstration funding is key for driving down costs, as well as for solving problems associated with deploying technologies in the real world, and for securing stakeholder support.
- Deployment incentives are required to continue bringing costs down enough that other policy mechanisms can take over in driving deployment and to overcome financing barriers for first of kind projects.

Public funding of RDD&D is important since it enables lower cost abatement in the long term than would be possible if only relying on private funding. This will smooth the transition to a lower emissions economy, regardless of the specific policy mechanisms put in place to drive the transition. Private capital cannot generally take the same risks as public funding sources, and is therefore better suited to deploying technologies that are close to or at commercial maturity. Public funders can support technologies that might be more cost effective in the long term, as well as consider in which areas of the economy decarbonisation will be required in the long term and the types of technologies that will be required to deliver it.

Australia has committed to double its clean energy R&D spend by 2020, amounting to $216 million per annum, as part of membership of Mission Innovation. Mission Innovation is a global commitment for participating countries to double government expenditure on clean energy R&D from 2015 levels by 2020. It will provide opportunities for Australia to collaborate with 23 participating countries and 28 leading private investors to support the next wave of clean energy technologies. The commitment excludes recoupable investments made by the Clean Energy Finance Corporation and expenditure on later stage deployment.

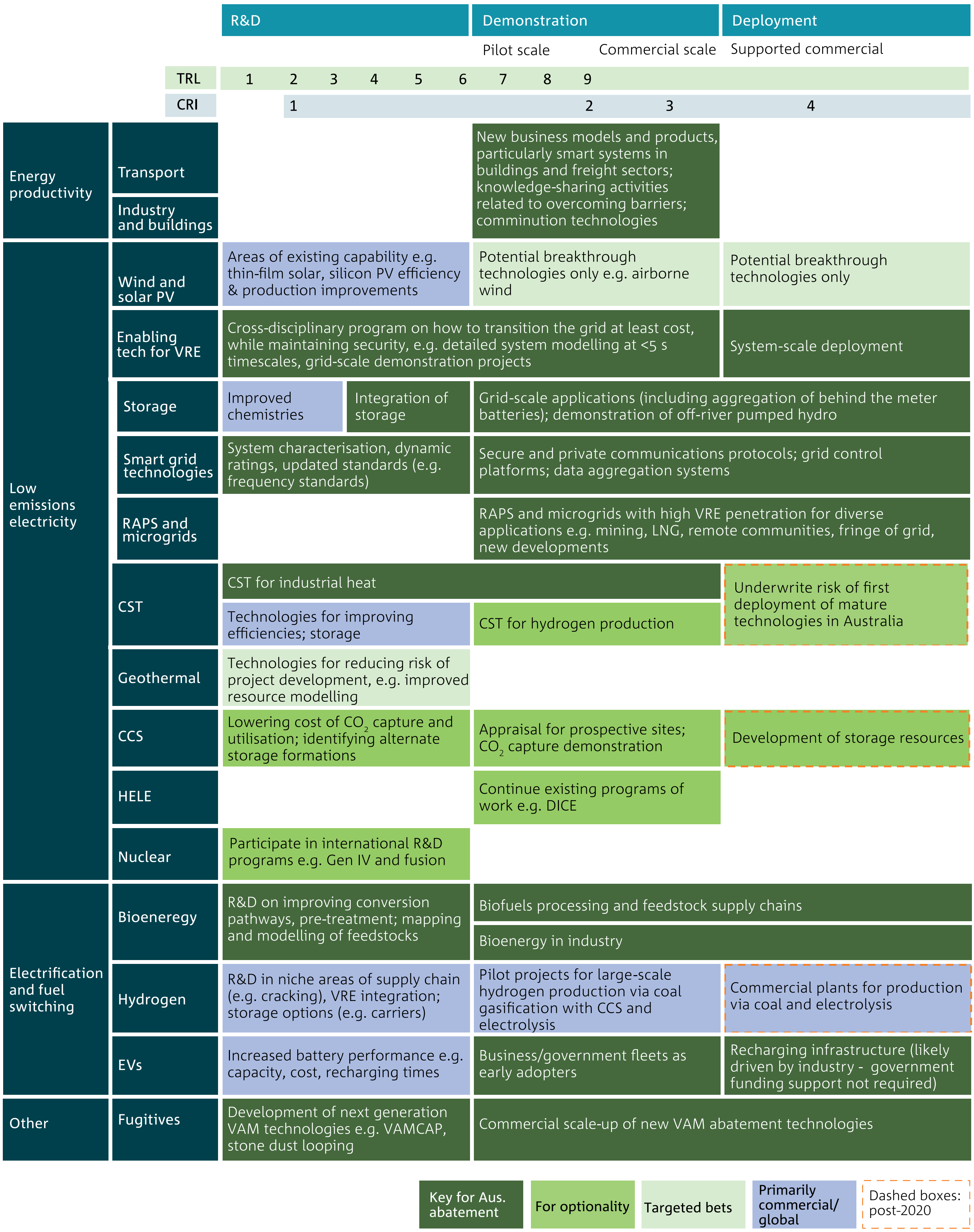


Figure 24. Recommended RDD&D funding (CST includes technologies for non-electricity applications)

Appendix A

PATHWAY 1: Energy productivity plus

A.1 Introduction

Pathway 1: Energy productivity plus is a scenario that considers the impact of ambitious energy productivity improvements in meeting Australia's 2030 target and achieving deeper decarbonisation beyond that.

Pathway 1 focuses on actions to reduce emissions from energy consumption at the point of use (demand side). This pathway differs from Pathways 2 and 3 which achieve abatement from significant changes to the electricity generation sector (supply-side). This pathway places strong emphasis on the potential for abatement in the buildings, industry and transport sectors[56]. The maximum potential of energy productivity in these sectors is assumed for this pathway and for Pathway 4[57], whereas BAU improvements in energy productivity are assumed in Pathways 2 and 3.

New build electricity generation in this pathway is assumed to continue to come from low emissions sources already currently deployed, i.e. mainly onshore wind, solar PV and gas[58]. A 45% limit was placed on wind and solar PV share[59], since addressing the challenges of reaching higher VRE shares is the focus of Pathway 2.

In the context of this pathway, energy productivity refers to the value derived (at point of use) from each unit of energy consumed. It does not include 'embodied' energy or any upstream losses (e.g. embodied energy in coal or gas used to generate electricity and losses incurred during transmission).

Focus for discussion in this appendix

	1 PATHWAY 1: Energy productivity plus	2 PATHWAY 2: Variable renewable energy (VRE)	3 PATHWAY 3: Dispatchable power	4 PATHWAY 4: Unconstrained
Buildings, industry and transport	**Ambitious energy productivity improvements**	**Business as usual energy productivity improvements**		**Ambitious energy productivity improvements**
			Hydrogen for transport and export	
New build electricity generation	**Existing low emissions technologies**: wind, solar PV (45% limit) plus gas	**Cheap, mature, low emissions generation**: mainly wind and solar PV **plus enabling technologies** e.g. batteries pumped hydro	Wind and solar (45% limit) plus **low emissions, dispatchable generation**: • Concentrating solar thermal with storage • High efficiency, low emissions fossil fuels with carbon capture and storage • Nuclear • Geothermal	**All low emissions technologies allowed, with no limit on wind and solar PV**
Fugitive emissions	**Uptake of cost-effective technologies**			

[56] The National Energy Productivity Plan (NEPP) aims to improve energy productivity (defined in the NEPP as economic output (GDP) per unit of primary energy) by 40 per cent to 2030, equivalent to 402 PJ of final energy savings. It is recognised that there is potential to achieve greater energy savings – up to 761 PJ – by implementing all identified cost effective energy efficiency activities (Australian Government, 2015, p. 13). Although a detailed comparison between modelling for this report and the NEPP is outside the scope of this report, the level of abatement modelled in this report (particularly for Pathways 1 and 4) is broadly aligned with the greater energy savings thought to be available. While the current suite of NEPP measures is intended to go some way to capturing the available savings, the 2016 NEPP Annual Report highlights the challenges in achieving abatement from activities in industrial sectors and heavy vehicles particularly. This underscores the importance of continued focus on energy productivity. Furthermore, in order to achieve the greater potential identified, additional or accelerated policy measures are required.

[57] The assumptions made regarding energy productivity improvements in Pathway 1 apply equally to Pathway 4.

[58] Note that gas counts as a low emissions power generation source in this roadmap since it was found to be compatible with Australia's decarbonisation target, although with limits to use which grow tighter with time.

[59] In this report, VRE share is defined as the average proportion of electricity (TWh) provided by VRE.

Improving energy productivity has emissions benefits when the amount of energy used is reduced, or when energy from a lower emissions source is used. This can be from a reduction in fuel combusted at the point of use (such as gas in a hot water system) and indirectly, via reduced electricity consumption (such as LED lights that reduce electricity consumption, and thus demand from the grid).

Improving energy productivity also creates additional benefits beyond reducing energy and emissions. For example, technologies may offer greater production throughput or have positive safety implications. For example with electrification of underground mining equipment, vehicles are more efficient and also eliminate harmful diesel emissions (which has the added benefit of further reducing ventilation energy demand).

A.1.1 TECHNOLOGY CATEGORISATION

Throughout this appendix, low emissions technologies are discussed in relation to four sectors:

- Buildings
- Industry
- Transport
- Fugitives

Technologies to reduce emissions in these sectors are categorised according to the pillars of decarbonisation, as described above in Section 2.2:

- Energy efficiency, using less energy to achieve a given outcome
- Low carbon electricity, from renewable sources, nuclear power or from fossil fuel generation with CCS
- Electrification and fuel switching from fossil fuels to bioenergy, and from coal and oil to gas
- Other or non-energy emissions, including process improvements and CCS in industry. For the scope of this roadmap, this category covers fugitive emissions from coal mining and oil & gas production

Pathway 1 focuses on each of these pillars except low emissions electricity. The pillars of decarbonisation that apply to each focus area in Pathway 1 and the sectors they belong to are summarised in Table 9 below.

TABLE 9. KEY TECHNOLOGY PILLARS BY FOCUS AREA, GROUPED BY SECTOR

	Sector	BUILDINGS	INDUSTRY				TRANSPORT	FUGITIVES
	Focus areas	Buildings	Heating	Material handling	Oil and gas	General industrial equipment	Transport	Fugitives
Energy efficiency		✓	✓	✓	✓	✓	✓	✗
Low carbon electricity		N/A	N/A	N/A	N/A	N/A	N/A	N/A
Electrification and Fuel switching	Electrification	✓	✓	✓	✓	✗	✓	✗
	Alternative fuels	✓	✓	✗	✗	✗	✓	✗
	Renewables	✓	✓	✗	✗	✗	✗	✗
Other		✗	✓	✗	✓	✗	✗	✓

A.1.2 PATHWAY FOCUS

The approach and high level assumptions used in this pathway are discussed in this section. The corresponding technology uptake and emissions impact is discussed in Section A.3.

Buildings and Industry

In order to determine priority technologies to focus on, direct combustion emissions were grouped according to end use (e.g. buildings, process heating, etc.) so the end uses with the largest emissions could be prioritised. Estimated emissions from electricity consumption in these end use areas were also considered when determining the focus areas.

The primary focus areas chosen were buildings, process heating, material handling, compression equipment and general industrial equipment (oil & gas), which together account for 64% of electricity and direct combustion emissions. Focus areas are groups of end uses, e.g. general industrial equipment covers all motor-driven equipment and consists of emissions from the operation of electric motors, pumping systems, ventilation systems, fans and blowers and compressed air systems across industry. These are described further in Section A.2 below.

Pathway 1 assumes a higher rate of energy efficiency and greater electrification of equipment and appliances compared to the BAU levels assumed in Pathways 2 and 3. A switch to less emissions-intensive fuels across industry was assumed across all of the pathways.

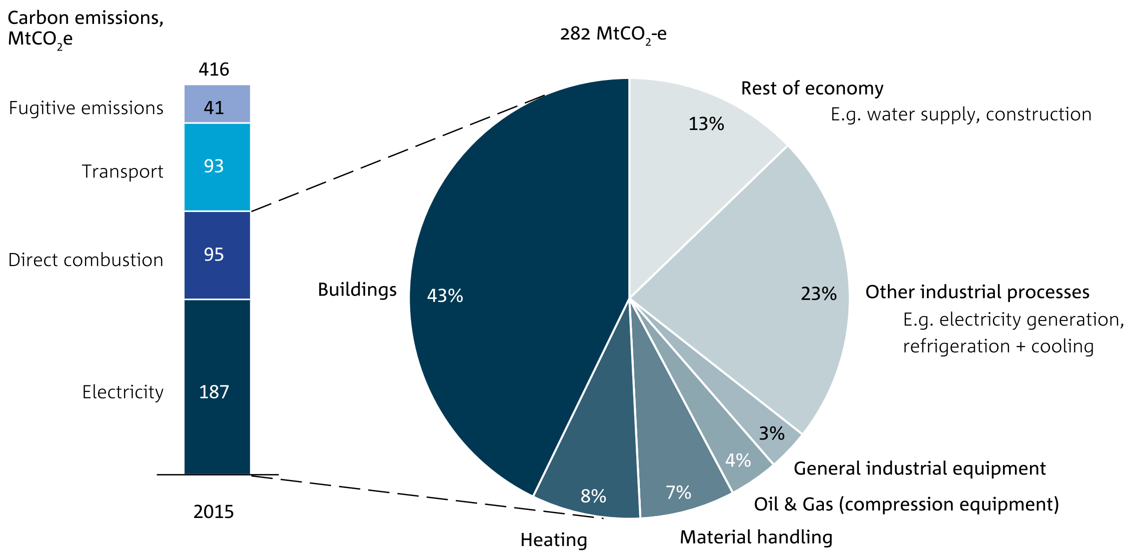


Figure 25. Electricity and direct combustion emissions, in 2015, by focus area (%)[60]

[60] For process heating, material handling and compression equipment – targeted end use focus areas only; other emissions from these categories are contained in 'Other industrial processes'.

Transport

Accounting for a significant share of emissions as a result of large end use energy consumption, the transport sector has significant scope for improvements in energy productivity. All key modes of domestic transport were analysed: road, aviation, rail and shipping. The key levers driving abatement are decreased demand and greater than BAU improvements in road vehicle efficiency and aviation efficiency.

Fugitive emissions

Abatement of fugitive emissions from coal mining and the production and distribution of oil & gas are also discussed in this pathway. The same assumptions regarding technologies for the abatement of these emissions are made in each pathway, and hence the discussion of these technologies presented for this pathway applies equally to Pathways 2 to 4.

Low carbon electricity

As discussed above, Pathway 1 focuses on demand side improvements, so achieving abatement from the low carbon electricity pillar is not a focus of this pathway. The electricity sector is discussed however, since it is impacted by demand side changes in electricity consumption assumed in this pathway. New build electricity generation is assumed to continue recent trends, with future capacity being met by the types of generation being built today and with VRE share capped at 45%, reflecting the risk in surpassing this level[61].

A.2 Pathway 1 technologies

Technologies to reduce emissions were investigated for the sectors described in section A.1.1: buildings, industry, transport and fugitives. This section provides a summary and brief description of the most promising technologies relevant to each sector. Further detail for the technologies are available in the LETR Technical Report, with the emissions implications of these technologies discussed in section A.3.

A.2.1 BUILDINGS

Responsible for one of the largest shares of emissions in Australia, the buildings sector can achieve deep decarbonisation using commercial technologies. LED lighting, high efficiency HVAC technologies and building envelope improvements are key to this abatement.

Key buildings technologies:

- LEDs: semiconductor devices that convert electricity into light; are much more efficient than traditional incandescent or fluorescent lighting
- Heat pumps for HVAC and hot water: Electric devices that use ambient heat for efficiency heating and cooling (discussed further in the heating section of the LETR Technical Report)
- Efficient refrigeration: equipment that uses more efficient refrigerant gases
- Improved building envelope: including efficient design, window glazing, insulation, cross ventilation, sealing and weatherproofing
- Sensors and controls: equipment to control equipment, improving efficiency of operation
- Higher efficiency appliances and equipment: including but not limited to air conditioning, hot water systems, pool pumps, televisions, washing machines and information technology

Achieving abatement in this sector can be challenging, as residential, commercial and industrial building sub-sectors are highly fragmented and buildings tend to be long-lived assets with low turnover. However, the emissions and financial opportunity afforded by abatement in this sector is significant, making it an area worth focussing on. The barriers, as well as the potential solutions needed to overcome those barriers associated with this sector, are discussed in Section A.4 below.

[61] Refer to Pathway 2 for further detail on the challenges and risks associated with higher shares of VRE.

A.2.2 INDUSTRY

Technologies were identified for the most emissions intensive end uses within each focus area. These end uses and also the sectors in which the focus area is most significant is shown in Table 10.

In addition to these focus areas, an overall rate of energy efficiency improvement was assumed in the modelling, reflecting improvements in other end uses not discussed in detail, such as dryers and ovens. This energy efficiency rate also takes into consideration improvements that are not necessarily technological in nature, such as fixing leaks in a compressed air system or optimising the way in which equipment is ramped up or shut down.

While CCS could potentially be applied to emissions from process heating and compression equipment, this is not assumed in this pathway. It is expected that other means of abatement would generally be cheaper and would therefore be deployed first. CCS for other purposes (e.g. electricity generation, hydrogen production or capturing pure streams of CO_2 from industrial processes) are discussed in Pathway 3.

Technology-specific emissions reduction opportunities for the focus areas in Table 10 were considered, as discussed below.

TABLE 10. SUMMARY OF EMISSIONS-INTENSIVE FOCUS AREAS WITH END USE EXAMPLES AND THE SECTOR(S) IN WHICH THAT ACTIVITY IS MOST SIGNIFICANT.

FOCUS AREA	END USE EXAMPLES	MOST SIGNIFICANT SECTORS
Process heating	Boiler systems; Furnace/kilns	Non-ferrous metal product manufacturing (aluminium); non-metallic mineral products (bricks, ceramics); chemical and chemical product manufacturing; food product manufacturing
Material handling	Materials handling/ excavation equipment; Comminution	Coal mining; Iron ore mining
Compression equipment (Oil & gas extraction)	Liquefaction compressor turbines	LNG
General industrial equipment	Motors; Pumping systems; Ventilation systems, fans and blowers; Compressed air systems	All sectors

Process heating

Heat is generated and used in many industrial processes, and is estimated to be the largest single source of emissions from electricity and direct combustion after buildings. Many technologies to improve efficiency and reduce emissions in heating are mature and commercially demonstrated overseas but not widely implemented or available at a competitive price in Australia.

The technologies for reducing emissions from process heating include high-efficiency boilers for manufacturing, as well as a range of electric heating technologies that work across industry and buildings. Heat pumps are widely available and economic for many applications of low and medium temperature heating.

Key technologies for process heating are:

- Equipment upgrade: implementing higher efficiency equipment using the same/similar heating process and fuel – e.g. higher efficiency boiler.
- Electrification and fuel switching: replacing equipment using direct fuels with electric equivalents, or switching to a less emissions intensive fuel – e.g. electric induction melting and switch from coal to gas
- Ambient or waste heat utilisation: utilising heat pump technologies, or capturing and re-using waste heat from industrial processes or electricity generation equipment
- Renewable heat: utilising solar, geothermal or bioenergy for heating

Renewable heat from solar and/or bioenergy offers a large opportunity for abatement. Pathway 1 assumes the replacement of some gas consumption with renewable heat in 2030, and more so in 2050. Solar heat technologies are less mature for high temperature applications, and like biomass, may be not suitable for some applications or geographies.

Further technological development may improve the performance of renewable heating technologies, particularly solar thermal, broadening its applicability for a wider range of processes. Bioenergy is discussed further in Section B.2, and CST technologies (for the purpose of electricity production) are detailed in Section C.2.

Material handling

The size and scale of mining operations in Australia results in significant emissions from material handling. The two most emissions-intensive processes in iron ore and coal mining are mobile material handling equipment and comminution (crushing and grinding). Changes in upstream activities (prior to handling and crushing) can reduce the amount of material required to be processed, leading to compounded reductions in both energy and water consumption and costs. Implementing technologies in these areas offers a large scope for energy efficiency improvements.

Key technologies for mobile material handling equipment:

- Larger, more efficient or hybrid haul trucks
- Operational improvements, including route and payload optimisation, improved driver practices and increased automation
- At some sites, haul trucks and loaders could be replaced with in-pit crushers and electric conveyors, offering greatly improved energy efficiency and avoiding diesel consumption.
- Key technologies for comminution (crushing and grinding):
- Vertical mills and high pressure grinding rolls that are much more efficient than current technologies and also do not require consumables (grinding media or water)

Key technologies for other processes:

- High intensity and selective drilling and blasting to reduce the amount of material handled throughout a mining operation
- Ore-sorting pre-concentration to exclude waste material earlier in the process to reduce downstream comminution energy requirements

Oil & gas production

Multiple technologies are available for energy productivity improvements in oil & gas production, particularly in LNG plants.

Given the need for large equipment decisions to be incorporated at the design stage, and with no new LNG plants projected beyond those currently under construction, the window for uptake of the most efficient technologies is limited. Despite this, opportunities for incremental improvements to equipment are available for existing plants.

- Using higher-efficiency ‘aero-derivative’ gas turbines to drive the LNG liquefaction process instead of conventional gas turbines
- Electric motors can also be utilised in some applications, reducing emissions when using sufficiently low emissions electricity.
- Floating (F)LNG: Due to the proximity of the FLNG facilities to the reservoir, they can be more energy efficient due to the high pressure feed gas direct from the reservoir, lowering gas compression requirements.
- Other opportunities include process design and advanced process control, waste heat recovery, cryogenic liquid expanders and integrated natural gas liquids (NGL) recovery processes.

General industrial equipment

Electric motor-driven equipment is used extensively across the economy in applications such as pumps, fans, compressors and other equipment and is a large consumer of electricity. Energy consumption can be reduced by implementing new and commercially available technologies and by reducing waste in existing installations through operational improvements.

Key technologies are:

- Efficient electric motors, incorporating rotor and magnet developments, such as brushless permanent magnet and synchronous-reluctance technology
- Variable speed drives and frequency drives: control systems that allow for motor output to be better matched to demand
- Additionally, operational improvements are key to reducing energy use, including reducing demand for compressed air, minimising leaks and continued maintenance as well as overall system optimisation (including load management design, optimised sizing of the pipes and efficient ancillary equipment energy).

Increased efficiency of electric motors has broad impact due to the widespread integration of electric motors in a wide range of consumer and industrial equipment. However, incremental increases in the efficiency of electric motors offers only a fraction of overall energy savings. The majority of the opportunity exists from optimising how the motor is used, optimising the equipment connected to the motor and correctly specifying the right size and type of equipment to achieve the desired task.

A.2.3 TRANSPORT

Reducing carbon emissions across the transport sector can contribute significantly to Australia's overall emissions abatement task. The transport sector has a multitude of technological and non-technological options available across all modes of transport. These include fuel substitution, improved vehicle efficiency and demand reduction.

Fuel substitution involves using alternative energy sources for vehicle propulsion. Key technologies are:

- EVs – use battery power to drive wheels with electric motors (detailed further in the EVs section of the LETR Technical Report)
- FCVs – rely on hydrogen powered fuel cells to generate electricity in order to drive the wheels with electric motors (discussed further in hydrogen section of the LETR Technical Report)
- Biofuels – Fuels derived from organic biomass via a range of different conversion methodologies (discussed further in the bioenergy section of the LETR Technical Report)
- Compressed Natural Gas (CNG) and LNG – used in heavy road vehicles and rail freight

Improved vehicle efficiency involves reducing the amount of fuel required per unit of distance travelled. Key technologies are:

- In road vehicles, technologies that improve the efficiency of the engine, transmission and other vehicle systems including aerodynamics. This may include hybrid drivetrains.
- In aviation, aircraft improvements to aerodynamics, light-weight structures, efficient engines and electrification of aircraft systems
- In rail, engine efficiency, heat recovery and weight reduction
- In shipping, more efficient hull design and propulsion systems

Demand reduction involves reducing the number vehicle of kilometres travelled. Key technologies are:

- In passenger transport, demand reduction from shifting to alternative modes of transport such as public transport and bicycles, enabled through improved urban design
- In freight, improved logistics and routing, mode shifting and innovative business models

The growing availability, performance and desirability of electric vehicles and other alternative drivetrain technologies like hydrogen fuel cells are poised to significantly change the emissions profile of the vehicle fleet. The impact is likely to be moderate until after 2030 however. Before this, efficiency improvements in ICE vehicles and demand reduction will be key to driving abatement.

Autonomous vehicles, alongside shared mobility systems that make use of the internet of things and connectivity, could disrupt the mobility landscape. The impact these trends will have on emissions is however highly uncertain. Autonomous vehicle may reduce the cost of transport and increase demand. Conversely, shared mobility enabled by autonomous vehicles could dramatically increase vehicle utilisation and hence turnover of the vehicle fleet and hence uptake of low emissions vehicles.

Biofuels are expected to remain the largest opportunity for significant long term emissions abatement in the aviation sector.

A.2.4 FUGITIVE EMISSIONS

The greatest source of fugitive emissions is from underground coal mining, and the greatest opportunity for abatement of fugitive emissions exists in reducing VAM emissions from underground coal mines. Technologies exist at the demonstration stage for VAM, as well as commercial technologies that may require adaptation for effective deployment in underground coal mines.

The key opportunity for abatement of fugitive emissions in LNG is CCS of vented CO_2. CCS in general requires a pure stream of CO_2, the expertise to safely inject the CO_2 underground and access to a suitable geological storage reserve. A pure stream of CO_2 is created in some LNG operations due to the need to remove the CO_2 from the gas during processing (usually this is just vented into the atmosphere). The skills and capabilities required to exploit gas fields are also applicable to reinjecting the CO_2. Some gas operations have access to potential storage reserves – depleted gas fields in general make good candidates for CO_2 sequestration. In some cases however, lack of a suitable nearby storage reserve may make CCS cost-prohibitive. An example of geo-sequestration of vented CO_2 is provided by the Gorgon project in WA, which is set to start injecting 3.4-4 million tonnes per annum of CO_2 in 2017, making it the world's largest CCS project (Global CCS Institute, 2016).

The other main source of fugitive emissions from LNG is flaring. Flaring is mainly an operational issue – for instance if a gas turbine shuts down flaring may be required to avoid dangerous build-up of pressure. As such, opportunities to reduce flaring mainly stem from improved operational practices, enabled by technological solutions such as advanced process control.

For domestic gas, most fugitive emissions result from venting and flaring methane, as well as leaks from transmission, distribution and storage. Venting and flaring can be reduced by process improvements, enabled by technological solutions such as advanced process control. Leaks can be reduced through improved maintenance and planning processes (ClimateWorks Australia, 2014).

Domestic gas fugitive emissions are driven by domestic consumption, and will drop with declining residential, commercial and industrial gas use. Conversely, more fugitive emissions can be expected if more gas is used for electricity generation, as is the case in some of the scenarios modelled in this report.

Emissions can also occur during exploration and production of domestic and export gas. Abatement of these emissions is primarily an operational issue, requiring improved maintenance to reduce leaks.

Further details are given in the fugitive emissions section of the LETR Technical Report.

