ENERGY TRANSITION HUB an Australian-German innovation partnership

Australia's power advantage
Energy transition and hydrogen export scenarios

Insights from the Australian-German Energy Transition Hub

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About the Australian-German Energy Transition Hub

The Australian-German Energy Transition Hub is a bilateral initiative for applied research on energy transition opportunities. The Hub is supported by the Australian Department of Foreign Affairs and Trade and the German Federal Ministry for Education and Research.

The Hub brings together leading research organisations that are central to energy transition in each country. The Hub is providing an innovative and effective architecture for collaboration. Virtual conferencing and regular collaborations through video conferencing are enabling close working relationships and knowledge exchange. It is fostering closer links between researchers, industry, and government entities.

The bilateral relationship between Australia and Germany is strengthened through Hub research, dialogue, and stakeholder engagement that helps to identify and harness the opportunities for both countries in the transition to a net-zero emissions world economy. It has highlighted the complementary opportunities created by Germany's *Energiewende* experience and Australia's substantial energy and mineral resources. This is clearly evident two years into the Energy Transition Hub. Faster identification of policy lessons and investment and trade opportunities, and a deeper exchange of useful research methods and findings, are being enabled through this initiative.

The Hub is co-led by the University of Melbourne and the Australian National University in Australia. In Germany, the Hub is co-led by the Potsdam Institute for Climate Impact Research, the Mercator Research Institute for Global Commons and Climate Change, and the University of Münster. In addition to these five core partners, the Hub now has eight research partners: five in Australia and three in Germany.

This document presents some of the principal findings of research supported through the Hub. A more comprehensive collection of research, web tools and engagement undertaken is available at the Energy Transition Hub website energy-transition-hub.org

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INTRODUCTION

Energy transition is happening globally and in Australia and Germany. It is occurring in response to rapidly changing technology costs and as countries move to implement policies in line with the Paris Agreement goals. This transition poses policy and technological challenges. If managed well, it can also deliver great economic opportunities in both Australia and Germany.

Insights about the implications of the global energy transition for Australia and Germany that have become evident from the Energy Transition Hub's work include:

1. Rapid deployment of renewables in Australia is an essential part of a cost-efficient transition to a net-zero emissions economy. There is the potential to create an export industry based on Australia's renewable energy resources (as much as, or even more than, doubling Australia's domestic electricity demand).
2. Substantial and complementary export opportunities emerge for Germany and Australia as a result of the move to energy networks powered by renewables, electrification of other sectors of the economy, the transition to zero-emissions synthetic fuels and growing demand for zero-emissions metals and energy intensive goods.
    - Australia, with its plentiful wind and solar energy resources, available land, and stable regulatory and institutional environment, is well positioned to become a leading exporter of renewable energy and renewable-based energy-intensive goods.
    - Germany, as a leading manufacturer and engineering innovator of energy transition technologies, can benefit from an increasingly global deployment of technologies for renewable energy generation, storage and the electrification of energy end-uses.
3. Large-scale carbon dioxide removal (CDR) is another essential component of any transition that limits warming to 1.5°C, or even to 2°C, unless the pace of mitigation to 2030 increases significantly. CDR is needed to complement the transformation in other sectors: it is not an alternative to rapid deployment of low-emissions technologies across the economy. CDR could create opportunities for Australia as a source of nature-based solutions, bioenergy with carbon capture and storage (BECCS) or direct air capture with CCS (DACCS), and for Germany as a provider of carbon capture and utilisation (CCU) technologies.
4. Policy has an important role to play. A cost-effective, timely energy transition that unlocks the potential for new industries, supports affected regions, and protects ecosystems is not guaranteed – it is an outcome achievable in both Germany and Australia with effective policy.

Recent work on these issues is summarised in a series of papers. This report addresses some of the questions that arise in relation to the first point.

A focus on Australia's transition strengths

Mastering the technological and socio-political challenges of energy transitions can unleash significant and long-lasting economic opportunities. Driven by policy support and decreasing technology costs, Australia and Germany have rapidly expanded their domestic renewable electricity supplies, mainly with wind power and solar photovoltaics (PV). To achieve the Paris Agreement's climate targets this trend needs to be solidified and renewable energy expanded in various forms to all energy end-use sectors. The emergence of new markets for technology, services and innovative clean energy carriers, such as hydrogen-based fuels, herald a fundamental shift in global energy trade patterns. If managed well, these global and national energy transitions present economic opportunities for countries with vast renewable and mineral resources and countries that are advanced in clean technology and related services (such as Australia and Germany).

In this report, the Australian-German Energy Transition Hub presents a range of scenarios in which Australia uses its extensive renewable resources to: i) secure a reliable and cost-effective domestic electricity supply; ii) avoid CO_2 emissions, leading to carbon neutrality by 2050; and iii) move beyond domestic supply to become a first mover and supplier in future global markets of green hydrogen. The scenarios are simulated in four energy-economic models of complementary scope and detail.

This is one of the first times that a scenario presenting 200 percent renewable electricity has been modelled (alongside other scenarios). The '200% Renewable Scenario' combines deep decarbonisation of domestic electricity supply with extensive electrification of energy demand for mobility, buildings and industrial processes, and renewable energy export in the form of hydrogen, green steel and electricity embodied in energy-intensive goods. One focus of this report is on how harnessing renewable export potentials (mainly hydrogen) synergistically interacts with a low-cost, reliable domestic electricity supply based on renewables. Future Hub publications will zoom further into the energy export economics and include a hydrogen supply curve.

The analysis focuses on Australia but is relevant for the bilateral energy partnership with Germany in two respects. It builds on technology leadership and an advanced energy transition: German companies could supply clean technology, products, and services to growing Australian markets related to renewable electricity plus generation, storage, and transport of hydrogen-based fuels. Zero-emissions fuel imports will help Germany to replace fossil hydrocarbons, particularly in demand sectors that cannot easily be directly electrified, such as aviation, freight transport, and some energy-intensive industries.

