Australia's National
Science Agency

Multi-sector energy modelling

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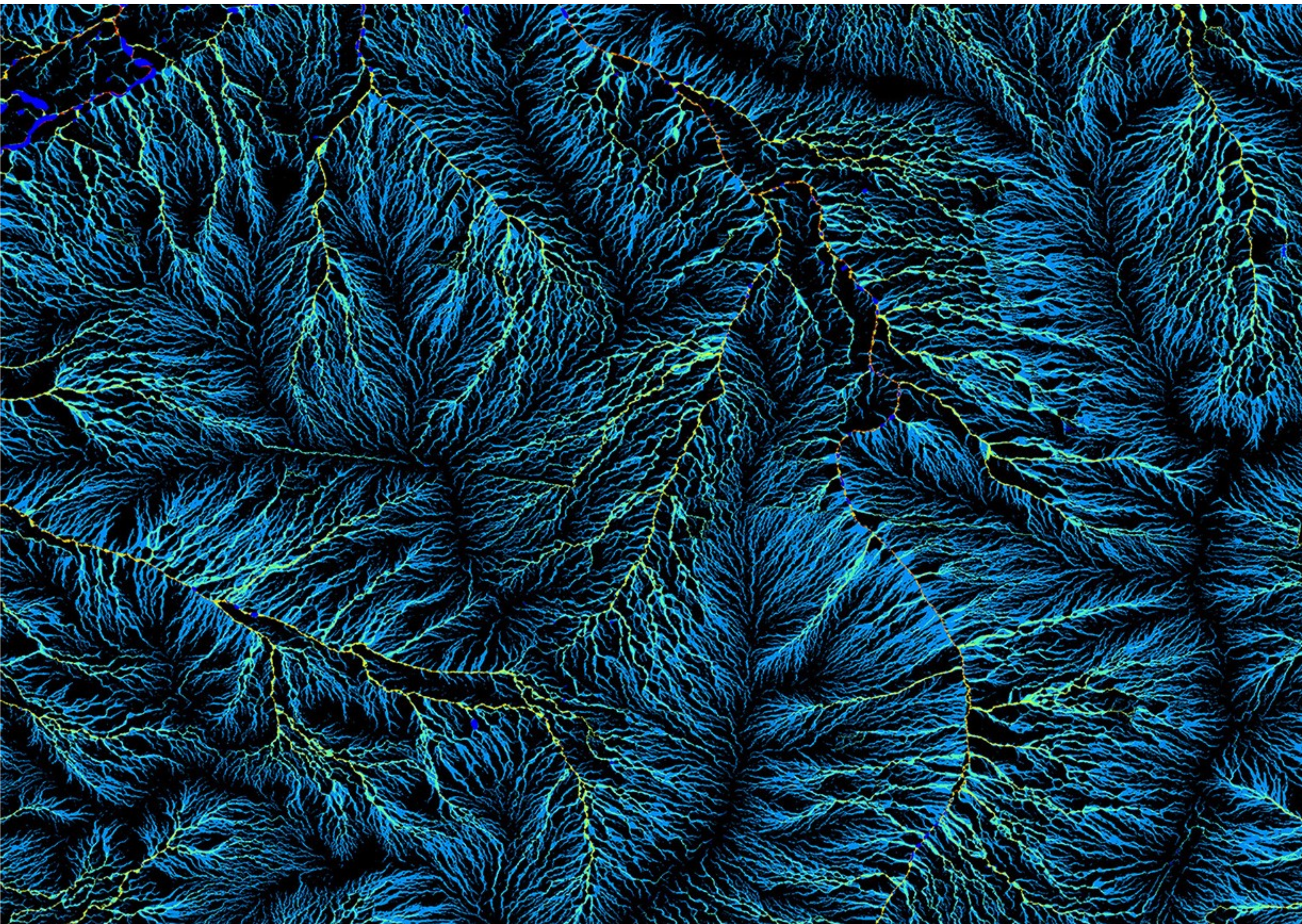

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Executive summary

AEMO commissioned CSIRO and ClimateWorks Australia to complete multi-sectoral modelling of four decarbonisation scenarios and to quantify the changing influences that will affect electricity demand under various emissions targets across the period 2019-20 to 2050-51. The project looks to inform sector-level emissions trajectories and the scale of energy efficiency, as well as electrification and other fuel switching that may be associated with decarbonisation of the broader economy.

A multi-sectoral view of decarbonisation allows for key dynamics and linkages to be explored across the different sectors, while understanding the changes over time in key sectors such as power generation, transport, industry and buildings, that are required to meet various decarbonisation objectives (for example, in Figure I). Understanding the residual emissions from hard-to-abate sectors is also key to determining the amount of carbon sequestration required through technology, carbon forestry, or other land sector sequestration methods.

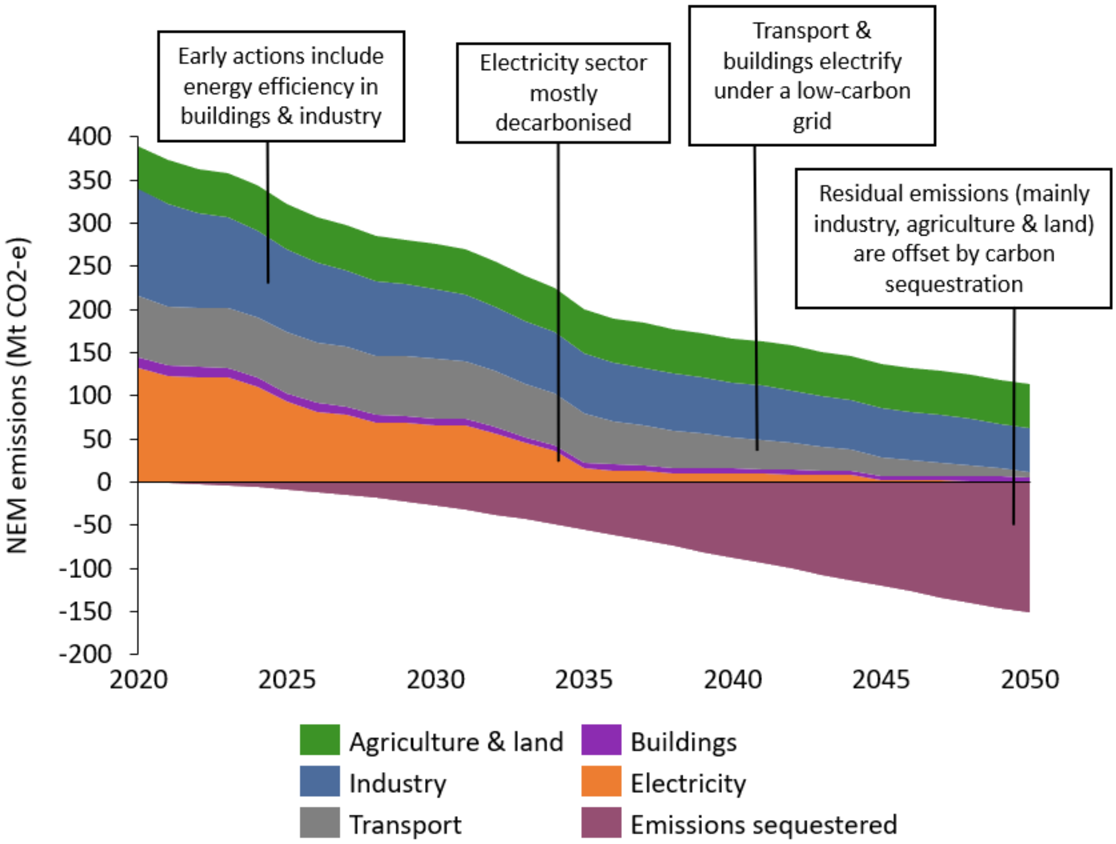

Figure I: NEM emissions by sector for one decarbonisation scenario (Step Change), showing key sectoral milestones in the transition towards net zero emissions

The modelling resulted in a number of key findings, that are outlined below.

Australia can meet net zero emissions on or before 2050 by aligning to the four pillars of decarbonisation.

Achieving net zero emissions across the economy and in every sector relies on the four pillars of decarbonisation (Figure II):

1. Energy efficiency, to improve energy productivity and reduce energy waste
2. Decarbonising electricity to zero or near-zero emissions
3. Electrification and a shift away from fossil fuels to zero- or near-zero emissions alternatives
4. Non-energy emissions reductions and offsetting of residual emissions

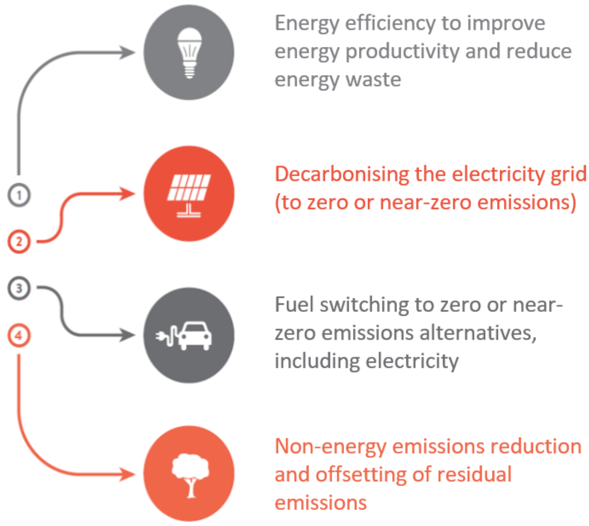

Figure II: The four pillars of decarbonisation, adapted from CWA, 2014

All of the four pillars of decarbonisation play a role in each of the scenarios. While each scenario is a view of a holistic potential future, each scenario explores a key theme. Net Zero 2050 plots a pathway towards a zero emissions economy that is broadly consistent with the present trajectory up to 2030, followed by an increase in uptake of the decarbonisation technologies needed to achieve net zero emissions in 2050, broadly consistent with a target 2.6°C of global warming. Step Change looks at more ambitious emissions reduction in line with limiting warming to less than 2°C, where energy efficiency, electrification and emission reductions across all sectors play a balanced role. Hydrogen Superpower presents a future where global commitments to limit warming to 1.5°C above pre-industrial levels lead to breakthroughs in the cost of hydrogen production, resulting in substantial growth of both domestic and export industries. Strong Electrification is a sensitivity on Hydrogen Superpower, where there is a strong global push to limit warming to within 1.5°C, but reductions in hydrogen production costs do not eventuate, resulting in strong electrification across the economy to stay within the required carbon budget.