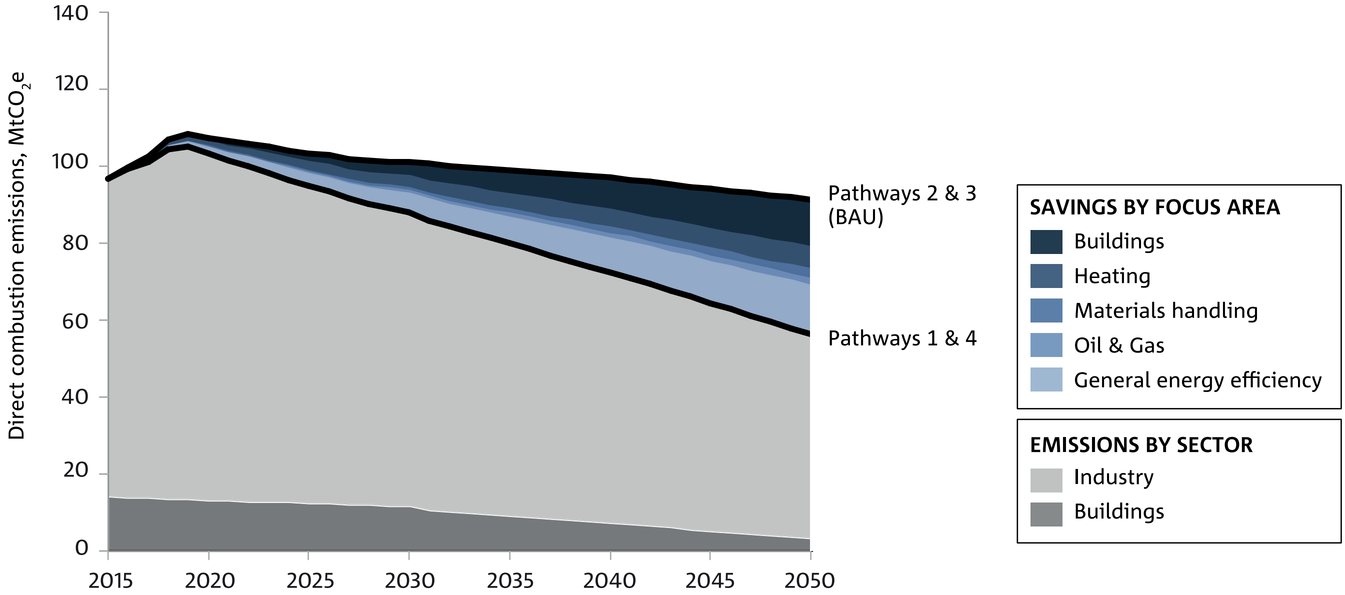


Figure 26. Direct combustion emissions and projected savings ($MtCO_2e$) 2014-2050 by focus area

A.3 Technology uptake and emissions impact

This section covers modelling results for Pathway 1. The impact of the assumed uptake of technologies on energy consumption and emissions of the electricity generation, buildings, industry and transport sectors as well as fugitive emissions is presented. Detailed modelling assumptions are presented in Appendix B of the LETR Technical Report.

A.3.1 BUILDINGS AND INDUSTRY SECTORS

Pathway 1 sees direct combustion emissions in the buildings and industry sectors reduced by 13 $MtCO_2e$ in 2030 compared to BAU, and by 35 $MtCO_2e$ in 2050. Pathways 2 and 3 follow the BAU emissions trajectory and Pathway 4 is the same as Pathway 1.

Assessing the reductions by focus areas, as shown in Figure 26, direct combustion emissions savings in buildings is the largest single source of abatement. Along with the contribution of general energy efficiency measures (actions not in a single focus area, as discussed in Section A.1.2 above) these two areas together account for nearly three-quarters of savings relative to BAU in 2050.

Note that the 'Pathways 2 & 3 (BAU)' line depicted in Figure 26 differs from the projected 2030 emissions in Figure 18. This is due to the assumption that Pathway 2 & 3 will see some impact of technologies and enhanced energy efficiency (beyond what is assumed in the 2030 emissions projection), albeit at a lesser level than what is assumed in Pathways 1 & 4.

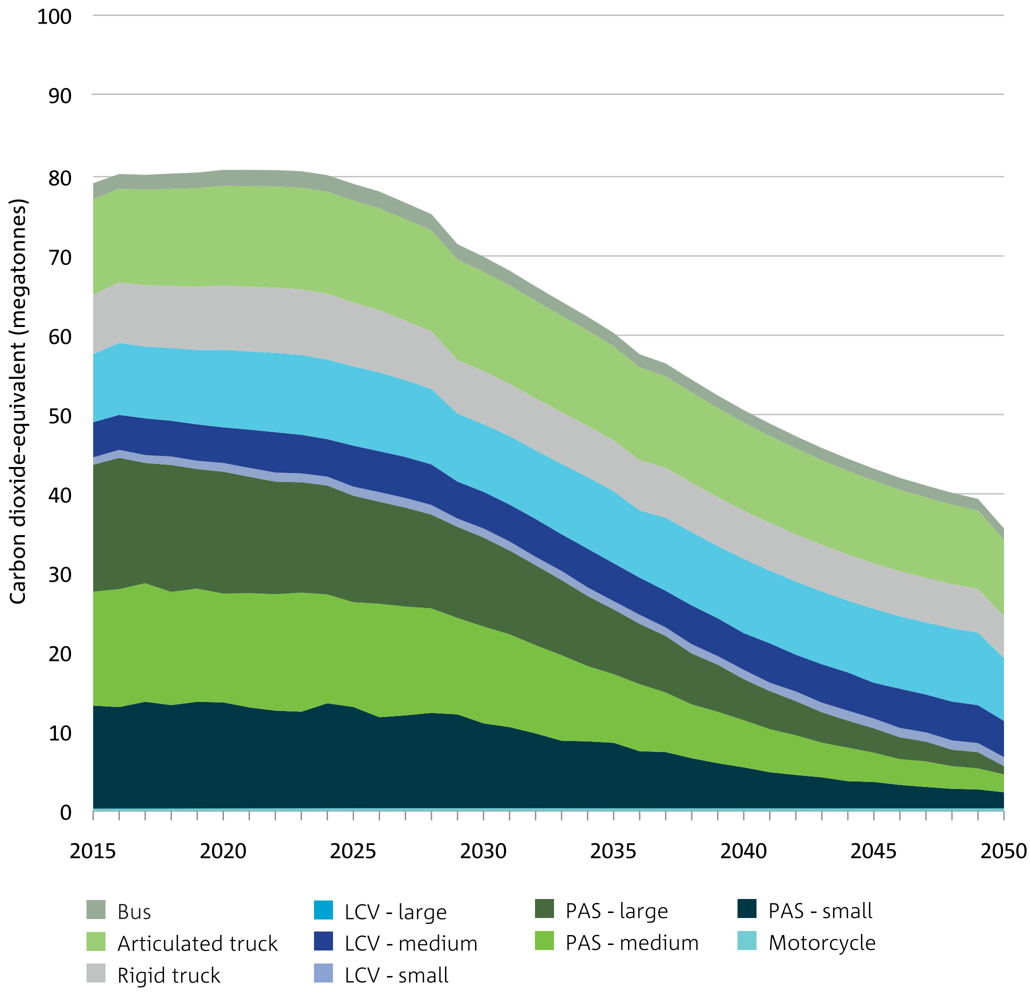


Figure 27. Road vehicle emissions ($MtCO_2e$) from 2015 to 2050 in Pathway 1 PAS = Passenger; LCV = Light Commercial Vehicle

A.3.2 TRANSPORT SECTOR

Road transport

Projected Pathway 1 emissions from road transport are shown in Figure 27. Low demand growth in passenger vehicle kilometres (Figure 28) and reduced petrol consumption due to increased efficiency of ICE vehicles (Figure 29) see emissions remaining relatively flat until ~2025 and then declining. Continued efficiency gains and only modest increases in demand, coupled with the introduction of electric vehicles, sees a 34 $MtCO_2e$ decline in annual emissions from road transport from 2030 to 2050.

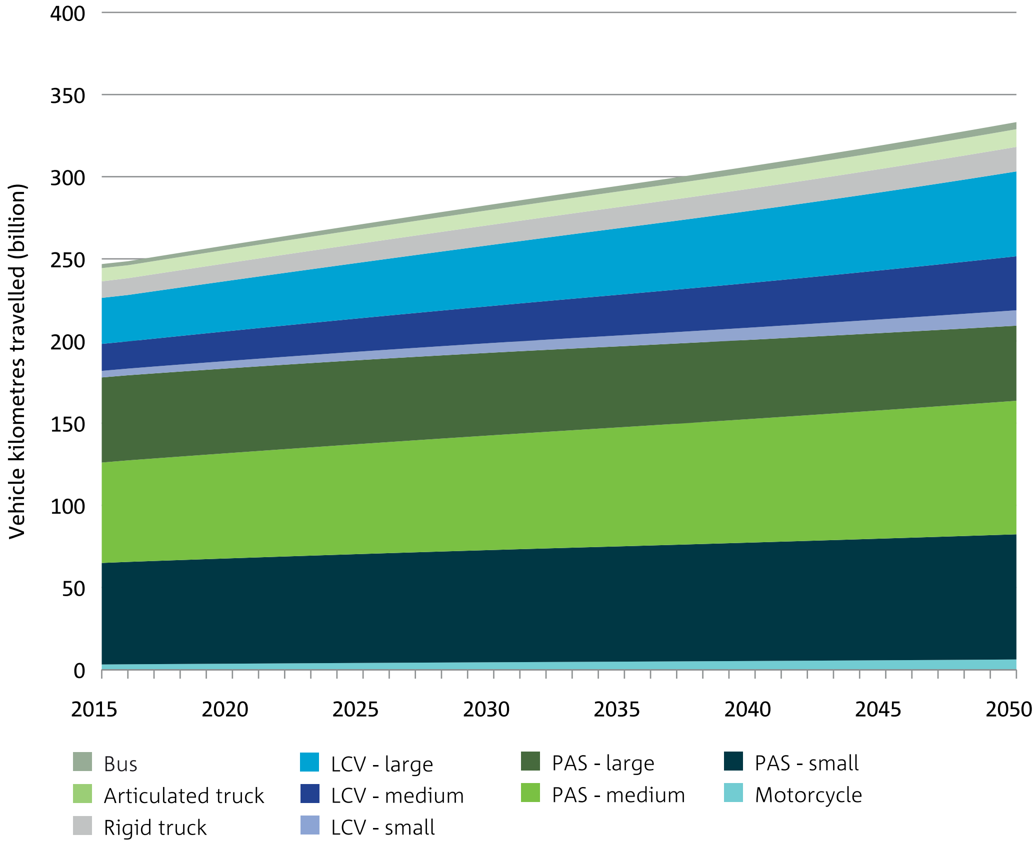


Figure 28. Road vehicle demand (billion vehicle kilometres travelled) from 2015 to 2050 in Pathway 1. PAS = Passenger; LCV = Light Commercial Vehicle

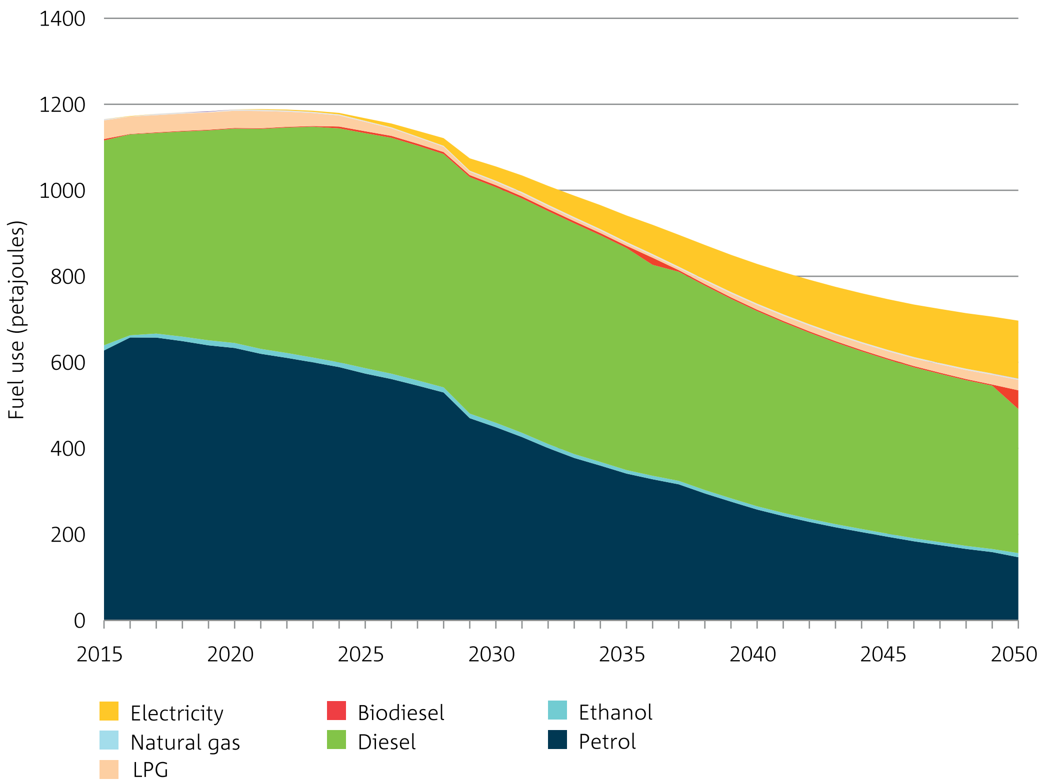


Figure 29. Road vehicle fuel use (petajoules) from 2015 to 2050 in Pathway 1

Non-road transport

Ambitious energy efficiency measures in aviation results in a plateau in fuel use from about 2035 as shown in Figure 30. The introduction of bio-jet fuel, along with biodiesel in rail and natural gas in marine transport, results in a flattening of emissions from 2035 to 2050 as seen in Figure 31.

A.3.3 FUGITIVE EMISSIONS

Technologies for VAM abatement in underground coal mines could feasibly be rolled out to all underground coal mines in Australia as early as 2027, and achieve an estimated 80% reduction in VAM emissions, equivalent to a 15 $MtCO_2e$ reduction vs BAU in 2030 (see fugitive emissions section of the LETR Technical Report for further details).

Assuming 33% of vented CO_2 from LNG can be cost-effectively reinjected underground, this would reduce fugitive emissions by 1.3 $MtCO_2e$ in 2030. Reducing emissions from flaring through improved operational practices, could reduce emissions by 0.3 $MtCO_2e$ per year in 2030.

In domestic gas, 1.8 $MtCO_2e$ abatement in 2030 could be achieved through process improvement in venting and flaring, reducing leaks in gas transmission, distribution and storage through improved maintenance and planning processes and through operational improvements in exploration and production.

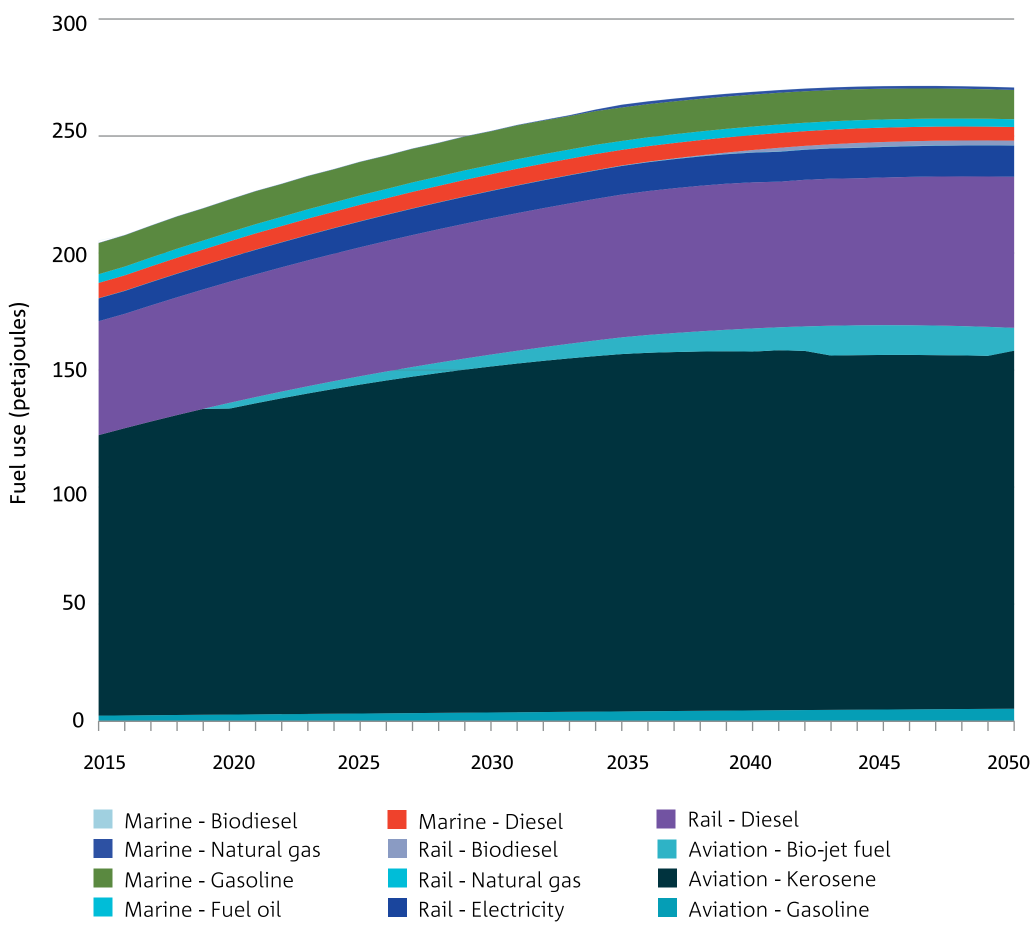


Figure 30. Non-road vehicle fuel use (petajoules) from 2015 to 2050 in Pathway 1

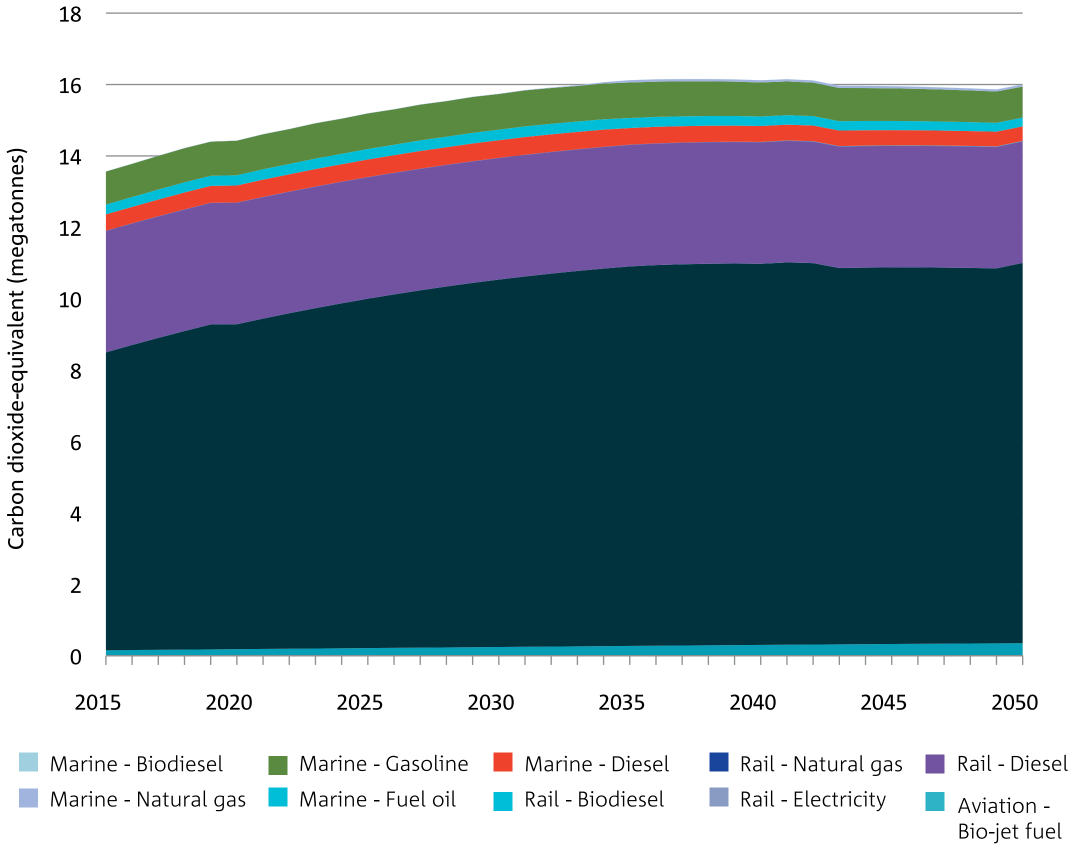


Figure 31. Non-road vehicle emissions ($MtCO_2e$) from 2015 to 2050 in Pathway 1

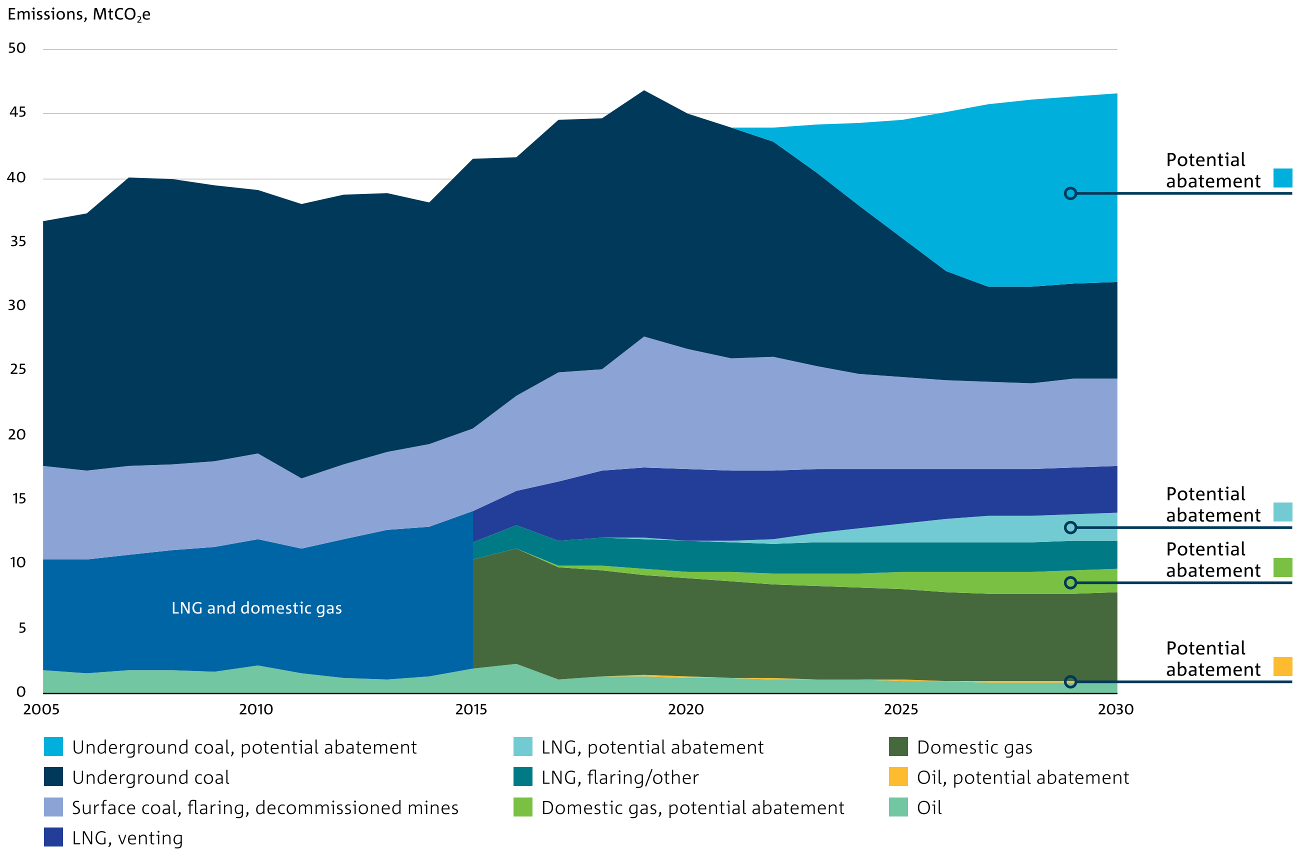


Figure 32. Total fugitive emissions abatement potential Assumes BAU gas consumption—domestic gas consumption, and hence fugitive emissions, increases or decreases depending on pathway.

The total abatement potential of fugitive emissions from coal mining and oil and gas production through the application of technology is shown in Figure 32, and further details are given in the fugitive emissions section of the LETR Technical Report.

A.3.4 ELECTRICITY SECTOR

The mix of electricity generation technologies projected in Pathway 1 is shown in Figure 33. With the maximum amount of VRE capped, other new grid generation is mostly gas combined cycle, making up an increasingly large share of the generation mix from 2030 onwards.

Emissions from the electricity generation sector in 2030 are based on the amount of abatement required to reach 27% abatement for the energy sector as a whole, after considering the quantity of abatement achieved in the other energy sectors (transport, direct combustion and fugitives). In 2030, this corresponds to a 52% reduction in emissions compared to 2005 levels, or 92 $MtCO_2e$ less than current projections for that year (Australian Government Department of the Environment and Energy, 2016). 2050 emissions correspond with 75% reduction compared to 2005, progressing linearly from the 52% abatement in 2030. Further abatement would be possible if VRE can make up a higher proportion of the electricity mix – this scenario is modelled and discussed in Pathway 4.

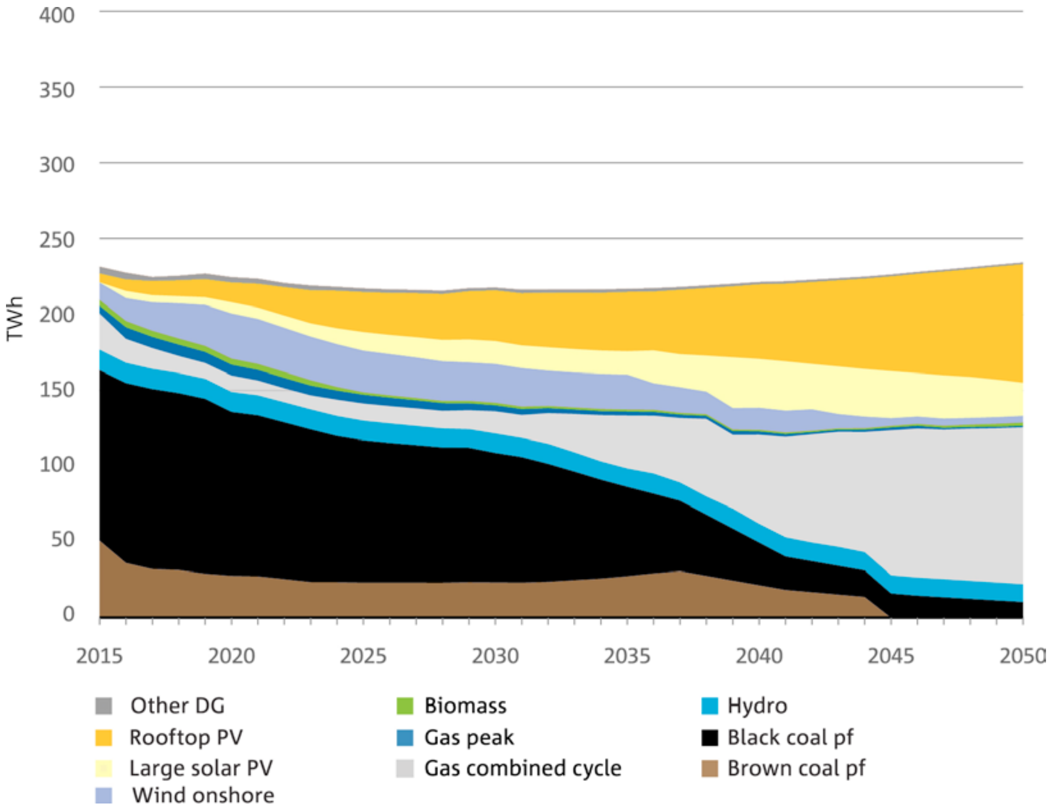


Figure 33. P1: Energy productivity plus electricity generation mix (TWh), 2015-2050

With large amounts of gas generation coming online from 2030-35 in Pathway 1, there may be a potential issue of these assets being 'locked in' should a more ambitious emissions reduction target for the electricity sector be set than the 75% abatement modelled. In this scenario, this is a discussion that would need to be had prior to making these investments.

Uptake of Pathway 1 technologies results in flat electricity consumption (Figure 34). This results from the assumed high rate of energy efficiency improvement of equipment and appliances in buildings and industry. The additional demand from electrification of previously fossil fuel powered processes in buildings and industry is more than offset by efficiency increases, in part due to the much higher efficiency of electric appliances compared to directly-fired fossil fuel equivalents. The prime example of this is heat pumps, which typically produce five units of heat energy from a unit of input electricity. Net improvements in buildings and industry offset increases in demand from both BAU growth and transport electrification (i.e. EVs).