While direct hydrogen exports from Australia to Germany seem unlikely today due to demand in the Asia Pacific, understanding future global markets and trade of hydrogen-based fuels, will become important for all countries with limited renewable resources. The complementary export opportunities of Germany and Australia are further detailed in the Hub's *Innovation and Export Opportunities* report (*ETH, 2019a*).

This first multi-model analysis of the Australian energy system was conducted by combining modeling experience and tools from both countries with local knowledge and data. Two decades of the German *Energiewende* have strengthened and consolidated German energy modeling capacity and experience specifically around modeling renewable energy sources and electrification. Researchers, industry experts, and energy analysts have developed and continuously refined numerous models, techniques, and scenarios. The analysis in this report has been conducted by a bilateral scenario group of 15 energy modelers and researchers from the five core Hub partner institutions, using four energy-economic models. The study brings German sector coupling modeling experience into the Australian context and modeling community. The term 'sector coupling' describes the integration of the various energy supply and demand sectors; it means the use of (renewable) electricity for meeting currently non-electric energy demands in transport, buildings and industry.

This report focuses on the electricity supply side, while considering extensive electrification of non-electric demand and electricity use for hydrogen generation and metal refining. Modeling the transition of electricity supply is a natural starting point. In Australia, electricity generation is a large source of CO_2 emissions. A zero-emissions electricity system can be the entry point and backbone of a net-zero economy. Other energy demands stemming from transport, industry and buildings can draw on the potential for substantial renewable electricity through electrification (e.g. battery-electric vehicles, electric furnaces and heat pumps), which is modeled in some of the scenarios.

After introducing the models and scenarios, this report is structured along four headline statements that present the results of the multi-model analysis with respect to: i) renewable energy expansion; ii) future costs of electricity (including effects of exporting renewables); iii) integration of variable renewables (including effects of exporting renewables); and iv) an outlook beyond electricity supply.

Box: Australia and Germany are in the middle of an energy transition to renewable sources

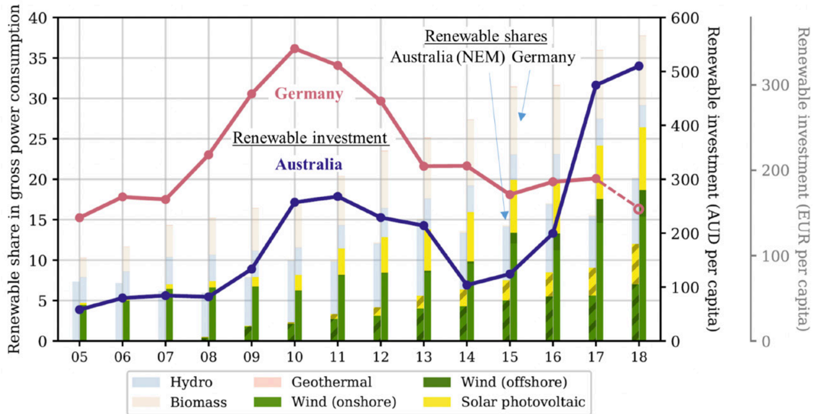

Figure 1: Share of renewable electricity in gross power consumption in Germany and Australia since 2005 (left axis) and per capita investment in renewable power generation capacity (right axis). While Germany's renewable shares are roughly twice as high as in Australia, a recent boom is pushing Australia's annual per capita renewable investments above those of Germany. Note that generation share data for Australia are for its National Electricity Market (NEM) only, while investment data is for the whole of Australia. Australia's NEM accounts for roughly 90 percent of electricity consumed across the country. Data from BMWi, 2019b; BloombergNEF, 2019; McConnell, Court, & Tan, 2019; United Nations, 2019; Reserve Bank of Australia, 2019. Preliminary estimation for Germany's investment 2018.

In Germany, policy support and decreasing costs have made renewables the number one source of electricity within two decades.

In 2000, Germany's energy transition kicked off with the introduction of guaranteed feed-in and tariffs for renewable electricity in the Renewable Energy Sources Act (*Bundesrepublik Deutschland, 2000*). Its success in driving the transition while rapidly reducing the cost of renewables within years made it an international exemplar (*Couture & Gagnon, 2010*). Today, with a series of refinements to the original instruments (including market premiums and a competitive auction system), renewable investments remain high with continuous and refined policy support. In 2018, annual net electricity generation from renewables (~40 percent) exceeded coal power generation for the first time. Net electricity generation and gross power consumption differ. The latter includes electrical losses and self-consumption of the power plants, which are not fed into the public power grid. This makes shares of renewable energy in net electricity generation higher than in gross power consumption.

Germany's energy transition strategy now focuses on: i) a continuous transition to an electricity supply system based on very high renewable shares of mainly fluctuating solar PV and wind power; ii) deeper direct electrification and flexibilisation of zero-carbon electricity in the transport, buildings and industry sectors; and iii) use of renewable-based synthetic fuels to cover remaining non-electric energy demands and backup (indirect electrification). At the core of this vision lies the concept of 'sector coupling', involving a closer, synergistic integration of renewable power supply and newly electrified demand across end-use sectors. Power-to-heat, power-to-fuel, and battery-electric vehicles help reduce emissions and increase demand flexibility to support the integration of variable renewable power. The strong concentration of wind turbines in windy Northeastern Germany, while nuclear plants are being phased out in the Southwest, is an increasing challenge for the electricity grid, for which the focus of further development is in the north-south direction.

The non-electric final energy demand in Germany accounted for 2071 TWh in 2017, compared to 520 TWh in electric final energy demand with a renewable generation share of 33 percent (*BMWi, 2019a*). Climate projection scenarios for Germany suggest a significant increase of electricity demand to around 1000 TWh or higher by 2050, despite substantial energy efficiency increases (*Ausfelder et al., 2017*). Transitioning to a zero-carbon energy system would further increase demand for wind and solar electricity. Given its limited renewable energy resources, Germany would benefit from the option to import renewable energy or renewable-based materials to overcome domestic supply bottlenecks.