Across all scenarios, uptake of energy efficiency, near 100% renewables by 2050, and uptake of electrification play a role, although the differences in drivers see varying roles for these pillars across each scenario. Deployment of targeted solutions to abate non-energy emissions is also required across all scenarios, with carbon sequestration required to offset the remaining emissions (largely in agriculture, and process or fugitive emissions in industry).

The timing of actions across these pillars varies in each scenario. While solutions such as electrification and switching to alternative fuels offer significant decarbonisation potential, deployment of green hydrogen or bioenergy supply at scale is likely to take some time to establish, and higher levels of emissions abatement from electrification is reliant upon decarbonisation of the electricity grid. Energy efficiency uptake offer emissions abatement potential across a wider time horizon, but especially in the near term.

Energy efficiency can accelerate the low-carbon transition, even before the grid decarbonises.

In the near-term, energy efficiency improvements (shown as energy avoided in Figure III) offer an effective means of decarbonisation. The scenarios with the strongest decarbonisation drivers in the near term (Step Change, Hydrogen Superpower and the Strong Electrification sensitivity) all see high levels of energy efficiency uptake in the early projection years. Some of this is expected to occur at no additional cost, based on historic rates of productivity improvement. Additional efficiency gains occur through investment in technologies that are available today, and emerging technologies that are expected to become available in later decades, potentially with policy support for this investment. Energy efficiency has a particularly prolonged role to play in Step Change and Hydrogen Superpower, given the lower reliance on electrification compared to the other scenarios.

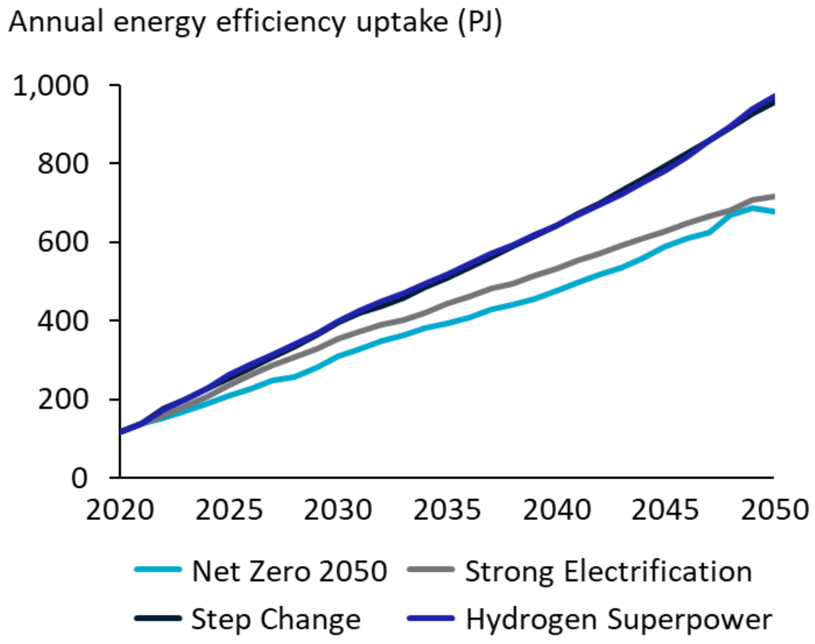

Figure III: Uptake of energy efficiency in the NEM in the four modelled scenarios, shown as PJ energy avoided per year, across all fuel types in the end-use sectors

Electrification is a cost-effective option to reduce emissions – which would lead to high growth in NEM demand

The combination of emissions abatement potential from a decarbonised grid, and accompanying energy efficiency benefits, makes electrification an attractive decarbonisation option, albeit to different extents, across all scenarios. Electrification technologies include heating and water services in buildings, material handling of commodities and process heating activities in the industrial and agricultural sectors, light passenger electric vehicles, and short-haul electric non-road transport.

Although growth in NEM demand is unusual compared to recent historical years, long-term growth in underlying demand is seen in these scenarios. In Net Zero 2050 and Step Change, electricity demand grows by 133% and 108% by 2050 respectively. In Hydrogen Superpower, this growth is 116% before the impacts of additional industries (green steel and hydrogen exports), and 468% after. The Strong Electrification sensitivity explores a much greater role for electrification under a 1.5 degree carbon budget, leading to 143% growth in NEM demand by 2050 (Figure IV).

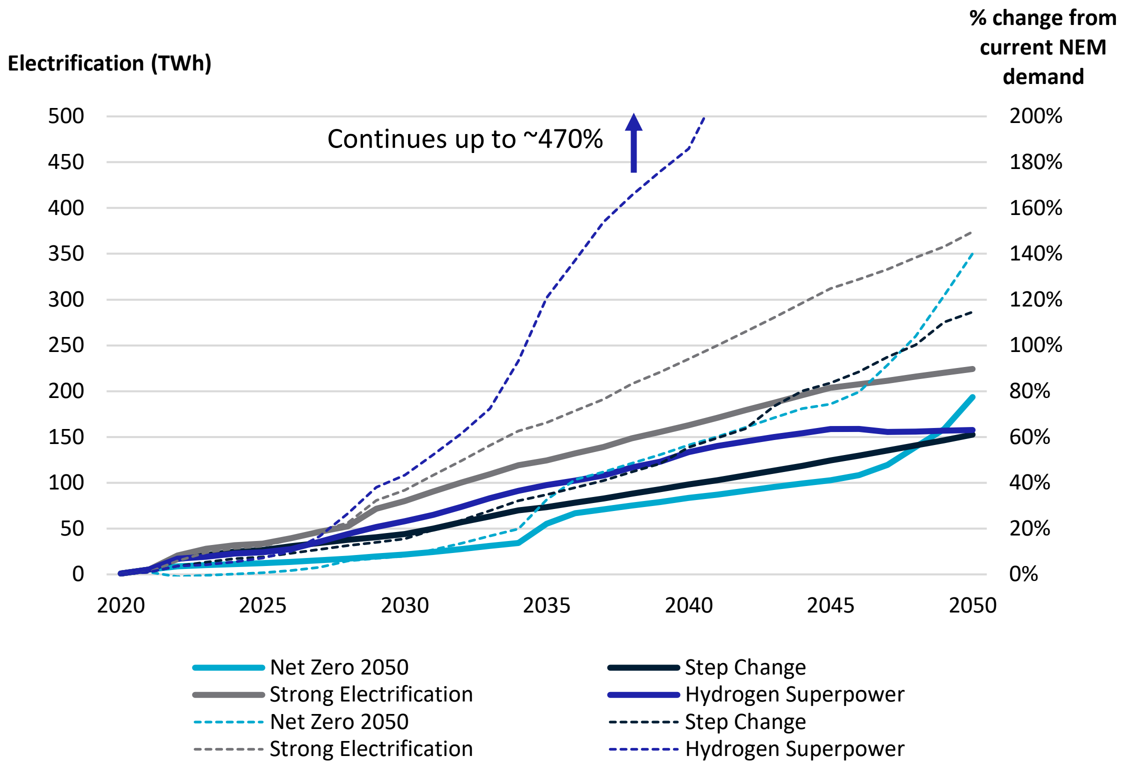

Figure IV: (Left axis) uptake of electrification in the NEM in the four modelled scenarios, shown as TWh added electricity demand per year. (Right axis) total NEM electricity demand in the end-use sectors (industry, buildings & transport), shown as % increase from NEM demand in 2020 per year

Aside from electrification, alternative fuels such as hydrogen and bioenergy are critical to decarbonising industry and transport

Hydrogen is available as an alternative fuel across the economy in all scenarios except for the Strong Electrification sensitivity where it is only available in transport. Hydrogen Superpower has lower costs of electrolysis and an ambitious decarbonisation objective and hence the highest uptake – hydrogen makes up over 30% of the primary fuel share in industry, and 9% in buildings by 2050. Hydrogen also features in transport particularly in heavy vehicles where range and maximising payload are priorities. In Net Zero 2050, it was found that there is a role for hydrogen domestically in the later years of the projection, where there is a push across the economy to rapidly decarbonise in order to reach Net Zero emissions. Step Change was intermediate between the others, with an earlier uptake of hydrogen than in Net Zero 2050, but not as early nor to the same level as Hydrogen Superpower.