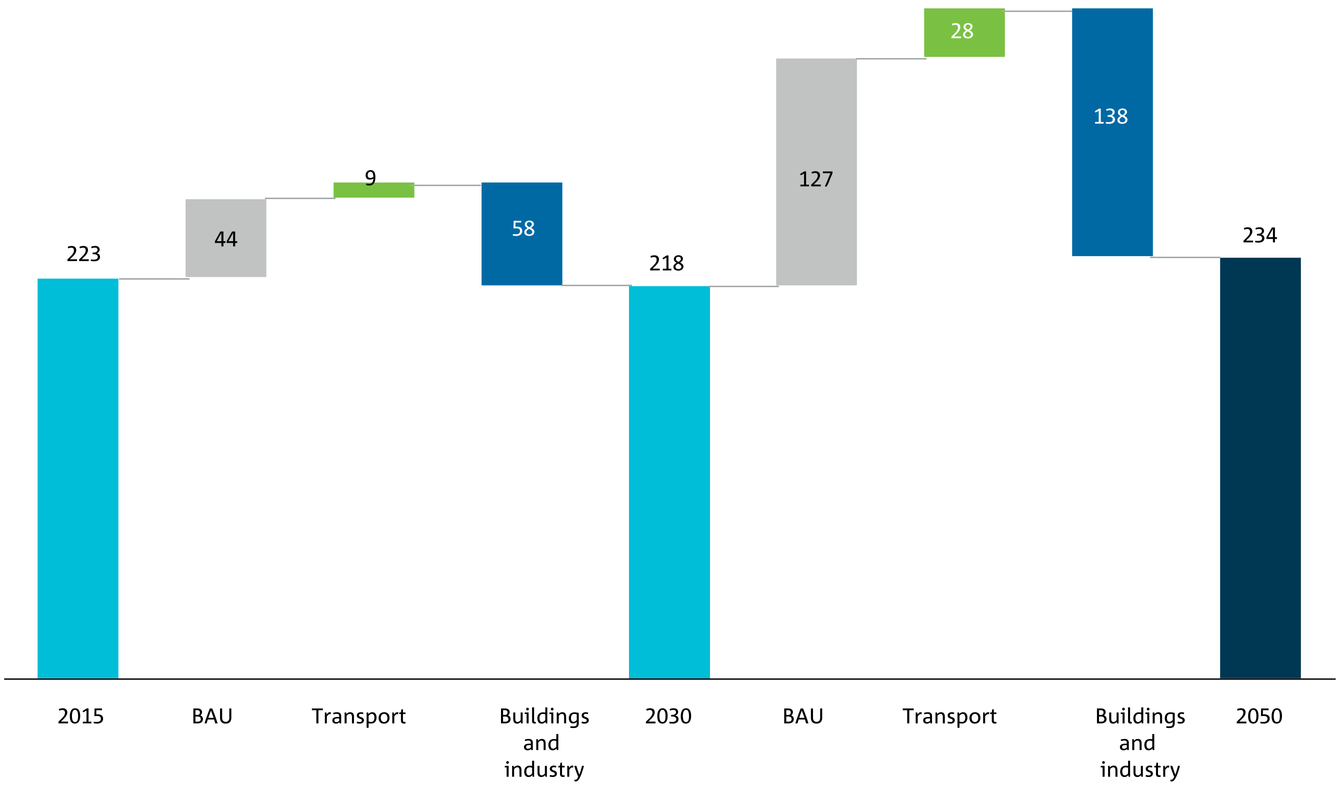


Figure 34. Changes in national electricity demand (TWh) between 2015, 2030 and 2050 in Pathway 1 showing contributions of BAU growth, increase from transport electrification and net effects of electrification and energy efficiency in buildings and industry[62]

A.4 Barriers and enablers

A.4.1 BARRIERS TO DEPLOYMENT OF PATHWAY 1 TECHNOLOGIES

In the buildings and industry sectors, the improvements energy productivity are affected by a range of barriers that impede decision makers, including businesses, individual building owners or tenants, in making the decision to proceed with a given opportunity. Disconnect between tenants and building owners (split incentives), discounted/non-cost reflective energy pricing (market distortions) and competing priorities within businesses (company motivation) are the most significant barriers.

Access to capital, required payback times and comparatively lower attractiveness of investments (financial or perceived attractiveness of an energy efficiency investment vs one that increases production throughput), as well as a lack of internal skills, data and information (company capability) are also barriers to uptake of high efficiency technologies for some companies.

The most significant barrier to achieving higher efficiency of road vehicles is the lack of high efficiency vehicles available in Australia. Another barrier is the higher upfront cost of EVs and higher efficiency ICE vehicles that can make the business case less attractive, despite these vehicles generally offering cost benefits in the long run.

The key barriers for Pathway 1 technologies are presented in Table 11.

[62] To arrive at these figures, BAU electricity consumption was taken from AEMO, without energy efficiency and solar PV assumptions. This served as the baseline upon which the new assumptions of contributions from transport electrification and buildings and industry were applied.

TABLE 11. KEY BARRIERS FOR PATHWAY 1 TECHNOLOGIES

TECHNOLOGY AREA	COST/TECHNICAL	REGULATION/MARKET OPPORTUNITY	STAKEHOLDER ACCEPTANCE	SKILLS/OTHER
Buildings	• Cost benefits of energy efficiency often go to the tenant while capital costs must be paid by the owner (split incentive)	• High market fragmentation and transaction costs • Minimum standards of buildings envelope and equipment lags behind most cost effective technology	• Consumers value equipment and appliances in buildings generally based on factors other than energy productivity (e.g. screen resolution in televisions) • Energy costs for buildings are often a small proportion of overall costs for the stakeholders in the built environment	• Best available technology, equipment and materials often not available at low cost in Australia e.g. most efficient window glazing • Professionals throughout the building design and construction supply chain do not currently see EP as part of their job and are not trained to identify or implement EP opportunities
Industry – Process heating	• Low financial attractiveness/weak business case; high hurdle rate • Reliability/continuity of supply (e.g. solar) • Practical issues with installation	• No requirement to reduce emissions from heating	• Lack of knowledge about new technologies • Lack of awareness around benefits of electrification • Lack of internal capability • Technology maturity: unlikely to be adopted unless widely accepted/ demonstrated in a similar industry	• Lack of skills around energy efficient and renewable-based heating operations
Industry - Mining equipment (material handling & comminution)	• Increased capital costs • Applicability of cutting-edge technologies to certain mines/ores	• Intensive focus on yield • Limited focus on energy savings • Cyclic booms and busts • Lack of regulations that account for externalities	• Low motivation and drive for lower emissions	• Lack of expertise and skills to adapt or maintain new cutting edge technologies
Industry – oil & gas	• High upfront capital costs makes retrofitting a challenging business case • Opportunity cost of lost production revenues due to shut down for retrofit	• Limited window during design phase to put in lower emission technologies in new plants • Less incentive to improve existing plant if production is in decline phase of lifecycle • No minimum energy efficiency standards for LNG plant design/ production	• Low motivation and drive for lower emissions • Limited focus on energy savings	• n/a

TABLE 11. KEY BARRIERS FOR PATHWAY 1 TECHNOLOGIES / CONT'D

TECHNOLOGY AREA	COST/TECHNICAL	REGULATION/MARKET OPPORTUNITY	STAKEHOLDER ACCEPTANCE	SKILLS/OTHER
Industry – General industrial equipment	• Low financial attractiveness/weak business case (e.g. long paybacks periods) • Tax incentives available for 'like for like' replacements, but not high-efficiency equipment	• Lower minimum standards when compared with other OECD countries, regulating overall industrial system efficiency • Least cost preferences of the original equipment manufacturers (OEMs)	• Lack of information and knowledge • Throughput focus	• Installation and maintenance complexity (including different physical size of replacement)
Transport – efficiency and demand	• Increased upfront vehicle cost	• Lack of regulations that account for the externalities from transport emissions (CO_2), resulting in less efficient vehicles being made available • No 'level playing field' for freight companies to encourage innovative operational practices or expenditure in new tech.	• Real/perceived risk of public transport and cycling • Location, availability and frequency of public transport and connections	• n/a
Transport - EVs	• High capital cost as compared with ICEs • Insufficient charging infrastructure supporting roll out • Electricity network cannot accommodate unmanaged charging (i.e. during peak periods)	• Lack of favourable regulatory framework that encourages uptake of EVs • Car industry derives more revenue from ICEs (e.g. maintenance)	• Consumer reluctance to accept EVs due to belief it will require adjustments in behaviour (e.g. 'range anxiety')	• Motor mechanics lack skills required to maintain EVs
Transport - Biofuels	• High cost of bio-refineries and biofuels as compared with crude • Biomass types have different characteristics and impurities so greater technical challenges for processing	• Uncertain market (price volatility) • Bioenergy is governed by a range of different regulations • Current policies preference other forms of renewable energy or inadvertently favour conventional rather than advanced 'drop-in' biofuels	• Concern over biomass competition with other food resources • Other environmental concerns such as non-CO_2 emissions, water use	• n/a
VAM abatement technologies	• Technologies require scale-up/adaptation • Adds cost to operations • Lack of available space in some mines	• Lack of economic or regulatory drivers for deployment	• Competing priorities	• n/a
CCS in LNG	• Additional cost placed on operations	• Lack of economic or regulatory drivers for deployment	• n/a	• n/a

A.4.2 KEY ENABLERS

In the previous section, the factors impeding the uptake of technologies were discussed. This section suggests enabling actions for the technologies discussed in three key areas: policy, stakeholder engagement and skills/business model. These enablers are actions that could be undertaken to aid the technologies to reach the necessary level of penetration to achieve the level of emissions abatement modelled.

In the buildings sector, a range of actions would be required to drive uptake of more efficient technologies to the level modelled in Pathway 1, including a national plan and comprehensive policy frameworks. This topic is covered in detail in the Low Carbon, High Performance report, published in May 2016 by the Australian Sustainable Built Environment Council (Australian Sustainable Built Environment Council, 2016). Recommended enablers from that work are summarised in Table 12.

In the transport sector, there are a number of actions that could be undertaken to enable uptake of low emissions technologies. Implementation of policy requiring new road vehicles to meet a suitably low level of CO_2 emissions is a key enabler of the uptake of more efficient vehicles (including, but not limited to, EVs). There are no specific CO_2 emissions standards currently in place in Australia.

Uptake could be further supported by providing incentives to lower the barrier of higher upfront purchase cost. Policy that requires companies to account for the cost of externalities in road freight and non-road operations could promote the implementation of less emissions intensive equipment. Across all modes of transport, support for the development of new mobility business models could enable transformative change in the sector.

In industry, the uptake of efficient technologies could be enabled by the implementation of measures to account for, and to drive abatement of, CO_2 emissions. This would provide another dimension through which to assess energy efficiency opportunities and improve the attractiveness of business cases, given that many opportunities are stymied by low financial attractiveness and competing company priorities. Improved data and information availability as well as training and education measures were identified as another key enabler to inform decision making.

BOX 2 | CASE STUDY

Germany – Plus-energy buildings making a positive contribution to emissions abatement

Contributing to Germany's target of 40% abatement by 2020 emissions from 1990 levels, the built environment sector is set to achieve substantial abatement through the implementation of a range of standards, programs and incentives.

Germany is a global leader in near-zero energy buildings – or 'passivhaus' as they are called in German – with its voluntary standard certifying buildings that achieve near-zero energy performance in place as early as 1990. Germany is setting the benchmark for these types of buildings, which will continue to become more widespread as a result of EU requirements for all new public buildings to be nearly zero-energy by 2018 and all new buildings by 2020. Furthermore, these near-zero energy buildings can become plus-energy buildings with the addition of rooftop solar PV, making a positive contribution to the broader energy system.

A number of other initiatives are also being undertaken in Germany to reduce emissions in the buildings sector, such as:

- Installation of an energy commissioner, responsible for energy efficiency of all federal buildings
- Specific research and funding programs targeting higher standards than what is required for both existing and newly built buildings (such as passivhaus)
- A national efficiency labelling program to promote upgrades for old heating systems
- Market incentive programs for uptake of renewables (including heating) on site

(Craig Morris, 2016)

BOX 3 | National Energy Productivity Plan (NEPP)

The NEPP aims to improve energy productivity (economic output per unit of primary energy) by 40% to 2030. It is estimated that this target is equivalent to 402 PJ of final energy savings and between 21 and 36 $MtCO_2e$ of emissions savings depending on the emissions intensity of electricity supply and fuels saved.

A suite of 34 policy measures was proposed to be implemented as part of the NEPP. These include policies to provide incentives, information, financing, innovation support, market reform and consumer protection to facilitate the uptake of measures to improve energy productivity across the economy. An evaluation of how the individual policies included in the NEPP relate to the enabling actions described within this report is not within the scope of this report.

It is recognised that there is potential to achieve much greater energy savings by implementing all cost effective activities. Although a detailed comparison between modelling for this report and the NEPP is out of scope, the level of abatement modelled in this report (particularly for Pathways 1 and 4) is broadly aligned with the greater potential thought to be available. While the NEPP measures will go some way to capturing the savings, additional policy efforts are required to achieve the full potential identified by the NEPP and hence the levels of abatement modelled in this report.

The key policy, stakeholder engagement and skills/business models enablers for Pathway 1 technologies are shown in Table 12.

TABLE 12. KEY POTENTIAL ENABLERS FOR PATHWAY 1 TECHNOLOGIES

TECHNOLOGY	POLICY	STAKEHOLDER ENGAGEMENT	SKILLS/BUSINESS MODELS
Buildings	• Financial instruments to help tenants and owners co-finance energy efficiency (EUAs) • Improvement in minimum standards • Processes that ratchet up minimum standards with time	• Improve data availability to clearly identify the potential of cost effective and energy efficient opportunities • Develop methods of valuing ‘multiple benefits’ such as improved staff productivity and health	• Industry-led initiatives to better value and market the non-energy benefits • Training and awareness programs for professionals and customers
Industry – Process heating	• Introduce policy to recognise and limit emissions and/or increase efficiency • Incentives to consider and adopt higher efficiency equipment	• Educate industry on current and future heat storage options • Improved knowledge sharing initiatives • Support demonstration projects	• Introduce certifications and accreditations in the relevant skill sets
Industry – Mining equipment (material handling & comminution)	• Stable long term industry-wide emissions reduction signal • Implementation of low interest capital access schemes	• New mine design methodologies that consider energy productivity and emissions reduction - not just tonnes processed or capex	• Improve data availability to clearly identify the potential of cost effective and energy efficient opportunities • Education and knowledge sharing – new technologies, examples of implementation
Industry – Oil & gas	• Measures to account for, and drive abatement of, CO_2 emissions • Implementation of low interest capital access schemes • Policies to encourage optimisation of operations for lowest emissions • Avoid policies with restrictive short payback periods	• Shift focus/attitude from ‘LNG is lower emissions than coal‘ to ’LNG is largest direct combustion GHG emitter in Australia and those emissions can be reduced cost-effectively while increasing LNG production’	• Education and knowledge sharing – new technologies, application of electric motors
Industry – General industrial equipment	• Higher MEPS • Incentives to consider and adopt higher efficiency equipment • Address taxation asymmetry, allow equal (or higher) incentives for high efficiency equipment	• Aligned incentives throughout the value chain • Energy audits	• Education and knowledge sharing – system optimisation, waste reduction, smart monitoring • Standardise system requirements (e.g. bolt patterns, equipment size) to allow more general application of most efficient equipment

TABLE 12. KEY POTENTIAL ENABLERS FOR PATHWAY 1 TECHNOLOGIES / CONT'D

TECHNOLOGY	POLICY	STAKEHOLDER ENGAGEMENT	SKILLS/BUSINESS MODELS
Transport – Efficiency and demand	• Policy measures such as vehicle emissions standards (new vehicles) and purchase incentives • Pricing of externalities • Incentivising full loading/ mandating against empty running of road freight	• Improved cycling routes and end-of-use facilities	• New business models based on mobility, car sharing • Connectivity for group travel or real-time tracking for concerned passengers
Transport - EVs	• Set EV deployment targets and implement incentives designed to encourage uptake (e.g. tax benefits) • Impose emissions standards on new vehicles • Allow for customers to sell electricity back to the grid • Incentivise customers to charge off peak via customer sign-up conditions or time of use tariffs	• Communicate continual improvements in driving ranges achieved as well as reductions in recharging times	• Encourage roll out of smart meters and home energy management systems • Strategically deploy commercial recharging stations • Ensure that government, automobile industry regulators, utilities continually coordinate their efforts in order to refine roll out strategies • Explore and encourage new EV ownership models (e.g. leasing)
Transport - Biofuels	• Implement internationally consistent, stable policies that favour use of 'drop-in' biofuels • Implement clear national sustainability criteria	• Communicate availability and use of waste feedstock • Develop national life-cycle assessment tools	• Develop supply chains
VAM abatement technologies	• Strengthen policy requiring/ incentivising uptake as needed	• Share learnings from demonstration projects	• Develop projects for ERF funding
CCS in LNG	• Introduce regulation requiring/ incentivising uptake	• Communicate as major enabler for development of higher CO_2 gas reserves which will become increasingly more the norm	n/a

RDD&D

Support for innovative business models and products to improve energy productivity, such as those that leverage the internet of things and connectivity, can help capture abatement opportunities in buildings as well as in transport. Other relevant areas for support in transport are government and business fleets driving uptake of EVs, and cost improvements for biofuels conversion pathways. Support for RDD&D and knowledge sharing related to renewable process heating solutions would contribute towards this option becoming more viable for industrial heat applications. Focus on scaling up VAM technologies will be critical for new, more efficient technologies to be available. Table 13 summarises recommended funding focus for Pathway 1 technologies.

TABLE 13. RECOMMENDED RDD&D FUNDING FOCUS FOR PATHWAY 1 TECHNOLOGIES

TECHNOLOGY	R&D	DEMONSTRATION	DEPLOYMENT
Buildings	n/a	• Support for innovative business models/products e.g. smart systems	• Awareness of cost-effectiveness of heat pump technologies for many applications
Industry – Process heating	• R&D for higher temperatures; storage technologies; hybrid systems	• Demonstration of existing solar thermal equipment in industry applications to build awareness and confidence	n/a
Industry - Mining equipment (material handling & comminution)	• Development of energy efficient material handling measures (both tech. & processes)	• Support roll-out of comminution technologies	n/a
Industry – Oil & gas	• Understand the impact of licensing and trade secrets on reducing innovation appetite • Further research focused on cost reduction of efficient technologies	n/a	n/a
Industry – General Industrial Equipment	n/a	• Advanced motors	n/a
Transport – Efficiency and demand	n/a	• Support for innovative business models/products, particularly smart systems in freight	
Transport - EVs	• Improved battery performance and cost	• Business/government fleets as early adopters	• Standard plugs • Charging infrastructure
Transport - Biofuels	• Focus R&D on improving yields and cost of advanced conversion pathways	• Incentivise demonstration bio-refineries (e.g. via grants)	• Encourage mapping and modelling of feedstock types in order to inform strategic deployment of bio-refineries and limit transport costs
VAM abatement technologies	• Next generation technologies	• Adaptation of existing commercial technologies • Commercial scale units for new technologies	• Funding deployment of VAM technologies (if not incentivised via other policy mechanisms)
CCS in LNG	• Monitoring and verification methodology and protocols, separation of high volumes of CO_2 from production gas streams	• Storage characterisation (Gorgon), CO_2 separation technologies	n/a

A.5 Supply chain opportunities

The supply chain opportunities in Pathway 1 extend beyond technology design, manufacture and provision/ maintenance steps to include the benefits obtained by the end user. This benefit comes about from the reduced energy costs associated with the operation of higher energy productivity equipment and processes. Benefits to the end user from increased energy productivity is the largest opportunity in Pathway 1 for Australian industry.

By way of example, vehicle emissions standards for new light vehicles would not require significant investment to implement or administer. Standards would however lead to more efficient vehicles being offered for sale, offering fuel cost savings to users. Savings from increased vehicle efficiency to levels that are broadly comparable to European and US targets by 2025 would result in a net cumulative benefit of nearly $14 billion to 2040. A net positive benefit was found to exist under all scenarios and sensitivities (Commonwealth of Australia, 2016).

Similarly, the value of energy efficiency and fuel switching opportunities in buildings is large: gross energy savings associated with all energy efficiency and fuel switching opportunities would total over $16 billion for households and over $12 billion for commercial buildings. After finance costs, the NPV of the energy savings to 2030 would total almost $12 billion for households and over $7 billion for commercial buildings (Australian Sustainable Built Environment Council, 2016).

It is well understood that many of the energy efficiency opportunities can not only offer sizeable savings from avoided energy costs, but also offer non-energy benefits such as increased throughput by reducing bottlenecks in industrial processes and improved comfort and worker productivity in buildings. (ClimateWorks Australia, 2010), (ClimateWorks Australia, 2013), (Reputex, 2015). The installation, operation and ongoing maintenance of high efficiency equipment presents an additional opportunity.

EVs will have the benefit of localising the fuel supply (i.e. electricity) as compared with ICEs that rely on petrol/diesel derived from mostly imported crude oil. By 2030, EV uptake could lead to 6.76 TWh of additional electricity demand and the displacement of ˜11,000 barrels of gasoline per day.[63]

BOX 4 | CASE STUDY

Coles – Reducing emissions using efficient technologies

By incorporating efficient technologies across all operations, Coles Supermarkets Australia Pty Ltd, reduces carbon emissions while continuing to grow. The latest technologies are being applied in the largest energy use areas of the store: refrigeration, lighting and climate control.

In addition to operating the first green-star rated supermarket in Australia (with smart, connected air conditioning and refrigeration systems), Coles saves energy in refrigeration by using night blinds, anti-condensate heater controls, natural refrigerants, cool room controllers and other refrigeration optimisations. Rooftop solar PV systems are being trialled. LEDs have been installed to save energy and emissions from lighting systems. Carefully managing fresh air in HVAC further reduces energy consumption.

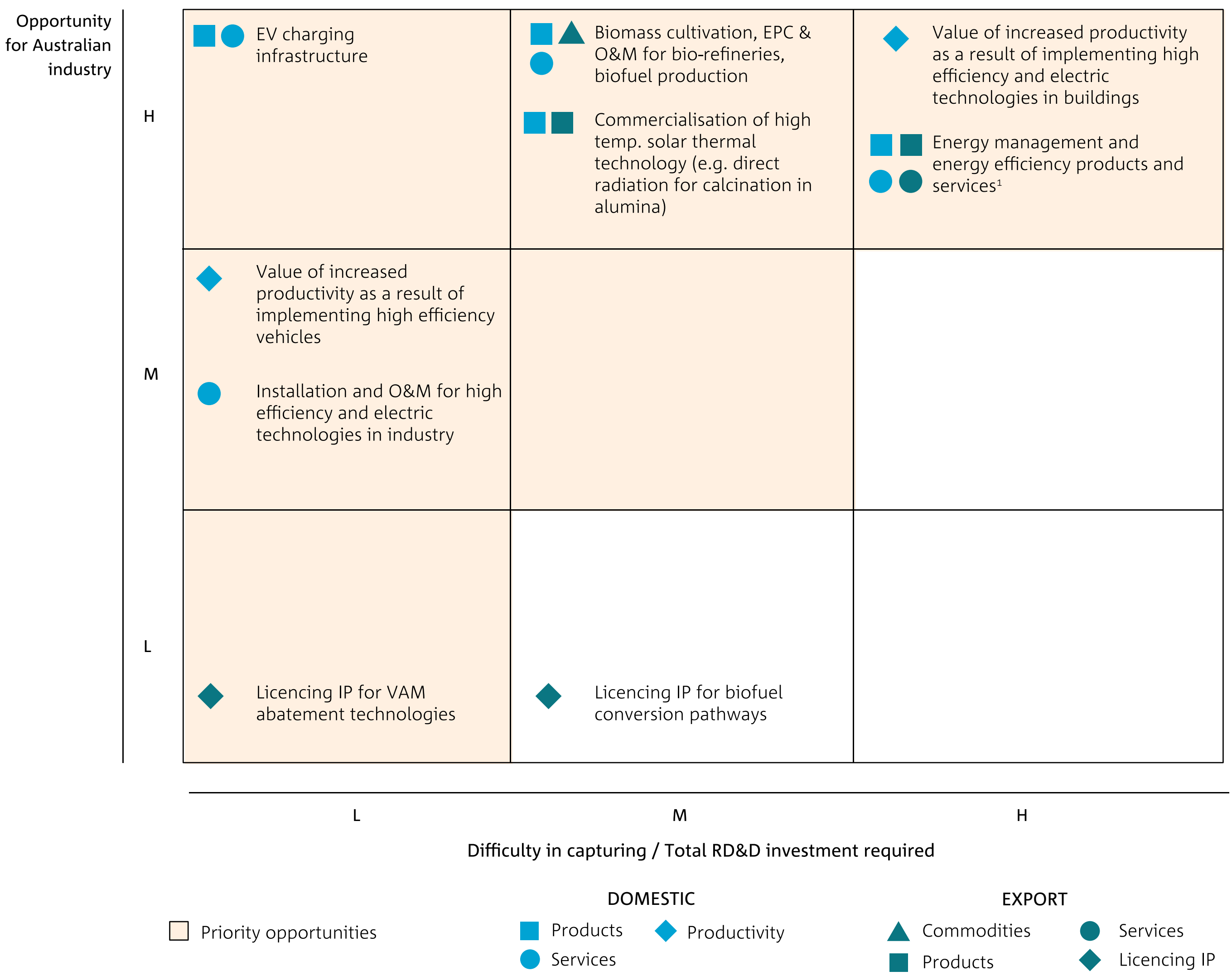
The scope of efficiency gains is not limited to the stores, with multiple actions undertaken to reduce transport emissions. Examples include smarter routing to maximise utilisation and minimise kilometres travelled, consolidation of line-haul transport, shifting some freight to rail and smarter international planning and logistics.

(Hoare, 2013) (Wesfarmers Limited, 2016)

63 This calculation is based on CSIRO modelling undertaken for Pathway 1 and a conversion factor of 1.68 TWh per million barrels of oil equivalent, as derived from (BP Approximate conversion factors: Statisitical review of world energy). It was also assumed that barrels of oil were used entirely for petrol.

High value RDD&D opportunities include the commercialisation of high-temperature solar thermal equipment and innovative energy management and energy efficiency products and services. These however are expected to be harder to capture, requiring higher levels of investment and, owing to their earlier stage of development, are subject to greater unknowns.

The Pathway 1 opportunities are summarised in Figure 35. Details on how the opportunities were evaluated and the criteria for high, medium and low classifications are given in Appendix B of the LETR Technical Report.



Footnote 1: E.g. smart building management systems, smarts in mining, ‘Uber for freight’, car pooling

Figure 35. Key supply chain opportunities for Pathway 1

Appendix B

PATHWAY 2: Variable renewable energy

B.1 Introduction

Pathway 2: Variable renewable energy is a scenario that assumes BAU improvements in energy productivity and relies largely on uptake of mature, low cost, VRE technologies, namely onshore wind and solar PV.

Bioenergy also plays a limited role in distributed applications. However, in contrast to the other pathways, deployment of VRE remains the primary source of electricity generation in order to achieve deeper decarbonisation by 2050. The focus of the pathway then is on understanding the key enabling technologies and other means that are required for the network to accommodate high VRE share.

As the share of VRE within the electricity network continues to increase, as generation becomes more decentralised and as uptake of DERs like rooftop solar PV and EVs increases, technical, regulatory and cultural challenges must be addressed to ensure continued system security and reliability. Enabling technologies such as batteries (or other forms of energy storage), smart grid technologies (e.g. smart meters and advanced inverters) and conventional power equipment such as synchronous condensers can all play an important role.

Several recent studies have looked at how to achieve 100% renewable electricity generation in Australia (Wright & Hearps, 2010) (AEMO, 2013) (Teske, Dominish, Ison, & Maras, 2016) (Riesz, Elliston, Vithayasrichareon, & MacGill, 2016), and concluded that such an outcome is technically feasible. The scenarios examined in these studies include a mix of VRE and dispatchable renewables. The shares of energy provided by VRE that have been investigated in these studies has been growing, the most recent having up to 68-77% of energy provided by VRE (Teske, Dominish, Ison, & Maras, 2016) (Riesz, Elliston, Vithayasrichareon, & MacGill, 2016). While VRE is typically the lowest cost form of renewable generation, VRE share is limited in these studies due to the system benefits of dispatchable and synchronous generation.