A combination of falling renewable investment cost, excellent renewable energy resources, and high electricity prices has led to a rapid expansion of wind and solar PV in Australia.

Australia also commenced its energy transition in the early 2000s with legislation of a national Mandatory Renewable Energy Target (*MRET Review Panel, 2003*). This target, while small (two percent), was rapidly achieved and later expanded to a 20-percent target by 2020 (*Expert Panel on the Renewable Energy Target Review, 2014*) and just recently the Clean Energy Regulator announced that enough capacity has been approved for the target to be met. The Renewable Energy Target operates as a certificate scheme, in which wholesale purchasers of electricity are required to buy these certificates from eligible renewable energy generators. This national scheme has been complemented by state-based feed-in tariffs for small-generation. Several states have also legislated their own renewable energy targets and have moved to reverse auction mechanisms for large-scale generation, similar to and drawing on the experience in Germany (*Kallies, 2016*).

As a result of falling technology costs and changing market conditions, Australia's national target for 2020 has already been achieved, with renewable energy contributing over 21 percent of electricity supply across the main east- and west-coast grids in 2018 (*Green Energy Markets Pty Ltd, 2019*). High gas prices and the retirement of old coal-fired power stations has contributed to high electricity prices (*ACCC, 2018*). The high cost of gas combined with falling technology renewable energy costs and excellent renewable energy resources has resulted in renewable energy generation being the most competitive new entry technology. Today, the cheapest form of new generation technology in Australia is wind, although solar PV is expected to overtake soon (*Rai, Esplin, Nunn, & Nelson, 2019*).

In the last two years, hydrogen as an energy carrier has gained renewed interest in Australia. This has been ignited by policy-driven demand in the Asia Pacific and low-cost renewables. The Japanese and South Korean governments have published strategies for moving towards a hydrogen economy with roadmaps and targets for hydrogen import. The Council of Australian Governments Energy Council established a hydrogen working group to develop a national strategy by the end of 2019 with the aim of positioning Australia's hydrogen industry as a major global player by 2030. Supporting this process, Australia's Chief Scientist has issued a proposal for a national hydrogen strategy and a briefing paper on hydrogen (*Finkel, 2018; Hydrogen Strategy Group, 2018*), while Bruce, Temminghoff, Hayward, and Schmidt (2018), and ACIL Allen Consulting (2018) have also recently published reports.

Six scenarios for Australia's energy future

Four numerical energy-economic models are used in a bilateral transition scenario group of 15 researchers from five partner institutes of the Hub. Each model explores different angles of six future scenarios based on its strengths and scope (see model table in Appendix for details):

- The Australian capacity expansion models **MUREIL** (*Wang, Dargaville, & Jeppesen, 2018*) and **OpenCEM** (*Zapata, McConnell, Haghadi, & MacGill, 2018*) are the two workhorse tools of the analysis, simulating least-cost pathways for the transition of the Australian power sector to 2050 across all scenarios.
- The **REMix** model (*Gils, Scholz, Pregger, Luca de Tena, & Heide, 2017; Scholz, Gils, & Pietzcker, 2017*) derives an accurate view for each hour of the Australian power system in 2050 for two scenarios, including the '200% Renewable Scenario'.
- The fourth model is the global energy-economy model **REMIND** (*PIK, 2019*), which is used to derive electricity sector targets consistent with economy-wide Australian CO_2 emissions targets and to provide a cross-sectoral outlook on emission abatement beyond electricity.

The general modeling approach is optimisation, specifically estimating the cost-minimal investment and operation for generation, transmission and storage technologies.

Six scenarios represent different possible futures of the Australian energy system (Figure 2). The scenarios mainly differ in their assumptions on: i) future ambition in climate mitigation (implemented as CO_2 reduction pathways); ii) electrification of non-electric energy demand in buildings, transport, and industry; and iii) export of renewable energy and hydrogen. The six scenarios are:

- A '**Status Quo Scenario**' considers only existing Australian climate and energy policies. Emission reduction targets that are not yet fully backed with policies are not implemented (e.g. nationally determined contributions - NDCs, state-level emission reduction targets such as net-zero targets). This scenario provides insight into how the Australian power system would develop without additional climate policies and serves as a benchmark to analyse how competitive Australian renewables can be in the absence of dedicated climate policies. The five other scenarios reflect different ambition levels for reducing emissions and developing a renewables-based Australian export industry.
- An '**NDC Scenario**' aligns with Australia's current emission reduction target for 2030 as specified in the NDC for the Paris Agreement. The country-wide 2030 greenhouse gas emission target is translated into a CO_2 target, decomposed into sectors, such as the power sector, and extrapolated to 2050. In addition, moderate electrification is assumed (40 percent of final energy in ground transportation and industry, 100 percent in buildings by 2050). A driving question is around how achieving the NDC target translates into cost-efficient renewable deployment.
- An '**Accelerated Scenario**' increases ambition beyond the current NDC target in line with the Climate Change Authority's proposal (45 percent reduction by 2030 relative to 2005, 80 percent by 2050). Strengthened national ambitions are envisaged in the UN international climate negotiations to change the course from current NDC-induced 3-4°C warming to the globally agreed 2°C warming target. The same assumptions as in the NDC scenario as used for the share of transport, buildings, heat and industrial processes that are electrified.
- A '**Leadership Scenario**' assumes that Australia joins a circle of international climate leaders by taking a pathway to emissions neutrality by 2050. Significant electrification is assumed: 80 percent of ground transportation and industry plus additional electricity demand for the production of domestic hydrogen.
- An '**Accelerated + Export Scenario**' with some renewable-based exports, and a visionary '**Leadership + Export Scenario**' (also called the '**200% Renewable Scenario**') in which Australia becomes a global leader both in climate mitigation and the export of zero-carbon energy, go far beyond today's electricity demand. They assume extensive electrification of non-electric demand for transport, buildings heat, and industrial processes and significant energy export drawing on the vast renewable electricity potential. Both these scenarios are closely aligned with estimates of hydrogen export from ACIL Allen's 'medium' and 'high' scenarios (*ACIL Allen Consulting, 2018*) (Figure 3).