Bioenergy features across all scenarios and plays a role in decarbonising some hard-to-switch fuels in industry. Although the overall volume of bioenergy does not vary as much across the scenarios as other fuels, in 2050 the uptake is highest in Net Zero 2050 due to the rapid need to reduce emissions in the final stretch of the emissions trajectory, and the ability for bioenergy to be deployed over a relatively short timeframe in industry. Bio-derived jet fuel, a form of bioenergy, plays a key role as a drop-in fuel to decarbonise aviation. The role for bioenergy is slightly diminished in the other scenarios where there is greater time for electrification and/or hydrogen to become established as an alternative fuel.

To achieve net zero emissions, there is a critical role for non-energy abatement solutions and carbon sequestration

These scenarios explore a variety of pathways to decarbonise energy emissions across the economy. However, non-energy emissions from agriculture, land and hard-to-abate industrial processes still make up a significant portion of Australia's emissions profile. In all scenarios, targeted non-energy emissions abatement options are deployed to address these emissions. For the remaining portion of emissions that cannot be abated using modelled technologies, negative emissions solutions are required, such as land-based emissions sequestration or CCS. While it is assumed that the role for sequestering emissions is reserved for only the hardest-to-abate emissions in the economy, every scenario modelled here features some level of carbon sequestration, largely from land-based methods but with a small component from CCS ranging from between 4-14% (Figure V). The maximum amount of carbon sequestration reached in each scenario amounts to 156 Mt CO_2-e/yr in Net Zero 2050, 153 Mt/yr in Step Change, 172 Mt/yr in Hydrogen Superpower and 142 Mt/yr in the Strong Electrification sensitivity. If this were to be met via carbon forestry, this would require the equivalent of 8.6-10.9 Mha land. However, other land-based sequestration methods will have different requirements.

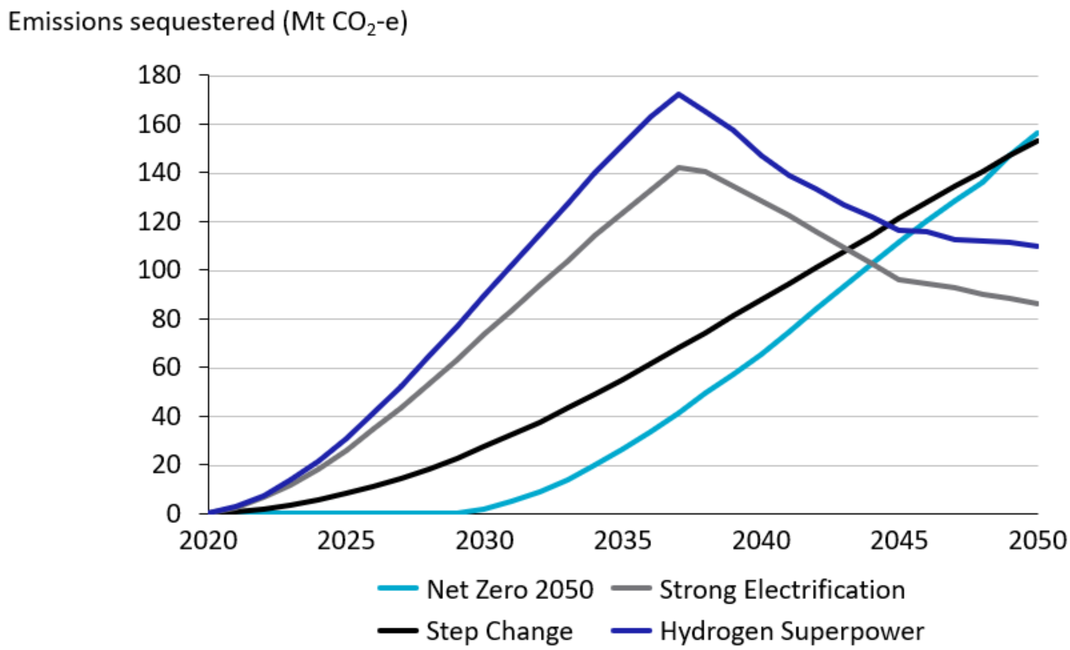

Figure V: Total emissions sequestered per year in NEM states in all scenarios, via either land-based sequestration methods or CCS

Industry can continue to grow in a decarbonised economy through low emissions energy sources

Continued industrial growth is a key feature of all scenarios, with industrial activity (in physical production terms) increasing by 35% from 2020-2050 in Net Zero 2050, 31% in Step Change, 61% in Hydrogen Superpower and 34% in the Strong Electrification sensitivity. The results of this modelling show that existing and emerging technologies in industry that assist in lowering the energy intensity / improve the energy productivity of industries, combined with sequestration of residual emissions, allow for industrial growth to continue while achieving ambitious emissions reductions. The Hydrogen Superpower scenario presents a future with even stronger industrial growth, through the establishment of a globally competitive green steel industry and hydrogen export sector.

Introduction

The CSIRO and ClimateWorks Australia (CWA) were commissioned by AEMO to assist in producing projections of electricity and fuel consumption, and emissions for the state and territory economies connected to the National Electricity Market (NEM). This modelling was engaged to better understand the interplay between various sectors as Australia's economy and energy sectors change over coming decades. Specifically, the report provides projections for four scenarios with varying technology and emissions profiles, resulting in varied fuel uptake across end-use sectors.

The four scenarios will be covered in more detail in Section 2.1, but are broadly defined as:

Net Zero 2050: represents the transition of the energy industry under current policy settings and technology trajectories, where the transition from fossil fuels to renewable generation is generally driven by market forces. Following 2030, additional effort through technology adoption achieves net zero emissions by 2050, broadly consistent with limiting global temperature rise to 2.6°C by 2100 over pre-industrial levels.

Step Change: higher decarbonisation ambitions are supported by rapidly falling costs for battery storage and variable renewable energy (VRE), which drive consumers' actions and relatively high levels of electrification of other sectors consistent with limiting global temperature rise to less than 2°C by 2100.

Hydrogen Superpower: represents a future with the strongest global decarbonisation targets, resulting in a thriving international hydrogen economy. In this scenario, Australia therefore sees the growth of a large export industry based around hydrogen and green steel (which uses hydrogen for production). To meet domestic emissions targets, consistent with limiting global temperature rise to 1.5°C, this scenario sees high levels of electrification and adoption of readily available renewable hydrogen, fuelled by low-cost abundant renewable energy and strong economic growth.

Strong Electrification: represents a sensitivity against Hydrogen Superpower with the same basic scenario conditions, but the projected reductions in hydrogen production costs do not eventuate and so Australia does not develop an export industry for hydrogen and hydrogen-related products. To meet the same emissions reduction targets there is therefore a need for stronger energy efficiency and electrification in all sectors.

The assumptions that underpin the modelling and analysis were communicated to stakeholders through the Forecasting Reference Group and agreed between CSIRO, CWA and AEMO prior to the commencement of modelling. There was further refinement based on practical evaluation of model results and stakeholder feedback throughout the project.

CSIRO and CWA implemented the scenarios, and their associated assumptions and constraints, to produce expert advice and analysis regarding the effects of multi-sector interactions on regional and sectoral consumptions and emissions for the NEM-connected states and territories (i.e. New South Wales, Australian Capital Territory, Victoria, Queensland, South Australia and Tasmania) for the period 2019-20 to 2050-51.

This report outlines the methodology, scenario assumptions and projection results, and is structured as follows:

- Section 1 outlines the methodology, providing an overview of the AusTIMES model and key aspects of modelling decarbonisation scenarios.
- Section 2 briefly discusses scenario narratives and the key assumptions that do or do not vary by scenario.
- Section 3 discusses NEM level projection results for the four scenarios focussing on emission outcomes, fuel mix changes in the electricity and end-use sectors, hydrogen and emissions sequestration from the land use sector.

1 Methodology

1.1 AusTIMES model overview

CSIRO implemented the four specified scenarios in the AusTIMES model, which is an Australian implementation of The Integrated MARKAL-EFOM System (TIMES) that has been jointly developed under the International Energy Agency (IEA) Energy Technology Systems Analysis Project (ETSAP)[1]. CSIRO is a Contracting Party to ETSAP and has developed an Australian version of the TIMES model (AusTIMES) in collaboration with ClimateWorks Australia (CWA), a joint partner on this project.

The TIMES energy system modelling framework has been used extensively in over 20 countries. TIMES is a successor to the MARKAL energy system model. The model satisfies energy services demand at the minimum total system cost, subject to physical, technological, and policy constraints. Accordingly, the model makes simultaneous decisions regarding technology investment, primary energy supply and energy trade. Extensive documentation of the TIMES model generator is available from the ETSAP website[1].

The TIMES model generator is a partial equilibrium model of the energy sector. In the energy domain, partial equilibrium models, sometimes referred to as 'bottom-up' models, were initially developed in the 1970s and 1980s (e.g. Manne, 1976; Hoffman and Jorgenson, 1977; Fishbone and Abilock, 1981). Partial equilibrium models are used because the analysis of energy and environmental policy requires technological explicitness; the same end-use service (e.g. space heating, lighting) or end-use fuel (e.g., electricity, transport fuel) can often be provided by one of several different technologies that use different primary energy resources and entail different emission intensities, yet may be similar in cost (Greening and Bataille, 2009). This means that in different scenarios, consumption of various primary energy sources may vary across sectors and technologies.

