Australian Energy Transition Research Plan

REPORT THREE

Energy System Dynamics

ACOLA RESEARCH BRIEFING PAPER

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ACKNOWLEDGEMENT OF COUNTRY

ACOLA acknowledges all Aboriginal and Torres Strait Islander Traditional Custodians of Country and recognises their continuing connection to land, sea, culture and community. We pay our respect to the Elders both past and present.

Australian Energy Transition Research Plan

The Australian Energy Transition Research Plan developed by ACOLA identifies three Research Priorities: Energy System Dynamics, Social Engagement Dynamics and Transition Dynamics. This Energy System Dynamics research briefing paper is the first of three reviewing existing research and exploring research opportunities for the energy transition in Australia.

1. Introduction

The energy system dynamics research theme encompasses the technologies that we will need, how they will be integrated, and the pathways for their deployment and the associated retirement of legacy energy systems.

This Energy System Dynamics research briefing paper is the first of three reviewing existing research and exploring research opportunities for the energy transition in Australia. The three Research Priorities of Energy System Dynamics, Social Engagement Dynamics and Transition Dynamics were identified in The Australian Energy Transition Research Plan (Research Plan) developed by the Australian Council of Learned Academics (ACOLA). This paper discusses the technologies required to support the transition, how they will be integrated, the pathways for their deployment, and the associated retirement of legacy energy systems.

Australia is well-positioned to benefit from innovation in low emissions technologies and to become a significant exporter of hydrogen, low- and zero-emissions metals, and critical minerals. However, existing policies are insufficient, and governments have a critical role in removing regulatory barriers for innovation and investment and addressing other obstacles for competition. There is a vital need for a better understanding of the window of opportunity for different energy storage technologies to compete with falling battery prices, as highlighted by the Australian Low Emissions Technology Roadmap (LETR).

Researchers play a critical role in modelling feasible scenarios for transition pathways for reaching net-zero by 2050. This requires defining specific criteria and accounting for key uncertainties with quantitative and qualitative methodologies.

Understanding the societal, economic and environmental impacts of these pathways will require the development of comprehensive indicators and other measures of success in the transition. There are many unknowns regarding the scaling conditions of different pathways, with research required to understand optimal technology scaling levels and identify the support needed to achieve it.

Systems integration has been extensively investigated in domestic and international literature given the urgent need to integrate Variable Renewable Energy (VRE) into the grid. Yet the interactions between multiple technologies must be investigated in more detail to maintain quality, flow, stability and balance. Though the Australian renewable energy industry has been progressing rapidly, it will need to overcome ongoing grid connection and transmission challenges. Research is required to understand how much the existing infrastructure can support the transition, and how to allocate investment to overcome these challenges. If integrated well, digital emerging technologies have great potential for both consumers and the power network, though more research is needed to mitigate their associated technical, social and security concerns.

In pursuing research on Energy System Dynamics, a mix of urgent and more strategic local and international research across all of the disciplines will need to be pursued, including multidisciplinary and interdisciplinary considerations. The energy transition needs to happen at a rapid pace and scale, and insights derived from this project and the Research Plan will provide critical knowledge for further and future domestic and global transitions.

2. Discussion of the Identified Research Priority

Following extensive consultation with stakeholders, ACOLA released the Research Plan (Report One). The Research Plan identified key research priorities for Australia's energy transition. These priorities offer those in the research ecosystem guidance on where and what research is being undertaken and what critical research is not being done, in order to direct efforts and funding to high priority areas. The key research priorities are organised into three themes consisting of three topics, with each topic consisting of three high-level driving questions for research over the next decade. These are classified as urgent (where robust answers are needed in the near future) or strategic (where robust answers are required in the longer term).

Three theme papers expand on each research priority from the Research Plan, taking a deep dive into the high-level driving questions. From these, the papers present a review of the existing Australian and international research base, noting critical research gaps, and highlighting where Australia must accelerate or establish research efforts for a successful transition.

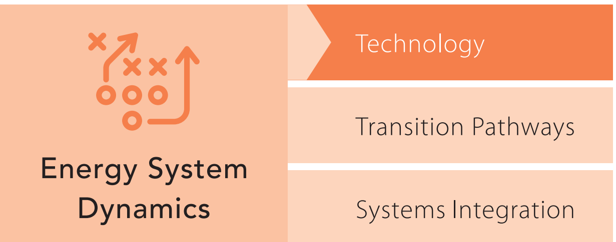
Further specific research questions are developed from each high-level driving question. The framing high-level questions from the Research Plan are highlighted in boxes. The additional research questions for each of the topics are highlighted throughout, and gathered at the conclusion of the paper.

This research theme, Energy System Dynamics, consists of the topics technology, transition pathways and systems integration. These encompass the technologies that we will need, how they will be integrated, and the pathways for their deployment and the associated retirement of legacy energy systems.

3. Literature Review

Domestic and international government bodies are the clear top-down drivers of energy policy settings and, therefore, any transition; however, industry, businesses and community exert important action from below. As seen in recent years, such as with banks declining to finance new coal mines and consumer buying patterns, non-government players can significantly influence the development of renewable energy policies. Indeed, their actions can enable, focus, motivate and drag political (in)action.

This paper aims to review the ongoing research in Australia, identify research gaps, and recognise what opportunities can be provided if Australia pursues research in this area.



3.1. Technology

3.1.1. Policy framework

> How might technology policies in Australia be further developed – for example with additional or alternative energy technologies, energy efficient mechanisms R&D programs, industry participation, or deployment support mechanisms – as our transition pathway evolves over time?

A critical element for the energy transition is the development and diffusion of clean technologies, known as eco-innovation, with simultaneous and coordinated withdrawal from carbon-intensive technologies based on fossil fuels. This process is delayed by many barriers, relating both to innovation and technological change, and to environmental externalities.

One of the most salient barriers to low-carbon innovation is the financing environment (Iyer et al., 2015; Polzin et al., 2016). Government incentives for innovation are therefore essential to stimulate investment by companies, covering part of their R&D costs and minimising their financial risks. There is, however, limited understanding of how innovation incentives are perceived by companies. Interviews in Australia show there is no specific promotion body or national-scale campaigns to inform firms about the existing innovation incentive schemes, besides some professional magazines, newspaper articles, and online blogs (Yigitcanlar et al., 2019). Direct incentives are seen as critical for increasing innovation capabilities of firms, while tax incentive and infrastructure development schemes are the most preferred incentive programs. On the other hand, the effectiveness of existing incentive programs has been marginal. There is a need for a wider understanding of the benefits of supportive policies on enhancing innovation capabilities.

RQ: What are the most effective incentive mechanisms for stimulating technological innovation in Australia, and how can they be leveraged (further) in energy transition research?

Australia is well-positioned to benefit from innovation in low emissions technologies. In 2017, the Commonwealth Scientific and Industrial Research Organisation (CSIRO) was engaged by the Australian Government to develop the Low Emissions Technology Roadmap (LETR) and identify technology options at Australia's disposal to meet its emissions abatement commitments under the 2015 Paris Agreement as well as provide new economic opportunities for Australian industry (Campey et al., 2017). The roadmap recognised both financial and non-financial barriers to investment that can slow the adoption of new technologies, including technical, social and stakeholder barriers. The key barrier, namely the risk to investors of deploying low emissions technology in favour of higher emission alternatives, is most critically addressed by government policies (Campey et al., 2017).

Post Paris, the Australian governments have implemented a range of policies to overcome investment barriers of present policies and institutions, such as the Clean Energy Finance Corporation (CEFC), Australian Renewable Energy Agency (ARENA) and State and Federal Renewable Energy Targets. While the CEFC's focus[i] has been progressive, aside from capital provision and de-risking there is also a much broader role needed to catalyse private investments into low-carbon investments (Geddes et al., 2018). It has been suggested that mechanisms, and potentially the CEFC, should focus on enabling financial sector learning, creating trust for projects and taking a first- or early-mover approach to help projects gain positive track records.

Considering the rapid development of technologies, 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 required rate.