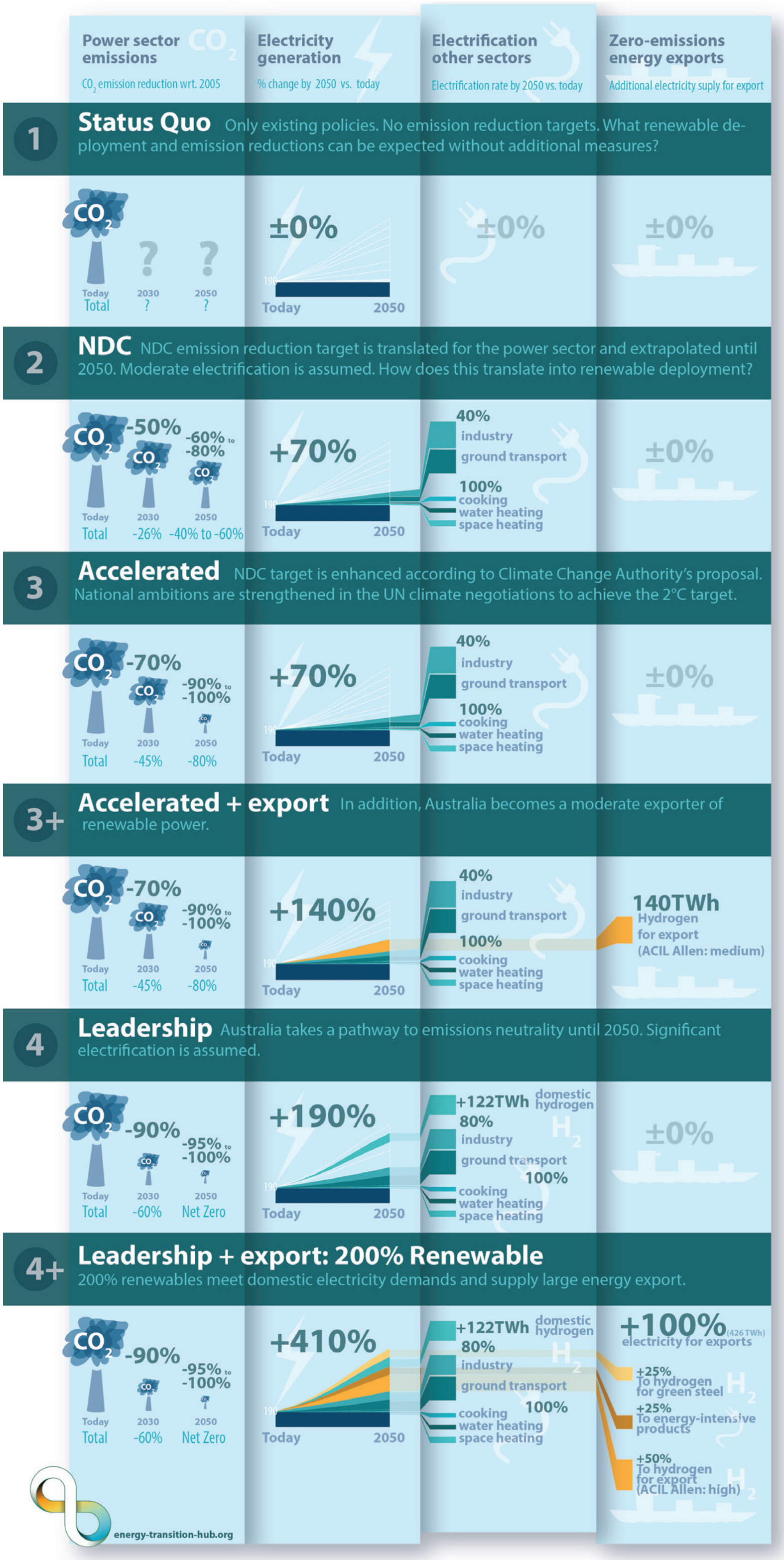

Figure 2: Summary of the six scenarios: assumptions on power sector emission reductions, power demand, electrification and export channels.

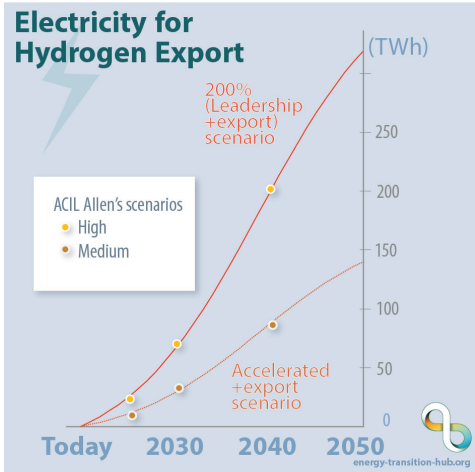

Figure 3: Scenario assumptions on the additional electricity demand induced by renewable hydrogen export from Australia. The assumptions are aligned with the 'medium' and 'high' scenarios by ACIL Allen Consulting (2018).

Model analysis using these six scenarios has already delivered a series of important and policy-relevant findings. Four of these key findings, which are detailed in the reminder of this report, are that:

1. Solar PV and wind power dominate Australia's electricity future.
2. Costs in a renewable-based system are similar or lower than today.
3. Multiple options secure reliable supply from 100 percent renewables.
4. Australia will need to expand its transformation beyond electricity supply.