Partial equilibrium modelling allows the incorporation of various technologies associated with each supply option and allows a market equilibrium to be calculated. It also allows for competing technologies to be evaluated simultaneously, without prior assumptions about which technology, or how much of each, will be used. Some technologies may not be taken up at all. This allows flexibility in the analysis: detailed demand characteristics, supply technologies, and additional constraints can be included to capture the impact of resource availability, industry scale-up, saturation effects, cost reductions and policy constraints on the operation of the market.

The advantage of using a system model approach rather than an individual fuel / technology / process modelling approach is that the infrastructure constraints can be explicitly included, such as life of existing stocks of assets (e.g., plant, buildings, vehicles, equipment, appliances) and consumer technology adoption curves for abatement options which are subject to non-financial

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[1] https://iea-etsap.org/ [accessed 12 July 2021]

investment decision making. By using a system approach, we can account for the different impact of abatement options when they are combined rather than implemented separately.

1.2 Main structural features

AusTIMES model has the following structural features:

- Coverage of all states and mainland territories (ACT, NSW, NT, QLD, SA, TAS, VIC, WA)[2]
- Time is represented in annual frequency in financial years (2015, 2020-2051)
- End-use sectors include agriculture (8 sub-sectors), industry (6 sub-sectors in mining, 19 sub-sectors in manufacturing, 5 sub-sectors in other industry), commercial and services (11 building types), residential (3 building types), road transport (10 vehicle segments) and non-road transport (aviation, rail, shipping)
    - Each sector has information regarding energy consumption and assumed efficiency gains, as well as options regarding which primary energy sources can be consumed, additional costed fuel switching or efficiency improvements, options for avoiding non-energy emissions and potential for carbon capture and storage (CCS)
- Representation of fuel types across the end-use sectors:
    - Industry and agriculture: Oil, black coal, brown coal, natural gas, hydrogen, electricity and bioenergy (representing bagasse in existing applications, ethanol, biodiesel and biogas)
    - Residential buildings: Natural gas, liquid petroleum gas, hydrogen, wood and electricity
    - Commercial buildings: Oil (as reported in Australian Energy Statistics), natural gas, hydrogen and electricity
- Representation of the annual operations of the supply-side of the electricity sector
- Five hydrogen production pathways including two electrolysis pathways: proton exchange membrane (PEM); and alkaline electrolysis (AE); steam methane reforming (SMR); SMR with CCS; coal gasification with CCS – although coal gasification was not selected.

1.3 Model calibration and inputs

The AusTIMES model for this study has been calibrated to a base year of 2019 based on the state/territory level energy balance (DISER 2020b), national inventory of greenhouse gas emissions (DoEE, 2019), stock estimates of vehicles in the transport sector (ABS, 2020a), data on the existing power generation fleet (AEMO, 2020) and installed capacity of distributed generation (Graham, 2021).

[2] For this work, the modelling results are only presented for the NEM-connected states and territories.

For this particular work additional inputs were sourced from AEMO and some of their other consultants regarding economic activity, population growth, distributed energy resources, capital costs of generation technologies, projected uptake of DER (i.e., rooftop solar PV, behind-the-meter batteries), and projected electric vehicle uptake for road transport. The assumptions applied are discussed in Section 2.2.

1.4 Objective function

TIMES is formulated as a linear programming problem. The objective function minimises total discounted system costs over the projection period (inter-temporal optimisation) while adhering to specific constraints. TIMES is simultaneously making decisions on investment and operation, primary energy supply, and energy trade between regions, according to the following equation:

$$NPV = \sum_{r=1,y=REFYR}^{R,2060} \frac{ANNCOST_{r,y}}{(1+d)^{(y-REFYR)}}$$

Where:

NPV: net present value of the total costs

ANNCOST: Total annual cost incorporating investment, operation and trade (where relevant)

d: general discount rate

REFYR: reference year for discounting

y: set of years for which there are costs

r,R: region

While minimizing total discounted cost, the model must satisfy a large number of constraints (the equations of the model) which express the physical and logical relationships that must be satisfied in order to properly depict the energy system. Details on the constraints are available in Part I of the TIMES model documentation.[3]

Additional structural details of the AusTIMES model is outlined in Appendix A.

1.5 Implementation of decarbonisation objectives in AusTIMES

The implementation of decarbonisation objectives in AusTIMES has a number of options:

1. Implementing an annual carbon price trajectory per scenario that results in sufficient emissions reduction to meet the scenario objective
2. Implementing an annual emission reduction target that reaches the desired quantum of emissions in a particular future year

[3] https://iea-etsap.org/docs/Documentation_for_the_TIMES_Model-Part-I.pdf [accessed 21 March 2021]

3. Specifying a carbon budget (a cumulative emissions target by a certain year).

Although AusTIMES is populated with data on a number of technologies, the costs of emissions abatement across all sectors (especially agriculture) are not fully populated in the model. The total cost of decarbonisation is therefore not provided as an output of this work.

Accordingly, the implementation uses an iterative approach (Figure 1-1):

1. Implement a carbon price trajectory in AusTIMES consistent with the decarbonisation scenario[4] (sourced from literature)
2. Calculate the abatement impact of non-costed solutions on demand for products, emissions intensity, and sequestration of emissions (e.g., carbon forestry)
3. Determine whether the carbon budget consistent with the scenario has been met
4. Adjust the shadow carbon price trajectory accordingly
5. Iterate for each scenario until the desired carbon budget is met at lowest cost.

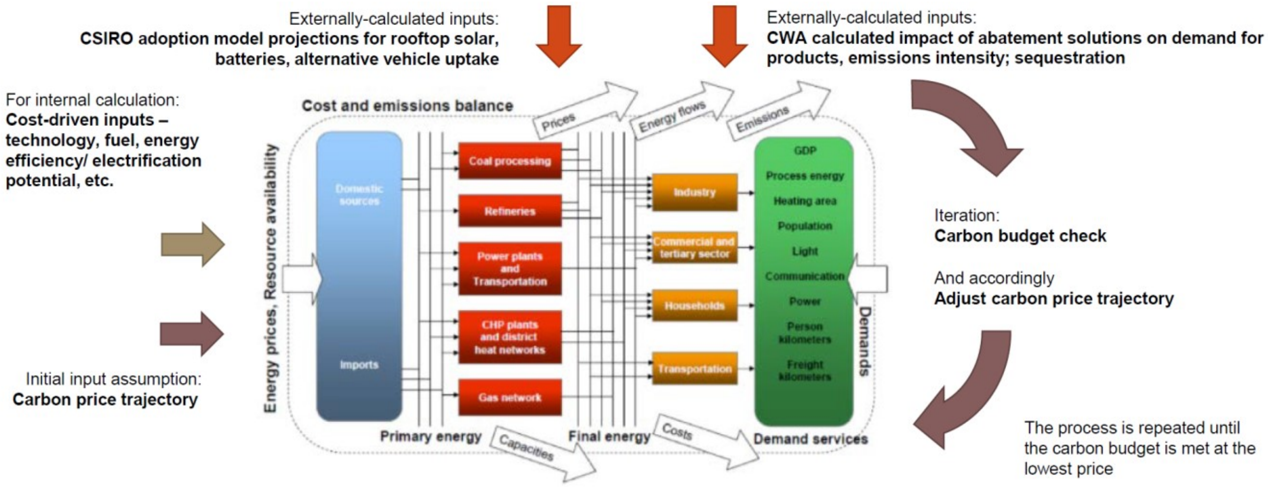

Figure 1-1: Implementation of decarbonisation scenarios in AusTIMES

The modelling for Step Change, Hydrogen Superpower and Strong Electrification used the iterative approach outline above. Net Zero 2050 was defined with an annual emission reduction target consistent with current policies until 2030 and a declining emissions trajectory to 2050 to achieve net zero emissions; this did not require the same iterative approach.

1.6 Carbon budgets

In applying the iterative approach outlined above, carbon budgets were set for three scenarios (Step Change, Strong Electrification and Hydrogen Superpower), which represent the total

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[4] Use of a carbon price as a way of implementing an emission reduction trajectory does not reflect any view about whether Australian State or Commonwealth governments would seek to use carbon price mechanisms to meet their emission targets. Ultimately any abatement policy can be translated to a shadow carbon price (e.g. renewable targets, low emission technology subsidies) and the simplified approach here of directly applying a carbon price plus a limited set of existing policies avoids the need to undertake a detailed policy design process which is not the purpose of this work. The approach of applying existing policies plus carbon prices to study abatement trajectories is consistent with other comparable works such as the IEA's *World Energy Outlook* and *Net Zero by 2050* reports.

cumulative emissions allowed between 2021-2050 in order for the scenarios to remain consistent with a particular temperature outcome.

For each scenario, an appropriate global carbon budget was chosen from a range of budgets published by the IPCC (Rogeli et al. 2018) that considers the expected global temperature outcome and probability of limiting temperature rise within that threshold. These global carbon budgets were translated into Australian-specific budgets from 2021-2050 by considering:

- Uncertainties in earth system feedbacks (Rogeli et al. 2018; Meinshausen 2019).
- Translation of a carbon dioxide budget into a carbon dioxide-equivalent budget including other GHG emissions (Meinshausen 2019).
- An assumption that Australia's 'fair share' of the global carbon budget is 0.97% (consistent with the modified contraction and convergence approach from Garnaut 2008; Meinshausen et al. 2019).
- Subtraction of historical and projected emissions up to 2021.