Australia has a number of opportunities for large-scale land-based deployment of negative emission technologies (NETs) with the potential to help meet national and international greenhouse obligations and build new low-carbon industries. Amongst land-based NETs, carbon capture and storage (CCS) developments are attractive because of the abundance of geological storage sites in Australia (Cook and Arranz, 2019). CCS has been demonstrated as an operational mitigation technology that is deployable now, but costs and the lack of policy drivers currently limit uptake (Global CCS Institute, 2019). Progress in the large-scale deployment of CCS in Australia has been slow, but there are future options for research and clean energy opportunities, such as the conjunctive use of the subsurface for clean energy (Cook, 2017). In addition, Bioenergy with CCS (BECCS) is technically viable now, but upscaling will be a challenge while avoiding competition with other land uses, notably food crops.

One of the world's largest storage project is in Western Australia as part of the Gorgon liquefied natural gas (LNG) project. Investigations are also underway into several large-scale CCS Flagship program opportunities. The Cooperative Research Centre for Greenhouse Gas Technologies (CO2CRC) Otway Project continues to be Australia's most significant collaborative CCS R&D initiative. In the future, direct air capture, which is the process of extracting CO_2 directly from the atmosphere, is anticipated to play a greater role in helping meet net-zero targets. More large-scale demonstrations are needed to refine this technology and reduce the capture costs (International Energy Agency 2021).

RQ: How can the current main technical and non-technical barriers for the uptake of negative emission technologies be overcome?

Renewable power-to-X (P2X) is emerging as a viable platform for storing excess renewables for subsequent dispatch for end-use as well as providing a low capital-intensive decarbonisation pathway to produce green fuel and chemicals. In P2X, "excess" and underutilised solar and wind resources are used to power technologies that can convert available abundant molecules such as water into hydrogen, or carbon dioxide and water to methane, syngas and oxyhydrocarbons. These energy carriers and chemical products can provide flexibility in renewable energy storage, transport, and subsequent conversion to decarbonise energy infrastructure (Daiyan et al., 2020). There are also numerous advantages to P2X storage compared to current alternative energy storage systems being trialled, such as battery and pumped hydro, which are scale-, time-, and site-specific and cannot be used to transport energy over large geographical distances.

The P2X challenge needs to be approached as an overall system solution for energy generation, storage and usage. The potential economic benefits of P2X is increasingly well-recognised by governments and industry, notably by companies engaged in the fossil fuel industry and its derivatives who are at the forefront of global decarbonisation efforts. Yet, more investigations are needed to identify the broader opportunities and benefits that are associated with the expansion of P2X technologies.

i The CEFC has focused on large-scale solar PV, onshore wind, waste-to-energy, bioenergy, energy efficiency, small-scale renewables and low emissions vehicles.

RQ: How can an holistic approach to combining renewable power-to-X and electrification be used to improve the effectiveness of the energy transition?

International cooperation can accelerate innovation beyond the capabilities of a single nation. For example, the Global Powers System Transformation Consortium aims to accelerate decarbonisation and its mission and activities are being developed by chief executive officers of grid system operators in Australia, the United Kingdom, Denmark, Ireland, Texas and California. These system operators are leading a Research Agenda Group to identify the common, cutting-edge research questions which can be used to inform large-scale national R&D investments (Global PST Consortium 2021). International collaboration allows nations to pool costs, and this can enable projects of greater scale, lessen duplication and integrate regional capabilities. International collaboration can help harmonise technical standards (Sivaram et al., 2020), and be particularly appropriate for emerging technologies as it can support knowledge diffusion and resource sharing (Victor et al., 2019). Yet, there are still barriers: collaborators must negotiate rights before outcomes are known, partners may lack trust, and domestic political support can fluctuate (Chan et al., 2017). Face-to-face interactions, long-term strategies and well-designed management plans are essential to facilitating effective collaboration. More research is needed to better understand how international collaboration can be effectively incentivised and the role of global industry players in driving this collaboration.

RQ: How can international collaboration be further incentivised to integrate regional specializations, and to expedite the innovation of new clean technologies?

3.1.2. National advantage

> Where does Australia have a competitive or comparative advantage in clean energy technology research and development, and how can this be exploited to support the energy transition?

While Australia has some of the world's most abundant and diverse renewable resources, particularly given our population, land area, critical minerals, strong skills and research capability, there is limited literature on Australia's comparative or competitive advantage. Government-commissioned studies provide some insights into technologies Australia could leverage for domestic application or international leadership, especially in critical minerals and hydrogen.

It is anticipated that a global hydrogen market could develop over the next 20 years and there is scope for Australia to become a significant exporter (ACIL Allen Consulting, 2018). Japan, Republic of Korea, Singapore and China are predicted to be key markets, and while Australia's proximity to these markets is advantageous we will need to address key barriers to compete against other likely key initial suppliers, i.e. Norway, Qatar, Chile and the USA. Our nascent capacity and capability in renewable energy, co-location with world class mineral deposits for ore reduction using hydrogen, a highly-educated labour force, experience in export infrastructure, proximity to key markets (low transport costs – particularly to the Asia-Pacific), access to overseas capital for energy investment, and the existence of established trading relationships, position Australia strongly. It will be critical that Australian governments take actions to rapidly remove market barriers to efficiently build supply and demand and accelerate Australia's hydrogen industry, as the technology matures and other countries become more competitive. With Australia's new National Hydrogen Strategy identifying seven key areas of action, focused research on policy setting that can lead to long-term comparative advantage for Australia will be critical.

According to IEA (2019), harmonisation of regulations is currently limiting the development of a clean hydrogen industry – in particular the development of an agreed hydrogen emissions certification scheme. As a result, project developers face hurdles where regulations and permit requirements are unclear, unfit for new purposes, or inconsistent across sectors and countries. Sharing knowledge and harmonising standards is key, including for equipment, safety and certifying emissions from different sources. Hydrogen's complex supply chains mean governments, companies, communities and civil society need to consult regularly.

Government and industry must work together to ensure existing regulations are not an unnecessary barrier to investment. Trade will benefit from common international standards for the safety of transporting and storing large volumes of hydrogen and for tracing the environmental impacts of different hydrogen supplies.

RQ: What are the efficient, effective and responsive regulations needed to support investment in low carbon technologies?

Australia has an opportunity to use renewable energy to make energy-intensive goods for export. The energy required to make some materials, including many metals, represents around one-third of the costs of production. This abundance of low-cost renewable energy gives Australia a competitive advantage to potentially produce low- and zero-emissions metals, such as green steel. However, these opportunities need to be pursued quickly before costs are sunk in processing facilities in other locations (Burdon et al., 2019).

RQ: What is the most effective role and mechanisms for state, territory and federal governments to enable Australia to become a leader in producing low and zero emissions metals?

Australia benefits from an abundance of largely untapped natural resources and critical minerals, such as lithium and rare earths (Campey et al., 2017). These could be leveraged to add value to basic resources, e.g. materials for batteries, and harnessed for new industries based on clean energy resources, e.g. the export of low emissions hydrogen. However, as stated in the Australian Energy Transition Research Plan (Clarke et al., 2021), energy leaders such as the US, China, UK and the EU continue to invest substantially in their technological and research capabilities and will play a key role in shaping market forces in the new energy economy. Australia should expand the support, and focus on building research competencies in areas where we have a comparative advantage, in addition to solving our unique domestic challenges.

RQ: What targeted programs and international collaboration opportunities are needed to avoid missing opportunities arising from demand for Australian critical minerals?

3.1.3. Research focus

> What are the specific core, niche or enabling technologies where Australia should make a concentrated research effort (should our energy technology research effort be more specialised)? How can this adapt to consider international developments?