Focus for discussion in this appendix

	1 PATHWAY 1: Energy productivity plus	2 PATHWAY 2: Variable renewable energy (VRE)	3 PATHWAY 3: Dispatchable power	4 PATHWAY 4: Unconstrained
Buildings, industry and transport	**Ambitious energy productivity improvements**	**Business as usual energy productivity improvements**		**Ambitious energy productivity improvements**
			Hydrogen for transport and export	
New build electricity generation	**Existing low emissions technologies**: wind, solar PV (45% limit) plus gas	**Cheap, mature, low emissions generation**: mainly wind and solar PV **plus enabling technologies** e.g. batteries pumped hydro	Wind and solar (45% limit) plus **low emissions, dispatchable generation**: • Concentrating solar thermal with storage • High efficiency, low emissions fossil fuels with carbon capture and storage • Nuclear • Geothermal	**All low emissions technologies allowed, with no limit on wind and solar PV**
Fugitive emissions	**Uptake of cost-effective technologies**			

Pathway 2 builds on these studies by analysing a system which reaches very high VRE share (~90%) by 2050, with energy reliability enabled largely through battery storage, and energy security enabled through means other than synchronous generators, e.g. synchronous condensers, or synthetic inertia provided by batteries with advanced inverters or by modern wind farms. The generation mix in this pathway is similar to that identified as a plausible future scenario in the ENA/CSIRO Electricity Network Transformation Roadmap (Energy Networks Australia and CSIRO, 2016).

In addition to increased deployment of VRE, Pathway 2 differs from Pathway 1 in the following ways:

- It assumes only BAU improvements in energy productivity across buildings, industry and transport.
- Electrification and fuel switching are assumed to occur at a comparatively slower rate in buildings and industry. However, electrification delivers greater long term decarbonisation due to the lower grid emissions intensity of Pathway 2.

The uptake of technologies related to fugitive emissions is the same as described in Pathway 1.

B.2 Pathway 2 technologies

B.2.1 ELECTRICITY GENERATION

Solar PV

PV solar cells capture energy through the absorption of photons (particles of light) that excite electrons within the cell and create a flow of electrons to produce electricity.

PV cells can be classified as either (Massachusetts Institute of Technology, 2015):

1. Wafer-based: A 'thin slice' semiconductor that does not require an additional base material or substrate
2. Thin-film: A semiconducting material that is required to be deposited onto an insulating substrate (e.g. glass or plastic).

Solar cells are combined to create modules. These can be aggregated in series or in parallel depending on the particular application. Both large-scale (typically greater than 1 MW) and rooftop solar PV (commercial/industrial and residential) are considered in Pathway 2.

Rapidly declining costs ($70-85/MWh by 2020) and improving efficiencies are likely to see large-scale and rooftop solar PV systems become one of the most widely deployed forms of renewable energy generation.

Within the solar PV context, competitive tension exists between mature silicon wafer-based cells and emerging thin-film technology. The latter, which is predicted to have greater efficiencies and a comparatively lower cost of manufacture, has the potential to significantly disrupt the silicon industry. Current R&D however is also focused on achieving incremental improvements in the production and operation of mature silicon cells.

For large-scale generation, solar PV is on the verge of displacing wind as the preferred technology given that it will soon be cheaper on a levelised cost of electricity (LCOE) basis. Rooftop solar PV, particularly residential systems, has shown steady national growth in the last 5 years. Uptake within commercial and industrial buildings however has been comparatively slow for reasons discussed in Section B.4.1 below.

Wind

In wind turbines, energy is extracted from the wind by turbine blades, which turn a shaft (the rotor) connected to a generator, in order to produce electricity. The rotor, along with a gearbox, drive train, generator and brake assembly are all held inside a casing, known as a nacelle, which sits atop a tower.

Current typical turbines have a capacity of ~3.5 MW and may be positioned either onshore or offshore.

Large-scale wind turbines are continuing to be deployed both globally and locally. While already a competitive form of energy generation (˜$80/MWh), increased uptake, lower cost financing as well as improved EPC and O&M will serve to further reduce cost.

Current R&D is focused on increasing turbine size (i.e. taller towers and longer blades) in order to improve capacity (i.e. from ~3.5 MW to ˜8 MW), smoother integration into the electricity network (e.g. via synthetic inertia) and centralised operation of multiple wind farms which allows for greater optimisation of resources.

In an Australian context, there is likely to be limited scope for deployment of offshore turbines. While a scenario with a significant increase in the number of wind farms may exhaust the availability of the best onshore locations, the large number of suitable onshore locations together with the higher cost and geographical constraints (e.g. narrow continental shelf, rough seas) off offshore locations are likely to prevent offshore wind from becoming an attractive investment (CO2CRC, 2015).

Biomass

Bioenergy involves the conversion of organic feedstocks (i.e. biomass) into heat and/or electricity (or fuels, as discussed earlier). Feedstocks typically include sugars, lignocellulose, triglyceride oils and waste (e.g. sewage and solid municipal waste). Depending on the nature of the biomass, the feedstock may be treated using a variety of methods (e.g. pelletisation, hydroprocessing) to remove impurities and improve energy density.

Biomass can be converted to heat/ electricity via processes that include:

- Direct combustion– Includes standalone plants designed to accept different feedstocks, as well as 'co-firing', wherein biomass can be combusted in a conventional coal-fired power station at concentrations of around 5% of total fuel.
- Combustion of biogas produced via anaerobic digestion of waste
- Biomass gasification, i.e. production of synthesis gas ('syngas') which may subsequently be combusted

In Australia, waste biomass is expected to continue to be used for heat and electricity production in niche, distributed applications (e.g. biogas from landfills). Currently this represents approximately 0.9% (˜800 MW) of electricity generation. However, with a series of projects currently under consideration, there is considerable scope to double bioenergy share by 2020 (CEFC, 2015).

Biomass co-firing in existing power stations is also likely to progress provided no extensive upgrades are required and the cost of the biomass (including feedstock, pre-treatment and transport) is not prohibitive. For example, Vales Point power station in NSW currently replaces between 2-5% of its coal feedstock with biomass without modifications to the plant (Office of Environment and Heritage, 2014).

Large-scale new build/retrofit generation plants that run on 100% biomass are unlikely to be cost competitive.

B.2.2 ENABLING TECHNOLOGIES FOR VRE

Achieving the high share of VRE implied by Pathway 2 requires certain technical considerations to be addressed. However, this appears to be possible at reasonable cost. This section considers the technologies required to support the required changes to the electricity network. Cost estimates for key technologies are provided in the LETR Technical Report.

Rationale for requiring enabling technologies for VRE

VRE sources differ from traditional thermal generation in a number of key ways that require enabling technologies and/or changes to the design of the grid when VRE reaches high share.

- **Variability:** Energy supplied by VRE technologies depends on the available resources (e.g. wind and sun). Variability can be seasonal (months), long term (hours), medium term (minutes) or short term (seconds).
- **No or low inertia:** VRE technologies typically lack the inertia[64] of traditional sources. Other means of fast frequency stabilisation are therefore required if large quantities of conventional generation are replaced with wind and solar PV.
- **Low fault current:** While traditional generators are able to provide the high currents required to trigger electrical protection systems in the event of faults, the same is not necessarily true for wind and solar PV.
- **Fault ride through:** Fault ride through refers to the ability of generators to keep providing power to the system when there is a sudden change in frequency or voltage in the grid (e.g. due to a contingency such as the failure of another generator or a transmission line). Historically, VRE generators have had fault ride through settings that can increase the impact of system faults. Since the South Australian blackouts in September 2016, AEMO has been working with State Government to update their fault ride through settings.

Highly distributed generation such as rooftop solar PV has a number of further characteristics that can create undesirable impacts at high penetrations if not addressed using appropriate technology: These include:

- **Reverse power flows**, resulting from the fact that these sources inject power back into the distribution network, which is currently designed for uni-directional (one way) power flow. Operational constraints for networks that are not designed for bi-directional power flow can limit the amount of energy that rooftop solar PV can provide to the grid in a given area.
- **Lack of observability and controllability** by the network operator (with currently deployed technology) which makes stable network operation challenging as DER penetration increases.

Technology overview

While small volumes of VRE may be introduced to the grid with relatively little impact on the rest of the system, as VRE shares increase, enabling technologies are required to address the key characteristics of VRE described above. These enabling technologies for VRE are discussed below, and are summarised in Table 14.

64 Inertia is the tendency of heavy objects to keep moving once they are in motion. In the case of electricity grids, the large generators that traditionally power the grid have heavy rotating masses that provide a large quantity of rotational inertia to the system. The frequency of the alternating current (AC) in the grid depends on the frequency at which these masses rotate. The fact that the masses have inertia means it takes a large amount of energy to slow them down or speed them up and this helps stabilise the frequency of the grid.

Batteries

A battery is a form of electrochemical storage, wherein chemical changes allow electrical energy to be stored and released on demand. A battery comprises multiple electrochemical cells connected in series and/or in parallel. Three key battery technologies, each with different characteristics have been identified as having significant market potential (Brinsmead, Graham, Hayward, Ratnam, & Reedman, 2015). They are:

1. Lithium ion
2. Advanced lead-acid
3. Flow batteries

Batteries can be used in both behind-the-meter (BTM) (i.e. residential and commercial) and utility-scale applications.

Batteries are a readily available technology that provide several grid stabilisation services and are a critical enabler of VRE.

While significant roll-out of energy storage in Australia is not expected to be necessary to manage medium and long term variability until renewable generation exceeds 40-50% of the total electricity supply, batteries can provide other services that could encourage adoption in the near term, e.g.:

- Managing short term intermittency (e.g. power drops due to clouds momentarily passing over solar PV). Lithium ion and advanced lead acid are most applicable due to their capacity for rapid response.
- Providing fast frequency response (FFR) (when combined with advanced inverters), otherwise known as synthetic inertia – managing variability at time scales of milliseconds to seconds. This involves rapidly adding or removing energy from the grid to keep the frequency stable. FFR typically refers to rapidly responding to a contingency event to stabilise the frequency.
- Power quality (PQ) – An alternate emerging approach is to constantly manage frequency (rather than just following a contingency) (DGA Consulting, 2016). Fast response batteries (e.g. lithium ion and advanced lead acid) can also help manage power quality issues such as fluctuations in voltage as well as harmonics and phase imbalance (variability at time-scales faster than ~20ms or among co-located circuits).

Note that FFR and frequency regulation can also be used by other inverter connected devices (e.g. solar PV and wind turbines). As costs continue to decline, BTM batteries are likely to continue to be widely deployed, supporting the adoption of rooftop solar PV. However, such capability needs to be supported with effective integration into networks as well as higher levels of visibility and decentralised controls for network operators to optimise network operations with high penetration of batteries and VRE.

Other storage (PHES)

Pumped hydro energy storage (PHES) systems operate using an elevated water reservoir. When available, VRE may be used to pump water from a lower elevation to the reservoir. Upon discharge, the energy is recovered by allowing the water to spin a turbine (with an attached generator) as it flows back to the lower elevation.

PHES may be 'on-river' or 'off-river'. The former are conventional hydroelectric systems located in dammed river systems (Blakers, 2015). The latter do not require existing rivers. Rather, they involve the construction of two reservoirs at different heights (e.g. at the top and bottom of a hill). Alternatively, the lower reservoir can be a pre-existing body of water such as the ocean.

PHES, compressed air energy storage and flywheels are three technological alternatives to batteries for utility-scale storage. Of these, the most likely to be adopted in Australia at scale is 'off-river' pumped hydro due to its potential low cost, the range of suitable locations and the maturity of its component technologies. In contrast to 'on-river' pumped hydro, it is expected to face lower costs (e.g. due to 'on-river' requirements for additional flooding control systems), fewer restrictions on suitable sites, less undesirable ecological impacts, and less public opposition. Another emerging technology involves storing energy in heat, for instance in molten silicon, and using this heat to generate steam to drive a turbine.

Smart grid technologies

Smart grid technologies enable orchestration of distributed energy resources (DERs) such as rooftop solar PV, batteries and EVs. This increases system flexibility and enables an increased penetration of both DERs and large-scale VRE. The range of smart grid technologies includes smart appliances, smart inverters, control platforms, market platforms, smart meters, telemetry and sensors, system models, demand forecasting, generation forecasting and cyber-security solutions.

Uptake of DERs is likely to be driven by consumer choice and will therefore occur largely independent of specific changes to regulations and market design. As uptake of DERs increases, smart grid technologies will be key to minimising system cost and maximising the services provided to the grid by DERs.

While many of the individual technologies are reasonably advanced, the key remaining challenge is to deploy them in integrated systems and improve network management capability and coordination of DERs at more granular, localised network levels.

Conventional power equipment

There are a number of types of power equipment that are currently deployed to support grid operation in electricity networks with conventional fossil fuel generation, that may need to be scaled up or adapted to a system with high VRE share. Technologies include reactive power control technologies, transmission and distribution lines and protection systems.

Reactive power control technologies are technologies that regulate voltage by removing or adding reactive power to the system. Synchronous condensers are a type of reactive power control technology that can also provide inertia and fault current.

Additional transmission and distribution lines can be built or existing lines upgraded to cope with increased renewables share. This may be to strengthen the network in remote areas where new, large-scale VRE is connected, or to provide additional interconnectors to allow greater transfer of energy between the different states to help manage the variability of VRE. This is typically an expensive option and technologies that are less capital intensive may be preferred.

BOX 5 | CASE STUDY

Hydro Tasmania - managing a low inertia system

Tasmania is already successfully managing some of the issues related to a high share of VRE. The Tasmanian grid routinely operates with low inertia, due to a high share of wind (308 MW of capacity in a system where demand ranges from 900-1800 MW), and the fact that a large proportion of power (up to 478 MW) is supplied from the Basslink HVDC interconnector from the mainland, which does not transfer inertia (although Basslink does provide some fast frequency response). Not only does the Tasmanian system have low inertia, but it is susceptible to large disturbances—tripping the Basslink interconnector could potentially cause a loss of 50% of supply (TasNetworks, 2016).

To manage this situation, Hydro Tasmania and TasNetworks have implemented a number of measures to increase system inertia and mitigate the impact of tripping of the interconnector, such as:

- Modification of hydro plant to provide faster frequency control
- Modification of open cycle gas turbines to operate in synchronous condenser mode, which means these plants can provide inertia and fault current even when not needed as generators
- Obtaining accurate mathematical models of renewable generators to understand their fault ride through characteristics
- Implementation of a Frequency Control System Protection Scheme (FCSPS) in which generators or loads are automatically ‘armed and disarmed’ so they are ready to respond in the event of the interconnector tripping

These technical solutions could also be applied more broadly in the NEM, although new market or regulatory mechanisms would be required to incentivise deployment.

Dispatchable generation

Dispatchable generation can be dispatched to help balance supply and demand, and includes non-renewable (e.g. peaking gas) and renewable sources (e.g. CST with storage). These forms of generation also provide inertia and fault current to electricity networks, although only when operating. (Some generators can also be run in synchronous condenser mode, in which they can provide inertia and fault current while not generating energy).

Other enablers

In addition to the enabling technologies described above, there are several other means of addressing variability:

- Geographical diversity (i.e. different weather conditions exists at any given time across a large network like the NEM). This requires appropriate interconnectors.
- Technology diversity (i.e. a mix of wind and solar)
- Building sufficient wind and solar PV generation capacity, such that there is enough capacity to cope with periods of lower generation, with excess power during periods of high resource availability curtailed or used to power 'opportunistic loads'[65]
- Demand response: Demand response provides an additional way to introduce flexibility into the system to manage VRE variability. Rather than changing generation to match supply with demand, demand response involves reducing or time-shifting demand to match supply.

Other means of addressing low inertia are:

- Modern wind farms are able to provide synthetic inertia, using the kinetic energy stored in the rotating turbines, and quickly providing it to the grid if there is a sudden dip in frequency. Some markets, such as Quebec (a standalone grid with peak demand of less than 40 GW) require new wind farms to be able to provide synthetic inertia, to help maintain the stability of the grid frequency. Inertia-compliant turbines now make up two thirds of Quebec's wind capacity, and provide a similar inertial response to contingency events per unit of capacity as synchronous generation (although taking longer to return the grid to its normal frequency). Wind farm developers are further improving the ability of wind turbines to provide synthetic inertia (Fairly, 2016). No Australian windfarms currently provide synthetic inertia, although some may have this capability.
- An alternative to providing additional inertia or fast frequency response from renewable generation is to make the grid more tolerant of larger and faster rates of change of frequency (RoCoF) (DGA Consulting, 2016). Additional, and faster responding, spinning reserve could also be used. Furthermore, batteries, PHES and EVs could be put on under-frequency load shedding alert (AEMO, 2013).
- Demand response can also be exploited for fast frequency control (DGA Consulting, 2016).

Enabling technologies for VRE are summarised in Table 14.

[65] Opportunistic loads are devices that require electricity, but which do not need to be operated at any particular time, and which can therefore take advantage of cheap excess electricity. An example is load-following electrolysers.

TABLE 14. ENABLING TECHNOLOGIES FOR VRE

ENABLING TECHNOLOGIES:		STORAGE	SMART GRID TECHNOLOGIES	CONVENTIONAL POWER EQUIPMENT	DISPATCHABLE GENERATION	OTHER ENABLERS:
Example technologies:		Batteries Pumped hydro	Advanced inverters; smart meters; telemetry & sensors; demand and generation forecasting	Synchronous condensers; transmission & distribution; protection systems	Peaking gas, closed cycle gas turbines; CST with storage; fuel cells	
Characteristics of VRE/issues caused by VRE:	Variability	✔ Batteries and PHES	✔ Forecasting	✔ Transmission and distribution	✔ Peaking gas	Geographical & technology diversity; excess VRE capacity; demand response
	Low inertia/ frequency control	✔ Batteries	✔ Advanced inverters	✔ Synchronous condensers	✔ Peaking gas	Synthetic inertia from wind farms; making system more tolerant of larger and fasters frequency deviations
	Low fault current	✔ PHES	✔ Telemetry and sensors	✔ Synchronous condensers, protection systems	✔ Peaking gas	Fault current from wind farms
	Reverse power flows/voltage control	✔ Batteries	✔ Smart meters, telemetry and sensors	✔ Distribution lines	×	
	Lack of observability/ controllability	×	Advanced inverters, smart meters	×	×	Improved data collection

In a system with sufficient fault level, fault ride through does not require technological enablers as such; rather it depends on regulators setting appropriate requirements guiding wind and solar farm developers to design systems accordingly.

B.2.3 VRE IN MICROGRIDS, REMOTE AREA POWER SYSTEMS AND STANDALONE POWER SYSTEMS

Most of the VRE rolled out in Australia in the coming decades is expected to be connected to the major grids (i.e. the NEM and the South-West Interconnected System (SWIS)). However, 6% of Australia's electricity use is off-grid (ARENA, 2014), and technological developments are expected to result in more energy users disconnecting from the grid (Energeia, 2016). Integration of renewables in off-grid systems can therefore also contribute to decarbonisation of the electricity sector.

There are three main types of off-grid settings:

1. Microgrids: Small grids that are connected to larger grids, but which can be operated independently, or 'islanded'.
2. RAPS: Remote communities and industries located too far from major grids to be economically connected.
3. SAPS: Individual users not connected to a grid. This may be due to remoteness, or a desire for energy independence.

B.3 Technology uptake and emissions impact

B.3.1 GENERATION MIX

The projected generation mix for Pathway 2 is shown in Figure 36 below.

Two scenarios are considered in Pathway 2. The base (centralised) scenario assumes uptake of rooftop solar PV consistent with the Australian Energy Market Operator's (AEMO) National Electricity Forecasting Report (NEFR) 2016 projection for the states and territories in the NEM. For Western Australia, rooftop solar PV uptake was obtained from the WA Independent Market Operator forecasts. The Northern Territory was assumed to have similar uptake rates to Western Australia. In the sensitivity (decentralised) scenario, the deployment of rooftop solar PV was projected by CSIRO modelling and sees a faster uptake of rooftop solar PV. This is based on the relative cost of electricity from rooftop solar PV compared with electricity from the grid and is subject to assumed limits on residential and commercial adoption of 70% and 30% respectively (see Appendix B of the LETR Technical Report for further details).

In both scenarios, due to retirements and for economic reasons, brown coal generation is phased out by around 2030, and black coal generation gradually declines to 2050 with an accelerated closure rate in the second half of the 2020s. Both scenarios see an increase in gas combined cycle generation in the period of 2030-2050. However, this capacity could potentially alternatively be supplied by variable renewable energy plus storage capacity, or by renewable dispatchable capacity, albeit likely at a greater cost.

In the centralised scenario, rooftop solar PV, large-scale solar PV and wind generation all show strong growth, with average annual capacity additions to 2030 of 1.3 GW/year, 1.2 GW/year and 1.0 GW/year respectively[66]. While this is a moderate increase, compared for instance to the average 0.9 GW/year of rooftop solar PV installed in Australia from 2011 through 2015 (Australian PV Institute, 2016), it does appear feasible if supported by appropriate policy. This is demonstrated by the level of industry response to ARENA's large-scale solar PV funding round, in which 12 projects totalling 482 MW were chosen in September 2016 for funding support, which is expected to more than triple Australia's large-scale solar capacity (ARENA, 2016).

In the decentralised scenario, compared to the centralised scenario, rooftop solar PV displaces much of the growth in large-scale solar PV and wind. Annual additions of rooftop solar PV reaches 7.8 GW/year in 2030 and peaks at 10.4 GW/year in 2034.

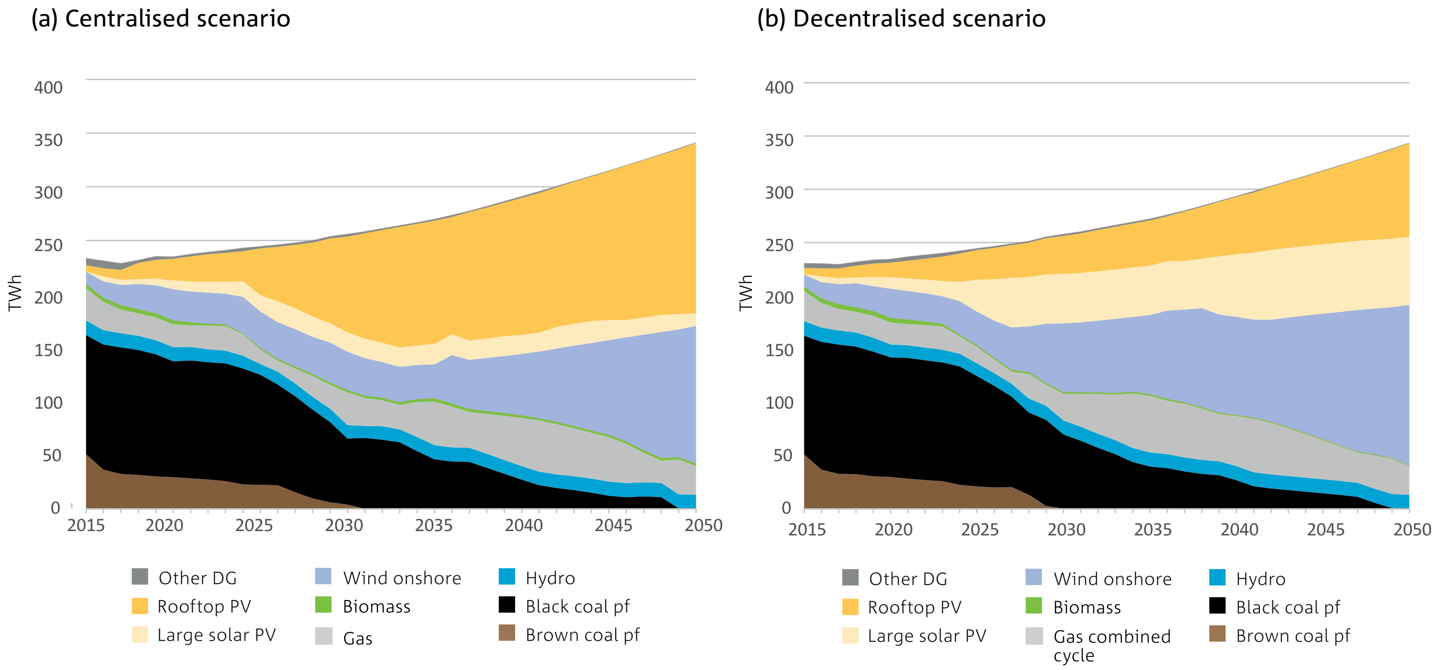


Figure 36. Pathway 2 projected electricity generation mix

[66] Maximum annual capacity additions up to 2030 are 2.5 GW, 5.0 GW and 3.8 GW respectively for rooftop solar PV, large-scale solar PV and wind.

B.3.2 BATTERY STORAGE

As discussed in Section 3.5, there are two key metrics to consider in a standalone alternating current (AC) electricity grid powered by a large amount of VRE – the average and the instantaneous share of power provided by VRE. The average share (usually just referred to as 'VRE share' in this report) is the percentage of energy (measured in MWh) provided by VRE over some period such as a year. It is also the metric that determines GHG emissions. Due to the variable and non-dispatchable nature of VRE, reaching high share of demand met by VRE requires additional sources of system flexibility, such as demand management or energy storage. This is particularly the case for solar PV, which compared to wind, has higher correlation in output from different generators and has a narrower daily time window in which it produces an output. University of NSW research indicates that solar PV generation could saturate at 8-15 GW in the NEM if storage is not present (Riesz, Elliston, Vithayasrichareon, & MacGill, 2016).

This section discusses one possible technological solution for achieving high VRE share, based largely on battery storage. Half-hourly modelling was undertaken to calculate the required capacity (energy and power[67]) of battery storage required to support the high share of VRE in Pathway 2, with each state in the NEM modelled separately (see Appendix B of the LETR Technical Report for details on the methodology). Batteries were investigated as one option to achieve the required system flexibility. Other options such as demand response as discussed above are also possible.