1. Solar PV and wind power dominate Australia's electricity future

Even in a scenario with no additional energy or climate policy, wind and solar PV deployment is driven by competitive cost advantages, and no new coal power plant is built (Figure 4). Wind and solar PV are already today the cheapest new forms of electricity in Australia on a generation cost basis (*Graham, Hayward, Foster, Story, & Havas, 2018; Parkinson, 2019*). This reflects a global robust cost trend (*Haegel et al., 2019; Wiser et al., 2016*) that has been underappreciated in many previous modeling studies (*Creutzig et al., 2017; Luderer et al., 2017*). All our models also find that additional costs associated with the variability of renewables are low enough that wind and solar PV generation firmed by electricity storage and transmission remain cheaper than conventional power generation.

While renewables dominate power supply in the long-term in all our scenarios and models, the speed of transition depends on the magnitude of emission reduction targets, and specifically the exit of existing coal power plants.

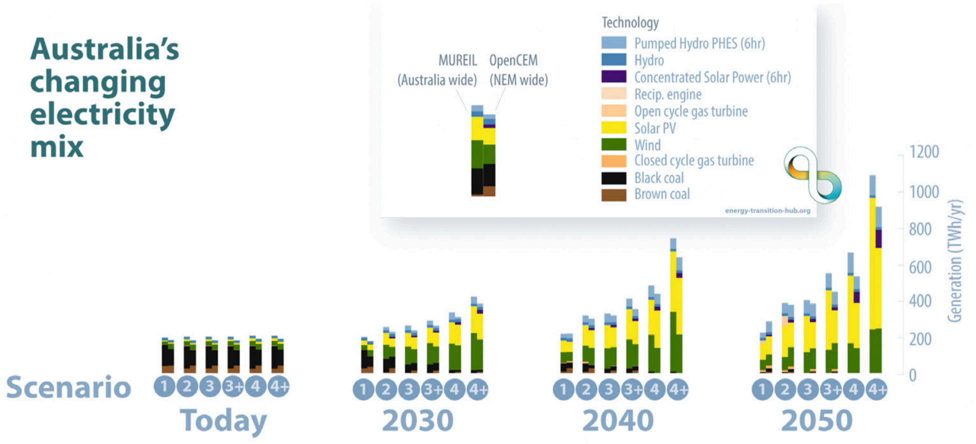

Figure 4: Electricity generation (TWh/year) for the six scenarios from 2020 to 2050. Across all scenarios, no new coal power is deemed economically viable, while renewable electricity expands.

The Status Quo Scenario does not apply an emission reduction target for the power sector or the economy. The transition is slow and existing coal power capacities operate until the end of their technical lifetimes. Renewable electricity shares increase up to about 40 to 50 percent of the share of generation in 2030, decreasing Australia's electricity emissions by around 40 to 48 percent compared to 2005 levels. This is slightly less than the contribution that we assume to be adequate from the power supply sector (around 50 percent) in reaching the economy-wide NDC target of -26 percent (on 2005 levels) - with our assumption informed by whole-system transition scenarios of the REMIND model. Additional energy and climate policy is needed to reach Australia's Paris Agreement 2030 emissions reduction target and 2050 emission neutrality, which all states and territories (except Northern Territory and Western Australia) are seeking to achieve (*Stock, Alexander, Stock, & Bourne, 2017*).

The NDC Scenario, which assumes electricity emission reductions in 2030 of around 50 percent and increased electricity demand, leads to a cost-efficient renewable expansion of 57 to 62 percent in 2030. For the more ambitious Accelerated and Leadership Scenarios, by 2030 the optimal renewable shares increase to 72 to 78 percent and 90 to 92 percent, respectively. In 2050, the domestic renewable share is 90 to 100 percent. This includes the low-ambition Status Quo Scenario, and the 200% Renewable Scenario (Leadership + Export). In contrast to Germany, the use of renewable resources in Australia can extend substantially beyond supplying today's domestic electricity demand. Even in scenarios with significant electrification across sectors and a doubling of domestic generation for renewable energy exports, Australia can rely mainly on wind and solar PV generation.

The Australian transition to renewable electricity is currently largely driven by market forces, in particular investment in cost competitive renewables. However, regulatory reform and policy will be needed to facilitate transformation in energy supply and use with minimal friction, and to make best use of the societal, business and economic benefits of a new energy system.

Proven policy approaches include mechanisms to reduce risks for investors and ensure low-cost financing, as well as incentive-based policies to internalise the societal benefits of zero-emissions energy. Regulatory and energy market reforms will be needed to ensure efficient investment in new electricity generation and other energy production, infrastructure for transmission and storage of energy, additional demand flexibility to help with a cost-effective integration of variable renewables. Getting regulatory settings right will help achieve lower energy costs and electricity prices. Governments are also needed to help manage the transition in regions where fossil-based industries are prominent.

Finally, governments have an important role to play in determining the opportunities for large-scale renewables-based export industries, including using hydrogen as an energy carrier (*ETH, 2019a*). They may also have important roles in paving the way for such industries by establishing suitable regulatory and fiscal frameworks, facilitating infrastructure development where applicable, and helping to coordinate cross-country investment and trade in new energy. Sound policy to support energy transition will minimise frictions and maximise its economic potential.

2. Costs in a renewable-based system are similar or lower than today

Generation costs (the levelised cost of electricity - LCOE) from renewable sources fall below those of conventional technologies. Additional costs stem from flexibly balancing demand and supply in space and time (from transmission, storage, operating and peak load reserves). In the scenarios, these costs are less than one third of the total system costs across all models and scenarios even for 100-percent (or 200-percent) renewable scenarios in 2050 (Figure 5). As a result, the average system cost and electricity prices of a renewable-based electricity system are similar or lower than those of today's system. In perfect markets, assumed in this modeling, long-term marginal costs (average system costs) translate into average wholesale electricity prices.