Technology research priorities has been mostly investigated in non-academic literature by governments, most notably in Australia through the LETR, following extensive consultation with technology experts, industry, government and non-government organisations. Three groupings of low emission technologies had been identified in 2017 (Campey et al.):

- Energy Productivity (technologies across buildings, industry and transport sectors)
- Low Carbon Electricity (Variable Renewable Energy (VRE), Energy storage, smart grid technologies, Microgrids, CST, high efficiency low emissions fossil fuel generation (HELE), biomass, Nuclear and Geothermal), and
- Other (hydrogen and fugitives)

Then, the Low Emissions Technology Statement identified Australia's big technology challenges and opportunities, as well as priority low emissions technologies to include clean hydrogen, energy storage, low carbon materials such as steel and aluminium, CCS and soil carbon (Department of Industry Science Energy and Resources, 2020), and in 2021, ultra-low cost solar (Department of Industry, Science, Energy and Resources, 2021)

In line with the 1st Low Emissions Technology Statement, ARENA defined four strategic priorities (ARENA, 2020):

- Optimise the transition to renewable electricity through investment in technologies that enable ultra low-cost generation, support flexible demand, improve the economics of energy storage and optimise large-scale integration of renewable energy
- Commercialise clean hydrogen, by supporting research, development and deployment of technologies that drive both domestic and export applications of clean hydrogen

- Transition to low emissions metals by focusing on the steel and aluminium value chains
- We will develop our approach to scaling up carbon capture and storage (CCS) and reducing the cost of soil carbon measurement, through consultation with industry, researchers and the Government. In line with the second Low Emissions Technology Statement, ARENA (2021) adopted the 30/30/30 target for ultra-low cost PV, aiming for solar PV to achieve 30% efficiency at 30% installed watt by 2030.

ARENA's support for research through all Technology Readiness Level (TRL) stages and via a range of programs and investment instruments means it has built up considerable expertise in incentivising and financing projects with strong industry link and impacts beyond research excellence. In 2017, ARENA investigated the domestic and global solar research, development and demonstration (RD&D) sector (ARENA, 2017). They sought to identify the highest-priority RD&D needs to accelerate the competitiveness of solar energy in Australia, and the most efficient investment approach to maximise research outcomes and economic and social returns. These include a mix of long-term academic research to identify future step changes in technology, depending on TRL stage, and near-term commercialisation research to underpin the transition from the laboratory to market adoption.

RQ: How should research, development and demonstration priorities be coordinated with the technology readiness level of low emissions technologies?

Energy storage systems (ESS) are one of the main pillars for a renewable-based energy system that help to increase system reliability by the temporal decoupling of electricity demand and supply. Numerous technologies are available for this purpose, each with individual characteristics to match the different economic and technologic requirements of the envisaged application or social acceptance (Baumann et al., 2019). As noted in the ACOLA Energy Storage paper (Godfrey et al., 2017), Australia can lead the world in developing and commercialising an integrated supply chain from mining to waste management of energy storage technologies.

In order to achieve this, leadership by governments will be required to support innovation, investment and the growth of high-tech industries to drive translation and commercialisation of research.

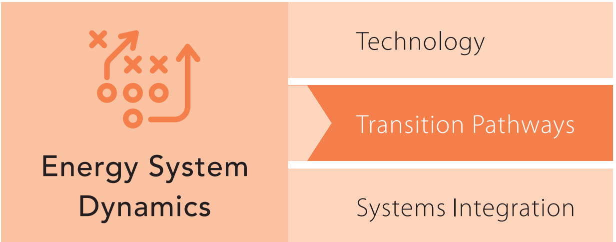
Currently, pumped hydro and lithium-ion batteries are considered the most mature technologies, with renewable hydrogen rapidly emerging as another important technology. Other means of storing energy include solar thermal storage and electrical thermal storage (Porteous et al., 2018). Choosing a suitable storage alternative is a problem that involves multiple stakeholders, often with diverging objectives that cannot be fulfilled by a single technology.

RQ: How can the mix of storage technologies with different scales and storage timeframes be integrated with renewable energy and transmission systems to optimise electricity supply and guarantee grid stability and economic growth?

RQ: What is the time window of opportunity for different energy storage technologies to compete with falling battery prices and how can findings assist investors and policy makers?

Australia has considerable wave and tidal ocean energy resources. Development of the emerging ocean renewable energy (ORE) industry in Australia offers opportunities to build Australia's blue economy, while actively contributing to committed carbon mitigation measures. Many interdisciplinary challenges are currently hampering development of the industry in Australia and globally, including technology, cost reduction, policy and regulations, potential for environmental effects, awareness and investment, amongst others. In October 2016, ORE technology and project developers, researchers, academics, policy makers and other stakeholders in Australia's emerging ORE industry came together to identify the challenges and possible pathways to grow ORE in Australia. Four themes were identified: Technology Development; Education and Awareness; Policy and Regulation; and Finance and Investment. A key element identified across all themes was the need for stronger coordination across the sector, and the need for a representing body to lead necessary initiatives to support growth and management of the ORE industry in Australia, as one element of a growing blue economy (Hemer et al., 2018).

RQ: Given concerns about land-based wind, what is needed to ensure Australia can efficiently and effectively implement ocean renewable energy (offshore wind and ORE), especially to manage technical, environmental and social acceptance issues?



3.2. Transition pathways

3.2.1. Scenarios

> What are the main feasible transition pathways, and where are the greatest uncertainties, based on current knowledge and forecasts?

Despite the inherent uncertainty and complexity of the emissions-reduction challenge, it is useful to employ a range of scenarios to explore the impact of different transition pathways and help to ensure that strategies are robust and resilient. Scenario analysis has been extensively used to test different transition pathways in the literature both at national and global context. Traditional strategic planning approaches fail to address the complexity of long-term energy transitions, as they have a predictive, deterministic, and reactive standpoint to future issues (Moallemi and Malekpour, 2018). Conventional modelling approaches are perceived to be inadequate, since they often simplify the qualitative characteristics of transitions and cannot cope with deeply uncertain futures. There is a need to better integrate qualitative, participatory modelling with quantitative approaches, to enable decision-makers to test various policy interventions under numerous possibilities.

RQ: How can qualitative participatory and quantitative modelling approaches be effectively integrated to identify feasible transition scenarios?

The scenarios generated by energy systems models provide a picture of the range of possible pathways to a low-carbon future. However, in order to be truly useful, these scenarios should not only be possible, but plausible. Diagnostic tests have been established to assess the feasibility of energy transition scenarios, with key criteria of the rate of deployment of low-carbon technologies, and the rate of switch between primary energy resources.

In 2014, as part of the global 2050 DDPP, Climateworks and the Australian National University published 'Pathways to Deep Decarbonisation by 2050: How Australia can prosper in a low carbon world' (ClimateWorks Australia et al., 2014), exploring in an Australian context:

- Ambitious energy efficiency: in all sectors leads to a halving of the energy intensity of the economy.
- Low carbon electricity: Low carbon electricity is supplied by renewable energy or a mix of renewable energy and either CCS or nuclear power at similar costs.
- Electrification and fuel switching: from fossil fuels to bioenergy, and from coal and oil to gas reduces emissions from transport, industry and buildings.
- Reducing non-energy emissions: are reduced through process improvements and CCS in industry, while a profitable shift from livestock grazing to carbon forestry offsets any remaining emissions.

As an update to the earlier work, Decarbonisation Futures (ClimateWorks Australia, 2020) provides a guide for Australian government and business decision makers on priority technologies, deployment pathways and benchmarks for achieving net zero emissions. The report identifies priority technologies and actions for achieving net zero emissions across all sectors of the Australian economy (Figure 1). They acknowledge there are still significant uncertainties regarding the potential and impacts of emerging technologies. For example, the adoption of automated vehicles across the transport sector is very hard to predict (ClimateWorks Australia, 2020).