Figure 37 illustrates how batteries can support VRE, showing three consecutive high battery use days in NSW in 2046 in Pathway 2, with most energy provided by wind and solar PV. The black line shows demand as a function of time. The coloured areas between the x-axis and the black line represent power provided by generators and batteries. Values below the x-axis represent charging

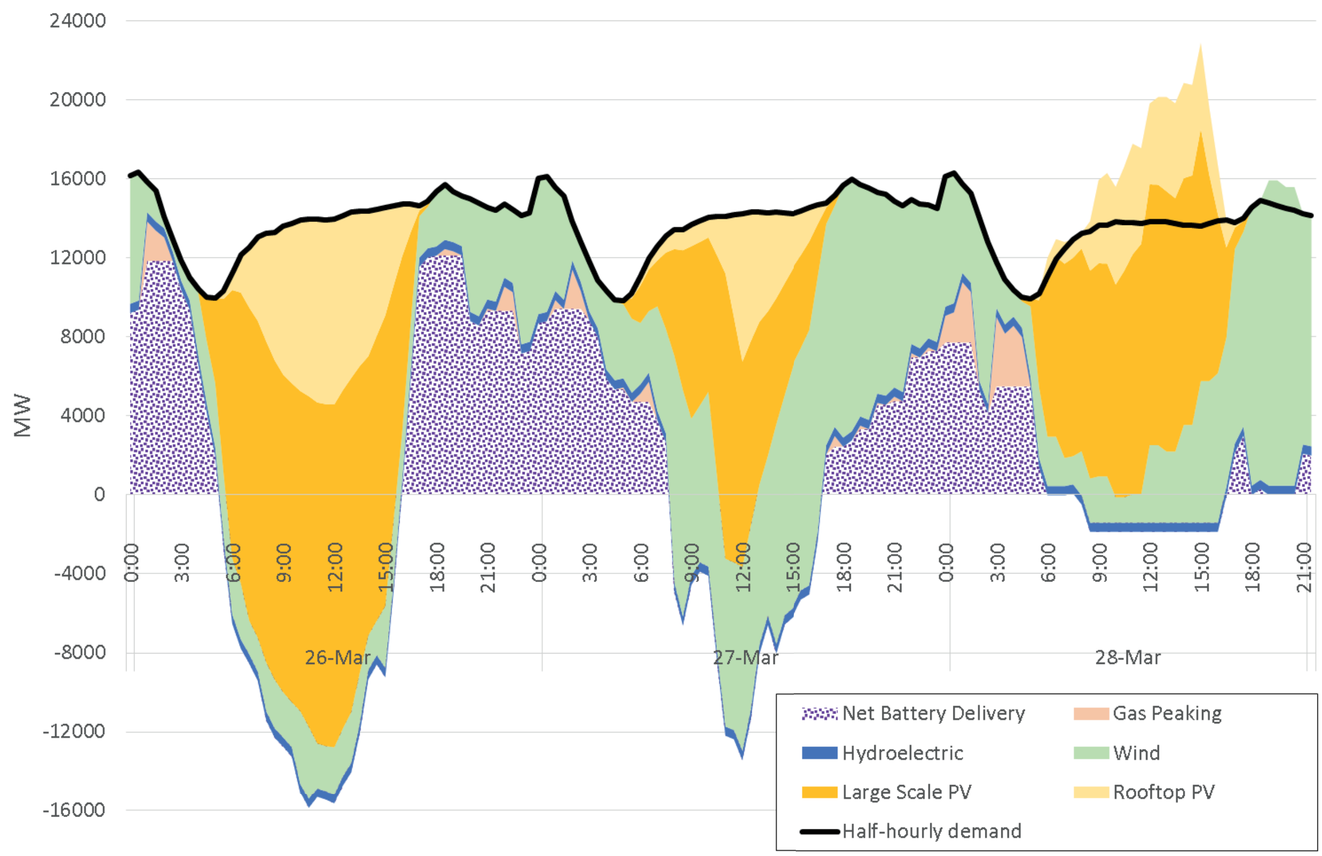


Figure 37. Example time series of electricity supply and demand in Pathway 2 showing role of battery storage; NSW, 2046, 3 example days

[67] The energy capacity of a battery is how much energy (measured in kWh or MWh) it can store. Using the analogy of a bathtub, the energy capacity is the amount of water that can be contained in the bathtub. The power capacity of a battery is the power (measured in kW or MW) with which it can charge or discharge. This is like the flow rate of water into or out of the bathtub. The ratio of energy to power capacity gives the hours of storage available at maximum discharge.

of the batteries, which tends to occur in the middle of the day, when there is excess solar power available. Values above the black line represent curtailed power (i.e. the power not needed, either to meet demand or to recharge the batteries[68]). At night, most of the power is delivered from the batteries and wind in this example, with some power also provided by gas peaking plants.

The VRE generation output modelled is based on historical weather patterns from 2003 to 2011 from (AEMO, 2013). As a conservative way of ensuring the modelled system is robust under highly unlikely weather conditions. A 'worst three week' period was constructed using three repeated weeks in a row of the worse single weeks by state and by renewable resource (i.e. least wind and sun), actually observed in this nine year period. See Appendix B of LETR Technical Report for further details.

Figure 38 shows how much battery power is needed relative to the installed VRE capacity, against VRE share. Up to ~90% share of energy delivered by VRE, around 0.75 GW or less of batteries is required for every gigawatt of VRE. Figure 39 shows the battery energy capacity, or hours of battery storage, required as VRE share increases. Below ~90% VRE share, less than 10 hours of storage at average load is required.

Above 90% VRE share, the required battery capacity (both power and energy) starts to increase rapidly. This is due to the fact that for VRE share to approach 100%, the share that can be provided by peaking gas and other non-zero emissions dispatchable sources must approach zero, and so more battery capacity is required to enable reliable operation during the few times of the year when solar and wind resources are poor for several days at a time across the NEM (the so-called 'wet windless week in winter'). Figure 38 and Figure 39 suggest that VRE share can reach 40-50% (i.e. significantly higher than current average levels across the NEM) before battery storage is needed for supply-demand matching. Increasing VRE share beyond this threshold is not possible without a low carbon source of flexibility (such as batteries) while maintaining the 100% reliability assumed in the modelling.

From the modelling, it was found that the lowest system cost outcomes are delivered by achieving energy balancing partly through building more renewable capacity than is required at times of high renewable resource availability,

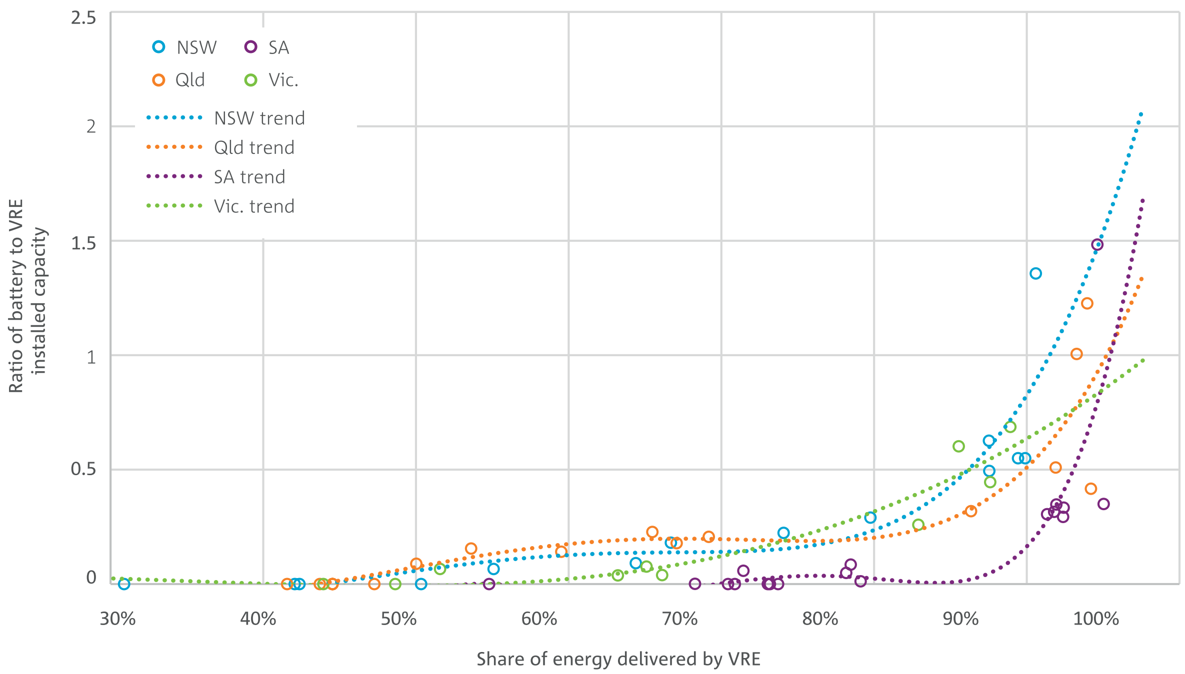


Figure 38. Ratio of battery and VRE generation capacity (GW) required to achieve energy balancing for modelled shares of energy (GWh) delivered by VRE

[68] While solar PV is shown apparently being curtailed, this is just due to the order in which each generation type is shown in the chart – the curtailed power could be from wind or solar PV.

such that some curtailment occurs. By 2050, the recommended capacity of VRE reduces the effective average capacity factor of wind and large-scale solar to 83% and 62% respectively of their average levels (at low penetration) when no curtailment is necessary.

Modelling results suggest that dispatchable capacity of 55%-73% (depending on state[69]) of peak demand, which is almost entirely peaking gas generation (55-67% of peak demand), is sufficient to meet demand requirements with an emissions reduction of 95%, corresponding to a VRE share of ~90%. This quantity of peaking gas generation results in an average capacity factor in the range of 6-7%, rather than the ~10% capacity factor occurring in the current circumstances with significantly less VRE share.

The timeframe for reaching 40-50% VRE share is shown in Figure 40. For Pathway 2, this level is reached in the mid to late 2020s.

B.3.3 TECHNOLOGIES FOR STABILISING FREQUENCY AND MANAGING FAULT CURRENT

In this section, it is shown that technologies for managing frequency and fault current could be needed from the early 2020s in the NEM, and earlier in South Australia.

An important metric in a system with high VRE share is the NSP. This is the percentage of power provided by non-synchronous sources such as VRE, batteries or HVDC at a given moment. It is the same as the instantaneous VRE share in an AC system without batteries or HVDC connections to other AC systems. The maximum value of the NSP in a system is necessarily greater than the average VRE share. For instance, a system where 50% of energy on average is provided by VRE will have moments where less than 50% is provided by VRE and other moments where the instantaneous share or NSP is more than 50%, and could be as high as 100% if not restricted by market operators. Achieving high NSPs is

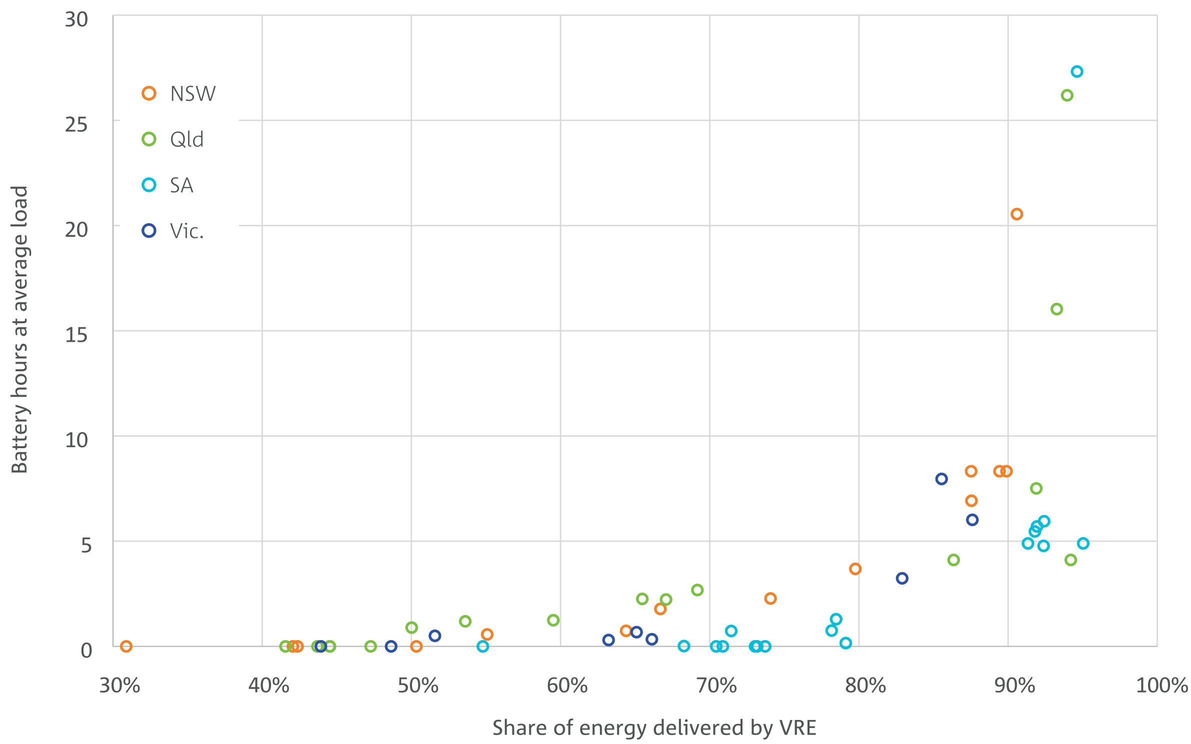


Figure 39. Hours of battery storage required to achieve energy balancing for modelled shares of energy delivered by VRE

69 For the mainland NEM. In Tasmania, dispatchable capacity equivalent to 93% of peak demand is required, and is provided by hydro with no need for gas generation.

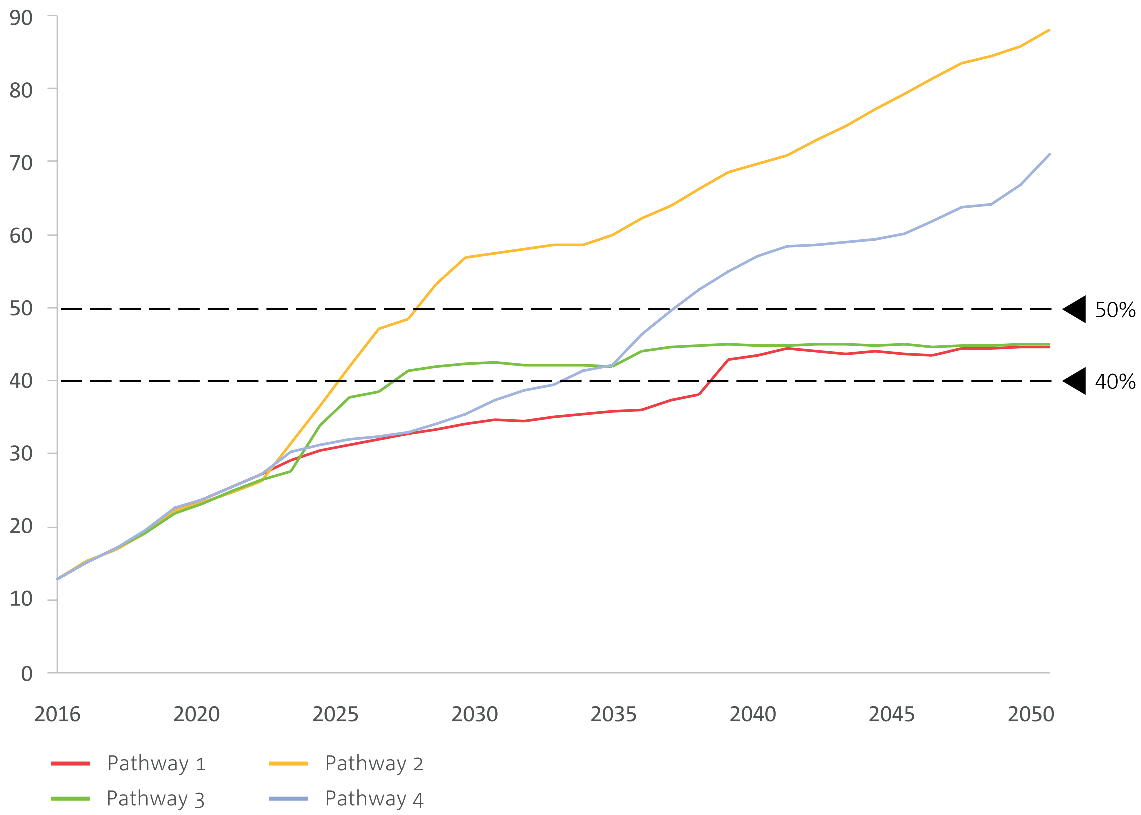


Figure 40. VRE share in each pathway as a function of time

technically challenging in isolated AC grids (such as the NEM viewed in its entirety)[70]. As the NSP increases, the share of power provided by synchronous generation falls, and consequently so does the system inertia. As the system inertia decreases, the system becomes more susceptible to disturbances, with higher RoCoF following contingency events such as the loss of a generator or large load. High RoCoF is problematic for synchronous generators and for overall system stability. Maintaining system security requires inertia to be added through some other means (such as synchronous condensers) or for some other form of frequency stabilisation to be deployed.

A declining share of synchronous generation also reduces system strength. Furthermore, system security and reliability requires that the total generation capacity that rides through faults is sufficient to meet demand. Thus, as VRE share increases, it becomes more important that VRE generators are able to ride through faults.

Given limited practical experience of large grids with high VRE share, grid operators have placed upper limits on NSP while they address these technical challenges. Up to 60% NSP has been allowed in Crete's isolated grid (IEA-ETSAP and IRENA, 2015), while Ireland is currently working on technical solutions to progressively increase its limit of 50% in 2015 to 75% by 2020 (Eirgrid Group, 2016). Note that in 2015, Ireland was able to meet 23% of demand with wind power while constrained by the 50% NSP limit (Vayu Energy, 2015). The AEMO 100% renewables study (AEMO, 2013) limits NSP to 85% in its modelling, noting that while reaching this level "would be extremely challenging operationally, techniques to manage low synchronous [capacity] systems do exist and are actively being developed around the world."

70 Small isolated grids have been demonstrated to run at 100% NSP; For instance, King Island runs at times on 100% VRE (Australian Energy Council, 2016).

Reaching the ~90% share of VRE in Pathway 2 implies running the grid with a maximum NSP of ~100% (i.e. to reach such a high average VRE share, VRE will need to be providing 100% of the energy at certain times to make up for other times when VRE share is lower due to a lack of available sun or wind). With further technological development this may be possible using synthetic inertia from wind farms and batteries as well as other enabling technologies (DGA Consulting, 2016). Alternatively, synchronous condensers could be added to the system; these act in the same way as synchronous generators insofar as inertia and fault current are concerned, although without providing net energy. This could enable the NSP to be reduced to say 75-85% (i.e. the limits targeted for Ireland in 2020 and mentioned by AEMO) without reducing the share of VRE.

In the half-hourly system modelling described in the previous section, soft limits were placed on the instantaneous share of VRE in the mainland NEM (i.e. the AC interconnected part of the NEM), and were progressively increased over time, as discussed in Appendix B of the LETR Technical Report). This corresponds to curtailing VRE at times of high generation relative to demand. This resulted in the instantaneous VRE shares shown in Figure 41. Also shown are the limits on NSP imposed in Ireland. The soft limits imposed in the modelling were chosen as conservative constraints, to reflect the fact that Australia is likely to lag Ireland in reaching high NSP. Note that achieving the high NSP values shown in Figure 41 would represent a significant technical challenge, especially reaching values greater than 50% from as early as 2020. Note also that since all pathways have similar average VRE share until around 2024 (see Figure 40), addressing high NSP will be required in all pathways.

In South Australia, where the average share of VRE is 39% (Australian Energy Council, 2016) NSP could already potentially reach 100% if not constrained. From a frequency/inertia point of view, this does not pose a significant security risk while South Australia remains connected to the rest of the grid via the Heywood AC interconnector. The 2016 National Transmission Network Development Plan (NTNDP) (AEMO, 2016) states that "sufficient inertia is projected to be available over the next 20 years to maintain a secure and reliable supply[71], but only if the network remains interconnected following disturbances. Following a synchronous separation event, South Australia is already at risk of widespread outages unless mitigation measures are put in place." Additionally, to ensure sufficient system strength in South Australia, AEMO has introduced a requirement for a minimum of two sufficiently large synchronous generators to be on-line at all times (AEMO, 2016). Since South Australia is already encountering limits to NSP, technical solutions for increasing these limits should be prioritised in South Australia to enable a higher share of generation from VRE. These solutions could then potentially be deployed elsewhere in Australia[72].

B.3.4 ADDITIONAL CONSIDERATIONS FOR ROOFTOP SOLAR PV

Anecdotal accounts suggest that some distribution network operators are constraining further installation of rooftop solar PV in certain locations in Australia with high existing penetrations of these systems[73], due to current or projected issues with integration at the localised level. This suggests solving technical considerations related to integrating rooftop solar PV is becoming required in areas where penetration is high. Locational data on PV penetration rates and resultant network impacts appears unavailable, and further work on this topic is recommended. Networks are actively exploring solutions to improve integration of DER into the grid.

B.3.5 TRANSPORT SECTOR

Compared with Pathway 1, in Pathway 2 there is a faster increase in transport demand and a slower improvement in vehicle efficiency (see Appendix B of the LETR Technical Report for a comparison of assumptions). As shown in Figure 42, this results in a later peak and a slower decline in GHG emissions. The same assumptions for EVs apply in Pathway 2 as in Pathway 1.

[71] Note this is based on 2030 electricity sector decarbonisation (and consequently VRE deployment) that is lower than that envisaged in this roadmap.

[72] Constructing an additional AC interconnector between South Australia and the rest of the NEM would improve South Australia's energy security. However, solutions other than interconnectors will be required as VRE share in the NEM as a whole reaches high levels.

[73] While the Australian average penetration (percentage of households) of solar rooftop PV is 15%, some suburbs of Greater Brisbane and Adelaide have penetrations above 50% (Australian Energy Council, 2016).

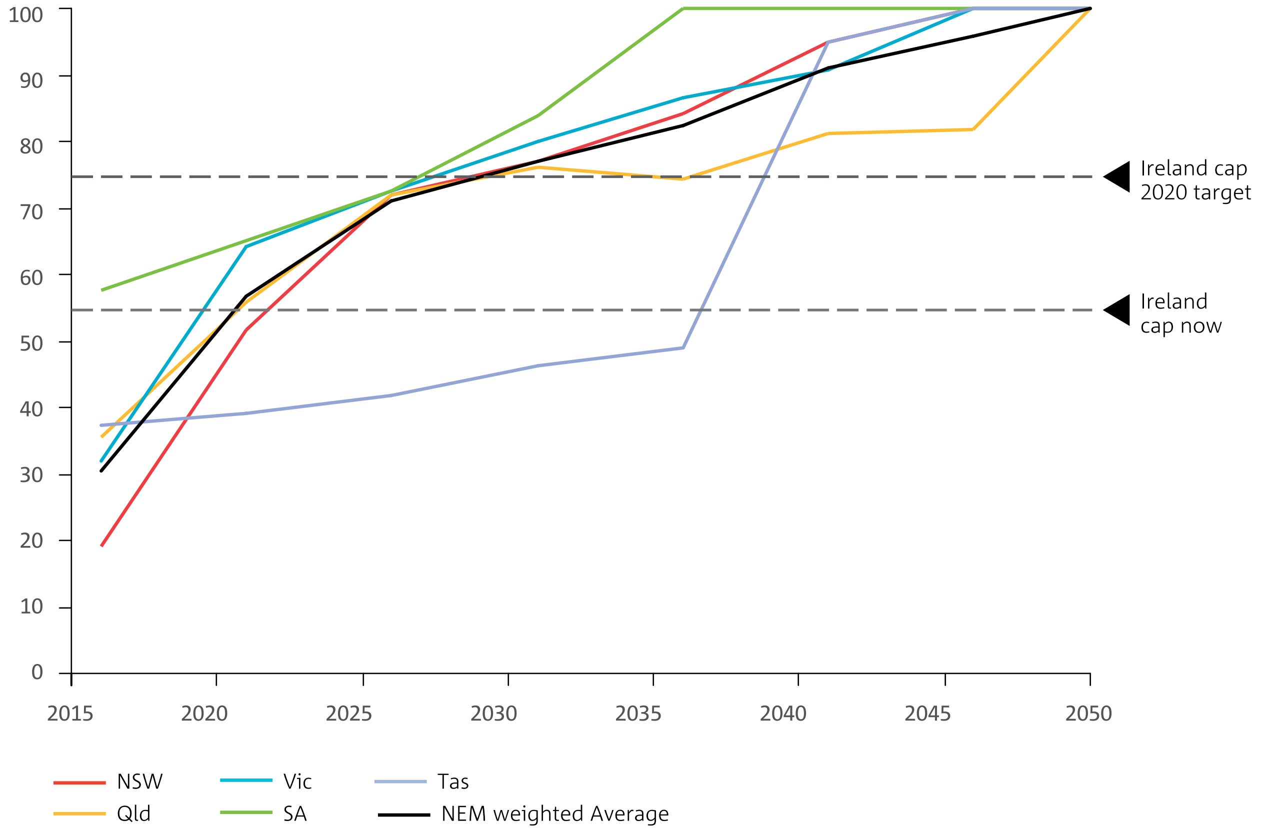


Figure 41. Maximum instantaneous share of VRE in Pathway 2, percent

B.3.6 OTHER SECTORS: DIRECT COMBUSTION AND FUGITIVE EMISSIONS

Uptake of technologies related to direct combustion result in the BAU emissions profile described in Section A.3.1. Detailed assumptions regarding rates of uptake are given in Appendix B of the LETR Technical Report.

For fugitive emissions, the deployment of technologies and emissions impact in Pathway 2 are as in Pathway 1.

B.4 Barriers and enablers

B.4.1 BARRIERS TO DEPLOYMENT OF PATHWAY 2 TECHNOLOGIES

Flat or decreasing grid demand and an oversupply of existing generation means that absent appropriate policy mechanisms, there is little demand for new large-scale generation. Thus, in the absence of a regulatory framework that incentivises the long term development of new low emissions electricity generation, it will be challenging to achieve the large increases in large-scale solar PV and wind shown in Pathway 2. A scarcity of available long term PPAs, which are needed in order to provide further investment security, is also likely to impede further deployment.

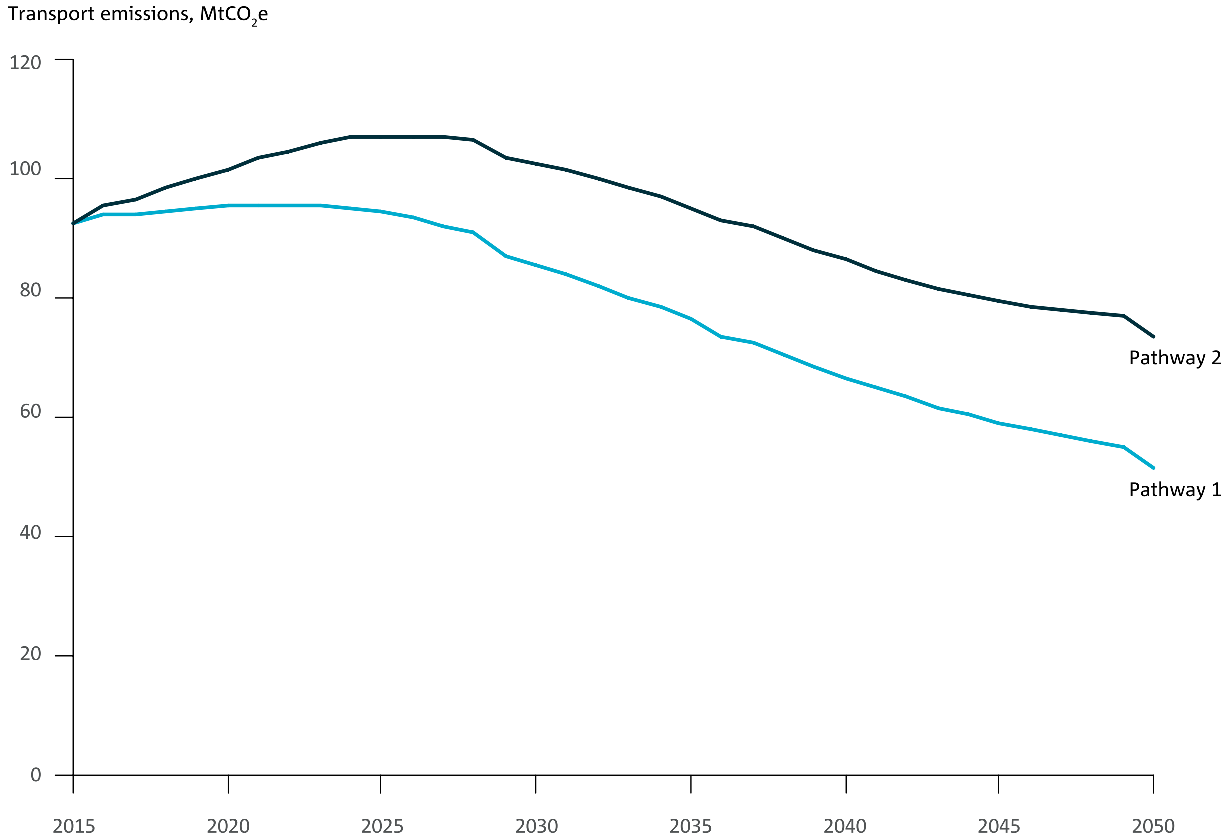


Figure 42. Comparison of transport emissions between Pathways 1 and 2

Rooftop solar PV has a different set of barriers. For residential solar PV, without widespread deployment of BTM batteries, a lack of market mechanisms to allow peer-to-peer trading of electricity limits the benefit that owners of rooftop solar PV systems can gain from energy produced in excess of their own needs. Further, split incentives (i.e. where landlords invest in solar but tenants reap the benefit of reduced energy bills) are also impeding deployment, particularly in light of an increasing 'rental population' within Australia.

Commercial/industrial rooftop solar PV has experienced slower growth that in the residential market, again largely due to split incentives, where the capital expenditure requirements for landlords are typically significantly higher than in the residential market.