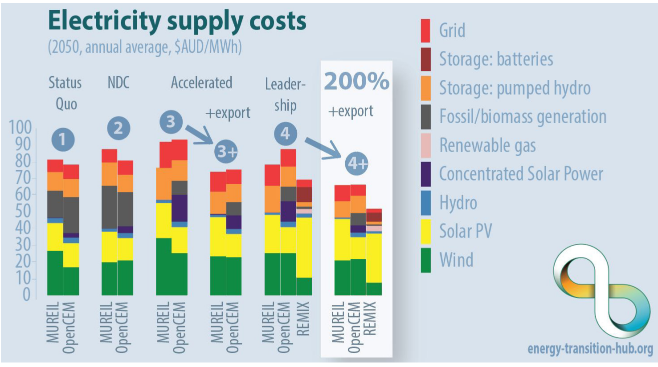

Figure 5: Average 2050 costs (total and by source) of supply per unit of electricity demand (domestic and export) across the scenarios and models. These long-term marginal costs comprise all costs (variable and fixed as annuities) for a 2050 equilibrium power system, while costs for hydrogen production and related infrastructure are not included. In perfect markets, these long-term marginal costs translate into average wholesale electricity prices. While average cost results are similar across models, the remaining differences are due to model-specific parameter assumptions, scope, detail and structure.

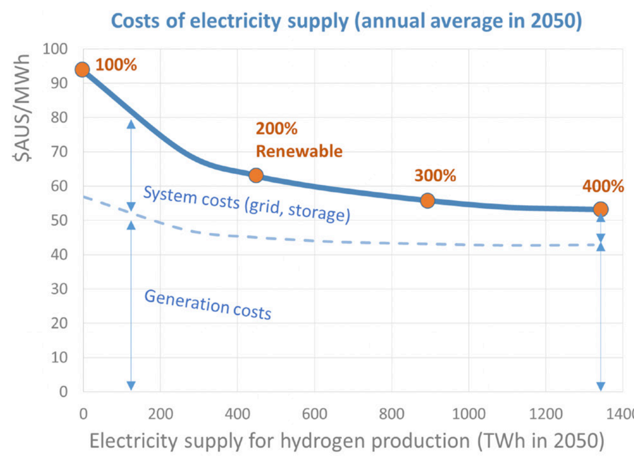

Figure 6: Average 2050 costs of supply per unit of electricity demand (domestic and export) as a function of hydrogen production from the MUREIL model. Going beyond 200 percent renewables further decreases the system cost element and overall costs of electricity supply.

In the export scenarios, (the Accelerated Export Scenario and the 200% Renewable Scenario), the average system cost element can be further reduced such that overall system costs decrease to 52-66 $AUD/MWh. These cost reductions can be obtained by the synergistic interplay of a renewable-heavy electricity system and hydrogen production. Future hydrogen production costs and average electricity costs can be minimised if electrolysers are located and integrated in the NEM, mainly because hydrogen can be stored and the associated electricity demand is flexible. Electrolysers in the NEM can operate during times of low and moderate electricity prices (e.g. they shave diurnal solar peaks), while ramping down during high-price hours. Through this flexible operation, electrolysers support the accommodation of variable wind and solar PV output, while slightly reducing storage and transmission requirements, and curtailment rates. On the other hand, electrolysers in the NEM benefit from achieving lower electricity costs than in a stand-alone operation. The cost reductions due to an integrated and optimised operation of electrolysers in a renewable-heavy NEM can overcompensate the gain of even better renewable resources at remote and isolated locations.

Going beyond 200 percent renewables by producing more hydrogen further decreases the average system cost element, overall costs of electricity supply (domestic and export) and costs of hydrogen production. Figure 6 shows scenario results from the MUREIL model applying the 200% Renewable Scenario framework (including significant electrification), while further scaling up Australia's hydrogen export economy. From no hydrogen production to a hydrogen production that adds 300 percent to electricity demand, the average costs of electricity supply decrease by 45 percent. The remaining costs are dominated by pure generation costs (LCOE) of wind power and solar PV.

3. Multiple options secure reliable supply from 100 percent renewables

Balancing electricity demand and variable renewable supply is required on all time scales (from seasons to hours), as illustrated for the 100 percent (and 200 percent) renewable system calculated by the hourly REMix model for the Leadership Scenario without exports (and with exports) in 2050 (Figure 7).

In the no-export scenarios, variable supply of wind and solar power can be accommodated mainly via mixing wind and solar PV, short-term storage, regional interconnection and capacity reserves.

Seasonal balancing can be best illustrated with time series of weekly generation aggregated for the whole Australian electricity system (Figure 7 top left). The 2050 power demand is almost flat during the year (despite a slight increase during winter months due to electric heating). Wind power generation is higher in winter, such that wind and solar PV show opposite seasonality, and energy demand can be met by a complementary combination of these two cheapest generation options. For meeting peak demand in winter weeks with low wind and solar generation, the models find various answers: capacity reserves from plants using biogas or renewable methane (represented only in the REMix model) or reservoir hydro power. Further seasonal balancing is provided by the flexible production of hydrogen for domestic use (no export in this scenario).

Balancing across days and hours is mainly achieved with two competing options: short-term storage technologies and demand flexibility. Storage technologies are off-river pumped hydro storage and concentrating solar power (which dominates in MUREIL and OpenCEM) or battery storage (which dominates in REMix). Both mainly operate in day-night cycles as solar PV is the main source of supply (Figure 7 bottom panels). The midday solar supply peak is smoothly spread across the day to meet diurnal demand. Depending on the model, the electricity storage capacity required in the Leadership Scenario in 2050 is between 45 GW (MUREIL/OpenCEM) and 100 GW (REMix), which is very high compared to an approximately 100-GW annual peak load. With its 2050 greenfield approach, REMix deploys more solar PV than the other two models as the solar PV cost advantage over wind power increases in time. MUREIL/OpenCEM deploy more wind in the decades leading up to 2050, resulting in less installed PV capacity and less short-term storage in 2050.