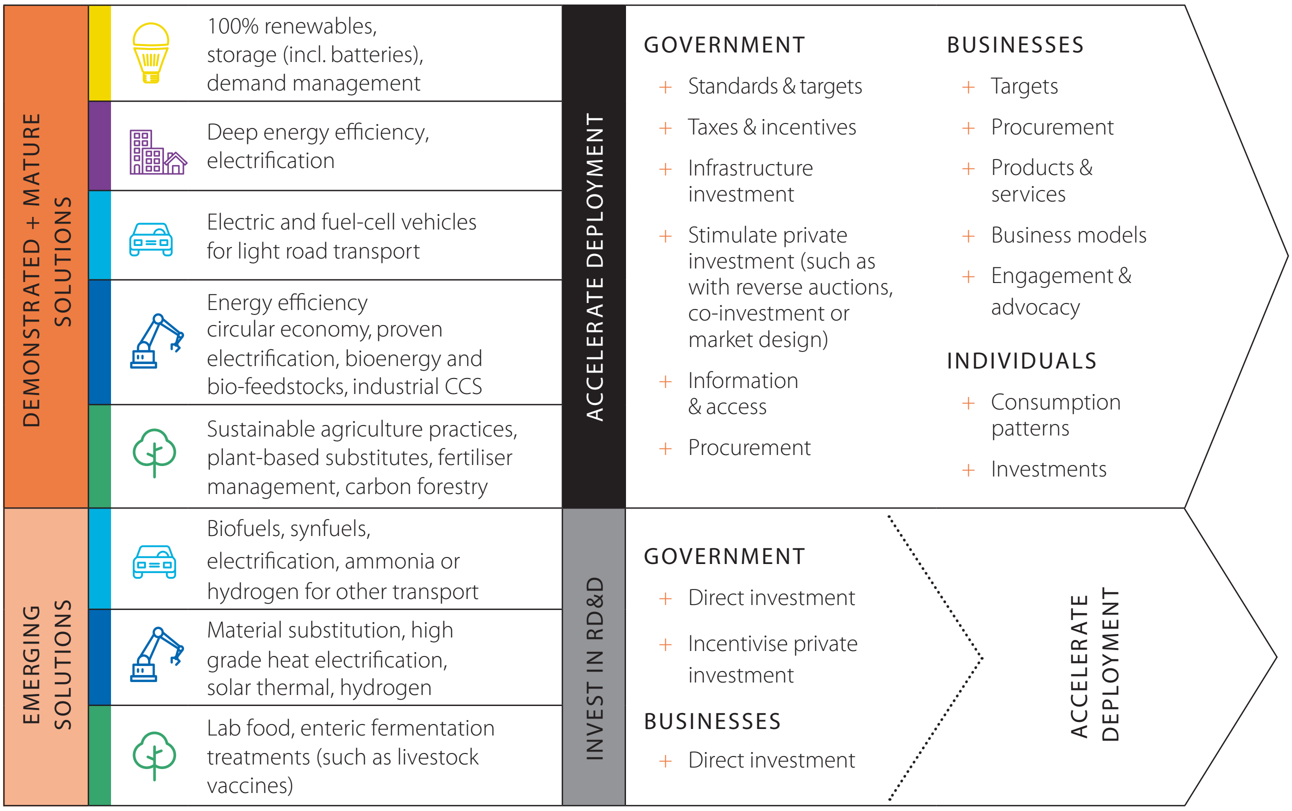


Figure 1: Summary of solutions and actions to support a transition aligned with the Paris goals

Another key factor affecting the list of solutions is the uncertainty in projecting the costs of renewable energies in the future. While forecasting methods outperform elicitation methods, both underestimated technological progress in almost all technologies, likely as a result of structural change across the energy sector due to widespread policies and social and market forces (Meng et al., 2021). Close consultation with a broad range of energy stakeholders will be critical to the selection of solutions and actions, and cannot be assumed.

RQ: How should the process of selecting solutions and actions be improved to account for the uncertainty in the capacity of emerging technologies?

In Australia, the Australian Energy Market Operator (AEMO) plays a key role in modelling scenarios. For example, AEMO (2020b) developed the Integrated System Plan (ISP) using cost-benefit analysis, and detailed engineering analysis. The model provides an integrated roadmap for the development of the National Electricity Market over the next 20 years and beyond and seeks to minimise the combined cost of generation and transmission investment. AEMO has also collaborated with CSIRO on the GenCost project which delivers an annual process of updating power generation and storage costs with a strong emphasis on stakeholder engagement (Graham et al. 2021). Despite these efforts, further work is still needed to derive realistic scenarios for future power generation, transmission, distribution and consumption.

RQ: How can existing planning tools be expanded to derive realistic scenarios for future power generation, transmission, distribution, consumption and optimal scaling levels of energy storage and investment needed to guarantee grid stability and economic growth?

3.2.2. Pathway implications

> What are the costs, benefits, impacts and risks to the Australian economy, society and environment of these pathways (what parts are most difficult, how important are clean energy exports, do we have comparative advantages)?

In order to achieve a successful transition, it is critical to develop indicators to assess progress. Work by Saddler (2021a) identified a set of four national-level indicators to quantify the progress of Australia's energy system transition, covering: emissions, energy supply, energy consumption, and the changing mix of fuel types and energy using technologies. In considering these, it is clear that a transition of electricity generation from almost exclusive reliance on coal towards a mix of lower emissions technologies is well underway. On the other hand, no significant progress has been made in transitioning energy used by transport and other mobile equipment; reliance on petroleum fuel remains and emissions are increasing steadily every year. Another key indicator of a successful transition could be the cost of energy associated with the transition pathway. There is a need for more research to be undertaken to figure out what indicators should be developed.

RQ: What set of indicators should be developed/ utilised to assess the successfulness of energy transition pathways in Australia?

Most countries, states/provinces and businesses around the world are already transitioning in some form towards clean economies, with governments recognising the opportunities and benefits. Even when disregarding the benefits of emissions reductions from a climate mitigation point of view, the economic benefits of the transition generously outweigh the cost (Kompas et al., 2019). Other co-benefits, beyond emissions reductions, include:

- access to more affordable investment capital
- enhanced agricultural productivity
- reduced energy use and costs for households and businesses
- improvements in biodiversity
- improved urban air quality
- improved comfort and lower health risks
- commercial benefits from developing and selling emissions reduction technology.

Recent literature on energy transitions from fossil fuel to renewables is focused almost exclusively on the technological, environmental and economic outcomes, with limited concern for social impacts (Chapman et al., 2018). Various indicators of social equity were assessed to prioritise the retirement and replacement of Australia's ageing fleet of coal-fired power plants. The assessment shows that from the cost and social equity perspectives, the retirement of the large brown coal power plants, including the recently retired Hazelwood power plant, and their replacement, where applicable, with wind power, provides the best overall outcomes.

In a comparison of the performance of Australia's energy transition with 23 other comparable countries (Saddler, 2021b):

- Australia was one of only three countries in which emissions from energy use actually increased between 2005 and 2019.
- Despite a growing population and a growing economy, in 2019, Australia had the second highest energy emissions per capita and GDP, behind the USA and Russia respectively.
- Emissions intensity of Australia's energy system in 2019 was second highest to Poland, primarily because both countries were, and still are, heavily reliant on coal for electricity generation and also, to some extent, for supplying industrial heat.
- Australia also performed poorly in terms of transport emissions per capita (22nd out of 24) and has only reduced these emissions by 1% since 2005.
- Australia is unique in being the only country of the top energy consuming nations to have exhibited an increase in energy use per person over the period 2005-2019.

Energy scenarios and national policies usually overlook impacts to the international environment. The manufacturing, maintenance and development phases are often not fully accounted for in decision-making. There is a need for frameworks such as the life cycle analysis (LCA) which considers the full range of impacts caused by each stage, from raw material extraction, manufacturing to decommissioning (Lovett et al., 2015). This should then be considered alongside other assessments, such as Environmental Impact Assessments and Strategic Environmental Assessments, to identify the full likely environmental impacts of energy development projects (Delafield et al., 2021).

RQ: What tools and methods are needed (such as Life cycle analysis) to comprehensively evaluate the broader environmental impacts of energy technologies and systems at local, regional and national scale?

The impact of climate variability and change (CV&C) has an associate risk on the future energy system. Analysis indicates that although energy demand is likely to increase threefold in the business-as-usual scenario, CV&C further increases demand to 150 petajoules for commercial buildings by 2050 (Vincent et al., 2019). However, a shift to electric and hydrogen fuel cell vehicles results in a 49–53% decrease in transport fuel demand and emissions. As expected, due to CV&C impacts, generation costs are projected to increase, while revenue can decline, while higher renewable energy integration can lower electricity prices. More importantly, by ignoring the influence of CV&C, we can face underestimation of future energy demand and installed capacity in Australia. Yet there are considerable uncertainties associated with CV&C and their non-economic risks to the whole energy system and clean energy export.