As discussed above, significant changes to the electricity system will be required to cope with high VRE share and high NSP. A key component of this is energy storage which currently has a high capital cost. Battery owners are also unable to access the full value for the services provided to the network under existing regulations (AEMC, 2015).

As with batteries, a key barrier to smart grid technologies are current regulations and market structures that prevent full commercial capture of the value enabled by these technologies.

Further detail on the key barriers for Pathway 2 technologies is shown in Table 15.

TABLE 15. KEY BARRIERS FOR PATHWAY 2 TECHNOLOGIES

TECHNOLOGY	COST/TECHNICAL	REGULATION/MARKET OPPORTUNITY	STAKEHOLDER ACCEPTANCE	SKILLS/OTHER
Solar PV – large-scale	• Cost of new build vs existing coal generation • Network limitations near some favourable sites	• Uncertainty in policy supporting VRE • Oversupplied electricity market and low demand for long term PPAs • Numerous solar farms in concentrated areas increases market competition and can diminish value of energy produced (i.e. energy is being produced at the same time so no diversity of supply)	• n/a	• Limited experience in EPC industry with large-scale solar • Lack of industry depth and breadth along certain parts of the supply chain (e.g. EPC) to enable rapid uptake
Solar PV - rooftop	• Perception of high upfront capital expense in low income households • Upfront capital costs for commercial/industrial due to bespoke design • Split incentives between owners/ tenants	• Growing tenant population prevented from accessing rooftop solar PV • Suitable location in apartment buildings owned by body corporate rather than individuals.	• Consumers have little understanding of tariff arrangements and options	• n/a
Wind	• Cost of new build vs existing coal generation • Network limitations near some favourable sites	• Uncertainty in policy supporting VRE • Oversupplied electricity market and low demand for long term PPAs • Numerous wind farms in concentrated areas can create further competition and diminish the value of energy produced	• Resistance from some members of the community due to negative perceptions of wind ('eyesores', 'wind turbine syndrome')	• n/a
Wave	• Costs likely to remain significantly higher than other forms of VRE	• As per other generation technologies	• Social acceptance largely untested	• n/a
Biomass to electricity	• Variability in biomass (e.g. water and impurities) leads to technical challenges	• Lack of incentives for producers of waste to avoid sending waste to landfill	• Lack of awareness of benefits of waste-to-energy	• n/a

TABLE 15. KEY BARRIERS FOR PATHWAY 2 TECHNOLOGIES / CONT'D

TECHNOLOGY	COST/TECHNICAL	REGULATION/MARKET OPPORTUNITY	STAKEHOLDER ACCEPTANCE	SKILLS/OTHER
Batteries (utility-scale and BTM)	• High cost of batteries (due to materials, margins, regulatory hurdles) • Uncertainty of battery performance under real world operating conditions	• Lack of market mechanisms for asset owners to monetise full range of grid services they could provide • Storage operators charging from the grid are required to purchase renewable energy certificates (LGCs and STCs), despite returning the electricity purchased back to the grid (neglecting losses). • Lack of standards regulating battery installation and use	• Bias towards build-out of network capacity over batteries due to regulatory incentives, perceived difficulty and safety concerns	• Limited experience with batteries • Lack of clarity in relation to optimal asset ownership structures (i.e. retailer, NSP or third party)
Other energy storage (off-river PHES)	• Lack of demonstration projects to determine costs		• Lack of awareness of off-river PHES	• n/a
Smart grid technologies	• Lack of defined operating model and standards for future grid	• Lack of market mechanism or price signal to encourage uptake of DERs with required specifications • Regulatory barriers to demand side participation e.g. 1 MW minimum size limit for providing demand side frequency control services	• Lack of awareness of technologies	• Lack of data to inform system design and design of products and services
VRE in RAPS, microgrids and SAPS	• High cost of systems due partly to a lack of standardised solutions • Incentives to use fossil fuels in off-grid	• Regulatory barriers to disconnecting communities from the grid	• Lack of acceptance due to limited number of demonstration projects	• Lack of experience of project developers

B.4.2 KEY ENABLERS

In order for the current electricity market to undergo steady displacement of fossil fuel generation with large-scale VRE, the implementation of stable policies that encourage long term investment is paramount. To complement this, new regulatory/commercial frameworks regarding PPAs (e.g. enabling tripartite contracting between suppliers of VRE, retailers and commercial & industrial customers) could help overcome lack of demand for PPAs and enable greater confidence for investors.

Additionally, there is considerable scope for improvement in the procurement and construction of large-scale VRE. Both efficiencies gained via shared learnings in terms of connections to the network, and better utilisation of existing and new infrastructure (e.g. transmission network), could significantly reduce capital and operating costs.

Regulatory and market reform may also help encourage adoption of enabling technologies such as energy storage and DER control. This topic is also covered in the Electricity Network Transformation Roadmap, a joint project between ENA and CSIRO (Energy Networks Australia and CSIRO, 2016).

TABLE 16. KEY POTENTIAL ENABLERS FOR PATHWAY 2 TECHNOLOGIES (NOT INCLUDING RDD&D)

TECHNOLOGY	POLICY	STAKEHOLDER ENGAGEMENT	INDUSTRY/SUPPLY CHAIN SKILLS
Solar PV – large-scale	• Implement stable and technology neutral policy to drive uptake of VRE post 2020 • Policy supporting optimised positioning and coordination of renewable energy generation sites for sharing of network connection costs • Remove barriers to demand side participation (applies to all VRE)	• Implement incentives (e.g. tax concessions) for institutional investors to have a higher proportion of renewables in their portfolios • Coordination among developers to minimise total network spend	• Knowledge sharing among EPCs to establish supply chains and drive down costs • Improve communication and cost allocation between utilities and developers • Improve design of PPAs (e.g. direct supply to industry customer as opposed to retailer) • Continue to develop training, accreditation and standards in order to build local industry
Solar PV – rooftop	• Market/regulatory reform to allow for peer to peer electricity trading providing landlords with new ways to derive revenue from the asset. This will also encourage development of new business models. • Incentivise uptake of rooftop solar PV in new build and existing buildings as part of building energy efficiency standards • Improve energy storage incentives	• Offer leasing models aimed at low income households • Provide targeted information to consumers and businesses demonstrating potential savings in electricity costs (with and without energy storage)	• Continue certification and training for technicians
Wind	• Implement stable and technology neutral policy to drive uptake of VRE post 2020 • Policy supporting optimised positioning and coordination of wind farms for sharing of network connection costs • Revise regulations to incentivise provision of synthetic inertia by wind farms	• Improved community engagement on wind farm developments, and greater awareness of the latest studies on potential environmental and health impacts • Coordination between developers to minimise total network spend	• n/a

TABLE 16. KEY POTENTIAL ENABLERS FOR PATHWAY 2 TECHNOLOGIES (NOT INCLUDING RDD&D) / CONT'D

TECHNOLOGY	POLICY	STAKEHOLDER ENGAGEMENT	INDUSTRY/SUPPLY CHAIN SKILLS
Biomass to electricity	• Ensure that waste-to-energy plant gate fees are lower than landfill levies	• Increase community awareness of benefits of waste-to-energy	• n/a
Enabling technologies for VRE	• Update regulations and markets to incentivise provision of services required to stabilise grid at high VRE share, e.g. FFR, demand response for frequency control, inertia	• Communicate potential of enabling technologies to allow high share • Collaborate with international grids at forefront of VRE penetration (e.g. EirGrid/SONI) to develop technology and regulatory frameworks	• Educate industry on enabling technologies
Batteries	• Improve regulations and market mechanisms to allow battery owners to access full range of benefits provided • Improve regulations governing installation and operation that allow innovation and industry growth without compromising safety	• Provide accessible information on benefits and risks associated with battery integration	• Conduct further studies/ modelling to determine best use cases, business models and ownership structures • Implement standardised training for battery installers • Encourage information sharing between generators and network service providers
Other energy storage (off-river PHES)		• Improve awareness of benefits of 'off-river' PHES over 'on-river'	• n/a
Smart grid technologies	• Develop DER-services valuation methods and markets • Set standards • Improve availability of data	• Continue to engage the industry on network transformation and DER integration/operation	• Develop industry upskilling program
VRE in RAPS, microgrids and SAPS	• Reform regulations to facilitate microgrids	• Share data and learnings from demonstration projects	

BOX 6 | CASE STUDY

Battery energy storage in the USA

In the USA, decarbonisation of the electricity sector will be critical in achieving the emissions abatement target of a 26-28% reduction from 2005 levels by 2025. Recognising the requirement for significant uptake of VRE, various states are beginning to implement policies to drive energy storage adoption. California, the most advanced state in this respect, has mandated a procurement target set by the Public Utilities Commission that requires the state's "big three" investor owned utilities to procure 1.3 GW of energy storage by 2020. This includes both utility-scale and BTM storage.

RDD&D

While Pathway 2 generation technologies are largely mature, R&D is recommended in areas where Australia can make a global impact by further improving efficiencies and reducing costs. For example, solar PV R&D should be targeted towards improvements in mature silicon (e.g. improved efficiencies) but also the development of emerging thin-film technologies given their potential impact on the industry.

For enabling technologies for VRE, RD&D support is required to understand the operation of large grids with high VRE share, and for demonstration projects for the key technologies. For batteries, continued R&D in novel chemistries can improve operation performance and lower costs. Supported demonstration and deployment is also likely to be required depending on the application (e.g. integration into the transmission network or a solar farm) and is recommended where necessary to assist in establishing supply chains and improving grid management.

The key requirement for RDD&D funding for smart grid technologies is structures and architectures that will underpin the future grid, such as secure communication protocols, grid control platforms and data aggregation systems.

TABLE 17. RECOMMENDED RDD&D FUNDING FOCUS FOR PATHWAY 2 TECHNOLOGIES

TECHNOLOGY	POLICY	STAKEHOLDER ENGAGEMENT	INDUSTRY/SUPPLY CHAIN SKILLS
Solar PV – large-scale	• Improvements in manufacturing and efficiencies of silicon PV • Development of thin film PV (e.g. perovskite)	• Support projects demonstrating novel technologies e.g. thin film perovskite in commercial applications	• Large-scale solar (if financial support is still required) • Integrated battery energy storage
Solar PV – rooftop			• n/a
Wind	• Optimising energy produced and improving integration with the grid and response to system security events • Studies relating to under-utilised land with potentially high wind resources	• Support potential breakthrough technologies e.g. airborne wind	• Integrated battery energy storage
Wave	• n/a	• Where required to drive export opportunities	• n/a
Biomass to energy	• Efficient, low cost waste pre-treatment technologies	• Plants demonstrating co-firing at higher concentrations of biomass (>5%) • Biomass pre-treatment technologies	• n/a
Enabling technologies for VRE (overall)	• Detailed system modelling to understand required enablers of high share of renewables (including optimal grid topology) and effect of high rate RoCoF in large grids as well as integration and stable grid operation at localised levels • Development of sophisticated control systems to allow inverter-connected devices to set and maintain frequency, allowing replacement of synchronous generation	• Demonstrate technologies and commercial arrangements for first-of-kind in Australia projects e.g. synthetic inertia from wind farms is likely to face high transaction costs working through technical and market design issues with AEMO and other organisations	• n/a

BOX 7 | CASE STUDY

Bladepile

Bladepile is a local manufacturer of innovative and cost-effective substitutes for regular screw piles. Screw piles are used as foundations in a range of applications in construction. Bladepile's screw piles are produced from high tensile steel and have greater holding force and load capacity than regular piles.

Bladepile identified an opportunity to expand their market base into solar farms which require a large number of piling structures on which to mount solar collectors. In 2014, Bladepile was contracted to provide 32,000 piles to the Moree Solar Farm in NSW which became the largest screw pile contract in Australia.

TABLE 17. RECOMMENDED RDD&D FUNDING FOCUS FOR PATHWAY 2 TECHNOLOGIES / CONT'D

<table>
<tr><th>TECHNOLOGY</th><th>POLICY</th><th>STAKEHOLDER ENGAGEMENT</th><th>INDUSTRY/SUPPLY CHAIN SKILLS</th></tr>
<tr><td>Batteries</td><td>• Technologies with potential for breakthroughs in cost and/or performance
• Application of different battery types to Australian contexts to improve value creation/ integration in systems</td><td>• Demonstration of full range of use cases (e.g. consumer, commercial, industrial, network, VRE generators) for both energy balancing and frequency stabilisation (including FFR), with information sharing to drive subsequent uptake</td><td>• Supported commercial where needed to build supply chain skills (e.g. solar/wind farms with energy storage)</td></tr>
<tr><td>Other energy storage (PHES)</td><td>• (Further) investigate potential for off-river PHES, factoring in land and water use</td><td></td><td></td></tr>
<tr><td rowspan="2">Smart grid technologies</td><td colspan="3">• Secure and private communications protocols
• Grid control platforms
• Data aggregation systems</td></tr>
<tr><td>• System characterisation, dynamic ratings and updated standards
• Customer energy use in response to price signals</td><td></td><td></td></tr>
<tr><td>VRE in RAPS, microgrids and SAPS</td><td>• n/a</td><td>• Roll out demonstration projects, with a focus on using modularised components</td><td>• n/a</td></tr>
</table>

B.5 Supply chain opportunities

Given the expectation for considerable local deployment of both solar PV and wind generation, there is likely to be significant EPC and O&M opportunities due to the labour intensity required. However, for solar PV in particular, additional opportunities such as the commercialisation of thin-film solar could lead to domestic manufacture of PV cells while drawing on existing printing, glass and plastic industries.

For large-scale VRE, there are also a number of Australian companies developing niche solutions relating to EPC and O&M that could be exported overseas as well as servicing the local market.

Despite it being unlikely that a large-scale battery production industry will develop locally, there are other opportunities for Australia to participate in global supply chains. The most notable of these is the extraction and processing of raw materials (e.g. lithium). Further, while distribution and installation will need to occur locally, there may be scope to develop a battery recycling industry given the need for improved utilisation of materials globally.

Australia also has a comparative advantage with respect to integration of DERs. Regulatory and market reform favouring these technologies may also facilitate the creation of new service offerings and business solutions (e.g. for home energy management) that can be exported overseas.

The key domestic opportunity from deploying VRE in RAPS is reduced electricity cost, resulting from reduced expenditure on network connection and diesel fuel. Additionally, with Australia's leading capability in incorporating VRE into RAPS and microgrids, a large potential export opportunity exists for the international market of off-grid communities that rely on diesel generation, or that lack access to electricity. Carnegie Wave Energy, an Australian wave energy technology developer, recently bought EMC, a microgrid EPC company, recognising the potential of this market, and changed its name to Carnegie Clean Energy. The Australian Government Department of Foreign Affairs and Trade (DFAT) has identified a number of opportunities for Australia to help deploy renewables in RAPS in the Indo-Pacific region.

Key supply chain opportunities for Pathway 2 are shown in Figure 43. Details on how the opportunities were evaluated and the criteria for high, medium and low classifications are given in Appendix B of the LETR Technical Report.

BOX 8 | CASE STUDY

Evergen

Australian company Evergen sells and manages energy systems comprising solar PV, batteries and energy management software. By considering factors such as the weather forecast, predicted demand and electricity prices, the software manages how the battery charges and discharges. This optimised system enables customers to save ~60% on their electricity bills with a payback period of around seven years.

Evergen was created after AMP Capital recognised that there was a commercial opportunity for home energy solutions that integrate solar PV and batteries and approached CSIRO to explore how this could be captured.

Evergen technology could also be used to allow customers' batteries to provide services to the electricity network. Capturing this potential can be supported by development of markets for these services. Development of markets would also help Evergen expand beyond its current base of residential customers to electricity intensive users by facilitating services such as demand response.

Another challenge faced by energy services companies is access to real time energy consumption data. Making this data available to third parties like Evergen (with customer consent) would allow them to offer improved services.

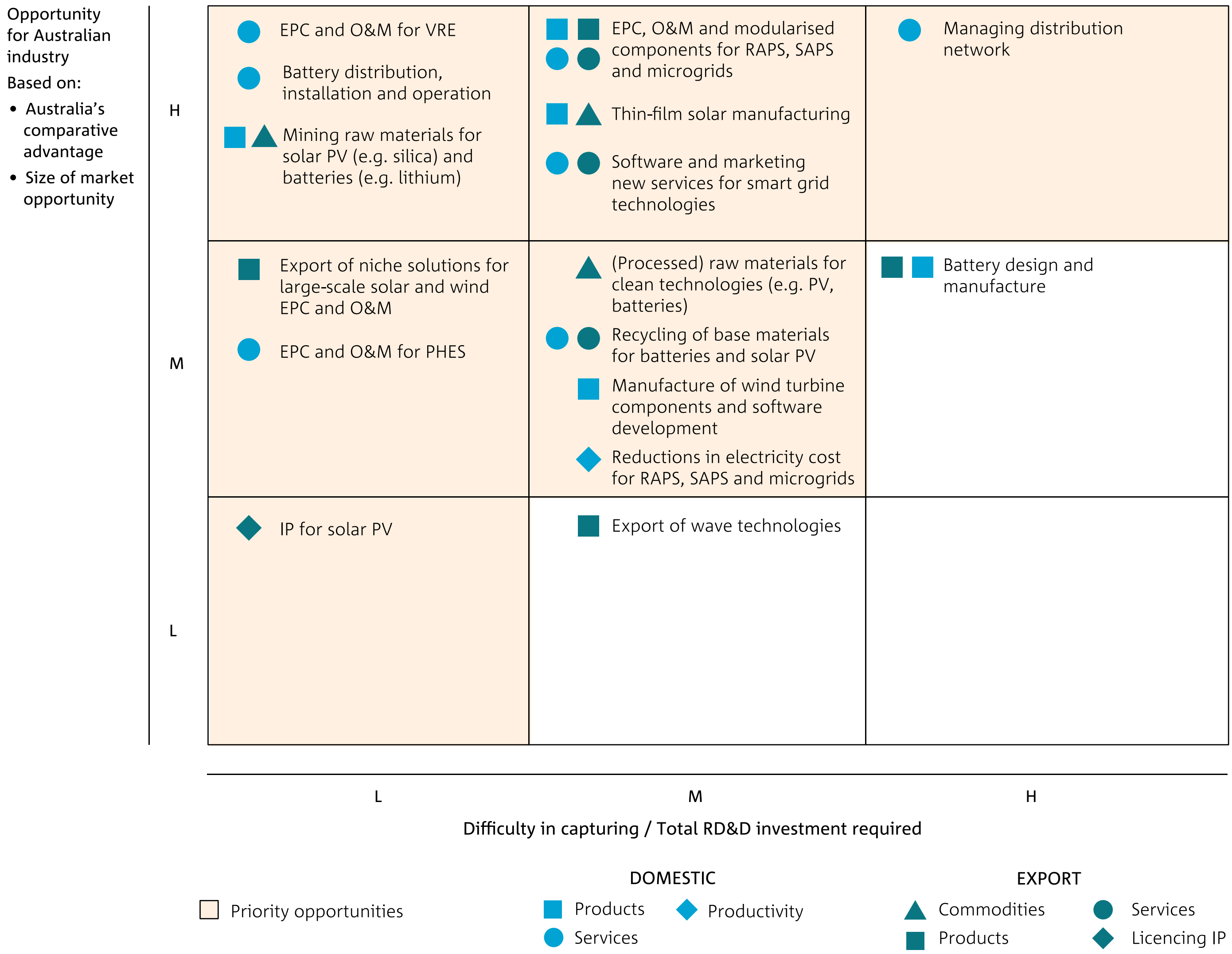


Figure 43. Pathway 2 opportunities for Australian industry

Appendix C

PATHWAY 3: Dispatchable power

C.1 Introduction

Pathway 3: Dispatchable power is a scenario that assumes BAU improvements in energy productivity, and which places a limit on the uptake of VRE. It focuses instead on the role of low emissions dispatchable generation to achieve decarbonisation post-2030. It also considers the role of hydrogen.

The key generation technologies are CST with storage, fossil fuel generation HELE (if new build) with CCS, nuclear and geothermal power. These generation technologies have similar characteristics to conventional thermal generation – they are dispatchable and synchronous, and provide inertia to the network. The electricity system therefore does not require the same degree of modification required in Pathway 2. However in an Australian context, with the exception of gas turbines, these technologies are currently either not technologically mature, not commercially available and/or not cost competitive with VRE. A number of these technologies have been found to have lower acceptance levels (than VRE) amongst the Australian community (Jeanneret, Muriuki, & Ashworth, 2014) and therefore may be subject to greater social licence barriers.

The role of hydrogen was also considered in this pathway due to its connection with other Pathway 3 technologies such as CST, HELE and CCS. Hydrogen can be used as an energy carrier (rather than a generation source). Hydrogen has applications in transport, electricity storage, industrial processes and heating. For Australia, its key role is likely to be in transport and as an export commodity.

A number of the Pathway 3 technologies are interdependent (i.e. they could enable or accelerate deployment of one another). For example, CST can be used to generate heat and/or electricity. Steam generated from CST may also be used to supplement pre-heating requirements for HELE

Focus for discussion in this appendix

	1 PATHWAY 1: Energy productivity plus	2 PATHWAY 2: Variable renewable energy (VRE)	3 PATHWAY 3: Dispatchable power	4 PATHWAY 4: Unconstrained
Buildings, industry and transport	**Ambitious energy productivity improvements**	**Business as usual energy productivity improvements**		**Ambitious energy productivity improvements**
			Hydrogen for transport and export	
New build electricity generation	**Existing low emissions technologies**: wind, solar PV (45% limit) plus gas	**Cheap, mature, low emissions generation**: mainly wind and solar PV **plus enabling technologies** e.g. batteries pumped hydro	Wind and solar (45% limit) plus **low emissions, dispatchable generation**: • Concentrating solar thermal with storage • High efficiency, low emissions fossil fuels with carbon capture and storage • Nuclear • Geothermal	**All low emissions technologies allowed, with no limit on wind and solar PV**
Fugitive emissions	**Uptake of cost-effective technologies**			

generation (which would otherwise be from burning additional coal and gas). Coal gasification and steam methane reforming (SMR) are key HELE technologies that produce syngas[74], which can then be combusted to generate electricity, or used to produce a range of other products including hydrogen. However, if emissions targets are to be achieved, CCS will need to be deployed to lower the emissions profile of these processes.

Given that the Pathway 3 technologies are yet to become commercially available in Australia, many of the enablers to deployment (discussed in Section C.4.2) should be recognised as steps that may be taken to maintain optionality and ensure that these technologies can be deployed when and if required. For the most part, these technologies are currently being demonstrated or deployed globally (e.g. CCS in Canada, hydrogen related technologies in Japan). Thus in order for Australia to efficiently benefit from and contribute to overseas development, domestic and global RDD&D strategies could be aligned.

Pathway 3 technologies generally use energy inputs such as solar, coal and gas. For the most part, operation of these technologies requires similar skills to traditional forms of generation (e.g. gas-fired power). Australia's vast natural resources (e.g. sunlight, coal, gas) and well-established coal and oil & gas industries means that it would be well placed to adopt Pathway 3 technologies by upskilling the current workforce and transitioning existing supporting infrastructure (e.g. drill rigs currently used for gas exploration could be made available for CO_2 storage site appraisal in CCS).

As per Pathway 2, Pathway 3 assumes business as usual progress in energy productivity (i.e. across buildings, industry and transport) and the same level of technology uptake relating to the abatement of fugitive emissions.

[74] Syngas, or synthesis gas, is a fuel mixture contains hydrogen, carbon monoxide and carbon dioxide.

C.2 Pathway 3 technologies

Each of the Pathway 3 technologies and their potential impact on the energy sector are discussed below. Further detail may be found in the LETR Technical Report.

CST

CST relies on mirrors to concentrate sunlight or 'direct normal irradiation' (DNI) onto a receiver containing a HTF. Heat is transferred from the HTF to water to produce steam via a heat exchanger. The steam may be used as heat for industrial processes or for electricity generation via a turbine. Four primary CST technology designs exist:

- **Power tower:** Mirrors, or heliostats, with dual-axis tracking focus DNI onto a central receiver mounted on a tower which absorbs the radiation
- **Parabolic trough:** Single-axis tracking mirrors curved in a parabolic trough concentrate DNI onto a receiver that is fixed along the trough focal point
- **Linear Fresnel reflector:** Single-axis tracking long heliostat mirrors concentrate DNI onto an elevated receiver
- **Parabolic dish:** Dual-axis tracking mirrors curved in a parabolic dish shape concentrate DNI onto a receiver at the dish structure focal point

As an alternative to solar PV, CST provides a well understood means of harvesting solar energy and has applications in the generation of electricity, heat for industrial processing and solar fuels.

While CST electricity generation is expected to remain relatively high cost in 2030 ($80-$140/MWh), it has a number of advantages over VRE (e.g. it provides inertia and fault current). The key differentiator however is that as compared with large-scale VRE, there is the option for integration of relatively inexpensive thermal energy storage which allows for the generation of dispatchable energy. Despite this, given its higher overall cost, CST is unlikely to become cost competitive in Australia before significant energy storage is required (i.e. when VRE share exceeds ~40-50%).

As discussed in the CST section of the LETR Technical Report, where more than five hours of energy storage is required, CST may prove more economical than deploying additional VRE with battery energy storage.

Solar fuels

CST is also expected to be used for the production of solar fuels. Although this is a less mature end use (as compared with electricity generation), CST can enable the production of solar fuels (e.g. hydrogen and 'synthetic fuels' such as petroleum and diesel) through the generation of high temperature heat (>750˚) (Hinkley J. , 2013). This may be achieved by substituting heat requirements for fossil fuel based production processes (e.g. steam methane reforming (SMR) and coal gasification). Alternatively, the heat can be applied to the direct splitting of water to produce hydrogen or the combined splitting of CO_2 and water to produce syngas. Solar fuels produced via SMR is the most mature of the technologies and, if adequately funded, could be available by 2030.

However, in the absence of a biomass feedstock (i.e. biofuel production) and/or removal of CO_2 from syngas via CCS (leaving only hydrogen), burning of synthetic fuels still has the same downstream emissions profile as petroleum based fuels. For this reason, only hydrogen (discussed further below) has been considered as a means of achieving material CO_2 abatement.

High efficiency low emissions fossil fuel generation (HELE)

HELE technologies include:

- **Pulverised coal:** (Ultra) supercritical coal-fired power generation operates at higher steam temperatures than conventional sub-critical generation (> 580˚C) to increase efficiencies.
- **IGCC:** Coal is gasified (i.e. reacted at high temperatures without combustion) to produce syngas, which is then combusted for electricity generation or used as a feedstock for a range of chemical processes. CO_2 is produced in a high pressure gas stream which makes it suitable for capture.
- **Gas turbines:** Include gas peakers and frame turbines. Developments include greater utilisation of waste heat through combined cycle generation.
- **Reciprocating combustion engines:** May use compression or spark injection ignition. Includes DICE which are a modified modular diesel engine that can accept a range of carbonaceous slurry fuels (e.g. coal, biomass).

HELE technologies operate at higher efficiencies than current fossil fuel based energy generation technologies. Consequently, they require less fuel per unit of electricity generated, which significantly reduces emissions. HELE technologies are at varying levels of maturity.

Gas turbines (i.e. gas combined cycle and gas peakers) are technologically mature, relatively low cost ˜$65-80/MWh) and have a relatively low emissions profile compared to coal (i.e. 373 kg CO_2/MWh versus 740 kg CO_2/MWh). Further, they are more suited to deployment alongside VRE given their greater flexibility, higher ramp rates and consequent ability to load follow VRE.

Note however that in order to meet the large additional demand for gas implied by Pathway 3 (base case gas price sensitivity) alongside an expanding LNG export industry, it is likely that significant additional unconventional gas reserves will be required. Recent surveys have suggested that coal seam gas has the lowest approval rating in terms of energy sources amongst the Australian community (Jeanneret, Muriuki, & Ashworth, 2014) and so there is significant social licence risk surrounding its expansion.

To achieve deeper decarbonisation after 2030 (e.g. ˜95% abatement below 2005 levels), most new build HELE (including gas generation) would likely require CCS. However, it is still expected to be cost competitive with other types of dispatchable generation (e.g. CST, nuclear). Note also that a 100% abatement target in electricity generation may preclude HELE even with CCS, given that complete capture of all upstream and downstream emissions from coal/gas may be technologically and cost prohibitive.