Demand flexibility originates mainly from sector coupling technologies (from newly electrified energy demand). This includes the controlled charging of some parts of the electric passenger vehicle fleet, and a flexible operation of cooling and heating systems allowed by thermal energy storage. Together, these technologies lead to a significant reduction in the demand for stationary batteries and pumped hydro storage, implying short-term storage would see even higher deployment if demand was inflexible. In addition, the pooling of variable supply and demand realised by enhancing and extending transmission grids serves to equalise short-term fluctuations. This is particularly beneficial in regions with high shares of wind power.

In the 200% Renewable Scenario, the wind and solar PV integration challenge reduces.

In the export-oriented electricity system analysed in the 200% Renewable Scenario, domestic demand (Figure 7, dotted white line) is met almost on the side by oversized capacity of mainly solar PV. In each week of the year, average electricity supply significantly exceeds average demand, while the surplus electricity is mainly absorbed through the electrolytic production of hydrogen for domestic use and export. Electrolysers roughly follow the patterns of solar PV: they operate with high flexibility in day-night cycles exhibiting a summer-peaking seasonal pattern. Such flexible operation requires large-scale hydrogen storage to decouple hydrogen production from transport and export.

In a hydrogen export economy, the additional balancing and flexibility requirements are reduced. This decreases system-related costs and average electricity prices, which converge towards the pure generation costs (LCOE) of renewable electricity (Figures 5 and 6). Short-term storage and transmission are still part of the optimised system. Both technologies are used to distribute power generation spatially or temporally, and increasingly also for smoothing electricity input to electrolysers, (increasing their capacity factor) and thereby bring down the costs of producing hydrogen. There is a significant co-benefit of generating hydrogen in a renewable-based system. Building up a hydrogen export economy is therefore an additional driver for deploying renewables for domestic demand.

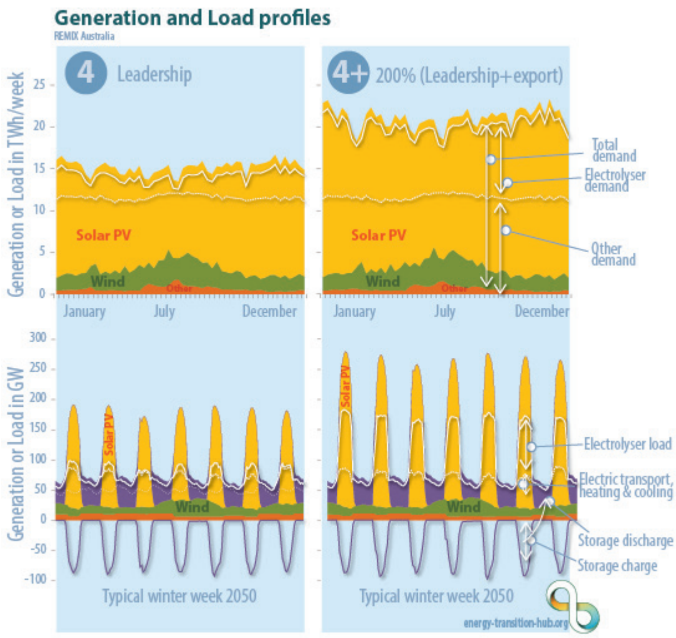

Figure 7: REMix model results show weekly sums of power generation and demand (top) and hourly system operation during a typical June week (bottom) for the Leadership Scenario without export (left) and with export (200% Renewable Scenario) (right).

4. Australia will need to expand its transformation beyond electricity supply

The results shown so far focus on the electricity supply side, while large parts of the demand side are indirectly covered in some scenarios by considering extensive electrification and electricity use for hydrogen generation and the refinement of metals.

As climate stabilisation (limiting global warming to any target including 1.5°C to 2°C) will require achieving net-zero emissions on a global scale (*Allen et al., 2009; Allen et al., 2018; Matthews, Gillett, Stott, & Zickfeld, 2009*), both Australia and Germany need to look beyond their electricity supply and transform all energy end-use sectors in industry, transport and buildings as well as land-use sectors.

Figure 8 shows how Australia and the EU could achieve a cross-sectoral transformation that goes beyond electricity supply. It provides a snapshot of total CO_2 emissions in 2050 across sectors in the Accelerated (80 percent CO_2 reduction economy-wide) and the Leadership Scenarios (100 percent CO_2 reduction economy-wide) from simulations of energy-economy model, REMIND.

The industry and transport sectors are significantly more difficult to decarbonise than the power sector. Key mitigation strategies in these sectors are energy efficiency improvements, direct electrification of energy end-uses (e.g. heat pumps, battery-electric vehicles), and the use of low-carbon fuels (biofuels, hydrogen or synfuels). However, as full decarbonisation of those sectors might not be possible or may be too costly, CDR through land-based carbon sinks, BECCS, or even DACCS exist as potential options in the offset of residual emissions (see ETH, 2019b). Australia has a relatively large potential for land-based CDR that could ease the route to a net-zero economy (*Jotzo et al., 2014*). However, transition in the electricity sector is still an indispensable first step. In comparison to the EU, Australia currently has larger per-capita emissions where a significant part comes from the electricity sector due to the prevalence of coal. A rapid transition to renewables would cut Australian emissions substantially.