RQ: What are the major risks (financial and non-economic) for the Australian energy system due to climate variability and change, and what measures are necessary to mitigate the risks?

3.2.3. Scaling conditions

> How will we reach the social, technical and economic conditions required for a successful transition of this scale? What are the scaling, economic adjustment and capital mobilisation issues?

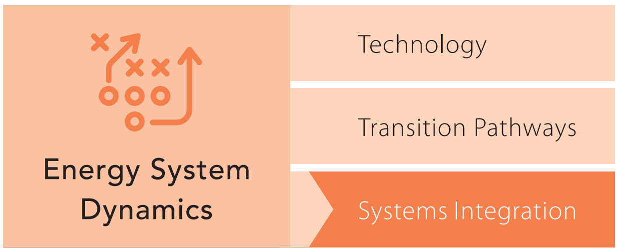
Work by the Australian-German Energy Transition Hub (Ueckerdt et al., 2019) concluded that Australia could run entirely on renewable electricity and produce double what it needs to create a massive green export industry by 2050. Currently, the Australian transition to renewable electricity is largely driven by market forces, in particular investment in cost-competitive renewables. However, regulatory reform and policy will be needed to facilitate a true transformation of energy supply.

RQ: How should the regulatory framework be improved to facilitate the scaling up of renewable investment?

The South Australian Government predicts the state could boast more than 500 per cent renewable energy by 2050 as it becomes a national and international exporter of clean energy (Government of South Australia, 2020). The Government plans to continue working with industry and energy operators to get the renewable electricity supply mix right and to support grid stability and economic growth.

Scaling up institutional investment in renewable energy requires a comprehensive effort on multiple fronts. Renewable assets generate significant social and economic benefits, and lower the risks of climate change and adverse regulatory actions. But they also come with their own risks that need to be mitigated. Meanwhile, many institutional investors operate within regulatory frameworks and capital markets that are not conducive to renewable investment (IRENA, 2020). Therefore, there is a need for new models of financing and investment. A comparison of the operation of 'alternative' forms of finance in national energy investment landscapes, focusing on the UK and Germany, suggested six principles key to 'just' energy finance: affordability, good governance, due process, intra-generational equity, spatial equity, and financial resilience (Halle et al., 2018).

RQ: How can the Australian, state and territory governments alleviate the challenges associated with massive capital mobilisation while ensuring that energy financing is just?



3.3. System integration

3.3.1. Integration

> What are the critical system integration issues for low/zero/negative emission energy technologies across sectors (including social, economic and technical considerations), and do we have the necessary interdisciplinary capabilities to address them?

Work by Australia's former Chief Scientist, Dr Alan Finkel AO, identified that the National Electricity Market (NEM) must focus on four key outcomes: increased security, future reliability, rewarding consumers, and lower emissions. These outcomes underpin the pillars of an orderly transition, better system planning and stronger governance (Finkel et al., 2017).

Variable renewables energies (VRE) such as solar photovoltaics and wind power are key to achieving the decarbonisation of the power sector. However, they differ significantly from conventional power generation sources, and as their share increases it can lead to numerous challenges in power systems, such as variability, unpredictability, and spatio-temporal specificity. Failure to deal with or mitigate these issues can jeopardise power system reliability. Given the urgent need to integrate VRE into the grid, this topic is extensively investigated in domestic and international academic literature.

For the first time in several years, AEMO did not forecast any supply shortfalls for the 2020/21 summer, despite maximum demand forecasts being similar or only slightly lower than in 2019/20 (AEMO, 2020b). The major factor in the improved outlook was the more than 5 GW of new renewable energy generation that recently entered the market, which has eased the supply shortages seen in previous years. However, an unplanned outage at the Liddell coal-fired power plant in late December 2020 once again highlighted the unreliability of Australia's ageing fossil fuel generation fleet. Data from the Australian Institute's Gas and Coal Watch program also shows that from 2017-2019 some of Queensland's newer gas and coal-fired power stations had disproportionately high rates of breakdown with the Kogan Creek plant being the most unreliable single generating unit in the National Electricity Market despite being Australia's newest coal-fired power station (Ogge et al. 2020).

Across all domains of the power system, solution technologies vary significantly in their potential to solve certain challenges (Sinsel et al., 2020). However, it is possible to identify groups of solution technologies that can help mitigate certain challenge groups. For emerging power system stability challenges, particularly related to low inertia and low system strength conditions, there is a need for suitable techno-economic considerations to integrate new solution technologies into system and market operation (Meegahapola et al., 2021).

RQ: How should we prioritise solution technologies to address various technical challenges of variable renewable energy integration?

In the initial phase of the power sector transformation, the primary concern was to establish renewables as technically and economically viable options. Now, the challenge has shifted towards the interaction of multiple technologies, such as batteries and P2X, in different stages of development and with different dynamics (Markard, 2018; Sandén and Hillman, 2011). Multi-purpose technologies are particularly interesting study objects as they may trigger cascading effects in different industries and across sectors. For example, the rapid improvement in battery technology is not only central for the current hype around electric vehicles, but also critical for integrating intermittent renewables (Stephan et al., 2017). Instead of establishing frameworks focusing on single technology and simple interactions, further research is needed to conduct empirical studies on complementarities and multi-purpose technologies.

RQ: What modelling approach should be developed to explore the interactions between multiple technologies with different dynamics and diffusion patterns?

Future 100% renewable energy systems will have to integrate different sectors, such as the power, heating, cooling and transport sectors to mitigate the negative impacts of economic development based on the use of fossil fuels. Integrating future energy systems with CO_2 capture and utilisation (CCU) technologies can contribute to deep decarbonisation. As these technologies can be operated flexibly, they can be used to balance the grid to allow for high levels of variable renewable energy in the power mix (Mikulcic et al., 2019). As highlighted in the recent CO_2 Utilisation Roadmap (Srinivasan et al., 2021), the captured CO_2 can be utilised as a feedstock for various value-added applications in the chemical industry and related sectors such as the food and beverage industries. With these benefits, there are identified limitations, challenges and research gaps to the integration of VRE sources and flexible CCU technologies.

This includes the orders-of-magnitude difference in scale between the potential market for CO_2 as feedstock and the required removal amount for climate stabilisation, unless further research can accelerate stabilisation technologies (Mikulcic et al., 2019).

RQ: How should variable renewable energy and CO_2 capture and utilisation technologies be integrated to have synergistic effects?

3.3.2. Infrastructure

> What national energy-related infrastructure changes are required, what investment is needed to support these changes, how can this investment best be funded?

The Australian renewable energy industry has been progressing rapidly. However, according to a recent report from Clean Energy Council in 2021, the industry will need to overcome ongoing grid connection and transmission challenges, which continue to plague renewable energy developers. While the market bodies made some progress on resolving these challenges, through the development of Snowy 2.0 and the Battery of the Nation hydro projects, more work and investment is required to ensure our energy transition can continue unimpeded.

RQ: To what extent can Australia's existing energy infrastructure support the transition to net zero-emissions and how should investment be allocated to overcome ongoing grid connection and transmission challenges?

The design of cost-effective power systems with high shares of VRE technologies requires a modelling approach that simultaneously represents the whole energy system combined with the spatiotemporal and inter-annual variability of VRE. Zeyringer et al. (2018) developed such a model which explores new energy system configurations, with a high spatial and temporal resolution power system model that captures VRE variability from hours to years. On this model, reinforcement of the transmission system consistently leads to a decrease in system costs while electricity storage and flexible generation, needed to integrate VRE into the system, are generally deployed close to demand centres. AEMO (2020a) have identified the least system cost investments needed for Australia's future energy system, including distributed energy resources (DER), VRE and supporting dispatchable resources and power system services. Yet, they recognised that significant market and regulatory reforms will be needed to bring the right resources into the system in a timely fashion.