Another HELE technology to be considered is DICE. While further RD&D is required before it is commercially available, DICE is a relatively efficient technology that provides a similar function to gas peakers (i.e. high ramp rates and modularity). It provides the additional benefit of being able to accept a number of different feedstocks such as coal and biomass (i.e. 'bio-DICE')) and is not impacted by volatile gas prices. Bio-DICE in particular also offers the potential to provide near zero net GHG emissions generation and be cost competitive with other forms of renewable generation (e.g. solar and wind) as shown in Appendix B of the LETR Technical Report.

CCS

CCS technology comprises a number of discrete components in its value chain:

- **Capture:** CO_2 may be captured from gas processing (e.g. LNG, hydrogen production), fossil fuel power generation, and industrial processes. Depending on the specific technology applied, typically 90-100% of the CO_2 may be captured.
- **Transport:** Transport of CO_2 generally occurs via a pipeline. Ships or trucks may also be used where commercially favourable.
- **Storage:** CO_2 may be injected into deep underground rock and oil & gas reservoir formations. Geological studies such as seismic surveys and test drilling are required to obtain confidence in storage sites. CO_2 can also be stored via mineral carbonation (which can also be used to produce useful products such as building materials – see 'utilisation' below).

Depending on specific project economics and opportunities, captured CO_2 may also be transported for:

- **Utilisation:** CO_2 may be used to create value in applications such as enhanced oil recovery (EOR), enhanced coal bed methane recovery (ECBM) or converted to other products (e.g. chemicals, algae, building materials).

Globally, CCS provides a critical means of decarbonisation across a number of different sectors.[75] However, implementation imposes an additional cost on operations (e.g. overall LCOE of ˜$95-160/MWh[76] for electricity generation in 2030, as per Appendix B of the LETR Technical Report). Therefore, even if utilisation (e.g. ECBM) is available, appropriate policy incentives/mandates are still likely to be required in order to support deployment.

In an Australian context, CCS may be used in a number of different industries:

- Electricity: In order for the electricity sector to achieve deeper decarbonisation, with the possible exception of gas turbines (as discussed above), any continued fossil fuel power generation will require CCS. CCS may be deployed with new build HELE or via retrofit of capture systems to existing generation. Both could be cost-competitive with other new build generation technologies after 2025 if the right economic drivers (e.g. policy) are in place. CCS can also be applied to biomass-fired electricity generation (i.e. BECCS). However this is likely to be expensive ($210-260/MWh in 2030) and so would require a policy regime that encourages/mandates negative emissions in order to be realised.
- Natural gas processing (for LNG) as discussed in Section A.2.3
- Hydrogen production via gasification of coal
- Industrial processing: Either by separating CO_2 produced from industrial processes (e.g. cement production)[77] or with CO_2 captured from direct combustion of gas and coal for heat

There is an ongoing risk that stored CO_2 could leak from certain types of reservoirs. Detailed assessments relating to the risk of leakage, response strategies as well as considerable measurement, monitoring and verification (MMV) is required in order to ensure confidence in the storage capability of different sites.

Nuclear

Nuclear energy may be generated via two types of reactions:

1. **Fission** – The nucleus of an atom is split into two smaller atomic particles and neutrons, resulting in the release of energy. The energy released is derived primarily from the kinetic energy in the fission products. Free neutrons then cause a chain reaction by colliding with other nuclei.
2. **Fusion** – Two or more nuclei are combined to form heavier nuclei, resulting in the release of energy. In order to be self-sustaining, the energy released from the fusion reaction must be greater than the heat input to maintain the fusion process.

Currently, all nuclear power plants rely on nuclear fission which generates heat to power a turbine. Fusion technology is currently in early stage development.

[75] The report is primarily concerned with the application of CCS in electricity generation, direct combustion and fugitive emissions. Emissions derived from industrial processes such as cement and steel manufacture may be able to technically incorporate CCS, however detailed analysis is outside the scope of the report.

[76] Note that based on stakeholder interviews conducted as part of the project, overall storage costs may be higher depending on the reservoir properties, transport distance and regulations imposed.

[77] This is out of scope for this roadmap, which focused on energy sector emissions.

Nuclear energy provides another avenue for achieving low emissions dispatchable energy. Globally, it is well established, meeting 11% of total electricity demand (International Energy Agency, 2015). Japan's Fukushima Daiichi accident in March 2011, in which an earthquake and tsunami resulted in meltdowns at the nuclear plant, caused a temporary decline in global deployment of nuclear energy. The industry has since recovered with 60 reactors currently under construction globally.[78]

While the technology is well understood, further development of nuclear reactors (e.g. 'Generation IV') is ongoing with the aim of reducing costs, improving safety and efficiency as well as minimising water requirements and radioactive waste. Another key development will be in the adoption of small modular reactors (SMR) which will have capacities of less than 300 MW, a comparatively lower capital cost and allow for more flexible integration within existing energy networks.

As discussed in Section C.4.1, adoption of nuclear for the purposes of electricity generation in Australia would require considerable legislative review and extensive stakeholder consultation given that it is currently prohibited under Australian law and subject to community opposition (Nuclear Fuel Cycle Royal Commission, Government of South Australia, 2016). Further, it would take an estimated 14 years before a nuclear plant could be operational due to the time required to establish an appropriate regulatory framework as well as procure, construct and commission the first reactor (Nuclear Fuel Cycle Royal Commission, Government of South Australia, 2016).

Aside from electricity generation, there is significant potential for Australia to expand its participation in the global nuclear supply chain (e.g. by expanding uranium mining operations or by further developing advanced manufacturing capabilities for the supply of specialised components). Greater opportunities may also be realised through the establishment of infrastructure supporting receipt and storage of radioactive waste from overseas. If successful, this could increase the scope for deployment of local nuclear generation.

Geothermal

Geothermal energy is derived from heat contained inside the earth. The heat, which exists at higher temperatures at greater depths below the earth's surface, can be harvested by deep drilling into a number of different subsurface formations. These are (CO_2CRC, 2015):

- Conventional hydrothermal systems (volcanic or magmatic)
- Unconventional hydrothermal systems (e.g. HSA, amagmatic)
- EGS (or 'hot rocks')
- Shallow direct use resources

The heat generated is then used to power a steam turbine in order to produce electricity.

Australia's potential geothermal resources are mainly EGS and HSA. It has been estimated that more than 360 GW of geothermal generation could be installed in the NEM (Huddlestone-Holmes & Russell, 2012). So far none of these resources have been successfully developed. Australia also has shallow direct use resources at ~100°C that have been used to generate electricity in isolated cases; unlike EGS and HSA, these resources are not sufficient to contribute to MW-scale generation.

Drilling is a major cost component of ESG and HSA due to the depth of the resource and hardness of the overlying rocks. Following a major assessment of Australia's geothermal prospects carried out in 2014 (ARENA, 2014), ARENA reset its investment strategy to focus on RD&D with a view to improving techniques to reliably locate resources with sufficient heat and achieve economic flow rates.

[78] Refer to http://www.world-nuclear.org/information-library/facts-and-figures/world-nuclear-power-reactors-and-uranium-requireme.aspx .

Hydrogen

Low emissions hydrogen can be produced via a number of processes:

- **Electrolysis:** Uses an electric current to split water molecules into hydrogen (H_2) and oxygen (O_2). This process is zero emissions if powered by renewable energy.
- **Thermochemical:** Uses a carbonaceous feedstock and water to produce hydrogen e.g. via coal gasification or SMR. These processes require use of biomass, CCS and/or CST in order to lower the emissions profile.
- **Emerging:** Involves splitting of water molecules using direct sunlight or biological mechanisms (e.g. bacteria, microalgae).

There are a range of applications for hydrogen:

- **Electricity:** Hydrogen can be used in fuel cells to produce electricity. Hydrogen combustion turbines are also in development.
- **Transport:** Hydrogen can be used to power FCVs.
- **Heat:** Hydrogen or hydrogen-derived products (e.g. enriched methane, ammonia) can be burned to provide heat
- **Industrial processing:** Low emissions hydrogen can be used to produce ammonia or as a reductant in metals processing and hydrocracking of oils.

Hydrogen may be transported via pipeline, ship or truck but generally requires some form of treatment (e.g. liquefaction, conversion to ammonia) in order to improve volumetric density (i.e. energy per unit of volume).

Hydrogen provides a flexible means of storing and transporting low carbon energy. Deployment of hydrogen-based technologies is therefore gaining considerable momentum on a global scale. This is particularly true for countries such as South Korea and Japan that do not have large domestic renewable energy resources and which are set to rely heavily on imported hydrogen in order to transition to a low carbon economy.

As discussed in Section C.5, hydrogen has the potential to become a key export opportunity for Australia. Low or zero emissions hydrogen is most likely to be produced at large-scale using electrolysis and/or coal gasification with CCS. Australia has vast resources required to support these processes (e.g. solar, coal reserves) and a number projects/feasibility studies are currently underway.

While likely to occur independently, development of a hydrogen export industry may increase the scope for local use. The most likely application is in transport where FCVs have the potential for uptake in both the passenger and heavy vehicle markets:

- For passenger vehicles, FCVs are unlikely to be cost competitive with EVs in 2030 (~$29,000 for a medium sized FCV vs ~$25,000 for a similar EV). However, FCVs may be preferred for long distance travel in the absence of widespread EV recharging infrastructure.
- Heavy vehicles typically operate at close to maximum weight capacity. FCVs may therefore be more suitable due to the superior energy density (MJ/kg) of hydrogen over batteries.

C.3 Technology uptake and emissions impact

C.3.1 ELECTRICITY SECTOR

The base case projected generation mix for Pathway 3 technologies is shown in Figure 44 below. Also included are a series of sensitivities that represent the key risks associated with a number of the technologies:

- **Sensitivity 1** – Introduces a high gas price in order to examine the impact of supply constraints.
- **Sensitivity 2** – Disallows HELE (except gas combined cycle), CCS and nuclear given that they are all subject to significant social licence risk. A high gas price is also applied.
- **Sensitivity 3** – Assumes that geothermal energy is not available due to a failure to overcome technical risks. Further, it is assumed that a social licence for HELE, CCS and nuclear has not been obtained and that a high gas price applies.

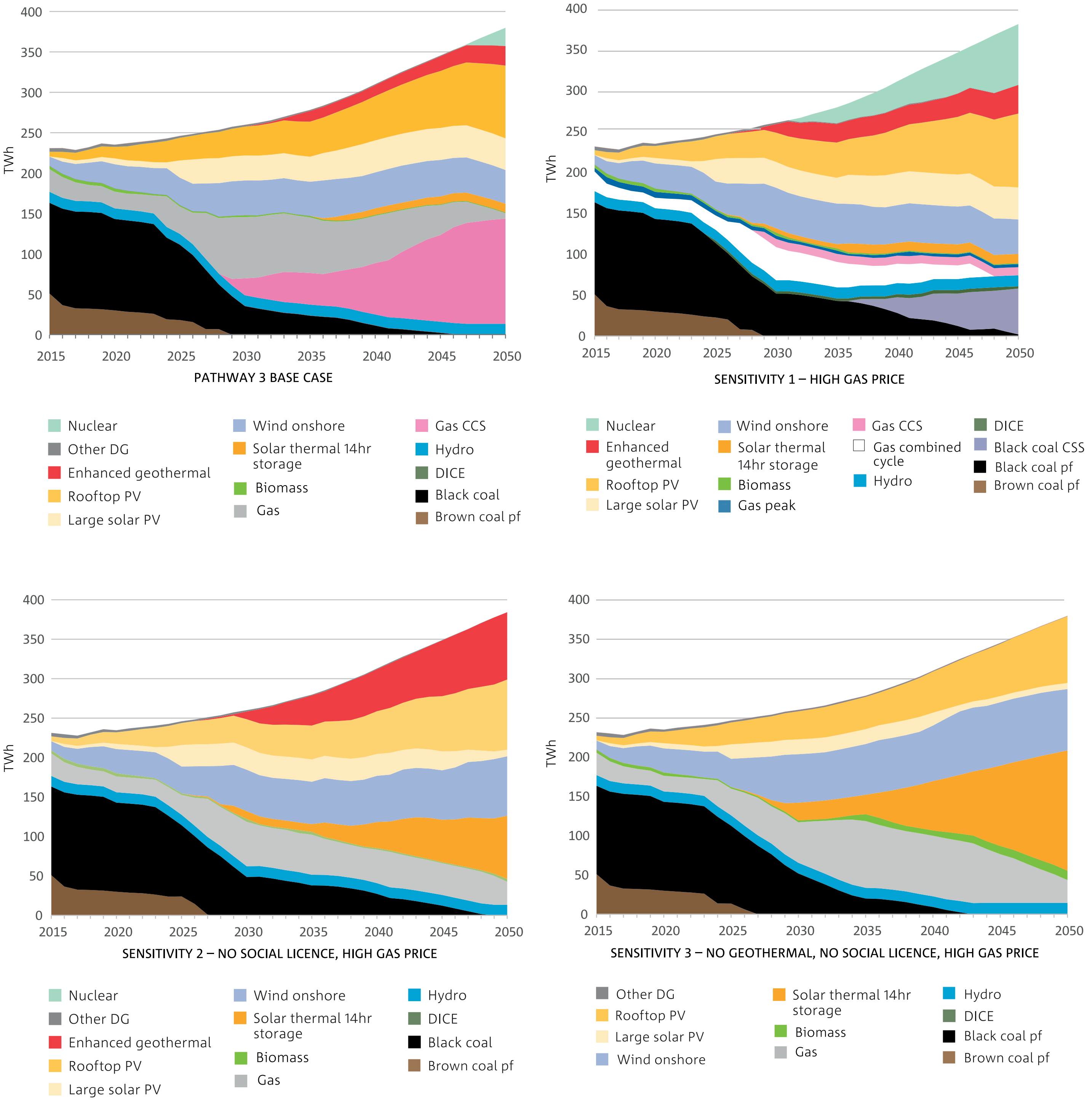


Figure 44. Pathway 3 generation mix

While it is acknowledge that PCC retrofit may provide a more cost effective option than HELE with CCS (i.e.$100-150/MWh), it has not been included in the modelling. This is due to the fact that the capital and operating cost can vary significantly depending on the type, age, condition and location of the asset.

Initially, Pathway 3 follows a similar trajectory to Pathway 2, wherein it relies heavily on the deployment of solar PV and wind in order to achieve short term abatement targets. However, after the 45% cap on VRE is reached in 2028, the alternative low emissions dispatchable technologies are deployed.

Other key points to note are discussed with respect to the different sensitivities:

Pathway 3 base case

For the base case, gas (both combined cycle and with CCS) is the primary source of new generation other than VRE. Gas combined cycle has an average annual capacity increase of 0.9 GW from 2025 to 2036. Once a more stringent abatement target is reached, it is then superseded by gas with CCS with average annual additions of 0.8 GW from 2037 onwards. Small additions for CST, geothermal and nuclear also occur.

The base case depends heavily on a low domestic gas price which may not be achievable if social licence barriers relating to unconventional gas production are not overcome.

Sensitivity 1 – High gas price

The assumption of higher gas prices (~50% higher than in the base case), has a significant impact on the deployment of gas-fired generation. Between 2021 and 2028, an average of only 0.5 GW is added annually. 1.3 GW of gas with CCS is deployed in 2027 with no new capacity added after that point.

In this sensitivity, black coal with CCS, geothermal and nuclear (most likely SMRs) are the key sources of new generation other than VRE with annual average additions of 0.4 GW, 1.0 GW and 0.39 GW respectively after 2030.

Note that in the modelling, CCS has only been included in relation to new build HELE as opposed to post-combustion capture (PCC) retrofit on existing coal-fired power generation. This is largely due to difficulty quantifying the costs given the age, design and operating efficiency of different generation facilities. However, it is acknowledged, particularly in light of recent developments overseas (e.g. Boundary Dam and Petra Nova, described further in the CCS section of the LETR Technical Report), that the cost of retrofit is decreasing and could become a viable emissions abatement option for Australia in the future.

Sensitivity 2 – No social licence, high gas price

In the event that social licence barriers relating to HELE, CCS and nuclear are not overcome, there is a stronger requirement for other low emissions dispatchable technologies, namely as geothermal and CST. The average annual additions from 2030 are 0.4 GW and 0.7 GW respectively.

Despite the higher gas price, gas combined cycle remains cost competitive with these alternative technologies and is still built at a rate of approximately 0.1 GW per year from 2030 to 2040.

Sensitivity 3 – No geothermal, no social licence, high gas price

As discussed, there is significant risk associated with geothermal in relation to locating and accessing (via drilling) appropriate resources at a viable cost. In the event that geothermal does not become viable, greater emphasis is placed on CST with storage, alongside VRE, in order to meet electricity demand. An average build rate of CST of 1.1 GW per year from 2024 would be required. Gas combined cycle would need to be deployed at a rate of 0.5 GW per year from 2022 to 2040.

A comparison of the total cumulative electricity supply chain spend to 2050 for these scenarios is set out in Figure 45 below. Here it is evident that a higher gas price does not result in a material change to totex (i.e. when comparing the base case to S1) but rather forces deployment of other technologies of similar cost[79].

[79] From a modelling perspective this indicates that the generation mix in the base case of Pathway 3 and the high gas sensitivity are both close to the minimum cost for this Pathway (with only a change in the gas price required to make the model shift to the alternative solution). It is implied in Figure 45 that the high gas price sensitivity is in fact slightly lower cost. However, the modelling framework minimises system costs to the year 2060 so that the model takes into account operating the selected technologies beyond the projection period. The generation mix in the base case of Pathway 3 is lower cost to the year 2060.

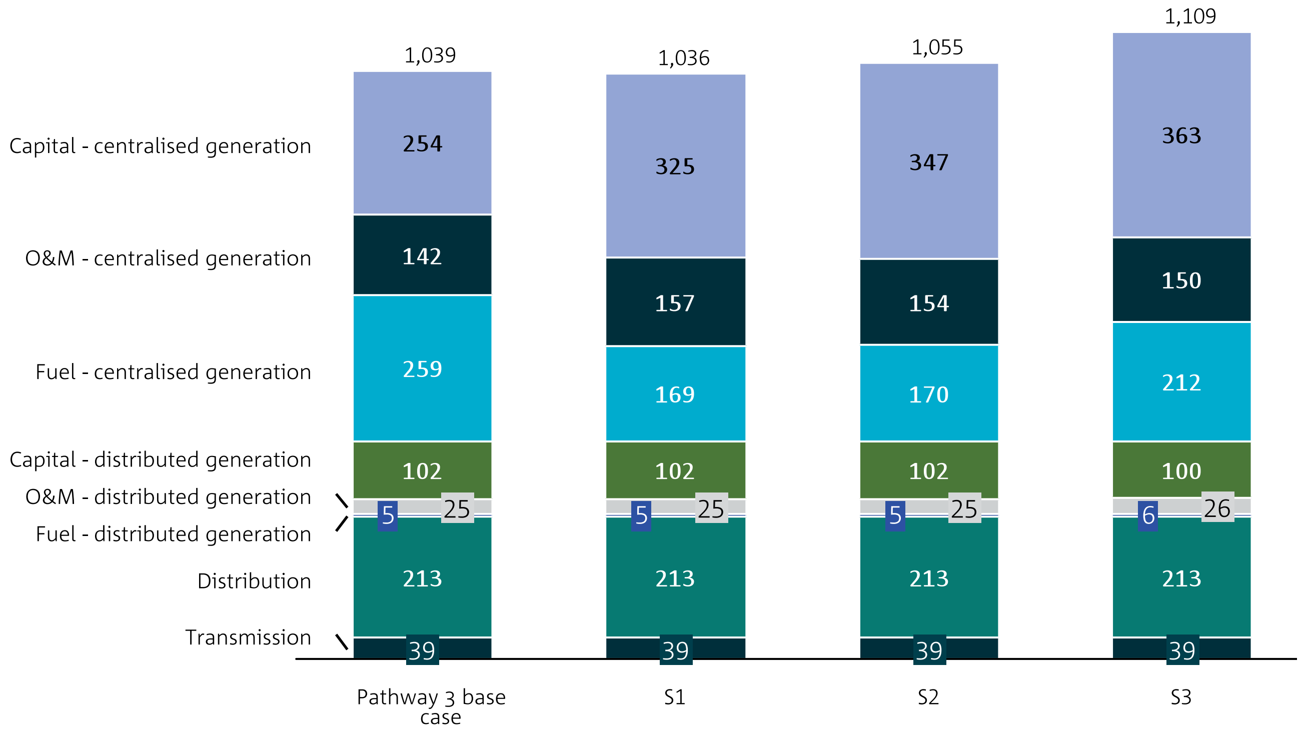


Figure 45. Comparison of Pathway 3 sensitivities 2050 cumulative electricity supply chain total expenditure $ billions

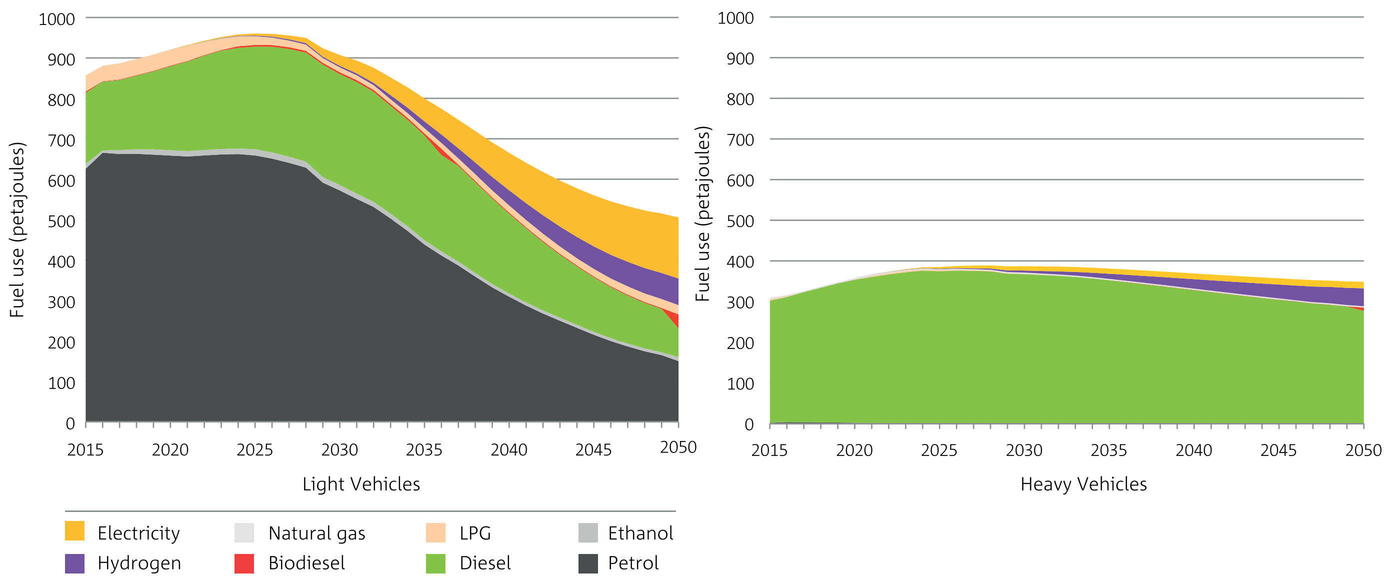


Figure 46. Projected fuel use in light and heavy vehicles in Pathway 3

Social licence barriers to coal have a greater impact on total expenditure, particularly where geothermal is not available. This is due to the fact that there is a higher contribution from CST which is more expensive.

C.3.2 TRANSPORT SECTOR

Fuel use for light and heavy vehicles in Pathway 3 is set out in Figure 46. The key difference with respect to Pathway 2 is that hydrogen has been included as a fuel source.

In this scenario, uptake of hydrogen FCVs occurs in the light vehicle market from 2020 with growth of approximately 2.2PJ per year to 65.7 PJ in 2050. Hydrogen also enters the heavy vehicle market from 2020 with use anticipated to grow by approximately 1.4 PJ per year to 44.1 PJ in 2050.

The primary energy use required for hydrogen vehicles is typically higher than EVs due to the considerable energy losses that occur during the conversion processes (i.e. hydrogen production, storage and use). Thus, if relying on grid electricity (as opposed to dedicated renewables) in order to produce hydrogen, FCVs currently have a significantly higher emissions profile than EVs. FCV emissions would also be higher than ICE emissions until the electricity grid achieves deeper decarbonisation, as shown in Figure 47 below. Given that uptake of FCVs is not expected to be significant until after 2030, this is not expected to pose a significant problem. In the meantime, hydrogen for FCVs should be produced from low emissions sources.

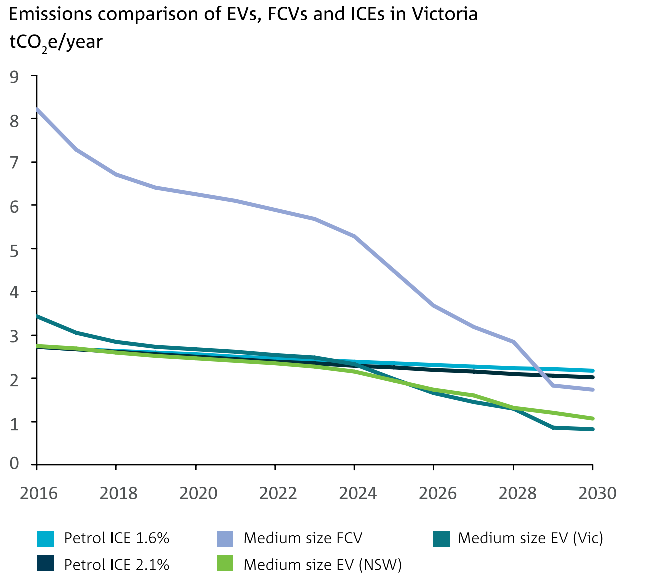


Figure 47. Emissions comparison of EVs (in Victoria and NSW), FCVs (Victoria) and ICEs. Assumes EVs charged from the grid and FCVs fuelled with hydrogen produced by electrolysis using electricity from the grid. Percentages shown for ICEs are annual efficiency increases. Assumes 13,200km of travel per vehicle per year.

This analysis assumes decarbonisation of the Victorian electricity network (the Australian state with the highest emissions intensity) and the NSW electricity network in line with Pathway 3. ICE annual efficiency increases of 1.6% and 2.1% are also presented for comparison.

C.3.3 OTHER SECTORS

Uptake of technologies related to direct combustion result in the BAU emissions profile described in Appendix A. Detailed assumptions regarding rates of uptake are given in Appendix B of the LETR Technical Report.

Deployment of technologies and emissions impact related to fugitive emissions in Pathway 3 are as described in Pathway 1.

C.4 Barriers and enablers

C.4.1 BARRIERS TO DEPLOYMENT OF PATHWAY 3 TECHNOLOGIES

As discussed above, the most obvious barrier to deployment of Pathway 3 technologies is their higher costs compared to VRE.

Some Pathway 3 technologies, namely HELE, CCS and nuclear, that have received lower levels of community approval than VRE (Jeanneret, Muriuki, & Ashworth, 2014), may have the additional requirement of overcoming significant social licence barriers. For HELE, both with and without CCS, significant CO_2 reductions may be achieved compared with existing thermal generation. However these technologies still have a higher emissions profile than VRE and may be subject to opposition from parts of the community given the continued use of fossil fuels.

As with other forms of low emissions electricity generation, the lack of favourable policy means that there is no incentive for private investors to invest in and deploy new technologies. The task of securing investment is even more challenging for proponents of ‘bulky’ inflexible generation that require several years for procurement and construction (e.g. CST, IGCC), particularly in light of uncertainty regarding future electricity network demand.

Of similar importance is the lack of regulatory frameworks that support the roll out and operation of specific technologies (i.e. guidelines relating to safety, skills accreditation and environmental impacts). For example, a lack of appropriate standards regarding permitting for geological storage of CO_2 can make the cost of appraisal prohibitive and prevent the development of a competitive market for prospective storage sites. The same is true for hydrogen, where a lack of guidelines supporting storage and dispensing pressures can impede the deployment of a network of local refuelling stations.

The key barriers for each of the Pathway 3 technologies is set out in Table 18 below.