The methodological approach is outlined in Appendix B, and specific carbon budgets for each scenario are documented in Section 2.2.3.

To validate that the scenarios meet their carbon budgets, the cumulative net emissions from 2021 until the economy reaches net zero are calculated. If each scenario meets the budget, the scenario is valid for its specified pathway.

1.7 Land-based emissions sequestration

Calculating net emissions requires the consideration of both residual and sequestered emissions across the economy. Residual emissions can be obtained as a direct output of AusTIMES. However, AusTIMES does not currently have the capacity to model emissions sequestration at scale aside from some select applications of CCS for industrial process emissions, electricity generation and hydrogen production. Therefore, exogenous land-based sequestration assumptions are combined with the residual emissions trajectory to produce a net emissions trajectory. The maximum amount of land-based sequestration available is shown in Figure 1-2.

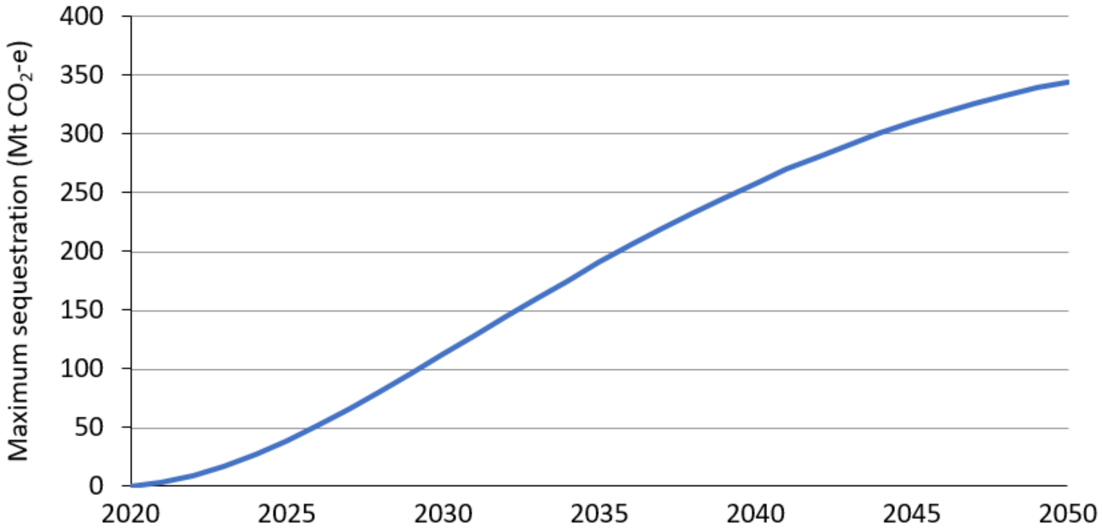


Figure 1-2: Maximum amount of land-based sequestration (in Mt CO_2-e) that is allowable for each scenario, based on LUTO modelling outputs

This maximum trajectory is derived from CSIRO's Land Use Trade-Offs (LUTO) model, which provides spatial analysis across the Australian intensive use zone, comprising 85.3 Mha of non-contiguous cleared cropping and intensive grazing agricultural land. This land is currently dominated by beef and sheep grazing, and cereal cropping. Within LUTO, economic returns for each 1km^2 parcel of land are calculated for a range of possible land uses, including carbon forestry (based on a shadow carbon price). The specific trajectory in Figure 1-2 represents a scenario where carbon plantings are required to be 5 times more profitable than existing land uses in order to be taken up. This results in annual sequestration of 344 MtCO_2-e/yr by 2050, across a planting area of 23.6 Mha. Plantings are assumed to be species with high carbon potential, and planting rate is constrained at or below 0.75 Mha/year[5].

Due to modelling limitations, this is a simplified approach that excludes a variety of land-based sequestration methods that are available today or becoming increasingly widespread, including options such as savanna burning, soil carbon methods, mixed-use carbon plantings with agriculture, or even 'blue carbon' methods. While it is hoped that modelling capabilities in this space will increase in future, it is useful to consider the carbon forestry sequestration curves produced in this report as a total amount of land-based sequestration. Realistically, this sequestration could be met through a diverse range of methods.

Scenario-specific land-based sequestration trajectories were determined largely by downscaling this maximum trajectory to the level of sequestration uptake that would satisfy the carbon budget in a given scenario, or achieve net zero emissions by 2050. Specific land-based sequestration assumptions are documented in Section 2.2.4.

Regional sequestration levels are based on the proportion of uptake from each state in the original maximum LUTO output (Bryan et al., 2016) and proportions do not vary between scenarios. Such outputs represent the carbon forestry sequestration expected from plantings in that state. The

[5] For further detail on LUTO and its assumptions, please refer to CWA et al. 2014, *Pathways to Deep Decarbonisation in 2050: How Australia can prosper in a low carbon world – technical report*, section 6.

emissions are determined nationally, so the contribution from individual states is not a specific consideration.

1.8 Link to distributed energy resources (DER) and electric vehicle adoption modelling

In parallel to the multi-sector energy modelling, AEMO has also commissioned consultants to project the uptake of embedded solar PV and behind the meter batteries, referred to together as DER. Similar work has also been performed on projecting adoption of alternative vehicle technologies.

As outlined in this Section, the uptake of rooftop solar PV, behind the meter batteries, and alternative vehicles, is also determined within AusTIMES. Recognising that the uptake of these technologies have economic and non-economic drivers, and to ensure consistency, the uptake of these technologies by scenario was used as an input into AusTIMES for the multi-sector energy modelling.

2 Scenario definition and key assumptions

2.1 Scenario overview

The four scenarios modelled in this study are Net Zero 2050, Step Change, Hydrogen Superpower, and Strong Electrification. A short narrative for each scenario is provided below with the settings for the key drivers summarised in Table 2-1.

2.1.1 Net Zero 2050 scenario

The Net Zero 2050 scenario reflects an energy system based around current government policies including the Nationally Determined Contribution (NDC) to the Paris Agreement on climate of a 26-28% reduction in GHG emissions below 2005 levels by 2030. This scenario represents the transition of the energy system under currently funded and/or legislated policies and commitments, using the most probable or current value for each key assumption, followed by an acceleration in decarbonisation post-2030 to a net zero emissions economy by 2050. The transition from fossil fuels to renewable generation in this scenario is generally driven by market forces.

Following 2030, additional effort through technology adoption is required to achieve net zero emissions by 2050. Uptake of DER, energy efficiency measures and the electrification of the end-use sectors accelerates. Some level of research and development in low-carbon technologies is required before 2030 to enable this transition.

Key features of Net Zero 2050 are:

- Central economic forecasts.
- Energy efficiency, electrification and fuel shifting uptake in earlier time horizons in broad alignment with current trends. Continued research and development supports continued cost reductions and stronger uptake of electrification closer to 2050. Hydrogen experiences a learning curve due to research and development, but this is inhibited due to slow technology deployment.
- Net Zero emissions are targeted in 2050 as an end point, however a cumulative budget is not explicitly defined, with only broad alignment to a temperature goal of 2.6°C.
- The pace of change towards meeting climate objectives is incremental up to 2030; meaning that a very ambitious pace of action is required in the later years to meet the net zero point in 2050.

2.1.2 Step Change scenario

In Step Change, government policy and corporate objectives result in a pace of change that goes beyond existing climate policy, setting emissions reduction targets consistent with limiting the global temperature rise to less than 2°C by 2100 over pre-industrial levels. These targets are supported by rapidly falling costs for battery storage and variable renewable energy (VRE), which drive consumers' actions and higher levels of electrification of other sectors. These ambitions are supplemented by strong economic and population growth.

The relevant purpose of this scenario is to understand the least cost options that could deliver faster decarbonisation of Australia's economy in the context of a balanced range of decarbonisation solutions, including strong DER uptake and energy efficiency improvements.

Key features of Step Change are:

- Central economic forecasts.
- Strong levels of energy efficiency, electrification (including in the transport sector) and fuel shifting uptake, supported by technological breakthroughs.
- Balance and diversity in the range of technological solutions deployed to reduce emissions, including land-based carbon sequestration, non-energy emissions avoidance and modest uptake of hydrogen.
- The scenario is compatible with the goals of the Paris Agreement, with emissions falling within a carbon budget consistent with less than 2°C of global warming, and net zero emissions reached by 2050.

2.1.3 Hydrogen Superpower Scenario

This scenario represents a world with very high levels of electrification and hydrogen production, fuelled by strong decarbonisation targets and leading to strong economic growth, particularly in industry.

The relevant purpose of this scenario is to understand the implications and needs of the power system under conditions that result in the development of a renewable hydrogen export economy and a domestic green steel industry which significantly increases grid consumption and necessitates developments in significant regional renewable energy generation. It also aims to assess the degree of fuel switching that may accompany a strong hydrogen export economy.

Key features of Hydrogen Superpower are:

- Strong domestic economic growth supported by very large renewable energy exports from hydrogen and green steel manufacturing.
- Strong consumer role in energy transformation, with high DER and zero emissions transport uptake.
- Strong international decarbonisation ambitions, with faster actions to limit global temperature rise to no more than 1.5^{o}C. The carbon budget constraint implies that Net Zero is reached before 2050, although there is no target date set.
- Significant VRE investments are required to service growing domestic and international hydrogen demand.
- Hydrogen is considered more available and has greater cost reductions, presenting increased fuel-switching opportunities in the domestic market as well. Energy efficiency is

still at a similar level to Step Change, even though the emissions budget is tighter, due to economic options to select renewable hydrogen over efficiency investments.