RQ: How can integrated modelling tools (representing Australia's whole energy system combined with the spatiotemporal and inter-annual variability of variable renewable energy) be utilised to identify infrastructure that need reinforcement?

Renewable energy maps in Australia indicate the distance between some renewable energy infrastructure and the market is significant, thus increasing the supply cost (Xian et al., 2020). In order to overcome this barrier, energy supply infrastructure must be well-planned and managed to improve the competitiveness of renewable energy, during and after infrastructure investment. Rather than technical feasibility, the greatest uncertainties around actual constraints are social, logistical, and political and will depend on the ability of policy to support such large transformation of land use and infrastructure in a way that is equitable (Lenzen et al., 2016).

RQ: What are the key social, logistical, and political barriers that can slow the development of infrastructure necessary for rapid grid integration of renewable energy, and how can these be overcome?

3.3.3. Digital

> How can emerging digital technologies be leveraged in energy systems integration; are we well-placed to utilise these technologies (do all stakeholders, including local communities, have the necessary data and analytical tools)?

Digitalisation refers to the integration of digital technologies into the energy system, from generation plants, transmission networks to consumer devices. While a new topic in industry and academic literature, the pace of energy sector digitalisation is increasing, and projections suggest that this trend will continue over the next decade (The Parliamentary Office of Science and Technology, 2021). Consumers are also increasingly managing their demand and investing in DER, batteries, and electric vehicles (EVs). Digital controls and falling costs make these assets easier and cheaper to adopt.

Existing software systems and capabilities were not designed to cater for large amounts of variable renewable generation. Therefore, AEMO has begun to develop the operating system, using a modular cloud-based approach that will enable the system to be built in a progressive and adaptive way. According to the recent low emissions technology statement (Department of Industry Science Energy and Resources, 2021), the next priority identified by AEMO is the development of a distribution system module. This module will allow various distribution networks and AEMO to integrate distributed energy resources and distribution networks with the transmission-level system in the grid simulation.

The ISP (AEMO, 2020a) assumes that the necessary regulations, standards, digital platforms and distribution-level investments are in place to allow DER investments to contribute to their full potential. However, this will not happen automatically. A number of technical and market changes are needed to manage two-way flows, the impacts of DER on faults on the system, peak demand, minimum demand and peak export from DER.

Kloppenburg and Boekelo (2019) call for attention to the rise of digital platforms in the energy field. The emergent energy platforms offer decentralised, digitally-enabled exchanges of energy from distributed resources. They can record flows of energy to administer connections of exchange between household users, develop algorithms to steer the flow of energy from and to household batteries, and enable crowdsourced investments into small-scale renewable energy production.

The main concern is that uncertainties caused by these platforms and their tendency to privatise energy provisioning may delay the equal distribution of renewable energy technologies' benefits, and therefore slow down the transition towards sustainable energy systems.

RQ: How can digital emerging technologies be better integrated in the demand and supply sides to create better benefits for consumers and improve the resilience of the energy system?

The need for a better understanding of socio-technical interactions in shared renewable energy systems (SRESs) may be exacerbated by the relevance of digital technologies to their governance (Hansen et al., 2020). Addressing the question of how the use of digital technology affects system governance, Hansen et al. (2020) applied the social-ecological system framework to a case study in Perth, Western Australia. The analysis finds that although the digital element enables the sharing of energy in the case study, it also increases the complexity of the social subsystem. While technology is often considered as the solution, successful governance of digitally-enabled SRESs may be more dependent on recognising the importance and complexity of social interactions needed to manage the technology. The UK Parliamentary Office of Science and Technology (2021) has also warned that digital systems could be targeted by cybercriminals and affect the capability of the system to deliver a reliable service.

RQ: What are the key technical and social concerns associated with the operation of energy systems due to added digital infrastructure, and how can they be overcome?

Through the exchange of data, digitalisation can improve energy system flexibility by helping supply to better match demand, and via the creation of innovative products and services for consumers. However, a key barrier identified by the UK Parliamentary Office of Science and Technology (2021) could be that the use of data in the UK energy sector has been constrained by a number of factors, such as limited sharing of data and data standardisation.

RQ: What standards are needed to facilitate the exchange and use of data between sectors?

4. Key research questions, gaps, priorities, and opportunities for Australia

Section 3 has identified numerous research questions, gaps, and priorities in current research. Australian-specific research across technology, transition pathways and system integration will need to be pursued and will require both multidisciplinary and interdisciplinary considerations.

What follows below is a categorisation of these research questions formulated from the research into a mix of research questions:

- Urgent questions – where robust answers are needed to the question posed to address issues in the near future; and
- Strategic questions – which requires research to find robust answers to the question posed to address issues in the longer term.

4.1 Technology

URGENT: Policy framework	URGENT: National advantage	Strategic: Research focus
Report 1 framing questions		
How might technology policies in Australia be further developed (additional or alternative energy technologies, energy efficient mechanisms R&D programs, industry participation, deployment support mechanisms) as our transition pathway evolves over time?	Where does Australia have a competitive or comparative advantage in clean energy technology research and development, and how can this be exploited to support the energy transition?	What are the specific core, niche or enabling technologies where Australia should make a concentrated research effort (should our energy technology research effort be more specialised)? How can this adapt to consider international developments?
Further research questions from this report		
What are the most effective incentive mechanisms for stimulating technological innovation in Australia, and how can they be leveraged (further) in energy transition research?	What are the efficient, effective and responsive regulations needed to support investment in low carbon technologies?	How should research, development and demonstration priorities be coordinated with the technology readiness level of low emissions technologies?
How can international collaboration be further incentivised to integrate regional specialisations, and to expedite the innovation of new clean technologies?	What is the most effective role and mechanisms for state, territory and federal governments to enable Australia to become a leader in producing low and zero emissions metals?	How can the mix of storage technologies with different scales and storage timeframes be integrated with renewable energy and transmission systems to optimise electricity supply and guarantee grid stability and economic growth?
How can the current main technical and non-technical barriers for the uptake of negative emission technologies be overcome? How can an holistic approach to combining renewable power-to-X and electrification be used to improve the effectiveness of the energy transition?	What targeted programs and international collaboration opportunities are needed to avoid missing opportunities arising from demand for Australian critical minerals?	What is the time window of opportunity for different energy storage technologies to compete with falling battery prices and how can findings assist investors and policy makers? Given concerns about land-based wind, what is needed to ensure Australia can efficiently and effectively implement ocean renewable energy (offshore wind and ORE), especially to manage technical, environmental and social acceptance issues?

4.2 Transition Pathways

URGENT: Scenarios	URGENT: Pathway implications	STRATEGIC: Scaling conditions
Report 1 framing questions		
What are the main feasible transition pathways, and where are the greatest uncertainties, based on current knowledge and forecasts?	What are the costs, benefits, impacts and risks to the Australian economy, society and environment of these pathways (what parts are most difficult, how important are clean energy exports, do we have comparative advantages)?	How will we reach the social, technical and economic conditions required for a successful transition of this scale? What are the scaling, economic adjustment and capital mobilisation issues?
Further questions from this report		
How can qualitative participatory and quantitative modelling approaches be effectively integrated to identify feasible transition scenarios?	What set of indicators should be developed/utilised to assess the successfulness of energy transition pathways in Australia?	How should the regulatory framework be improved to facilitate the scaling up of renewable investment?
How should the process of selecting solutions and actions be improved to account for the uncertainty in the capacity of emerging technologies?	What are the major risks (financial and non-economic) for the Australian energy system due to climate variability and change, and what measures are necessary to mitigate the risks?	How can the Australian, state and territory governments alleviate the challenges associated with massive capital mobilisation while ensuring that energy financing is just?
How can existing planning tools be expanded to derive realistic scenarios for future power generation, transmission, distribution, consumption and optimal scaling levels of energy storage and investment needed to guarantee grid stability and economic growth?	What tools and methods are needed (such as Life cycle analysis) to comprehensively evaluate the broader environmental impacts of energy technologies and systems at local, regional and national scale?	