However, to create a net-zero economy additional challenges, especially on the energy demand side, will have to be overcome. Australia has a relatively high per-capita demand for transport energy (64 GJ/cap per year in 2015) which is twice as high as in Japan or the EU (*IEA, 2018*). Australia also expects higher population growth over the next 30 years, which increases the importance of energy efficiency and electrification in meeting emissions reduction targets. Besides road transportation, solutions for the aviation and long-distance shipping sectors are required. Those sectors cannot be directly electrified but would need to rely on zero-emissions synthetic or biofuels or be offset by CDR. Energy-intensive industries such as steel, cement and chemicals, will need to phase out fossil fuel use (for combustion and potentially feedstocks). The transformation of energy end-uses is still in its infancy today and spelling out future solutions will require further investigation of technological innovation, green supply chains and global markets

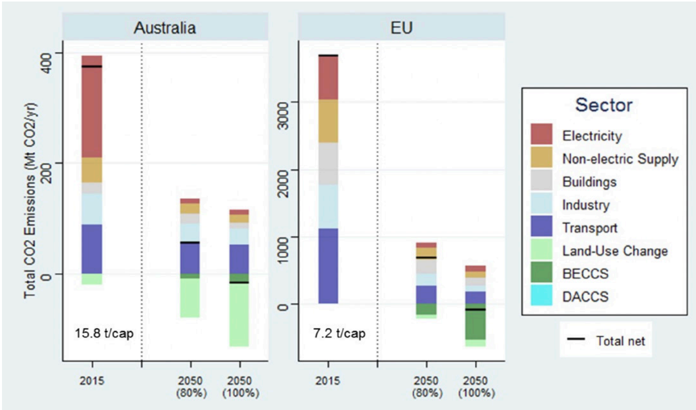

Figure 8: *Current CO2 emissions (2015) and 2050 CO2 emissions in the Accelerated (80 percent reduction) and Leadership Scenario (100 percent reduction) across sectors. The black bar shows total net emissions. The 2050 scenarios are simulations from the global energy-economy model, REMIND. Historic (2015) emissions are from the CEDS database.*

Our results are in line with the general findings of earlier Australian studies on decarbonisation pathways for near-zero emissions by 2050 (*Hatfield-Dodds et al., 2015; Jotzo et al., 2014*) and analyses of global decarbonisation pathways (*Luderer et al., 2018*). These studies also include non-CO_2 greenhouse gas emissions that are generally difficult to abate and argue that net-zero emissions can still be reached by expanding CDR through land-use change to a greater extent than included in our scenarios. *Jotzo et al. (2014)* perform a more detailed bottom-up analysis of mitigation options in the transport and industry sectors, and through this suggest a slightly higher reduction potential in those sectors compared to our results (see ETH, 2019a) for a discussion of industrial opportunities of decarbonisation). Integrated assessment models tend to underestimate the abatement potential in energy demand sectors compared to bottom-up assessments; this is an area of ongoing research and improvement.

A number of recent decarbonisation studies on the EU (*Fragkos, Tasios, Paroussos, Capros, & Tsani, 2017; Vrontisi, Fragkiadakis, Kannavou, & Capros, 2019*) paint a detailed picture of European mitigation options and pathways. These studies provide detailed discussions on the relevance of different mitigation strategies (energy efficiency, renewable expansion, electrification of heat, synthetic fuels, lifestyle changes), and their scenarios show similar residual emissions from the energy demand side, that would need to be offset by CDR for a net-zero target.

Better understanding net-zero emission pathways for Australia and Germany can benefit from further connecting the energy modeling communities in both countries. With sector coupling and global interactions, such as changing energy trade flows, global and national energy transitions are increasingly complex. Sharing national perspectives and understanding the global context, as well as bilateral opportunities, is crucial for deriving transition pathways that provide both vision and guidance to societies and political decisions.

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Appendix: Model descriptions

Model name (acronym)	MUREIL	OpenCEM	REMix Australia	REMIND
Extended name	Melbourne/Monash Renewable Energy Integration Lab	Open source Capacity Expansion Model	Renewable Energy Mix Australia	Regional Model of Investments and Development
Short description	An electricity sector model that aims to derive cost-optimal transition pathways from the current generation mix to a low-carbon system in 2050 with special focus on energy export via hydrogen and HVDC links	An open source electricity sector modelling tool that aims to support transparent and well-informed analysis of technology and policy options for future planning of Australia's electricity system	REMix relies on a global high-resolution database for renewable energy potentials. Its application is focused on the evaluation of flexibility requirements in the future energy system and its provision by energy storage, transport and sector coupling	Global Integrated Assessment model with 13 world regions based on a macroeconomic growth model and an energy system model. It simulates cost-optimal mitigation pathways including different energy supply sectors, energy end-use sectors and negative emission options
Institution	University of Melbourne/Monash University	IT Power, University of Melbourne, University of New South Wales	German Aerospace Center (DLR)	Potsdam Institute for Climate Impact Research (PIK)
Type of model / objective function	Cost minimisation	Cost minimisation	Cost minimisation	Macroeconomic welfare maximisation
Type of program	Hourly resolution with representative days: 28-84 sampled days or one full year	Hourly resolution	Hourly resolution	Short-term variability is reflected in a residual-load-duration curve approach 2005-2050: five- year time steps until, 2060, 2150: ten-year time steps
Time horizon	Flexible, default: 2050	Flexible, default: 2050	Mostly applied to single years, i.e., no transformation path	2100
Geographical scope	Australia and Indonesia (adaptable to generic system)	Australia’s National Electricity Market (adaptable to generic system)	Mostly applied to Germany and Europe, global application possible	Seven aggregated regions, among them the European Union, and six individual countries (China, India, Japan, United States of America, Russia and Australia)
Geographic resolution	Australia’s NEM, Northern Territory, Western Australia and Indonesia’s Java-Bali ~ 25 nodes with 60 renewable zones	National Transmission Development plan zones (21 zones for transmission expansions) and 36 Renewable Energy Zones for generation expansion	Australia is modelled in 27 regions	13 world regions
Sector coupling / 'electrification'	Assumes increasing demand in the electricity sector from electrification of domestic heating, transportation, and industry; power-to-gas	Only incorporated through exogenous assumptions	Detailed heat sector model including heat pumps, CHP and heat storage, battery electric vehicles, power-to-gas, gas transport and storage	Can substitute non-electric energy with electric energy in constant elasticity of substitution function in the buildings, industry and transport sectors. Includes electrolysis as H_2 production technology
Balancing reserves	Yes	Reserve margin included for capacity expansion model (exogenous)	Yes	Five-year time step is used, so no hourly power balancing possible. A parameterisation ensures that rising shares of wind and solar require more grid and storage infrastructure