- While not featured as strongly as hydrogen, energy efficiency and electrification uptake is still strong, supported by the strong research & development efforts enabled by ambitious decarbonisation targets.

2.1.4 Strong Electrification sensitivity

Strong Electrification is a sensitivity to the Hydrogen Superpower scenario. In line with Hydrogen Superpower it features an international decarbonisation ambition compatible with limiting global warming to within 1.5°C above pre-industrial levels. However, Strong Electrification features a diminished role for hydrogen, and expanded role for electrification.

The purpose of Strong Electrification is to understand the potential upper bounds of electrification and energy efficiency that might be required to achieve strong emissions reductions without the widespread availability of hydrogen.

Key features of Strong Electrification align to Hydrogen Superpower, with the following differences:

- Poor availability and cost reductions in hydrogen for most end uses; only notable purpose being as a transport fuel
- Increased levels of electrification available across all sectors, with barriers to electrification uptake reduced.
- Industrial growth is more moderate without the growing hydrogen economy and green steel industry.

2.1.5 Summary

A summary of the four scenarios as distinguished by their key drivers is in Table 2-1.

Table 2-1: AEMO scenario definitions

Scenario	Net Zero 2050	Step Change	Hydrogen Superpower	Strong Electrification
Economic growth and population outlook	Moderate	Moderate	High	High
Energy efficiency improvement	Low	High	Moderately high	Moderate
Demand Side Participation (DSP)	Moderate	High	High	High
Distributed PV (per capita uptake tendency)	Moderate	High	High	High
Battery storage installed capacity	Moderate	High	High	High

Battery storage aggregation / VPP deployment by 2050	Moderate	High	High	High
Battery Electric Vehicle (BEV) uptake	Moderate	High	High	Very High
Fuel Cell Electric Vehicle (FCEV) uptake	Low	Low	Moderately low*	Low
BEV charging time switch to coordinated dynamic charging by 2030	Moderate	High	Moderate/High	High
Non-Transport electrification	Low to moderately high	Moderately high	Moderately high	High
Hydrogen uptake	Minimal (industry, transport and some pipeline blending)	Minimal (industry, transport and some pipeline blending)	Large NEM-connected export and domestic consumption	Only for transport
Shared Socioeconomic Pathway (SSP)	SSP2	SSP1	SSP1	SSP1
International Energy Agency (IEA) 2020 World Energy Outlook (WEO) scenario	Stated Policy Scenario (STEPS)	Sustainable Development Scenario (SDS)	Net Zero Emissions by 2050 case (NZE2050)	Net Zero Emissions by 2050 case (NZE2050)
Representative Concentration Pathway (RCP) (mean temperature rise by 2100)	RCP4.5 (~2.6°C)	RCP2.6 (~1.8°C)	RCP1.9 (<1.5°C)	RCP1.9 (<1.5°C)
Decarbonisation target	26-28% reduction by 2030 Economy-wide net zero target by 2050.	Consistent with limiting temperature rise to 2 degrees.	Consistent with limiting temperature rise to 1.5 degrees.	Consistent with limiting temperature rise to 1.5 degrees.

*More uptake of FCEVs in heavy vehicles

2.2 Key assumptions

This section outlines the key data assumptions applied to implement the scenarios.

2.2.1 Electricity sector

The input assumptions that vary by scenario are shown in Table 2-2.

Table 2-2: Electricity sector input assumptions that vary by scenario

Scenario	Net Zero 2050	Step Change	Hydrogen Superpower	Strong Electrification
Generator and storage build costs	CSIRO GenCost 2021 Central	CSIRO GenCost 2021 High VRE	CSIRO GenCost 2021 High VRE	CSIRO GenCost 2021 High VRE

Generator retirements	In line with expected closure years, or earlier if economic or driven by decarbonisation objectives beyond 2030.	In line with expected closure year, or earlier if economic or driven by decarbonisation objectives	In line with expected closure year, or earlier if economic or driven by decarbonisation objectives	In line with expected closure year, or earlier if economic or driven by decarbonisation objectives
Fuel price settings (natural gas)	Lewis Grey Advisory (2020), Central	Lewis Grey Advisory (2020), Step Change	Lewis Grey Advisory (2020), Step Change	Lewis Grey Advisory (2020), Step Change
Fuel price settings (coal)	WoodMackenzie 2020, Central	WoodMackenzie 2020, Low	WoodMackenzie 2020, Low	WoodMackenzie 2020, Low

There are a number of data assumptions for the electricity sector that do not vary by scenario. These assumptions mainly relate to existing generators, some elements for new generation technologies, and state or national policies. These assumption apply to all scenarios. The assumptions that are not varied by scenario are outlined in the ISP assumptions workbook and are listed below (Table 2-3).

Table 2-3: ISP assumptions workbook used across the scenarios

MODEL INPUT	DATA SOURCES
Nameplate capacity of existing generators	"Maximum capacity" tab https://aemo.com.au/-/media/files/electricity/nem/planning_and_forecasting/inputs-assumptions-methodologies/2021/draft-2021-22-inputs-and-assumptions-workbook.xlsx?la=en
Cost and performance data on existing power stations	"Existing Gen Data Summary" tab https://aemo.com.au/-/media/files/electricity/nem/planning_and_forecasting/inputs-assumptions-methodologies/2021/draft-2021-22-inputs-and-assumptions-workbook.xlsx?la=en
Expected closure year	"Retirement" tab https://aemo.com.au/-/media/files/electricity/nem/planning_and_forecasting/inputs-assumptions-methodologies/2021/draft-2021-22-inputs-and-assumptions-workbook.xlsx?la=en
Capacity factor constraint (Coal)	Maximum capacity factor 75% NSW coal "Generation limits" tab https://aemo.com.au/-/media/files/electricity/nem/planning_and_forecasting/inputs-assumptions-methodologies/2021/draft-2021-22-inputs-and-assumptions-workbook.xlsx?la=en
Minimum capacity factor constraints (GPG)	"Generation limits" tab https://aemo.com.au/-/media/files/electricity/nem/planning_and_forecasting/inputs-assumptions-methodologies/2021/draft-2021-22-inputs-and-assumptions-workbook.xlsx?la=en
Installed capacity of distributed generation	DER adoption modelling (CSIRO)
Regional reserves	"Reserves" tab https://aemo.com.au/-/media/files/electricity/nem/planning_and_forecasting/inputs-assumptions-methodologies/2021/draft-2021-22-inputs-and-assumptions-workbook.xlsx?la=en
Regional cost factors	"Regional Build Costs Summary" tab https://aemo.com.au/-/media/files/electricity/nem/planning_and_forecasting/inputs-assumptions-methodologies/2021/draft-2021-22-inputs-and-assumptions-workbook.xlsx?la=en
GHG emission factors	"Emissions" tab https://aemo.com.au/-/media/files/electricity/nem/planning_and_forecasting/inputs-assumptions-methodologies/2021/draft-2021-22-inputs-and-assumptions-workbook.xlsx?la=en
Emissions policies (national)	26% - 28% reduction in emissions by 2030 (NEM)
Renewable policies (national)	Renewable Energy Target (RET) consisting of: large-scale RET (LRET): 33,000 GWh of large-scale renewables, so that 23.5% of Australia's electricity in 2020 will be generated from renewables (33,000 GWh maintained until 2030). Small-scale renewable energy scheme (SRES): incentives for home-owners and small businesses to install eligible small-scale renewable energy systems and solar water-heating systems.
Renewable policies (state)	Queensland Renewable Energy Target (QRET): 50% renewable electricity generation by 2030 Victoria Renewable Energy Target (VRET): 40% renewable electricity generation by 2025; 50% renewable electricity generation by 2030. Tasmanian Renewable Energy Target (TRET): 100% renewable electricity generation by 2022; 150% renewable electricity generation by 2030; 200% renewable electricity generation by 2040. NSW Electricity Infrastructure Roadmap Current DER policies

2.2.2 End-use sectors

This section specifies the key assumptions, including definitions and quantification, for the end-use sectors detailed in Section 1.2. Detailed numerical data has been provided in the AEMO multi-sector energy modelling assumptions workbook.

Energy efficiency improvements can strongly affect the end use consumption and can be broken down into three main categories:

- **Autonomous:** All end-use sectors experience a business-as-usual energy efficiency improvement at **no cost** which is known as autonomous energy efficiency. The rates of efficiency gain do not vary across scenarios, and range from 0.2%-1.76% p.a. in residential buildings, 0.13-1.33% p.a. in commercial buildings, and 0.4% p.a. in industry. These are detailed for each end-use sector in the following sections. These are informed by long-term energy efficiency trends.
- **Endogenous:** These are **costed** options which are implemented if they are economically attractive based on a combination of capital costs, technology-specific hurdle rates, equipment lifetime and fuel costs. Hurdle rates are further explained below. The final uptake of endogenous efficiency is determined by the model and not an input. This category largely represents technologies that are commercially available today. Examples for the buildings sector include technologies such as LED lighting, heat pump hot water systems, and improved HVAC systems. In industry, this captures a broad range of technologies under the broad categories of process improvements, small equipment upgrades and large equipment upgrades.
- **Exogenous:** These are **non-costed** options that capture emissions abatement potential from the development and implementation of innovative, but uncertain, technologies. Cost data for these options is limited therefore the potential is explored by exogenously imposing the levels of uptake to align with the scenario narratives based on extensive research previously conducted for the *Decarbonisation Futures* report (Butler et al., 2020).