4.3 Systems integration

URGENT: Integration	URGENT: Infrastructure	STRATEGIC: Digital
Report 1 framing questions		
What are the critical system integration issues for low/zero/negative emission energy technologies across sectors (including social, economic and technical considerations), and do we have the necessary interdisciplinary capabilities to address them?	What national energy-related infrastructure changes are required, what investment is needed to support these changes, how can this investment best be funded?	How can emerging digital technologies be leveraged in energy systems integration; and are we well-placed to utilise these technologies (do all stakeholders, including local communities, have the necessary data and analytical tools)?
Further questions from this report		
How should we prioritise solution technologies to address various technical challenges of variable renewable energy integration (quality, flow, stability and balance)?	To what extent can Australia's existing energy infrastructure support the transition to net zero-emissions and how should investment be allocated to overcome ongoing grid connection and transmission challenges?	How can digital emerging technologies be better integrated in the demand and supply sides to create better benefits for consumers and improve the resilience of the energy system?
What modelling approach should be developed to explore the interactions between multiple technologies with different dynamics and diffusion patterns?	How can integrated modelling tools (representing Australia's whole energy system combined with the spatiotemporal and inter-annual variability of variable renewable energy) be utilised to identify infrastructure that need reinforcement?	What are the key technical and social concerns associated with the operation of energy systems due to added digital infrastructure, and how can they be overcome?
How should variable renewable energy and CO_2 capture and utilisation technologies be integrated to have synergistic effects?	What are the key social, logistical, and political barriers that can slow the development of infrastructure necessary for rapid grid integration of renewable energy, and how can these be overcome?	What standards are needed to facilitate the exchange and use of data between sectors?

5. Action

The research questions identified in section 4 above represent the most pressing questions in the energy system dynamics of the energy transition. There are vast potentials for Australia regarding emerging technologies and possible transition pathways, but careful planning, evaluation and management of policy incentives and barriers are critical. The integration of multiple technologies, as well as the modelling of complex future pathways, will require interdisciplinary expertise and methodologies, considering the social, cultural, technical, geopolitical and economic dynamics, benefits and impacts.

By undertaking research in the areas identified through the literature assessment, the energy transition is likely to progress with greater individual and community support, supported by effective policies and regulatory architecture, within a supportive and engaged socio-political climate.

6. References

ACIL Allen Consulting. (2018). *Opportunities for Australia from Hydrogen Exports*. ARENA. https://arena.gov.au/assets/2018/08/opportunities-for-australia-from-hydrogen-exports.pdf.

Australian Energy Market Operator. (2020a). *2020 Integrated System Plan*. https://aemo.com.au/-/media/files/major-publications/isp/2020/final-2020-integrated-system-plan.pdf?la=en&hash=6BCC72F9535B8E5715216F8ECDB4451C.

Australian Energy Market Operator. (2020b). *Summer 2020-21 Readiness Plan*. https://aemo.com.au/-/media/files/electricity/nem/system-operations/summer-operations/2020-21/summer-2020-21-readiness-plan.pdf.

Australian Renewable Energy Agency. (2017). *Advancing Solar in Australia Through RD&D Investment*. https://arena.gov.au/assets/2017/05/Final-report_SOLAR-RDD-REVIEW_For-Web_LowRes-2.pdf.

Australian Renewable Energy Agency. (2020). *General Funding Strategy 2021/22 — 2023/24*. https://arena.gov.au/assets/2021/09/2021-22-to-2023-24-arena-general-funding-strategy.pdf

Australian Renewable Energy Agency. (2021). *Latest low emissions technology statement continues the drive towards net zero*. https://arena.gov.au/news/latest-low-emissions-technology-statement-continues-the-drive-towards-net-zero/

Baumann, M., Weil, M., Peters, J. F., Chibeles-Martins, N., & Moniz, A. B. (2019). A review of multi-criteria decision making approaches for evaluating energy storage systems for grid applications. *Renewable and Sustainable Energy Reviews*, *107*, 516-534.

Burdon, R., Hughes, L., Lord, M., Madeddu, S., Ueckerdt, F., Wang, C., Houston, A., Jotzo, F., Löschel, A., Luderer, G. & Meinshausen, M. (2019). Innovation and export opportunities of the energy transition. *Energy Transition Hub*

Campey, T., Bruce, S., Yankos, T.*, Hayward, J., Graham, P., Reedman, L., Brinsmead, T., & Deverell, J. (2017). *Low Emissions Technology Roadmap*. CSIRO.

Chan, G., Goldstein, A.P., Bin-Nun, A.Y., Anadon, L.D., & Narayanamurti, V. (2017). Six principles for energy innovation. *Nature*, *552*, 25–27.

Chapman, A. J., McLellan, B. C., & Tezuka, T. (2018). Prioritizing mitigation efforts considering co-benefits, equity and energy justice: Fossil fuel to renewable energy transition pathways. *Applied Energy*, *219*, 187-198.

Clarke, D., Baldwin, K., Baum, F., Godfrey, B., Richardson, S., & Robin, L. (2021). *Australian Energy Transition Research Plan. Australian Council of Learned Academies*. https://acola.org/wp-content/uploads/2021/06/acola-2021-australian-energy-transition-plan.pdf

Clean Energy Council. (2021). *Clean Energy Australia Report 2021*. https://assets.cleanenergycouncil.org.au/documents/resources/reports/clean-energy-australia/clean-energy-australia-report-2021.pdf

ClimateWorks Australia, ANU, CSIRO, & CoPS. (2014). *Pathways to Deep Decarbonisation in 2050: How Australia can prosper in a low carbon world*.

ClimateWorks Australia. (2020). *Decarbonisation Futures – Solutions , actions and benchmarks for a net zero emissions Australia*. https://www.climateworksaustralia.org/wp-content/uploads/2020/04/CWA-DECARBONISATION-FUTURES-2020-TECH-REPORT.pdf

Cook, P.J. (2017). CCS Research Development and Deployment in a Clean Energy Future : Lessons from Australia over the Past Two Decades. *Engineering*, *3*, 477–484.

Cook, P.J., & Arranz, A.M. (2019). *Negative emission technologies*.

Daiyan, R., MacGill, I., & Amal, R. (2020). Opportunities and Challenges for Renewable Power-to-X. *ACS Energy Letters*, *5*(12), 3843–3847.

Delafield, G., Donnison, C., Roddis, P., Arvanitopoulos, T., Sfyridis, A., Dunnett, S., Ball, T., & Logan, K. G. (2021). Conceptual framework for balancing society and nature in net-zero energy transitions. *Environmental Science & Policy*, *125*, 189–201.

Department of Industry Science Energy and Resources. (2020). *First Low Emissions Technology Statement – 2020*. https://www.industry.gov.au/sites/default/files/September%202020/document/first-low-emissions-technology-statement-2020.pdf

Department of Industry Science Energy and Resources. (2021). *Technology Investment Roadmap: Low Emissions Technology Statement 2021*. https://www.industry.gov.au/sites/default/files/November%202021/document/low-emissions-technology-statement-2021.pdf.

Finkel, A., Moses, K., Munro, C., Effeney, T., & O'Kane, M. (2017). *Independent Review into the Future Security of the National Electricity Market – Blueprint for the Future*. https://www.energy.gov.au/sites/default/files/independent-review-future-nem-blueprint-for-the-future-2017.pdf

Geddes, A., Schmidt, T.S. & Ste, B. (2018). The multiple roles of state investment banks in low-carbon energy finance : An analysis of Australia , the UK and Germany. *Energy Policy*, 115, 158–170.

Global CCS Institute. (2019). *The Global Status of CCS – 2019*. Canberra, Australia.

Global PST Consortium. (2021). *About G-PST*. https://globalpst.org/who-we-are/

Godfrey, B., Dowling, R., Forsyth, M., Grafton, R.Q., & Wyld, I. (2017). *The Role of Energy Storage in Australia's Future Energy Supply Mix*. https://acola.org/hs1-energy-storage-australia/.