TABLE 18. KEY BARRIERS FOR PATHWAY 3 TECHNOLOGIES

TECHNOLOGY	COST/TECHNICAL	REGULATION/MARKET OPPORTUNITY	STAKEHOLDER ACCEPTANCE	SKILLS/OTHER
CST	• High capital cost • Output is heavily impacted by cloud	• Oversupplied energy market and low demand for large-scale PPAs	• Lack of awareness of value provided by CST (e.g. dispatchability, inertia) relative to solar PV	• Lack of local supply chains (other than manufacturers of heliostats and receivers) and experience in procuring large-scale plants
HELE	• High cost of certain HELE technologies (e.g. IGCC) • Greater emissions intensity compared to renewable alternatives	• Oversupplied energy market and low demand for large-scale PPAs • Difficult for HELE to attract new investment due to social licence as well as unpredictability over demand for ‘bulky’ generation • Availability/price of gas	• Social licence barriers to continued use of fossil fuels	• n/a
CCS	• High cost of infrastructure/ technologies along the CCS value chain • High risk and high cost associated with storage appraisal • Uncertainty over ability of geological sites to store CO_2	• Lack of a mature regulatory framework incentivising and regulating CCS • Uncertainty over future economic conditions under which a full scale CCS project would operate	• Concern over continued use of coal/gas and safety of CCS • Limited awareness of CO_2 utilisation opportunities and benefits	• Limited experience in integrating discrete components into an end-to-end CCS network for electricity generation
Nuclear	• High capital cost of mature generation	• Nuclear generation is currently prohibited under Commonwealth legislation • Demand risk for large-scale PPAs • Mature generation technologies are ‘bulky’ so difficult to secure investment in light of demand uncertainty	• Community concern over safety of operation and waste management	• No established nuclear electricity generation industry

TABLE 18. KEY BARRIERS FOR PATHWAY 3 TECHNOLOGIES / CONT'D

TECHNOLOGY	COST/TECHNICAL	REGULATION/MARKET OPPORTUNITY	STAKEHOLDER ACCEPTANCE	SKILLS/OTHER
Geothermal	• High drilling costs, driven by large depth and competition with the O&G sector • Difficulty 'finding and flowing' suitable resources	• Oversupplied energy market and low demand for large-scale PPAs	• Stakeholder acceptance untested	• Small local industry and absence of large companies looking to invest in geothermal technology
Hydrogen	• High cost of technology for production for export as well as local transport (i.e. FCVs and refuelling infrastructure) • High cost and technical challenges for storage in long distance transport	• Lack of mature standards (local and global) regulating overall use of hydrogen across the energy sector	• Safety concerns • Pre-conceived opinions around complexity and technical challenges associated with hydrogen	• Small local supply chains with limited experience in large-scale hydrogen production

C.4.2 KEY ENABLERS

The successful deployment of Pathway 3 technologies would depend heavily on the implementation of stable long term policies that incentivise uptake and create predictable market demand for low emissions generation. To minimise system cost, these policies would not preference certain technologies (e.g. mature VRE) over others, but rather create a competitive market for deployment of all types of suitably low emissions generation.

Further, it is important for policy to capture the full value of the energy generated and service provided (e.g. inertia, capacity and other ancillary services). This has been demonstrated in Chile where policy has been implemented to address the need for energy diversification, i.e. mitigating the risk of extensive reliance on solar PV by deploying other low emissions technologies (see Box 9).

BOX 9 | CASE STUDY

CST in Chile

Chile has introduced a scheme that requires all utilities to source 20% of their power from non-conventional renewable energy by 2025. In addition to achieving emissions abatement, this strategy seeks to promote diversity in the network in order to improve reliability. Chile already has 30 large-scale solar plants (PV and CST) in operation with a further 15 currently in planning phase or undergoing construction. 20 year PPAs are auctioned at a minimum contract price of US$70/MWh.

As mentioned in Section C.4.1, it is also important to implement a framework that regulates issues such as safety, security and environmental impacts in order to ensure efficient deployment.

A competitive market for new forms of electricity generation will also foster new business models which can serve to reduce the cost of technologies.

This may be as simple as utilising pre-existing infrastructure (e.g. coupling a CST plant with other facilities that require heat or utilising existing pipelines and reservoirs for transport and storage of CO_2).

Further, widespread stakeholder consultation that communicates the risks and benefits associated with each technology is integral to obtaining social licence.

TABLE 19. KEY POTENTIAL ENABLERS FOR PATHWAY 3 TECHNOLOGIES (NOT INCLUDING RDD&D)

TECHNOLOGY	POLICY	STAKEHOLDER ENGAGEMENT	SKILLS/BUSINESS MODELS
ALL GENERATION TECHNOLOGIES	• Stable long term policy to drive uptake of low emissions generation • Market/ regulatory reform to better incentivise provision of dispatchable generation, inertia, etc.	• n/a	• n/a
CST	• See 'All generation technologies'	• Increase industry awareness of benefits of dispatchability, inertia, etc.	• Encourage experienced EPC contractors from overseas to develop first CST plants in Australia while developing local supply chains • Facilitate shared learnings from early projects
HELE	• See 'All generation technologies'	• Conduct widespread communication of impact of HELE (with CCS) in reducing emissions • Communicate role of gas turbines as a low emissions transition option and complement to VRE	• For 'bulky' generation, conduct rigorous modelling to understand demand profiles and secure PPAs where possible
CCS	• See 'All generation technologies' • Ensure 'utilisation' explicitly included in policies incentivising CCS • Continue to implement consistent regulatory regimes • Continue to implement policies to foster a competitive environment for geological storage (e.g. permitting)	• Effectively communicate risks and benefits of CCS • Ensure that 'utilisation' is promoted and explicitly referred to in relevant policies	• Adapt learnings from international projects including potential commercial models • Explore options for joint development of infrastructure (e.g. pipelines, drill rigs) and modelling for network optimisation • Continue to update pre-competitive storage data • Develop standardised training with knowledge gained reflected in technical standards

Continual community engagement has been found to be particularly successful in overcoming local concerns in relation to deployment of CCS (Ashworth, et al., 2013). Stakeholder engagement is also important in creating awareness of the impact that each technology can have. For instance, continued industry consultation can be used to demonstrate the numerous potential roles for hydrogen locally as well as associated opportunities for export.

TABLE 19. KEY POTENTIAL ENABLERS FOR PATHWAY 3 TECHNOLOGIES (NOT INCLUDING RDD&D) / CONT'D

TECHNOLOGY	POLICY	STAKEHOLDER ENGAGEMENT	SKILLS/BUSINESS MODELS
Nuclear	• See 'All generation technologies' • Legislative change to enable nuclear generation under a nationally consistent framework • Implement long term strategy and regulatory framework for the industry	• Undertake widespread stakeholder consultation including providing fact-based information on risks and benefits of nuclear power	• Continue to develop strategies for managing radioactive waste and follow global developments in waste recycling • Develop requisite training, education and regulation as part of a nuclear program
Geothermal	• See 'All generation technologies'	• n/a	• n/a
Hydrogen	• Policy to support low emissions vehicles • Develop domestic regulations that align with global hydrogen operating standards as they develop	• Communicate results from safety testing in FCVs, storage etc.	• Strategically deploy production plants so they are in close proximity to existing infrastructure (e.g. ammonia production, coal reserves) • Ensure deployment of hydrogen infrastructure is well coordinated amongst different stakeholders (e.g. gas producers, transport) • Implement training, accreditation and standards to encourage transition and upskilling from oil & gas industry

BOX 10 | CASE STUDY

Canada, Boundary Dam CCS

Canada has established the first carbon capture plant to be retrofitted onto a full-scale coal-fired power station. The captured CO_2 is primarily used for the purpose of EOR in nearby depleted oil fields but was also designed for geological storage to account for instances of low CO_2 demand. Approximately one million tons of CO_2 is injected every year.

In the Canadian context, although EOR provides a market for captured CO_2, CCS is not viable without material support from government in the form of either a market mechanism or direct funding. Thus, while the emissions performance standards enacted by the Canadian Federal Government ultimately mandated that Boundary Dam significantly reduce CO_2 levels from the plant, direct funding was also provided to the project. Given the age of the plant (45 years), approximately one third of the total expenditure was required for system upgrades. 50 MW out of a total 160 MW generated is required to run the capture plant.

BOX 11 | CASE STUDY

Heliostat SA

Heliostat SA manufacture heliostats for use in power tower CST. The company is an offshoot of an automotive parts supplier in South Australia known as 'Precision Components'. Given the decline of the local car manufacturing industry, the company leveraged the Australian Government's Automotive Diversification Programme to understand new potential industries that would allow for a relatively simple transition from its existing manufacturing processes. This led to a decision to apply CSIRO IP to the production of compact heliostat technology for high volume production and high performance from relatively cheap materials. Heliostat SA signed Memoranda of Understanding with Mitsubishi Hitachi Power Systems for the installation of 150 heliostats in Japan, as well as with Global Wind Power Limited, which is looking to develop the first 1 GW CST plant in India. Overall this represents an example of a nimble manufacturing company which, by commercialising Australian IP, was able to adapt manufacturing processes that were servicing a shrinking local market, to develop products suited to a growing global market.

RDD&D

As mentioned earlier, Pathway 3 technologies are generally well understood, but are at varying levels of commercial readiness both locally and overseas. For each of these technologies, there is a decision for government regarding the level of investment it is prepared to make in order to have the option of local deployment in the future.

From an RD&D perspective, the primary focus will be on achieving incremental improvements in performance, as part of global development but also to reduce operational cost and risk in Australia. For instance, in the case of HELE, considerable RD&D efforts are being made locally to develop oxyfuel systems which enable coal to be combusted in oxygen (as opposed to air). This allows for the production of higher concentrations of CO_2 within the flue gas and lowers the cost of CO_2 capture.

Other technologies such as DICE have a high technology readiness level (using coal slurry as a fuel) and require demonstration under real world operating conditions in order to be commercialised. These more flexible technologies in particular could help overcome barriers typically associated with new build 'bulky' generation (as discussed in Section C.4.1). Other technologies such as CCS with coal-based hydrogen production have been proven individually, but require pilot projects to demonstrate integrated operation before a final investment decision on commercial plants can be reached.

Lastly, there are mature technologies such as large-scale CST that require government funding in order to underwrite the risk associated with deployment of first-of-kind projects in Australia. Others, such as CCS, require funding in order to ensure they are commercially viable and unlock private sector investment, as was found to be the case in Boundary Dam, Canada (see Box 10).

TABLE 20. RECOMMENDED RDD&D FUNDING FOCUS FOR PATHWAY 3

TECHNOLOGY	R&D	DEMONSTRATION	DEPLOYMENT
CST	• Raising system efficiencies and improving energy storage technologies	• Potential breakthrough technologies e.g. modular CST • CST for hydrogen production	• Pipeline of early stage projects to remove first-of-kind risk and reduce deployment costs
HELE	• Niche areas of existing capability within global research programs e.g. alloys supporting use of higher temperature steam	• Flexible HELE generation (e.g. DICE) • Oxyfuel power generation	• n/a
CCS	• CO_2 capture and separation technologies • Emerging utilisation technologies • Identifying alternative storage formations	• Appraisal of prospective storage • CCS for coal-based hydrogen production • Capture technologies	• Development of storage resources
NUCLEAR	• Specialised nuclear components (e.g. materials, software)	• n/a	• n/a
GEOTHERMAL	• Low cost research aimed at improving the success rate of drilling	• n/a	• n/a
HYDROGEN	• Niche areas of the hydrogen supply chain (e.g. ammonia cracking, solar fuels)	• Pilot projects for large-scale hydrogen production via coal gasification with CCS and electrolysis • Hydrogen transport (e.g. liquefaction and other carriers)	• Commercial large-scale hydrogen production • Retrofit fuel stations and bus/truck depots with hydrogen refuelling technology

C.5 Supply chain opportunities

Pathway 3 technologies such as CST, HELE with CCS and hydrogen production are all optimal when operating at scale (i.e. > 100 MW). Local deployment is therefore expected to provide significant EPC and O&M opportunities associated with new plant, often in remote regions of Australia. In the case of CCS, there may also be opportunities to participate in nearby markets by operating storage reserves in South East Asia.

Australia has a skilled workforce with deep expertise in the coal and oil & gas sectors. Technologies such as hydrogen, HELE, CCS and geothermal all require a similar skill base. Therefore, with the assistance of new training and accreditation programs, Australia would be well placed to transition the current workforce and infrastructure (e.g. drill rigs) to these new forms of electricity generation.

Australia also has significant R&D capabilities with respect to a number of the Pathway 3 technologies. This includes for example the development of ammonia cracking technologies that allow for the separation of hydrogen from ammonia (which is a favourable carrier of hydrogen for long distance transport). Australia also has strong capabilities in relation to specialised components for nuclear generation (e.g. materials development for nuclear reactors) which may continue to be leveraged. However, given the high cost of manufacturing in Australia and larger overseas markets, IP is often licenced to overseas manufacturers.

One exception to this has been in relation to CST, where despite the absence of large-scale deployment in Australia, there has been direct collaboration between the research community and industry to develop and manufacture heliostats for export to Asia (see Box 11).

A number of the Pathway 3 technologies are also closely linked to commodity export opportunities. Even with strong uptake of HELE and CCS technologies globally it is likely that a significant proportion of Australia's coal reserves will remain unexploited if the world acts to limit global warming to 2°C (McGlade, 2015). However, these technologies will allow greater use of these resources than if they are not deployed. This could help prolong the current industry during the transition to a low carbon economy.

The key commodity growth opportunity that could enable Australia to utilise its vast resources (e.g. coal, solar) to export low or zero emissions energy is low emissions hydrogen. For the Japanese market alone, this opportunity could be worth $1-4 billion per year.[79] Note that while the revenue derived from hydrogen (~$22m/PJ) on an energy equivalent basis is less than LNG (~$55m/PJ), this could change if demand for low emissions hydrogen increases. Furthermore, hydrogen provides a means to diversify Australia's energy exports.

Key supply chain opportunities for Pathway 3 are set out in Figure 48 below. Details on how the opportunities were evaluated and the criteria for high, medium and low classifications are given in Appendix B of the LETR Technical Report.

BOX 12 | CASE STUDY

Low emissions hydrogen for export

Feasibility studies into two potentially large-scale low emissions hydrogen export projects are currently underway.

Kawasaki Heavy Industries is seeking approval to test the viability of establishing a supply chain for hydrogen energy production, transportation and storage between Australia and Japan. The Australian components of the supply chain would include (1) the conversion of brown coal to hydrogen gas in the Latrobe Valley, (2) liquefaction of the gas in the Port of Hastings area and (3) loading and shipping the liquefied hydrogen to Japan via a new range of seaborne liquid hydrogen carriers. If the testing proves successful, a commercial facility may be established to produce low emission hydrogen requiring significant investment and local employment. Critical to this is the application of CCS.

'Renewable Hydrogen' is another company currently assessing the feasibility of large-scale hydrogen production, in this case via electrolysis in the Pilbara. The intention is to build a solar farm that feeds directly into a series of electrolysers in order to produce zero emissions hydrogen. The system would be built adjacent to the Yara Pilbara Fertilisers plant where hydrogen can be converted into ammonia, a suitable carrier for long distance transport (i.e. shipping to Japan). The ammonia could then be converted back to hydrogen for use at the end of the supply chain.

[80] This assumes that Australia's hydrogen exports to Japan reach between 4-20% of current LNG exports (by PJ). The lower end represents the amount targeted by KHI's Hydrogen Energy Supply Chain (HESC) project. Assumed hydrogen price is $3/kg.

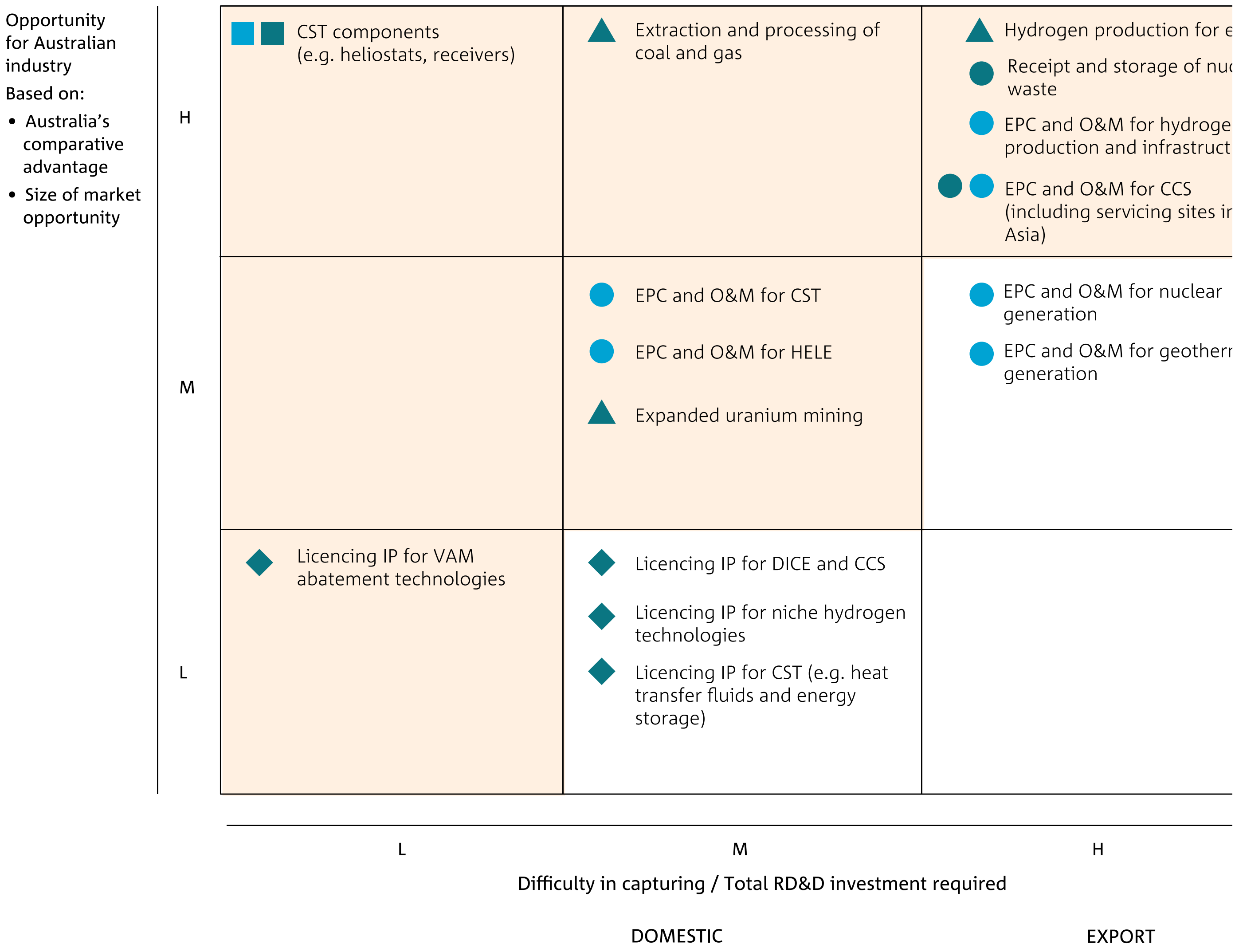


Figure 48. Key supply chain opportunities for Pathway 3

Appendix D

PATHWAY 4: ‘Unconstrained’

D.1 Introduction

Pathway 4: Unconstrained is a scenario in which it is assumed that all the key technology options are available to meet emissions reductions, i.e. ambitious improvements in energy productivity as per Pathway 1, no limits to deployment of VRE as per Pathway 2 and no limits to the dispatchable power generation technologies mentioned in Pathway 3, as well as hydrogen for transport and export.

The description of the relevant technologies, as well as the relevant barriers, enablers and supply chain opportunities are discussed in the appendices for the other pathways. Insights related to Pathway 4 are discussed along with those for the other Pathways in Section 3. Technology uptake and emissions impact for electricity generation and transport are described below. Direct combustion and fugitive emissions results are similar to Pathway 1.

■ Focus for discussion in this appendix

	1 PATHWAY 1: Energy productivity plus	2 PATHWAY 2: Variable renewable energy (VRE)	3 PATHWAY 3: Dispatchable power	4 PATHWAY 4: Unconstrained
Buildings, industry and transport	**Ambitious energy productivity improvements**	**Business as usual energy productivity improvements**		**Ambitious energy productivity improvements**
			Hydrogen for transport and export	
New build electricity generation	**Existing low emissions technologies**: wind, solar PV (45% limit) plus gas	**Cheap, mature, low emissions generation:** mainly wind and solar PV **plus enabling technologies** e.g. batteries pumped hydro	Wind and solar (45% limit) plus **low emissions, dispatchable generation**: • Concentrating solar thermal with storage • High efficiency, low emissions fossil fuels with carbon capture and storage • Nuclear • Geothermal	**All low emissions technologies allowed, with no limit on wind and solar PV**
Fugitive emissions	**Uptake of cost-effective technologies**			

D.2 Technology uptake and emissions impact

D.2.1 ELECTRICITY

Pathway 4 electricity generation mix is shown in Figure 49 below.

As is the case in Pathway 2, electricity sector abatement in Pathway 4 is largely driven by an increased uptake of VRE. Average annual capacity additions to 2030 for rooftop solar PV, large-scale solar PV and wind are 1.2 GW, 0.3 GW and 0.4 GW respectively.

High energy productivity has also contributed by lowering grid electricity demand (as with Pathway 1), while hydrogen production increases total electricity demand from around 2035. Similar to Pathway 1, both black and brown coal-fired power are phased out later than in Pathways 2 and 3, since 2030 electricity sector abatement is lower in Pathways 1 and 4 than in Pathways 2 and 3.

Again, gas is deployed in order to facilitate the transition away from coal-fired generation. New gas combined cycle capacity is added at an average rate of 0.4 GW from 2030 to 2045. However, as more stringent emissions targets apply, this is displaced by gas with CCS in 2041, with an average of 0.7 GW added each year to 2050.

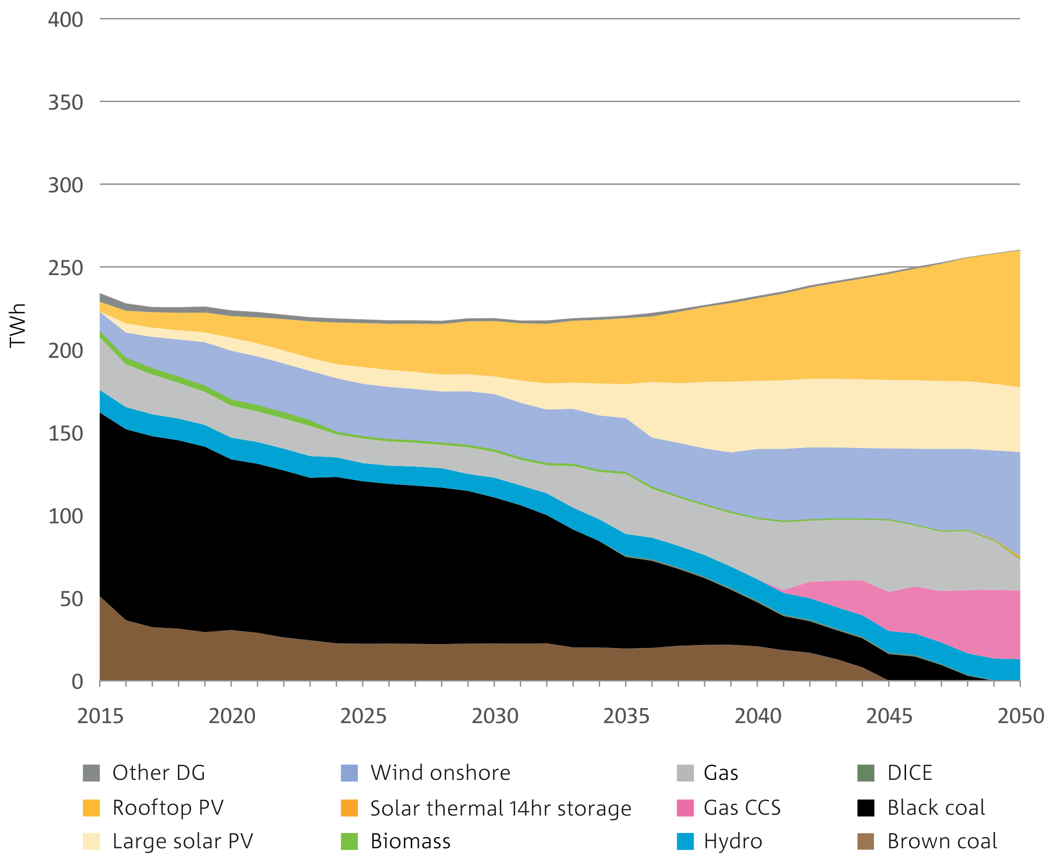


Figure 49. Pathway 4 electricity generation mix

D.2.2 TRANSPORT

Projected fuel use in light and heavy vehicles for Pathway 4 are shown in Figure 50 below.

In Pathway 4, hydrogen FCVs and EVs follow a similar trajectory as a proportion of total use within the light and heavy vehicle market as that seen in Pathway 3. Overall however, total usage is less due to less demand for transport as a consequence of higher energy productivity (e.g. including demand reduction driven by factors such as teleconferencing) as in Pathway 1. For the light vehicle market, hydrogen FCV and EV energy use reaches 50 PJ and 101 PJ respectively in 2050. For heavy vehicles in 2050, hydrogen use reaches 28 PJ and EVs energy uses reaches 11 PJ.

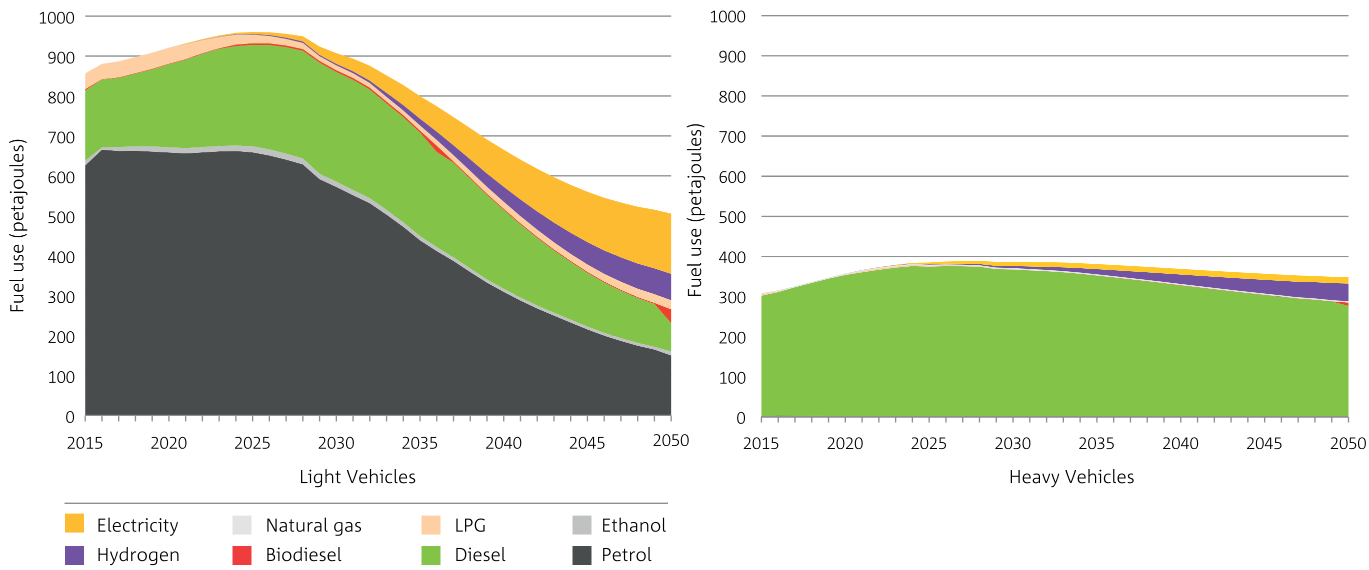


Figure 50. Projected fuel use in light and heavy vehicles in Pathway 4

Appendix E

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Clean Energy Regulator
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Department of Foreign Affairs and Trade
Department of Defence
Department of Industry Innovation and Science
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