Fuel switching, such as electrification, also has the potential to notably impact the consumption of different sources of primary energy. Fuel switching is only endogenously determined through cost minimisation. It is implemented if economic based on a combination of capital costs, technology-specific hurdle rates, equipment lifetime and fuel costs. More details on the structure of end-use sectors in AusTIMES can be found in Appendix A.2.

As noted above, the hurdle rate influences the uptake levels of endogenous energy efficiency and electrification. These hurdle rates are used to capture non-financial barriers caused by a variety of social, technical, infrastructure, behavioural and cultural factors which prevent abatement options from being fully adopted, even when they are cost effective. Examples of these barriers include split incentives, competing priorities or lack of information about potential cost-saving abatement options. They are also used to represent the uncertainties such as policies and social factors that could hinder the uptake of deeper efficiency improvements and electrification. A high hurdle rate represents large barriers and a poor success in overcoming those barriers. A low hurdle rate represents smaller barriers and a good success in overcoming those barriers.

These hurdle rates have been informed by recent CWA analysis for similar, but not identical, scenarios. The specific hurdle rates for each sector are shown in the tables in the following sub-sections. Factors affecting these parameters include the desired outcome of the scenario to be consistent with the narrative (e.g. low/moderate/high), co-dependency between themselves (e.g. more rapid electrification minimises the 'pool' of energy use upon which energy efficiency acts) but also dependencies on settings elsewhere in the economy (e.g. cost of electricity).

2.2.2.1 Residential buildings

The table below details the key input assumptions for the Residential sector. Detailed numerical data is provided in the AEMO multi-sector energy modelling assumptions workbook.

Table 2-4: Residential buildings input assumptions

Model Input Assumptions	Net Zero 2050	Step Change	Hydrogen Superpower	Strong Electrification
Household activity projection (millions of dwellings)	2016 ABS census on number of dwellings (driven by ABS Series II household projections) scaled to BIS Oxford Economics Macroeconomics Forecasts on population growth			
Compound annual growth rates:	1.28% p.a. from 2020 to 2050	1.28% p.a. from 2020 to 2050	1.61% p.a. from 2020 to 2050	1.46% p.a. from 2020 to 2050
Autonomous energy efficiency	Now - 2030: Ranging from 0.26% p.a. to 1.76% p.a. 2031-2050: Ranging from 0.20% p.a. to 0.66% p.a.			
Endogenous energy efficiency hurdle rate	40%	7%	15%	25%
Exogenous energy efficiency potential	None	None	Limited (~5 PJ/yr avoided by 2050)	None
Electrification/fuel-switching hurdle rate	2020-2034: 40% 2035 onwards: 15%	15%	15%	7%
Hydrogen uptake	Endogenously determined based on production cost of hydrogen compared to that of natural gas. See Section 2.2.5 for more details.			No hydrogen uptake in residential buildings
	Maximum 10% blended in pipelines by 2030 Maximum 30% blended in pipelines by 2050	Maximum 10% blended in pipelines by 2030 Maximum 30% blended in pipelines by 2050	Maximum 23% blended in pipelines by 2030 Maximum 90% blended in pipelines by 2050	

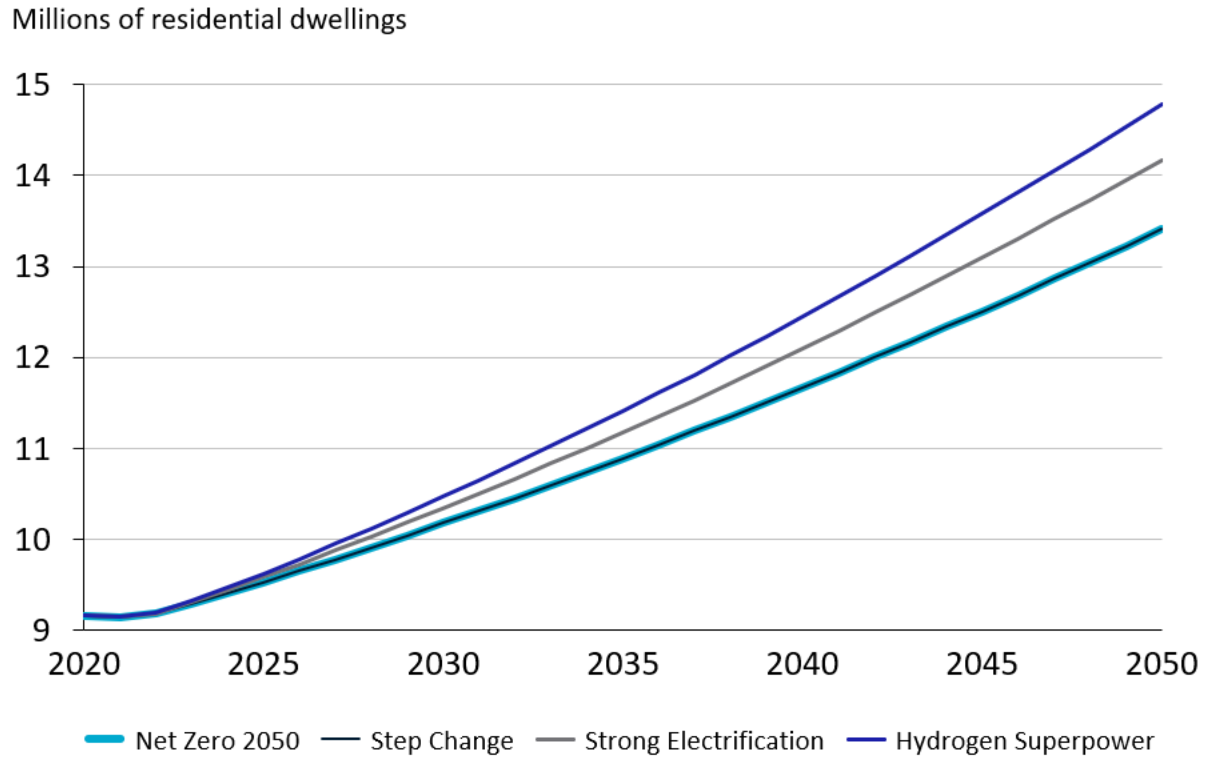


Figure 2-1: Residential baseline activity projection for the four scenarios in NEM states (note: Net Zero 2050 and Step Change share the same projections)

2.2.2.2 Commercial buildings

Table 2-5 below details the key input assumptions for the Commercial sector. Detailed numerical data is provided in the AEMO multi-sector energy modelling assumptions workbook.

Table 2-5: Commercial buildings input assumptions

Model Input Assumptions	Net Zero 2050	Step Change	Hydrogen Superpower	Strong Electrification
Commercial activity projection (millions m² of floorspace)	Uniform across all scenarios at compound annual growth rate of 2.09% p.a. from 2020 to 2050. This is informed by floorspace projections for commercial building archetypes from the Commercial Buildings Baseline Study (Pitt and Sherry, 2012). There is no clear indication of how the difference in economic growth impacting gross value added (GVA) of commercial sectors affects building stocks (i.e. the same building can have different economic activity). Therefore, the difference in economic growth is not considered in the commercial buildings floorspace projection.			
Autonomous energy efficiency	Now - 2030: Ranging from 0.13% p.a. to 1.33% p.a. 2031-2050: Ranging from 0.10% p.a. to 0.79% p.a.			
Endogenous energy efficiency hurdle rate	40%	7%	15%	25%
Exogenous energy efficiency potential	None	None	Limited (~29 PJ/yr avoided by 2050)	None
Electrification/fuel switching hurdle rate	40%	15%	15%	7%

Hydrogen uptake	Endogenously determined based on production cost of hydrogen compared to that of natural gas. See Section 2.2.5 for more details.			No hydrogen uptake in commercial buildings.
	Maximum 10% blended in pipelines by 2030	Maximum 10% blended in pipelines by 2030	Maximum 23% blended in pipelines by 2030	
	Maximum 30% blended in pipelines by 2050	Maximum 30% blended in pipelines by 2050	Maximum 90% blended in pipelines by 2050	