Government of South Australia. (2020). *Climate Change Action Plan 2021 – 2025*. https://cdn.environment.sa.gov.au/environment/docs/climate-change-action-plan-2021-2025-summary.pdf

Graham, P., Hayward, J., Foster J., & Havas, L. (2021). *GenCost 2020-21: Final report. Australia*.

Hall, S., Roelich, K.E., Davis, M.E., & Holstenkamp, L. (2018). Finance and justice in low-carbon energy transitions. *Appl. Energy*, *222*, 772–780.

Hansen, P., Morrison, G. M., Zaman, A., & Liu, X. (2020). Smart technology needs smarter management: Disentangling the dynamics of digitalism in the governance of shared solar energy in Australia. *Energy Research & Social Science*, *60*, 101322.

Hemer, M. A., Manasseh, R., McInnes, K. L., Penesis, I., & Pitman, T. (2018). Perspectives on a way forward for ocean renewable energy in Australia. *Renewable Energy*, *127*, 733-745.

International Energy Agency. (2019). *The Future of Hydrogen*. https://www.iea.org/reports/the-future-of-hydrogen.

International Energy Agency. (2021). *Direct Air Capture*. https://www.iea.org/reports/direct-air-capture.

International Renewable Energy Agency. (2020). *Mobilising institutional capital for renewable energy*. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Nov/IRENA_Mobilising_institutional_capital_2020.pdf.

Iyer, G., Hultman, N., Eom, J., McJeon, H., Patel, P., & Clarke, L. (2015). Diffusion of low-carbon technologies and the feasibility of long-term climate targets. *Technological Forecasting and Social Change*, *90*, 103-118.

Kloppenburg, S., & Boekelo, M. (2019). Digital platforms and the future of energy provisioning: Promises and perils for the next phase of the energy transition. *Energy Research & Social Science*, *49*, 68-73.

Kompas, T., Keegan, M., & Witte, E. (2019). *Australia's Clean Economy Future: Costs and Benefits*. Melbourne Sustainable Society Institute. https://www.sgsep.com.au/assets/main/Australias_Clean_Economy_MSSI_Issues_Paper12.pdf.

Lenzen, M., McBain, B., Trainer, T., Jütte, S., Rey-Lescure, O., & Huang, J. (2016). Simulating low-carbon electricity supply for Australia. *Applied Energy*, *179*, 553-564.

Li, H. X., Edwards, D. J., Hosseini, M. R., & Costin, G. P. (2020). A review on renewable energy transition in Australia: An updated depiction. *Journal of Cleaner Production*, *242*, 118475.

Lovett, A. A., Dockerty, T. L., Papathanasopoulou, E., Beaumont, N. J., & Smith, P. (2015). A framework for assessing the impacts on ecosystem services of energy provision in the UK: an example relating to the production and combustion life cycle of UK produced biomass crops (short rotation coppice and Miscanthus). *Biomass and Bioenergy*, *83*, 311-321.

Markard, J. (2018). The next phase of the energy transition and its implications for research and policy. *Nature Energy*, *3*(8), 628-633.

Meegahapola, L., Mancarella, P., Flynn, D., & Moreno, R. (2021). Power system stability in the transition to a low carbon grid: A techno-economic perspective on challenges and opportunities. *Wiley Interdisciplinary Reviews: Energy and Environment*, *10*(5), 399.

Meng, J., Way, R., Verdolini, E., & Anadon, L. D. (2021). Comparing expert elicitation and model-based probabilistic technology cost forecasts for the energy transition. *Proceedings of the National Academy of Sciences*, *118*(27).

Mikulčić, H., Skov, I. R., Dominković, D. F., Alwi, S. R. W., Manan, Z. A., Tan, R., ... & Wang, X. (2019). Flexible Carbon Capture and Utilization technologies in future energy systems and the utilization pathways of captured CO2. *Renewable and Sustainable Energy Reviews*, *114*, 109338.

Moallemi, E. A., & Malekpour, S. (2018). A participatory exploratory modelling approach for long-term planning in energy transitions. *Energy Research & Social Science*, *35*, 205-216.

Ogge, M., Quicke, A., & Browne, B. (2020). Coal Out: *Fossil fuel power station breakdowns in Queensland*. The Australia Institute. https://australiainstitute.org.au/wp-content/uploads/2020/12/P912-Gas-Coal-Breakdowns-QLD-WEB.pdf.

Polzin, F., von Flotow, P., & Klerkx, L. (2016). Addressing barriers to eco-innovation: Exploring the finance mobilisation functions of institutional innovation intermediaries. *Technological Forecasting and Social Change*, *103*, 34-46.

Porteous, C., Godfrey, B., & Finkel, A. (2018). *Taking Charge: The Energy Storage Opportunity for Australia*. Office of the Chief Scientist Occasional Paper. https://www.chiefscientist.gov.au/sites/default/files/Energy-storage-paper.pdf.

Saddler, H. (2021a). *Australian Energy Transition Indicators*. https://ccep.crawford.anu.edu.au/sites/default/files/publication/ccep_crawford_anu_edu_au/2021-06/ccep2106_saddler_hugh_australian_energy_transition_indicators.pdf.

Saddler, H. (2021b). *Back of the pack – An assessment of Australia's energy transition*. The Australia Institute. https://australiainstitute.org.au/wp-content/uploads/2021/08/P1096-Back-of-the-Pack-110821.pdf.

Sandén, B. A., & Hillman, K. M. (2011). A framework for analysis of multi-mode interaction among technologies with examples from the history of alternative transport fuels in Sweden. *Research Policy*, *40*(3), 403-414.

Sinsel, S. R., Riemke, R. L., & Hoffmann, V. H. (2020). Challenges and solution technologies for the integration of variable renewable energy sources—a review. *renewable energy*, *145*, 2271-2285.

Sivaram, V., Cunliff, C., Hart, D., Friedmann, J., & Sandalow, D. (2020). *Energizing America – A Roadmap to Launch a National Energy Innovation Mission*. Columbia University SIPA Center on Global Energy Policy. https://www2.itif.org/2020-energizing-america.pdf?_ga=2.121856076.656531701.1642988762-1291993059.1642988762.

Srinivasan, V., Temminghoff, M., Charnock, S., Moisi, A., Palfreyman, D., Patel, J., Hornung, C., & Hortle, A. (2021). *CO2 Utilisation Roadmap*.

Stephan, A., Schmidt, T. S., Bening, C. R., & Hoffmann, V. H. (2017). The sectoral configuration of technological innovation systems: Patterns of knowledge development and diffusion in the lithium-ion battery technology in Japan. *Research Policy*, *46*(4), 709-723.

The Parliamentary Office of Science and Technology, 2021. *Energy Sector Digitalisation*. https://researchbriefings.files.parliament.uk/documents/POST-PN-0655/POST-PN-0655.pdf.

Ueckerdt, F., Dargaville, R., Gils, H.C., McConnell, D., Meinshausen, M., Scholz, Y., Schreyer, F., & Wang, C. (2019). *Australia's power advantage Energy transition and hydrogen export scenarios*. Energy Transition Hub. https://www.energy-transition-hub.org/files/resource/attachment/australia_power_advantage_0.pdf.

Victor, D.G., Geels, F.W., & Sharpe, S. (2019). *Accelerating the Low Carbon Transition: The Case for Stronger, More Targeted and Coordinated International Action*. https://www.brookings.edu/wp-content/uploads/2019/12/Coordinatedactionreport.pdf

Vincent, N., Chaiechi, T., & Alam, A.B.M.R. (2019). A techno-economic and environmental assessment of long-term energy policies and climate variability impact on the energy system. *Energy Policy*, *128*, 329–346.

Yigitcanlar, T., Sabatini-Marques, J., da-Costa, E. M., Kamruzzaman, M., & Ioppolo, G. (2019). Stimulating technological innovation through incentives: Perceptions of Australian and Brazilian firms. *Technological Forecasting and Social Change*, *146*, 403-412.

Zeyringer, M., Price, J., Fais, B., Li, P. H., & Sharp, E. (2018). Designing low-carbon power systems for Great Britain in 2050 that are robust to the spatiotemporal and inter-annual variability of weather. *Nature Energy*, *3*(5), 395-403.

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