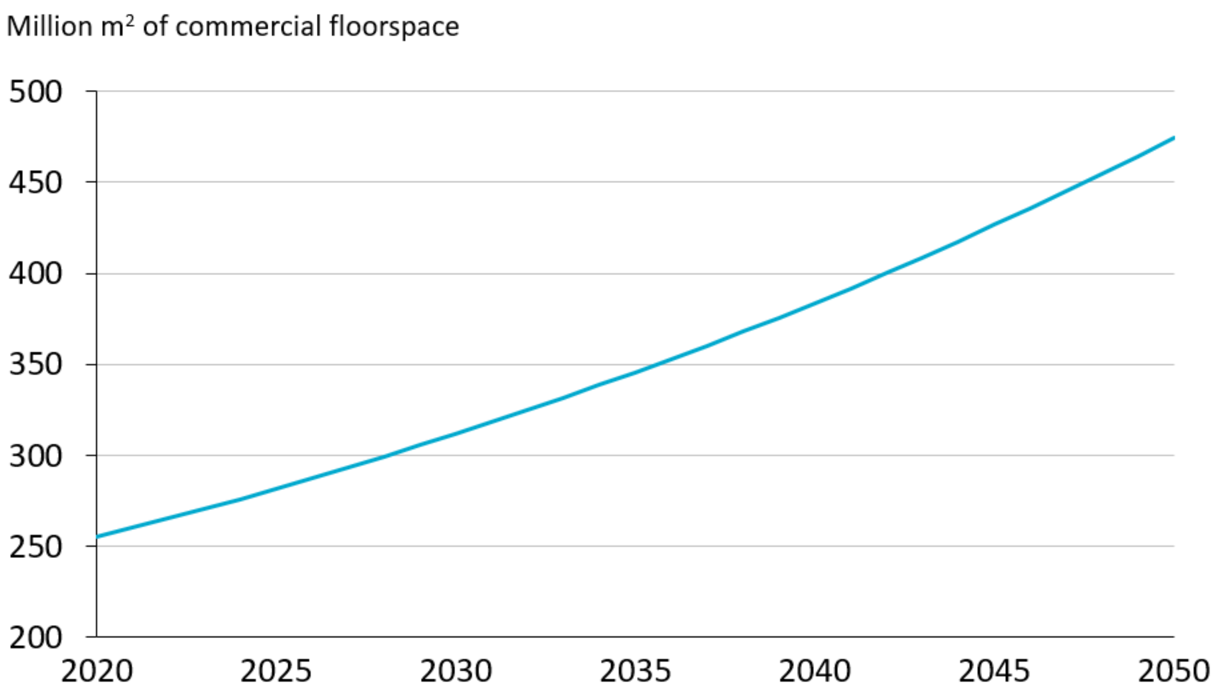


Figure 2-2: Commercial baseline activity projection (million m^2 of floorspace) (uniform across the four scenarios) in NEM states

2.2.2.3 Industry

Table 2-6 below details the key input assumptions for the industrial sector. Detailed numerical data is provided in the AEMO multi-sector energy modelling assumptions workbook.

Table 2-6: Industry input assumptions

Model Input Assumptions	Net Zero 2050	Step Change	Hydrogen Superpower	Strong Electrification
Industrial activity projection	Activity growth rates of most industrial subsectors are based on the Gross Value Added (GVA) projections of ANZSIC Divisions B to E provided by BIS Oxford Economics Macroeconomic Forecasts, except coal and natural gas mining, and green steel production (DRI Steel).			
Compound annual growth rates:	Overall, 1.03% p.a. from 2020 to 2050	Overall, 0.95% p.a. from 2020 to 2050	Overall, 1.13% p.a. from 2020 to 2050	Overall, 1.74% p.a. from 2020 to 2050
Coal mining activity projection (influenced by fossil fuel export outlook)	Consistent with Stated Policy Scenario (STEPS) and Sustainable	Consistent with Sustainable Development Scenario (SDS) at	Consistent with IPCC 1.5C scenarios at -5.7% p.a. from 2020 to 2050	Consistent with IPCC 1.5C scenarios at -5.7% p.a. from 2020 to 2050

	Development Scenario (SDS) at -2.7% p.a. from 2020 to 2050	-4.3% p.a. from 2020 to 2050		
Natural gas mining activity projection (influenced by fossil fuel export outlook)	Consistent with IEA World Energy Outlook Stated Policy Scenario (STEPS) and Sustainable Development Scenario (SDS) at 0.6% p.a. from 2020 to 2050	Consistent with IEA World Energy Outlook Sustainable Development Scenario (SDS) at 0.0% p.a. from 2020 to 2050	Consistent with IPCC 1.5C scenarios (IPCC, 2018) at -0.9% p.a. from 2020 to 2050	Consistent with IPCC 1.5C scenarios (IPCC, 2018) at -0.8% p.a. from 2020 to 2050
DRI Steel activity projection	None	None	50Mt/yr of DRI steel nationally[6] by 2050	None
Autonomous energy efficiency	0.4% p.a. efficiency improvement is assumed across all subsectors except for green steel (consistent with analysis of long-term energy efficiency trends that have occurred in industry). This compounds such that industrial processes are approximately ~15% more efficient by 2050, before other exogenous and endogenous efficiency impacts.			
Endogenous energy efficiency hurdle rate	40%	7%	15%	25%
Exogenous energy efficiency potential	None	None	Limited (~22 PJ/yr avoided by 2050)	Limited (~19 PJ/yr avoided by 2050)
Electrification/fuel switching hurdle rate	2020 onwards: 40% 2035 onwards: 20%	15%	15%	7%
Non-energy emissions abatement (e.g. process and fugitive emissions)	2020 - 2040: None High (~22Mt/yr avoided by 2050)	High (~21Mt/yr avoided by 2050)	Moderate (~11Mt/yr avoided by 2050)	High (~19Mt/yr avoided by 2050)

[6] Based on an uptake curve aligned to the Targeted Deployment scenario from Australia's National Hydrogen Strategy. Note that the model is allowed to endogenously determine the optimal location for green steel Australia-wide. In the case of this scenario, 74% of green steel production is located in the NEM, amounting to 37 Mt/yr by 2050.

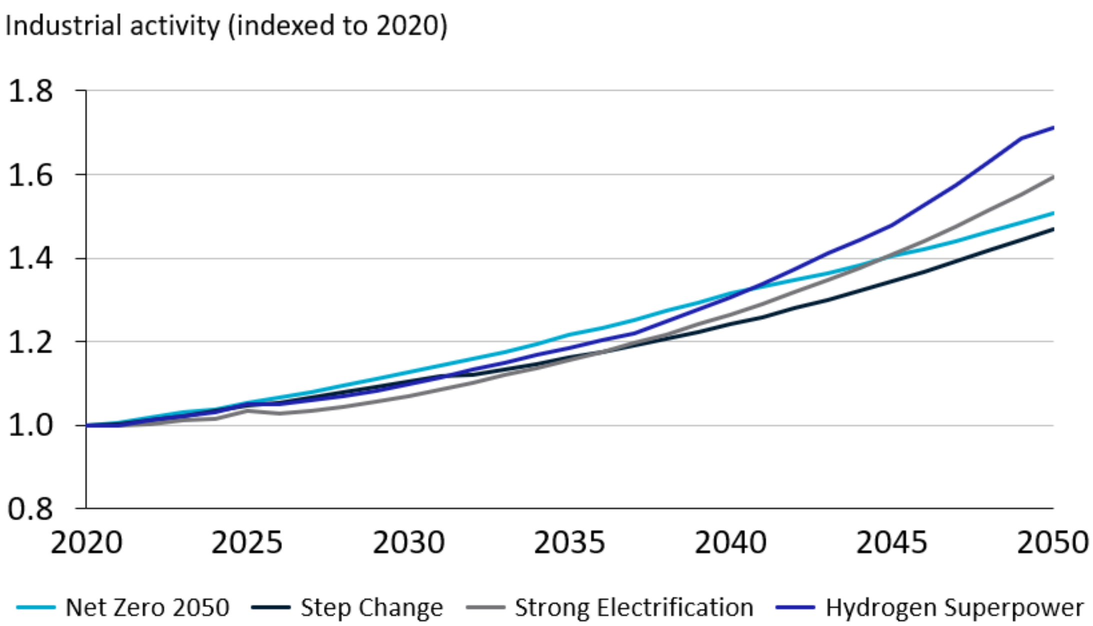


Figure 2-3: Industrial baseline activity projection for the four scenarios in the NEM. Industrial activity in Hydrogen Superpower includes additional activity from new green steel industries

2.2.2.4 Agriculture

Table 2-7 below details the key input assumptions for the agricultural sector. Detailed numerical data is provided in the AEMO multi-sector energy modelling assumptions workbook.

Table 2-7: Agriculture input assumptions

Model Input Assumptions	Net Zero 2050	Step Change	Hydrogen Superpower	Strong Electrification
Agricultural activity projection	Activity growth rates are based on the Gross Value Added (GVA) projections of ANZSIC Division A provided by BIS Oxford Economics Macroeconomic Forecasts.			
Compound annual growth rates:	1.76% p.a. from 2020 to 2050	1.55% p.a. from 2020 to 2050	1.84% p.a. from 2020 to 2050	1.68% p.a. from 2020 to 2050
Autonomous energy efficiency	0.4% p.a. is assumed across all subsectors (consistent with analysis of long-term energy efficiency trends that have occurred)			
Endogenous energy efficiency hurdle rate	40%	7%	15%	25%
Exogenous energy efficiency potential	Minimal (~0.2 PJ/yr avoided by 2050)	Minimal (~0.2 PJ/yr avoided by 2050)	Minimal (~0.5 PJ/yr avoided by 2050)	Minimal (~0.4 PJ/yr avoided by 2050)
Electrification/fuel switching hurdle rate	2020 onwards: 40% 2035 onwards: 20%	15%	15%	7%
Non-energy emissions abatement (e.g. enteric fermentation reduction methods and improved manure management)	2020 - 2040: None Moderate (~19Mt/yr avoided by 2050)	Moderate (~17Mt/yr avoided by 2050)	Moderately high (~46Mt/yr avoided by 2050)	High (~53Mt/yr avoided by 2050)

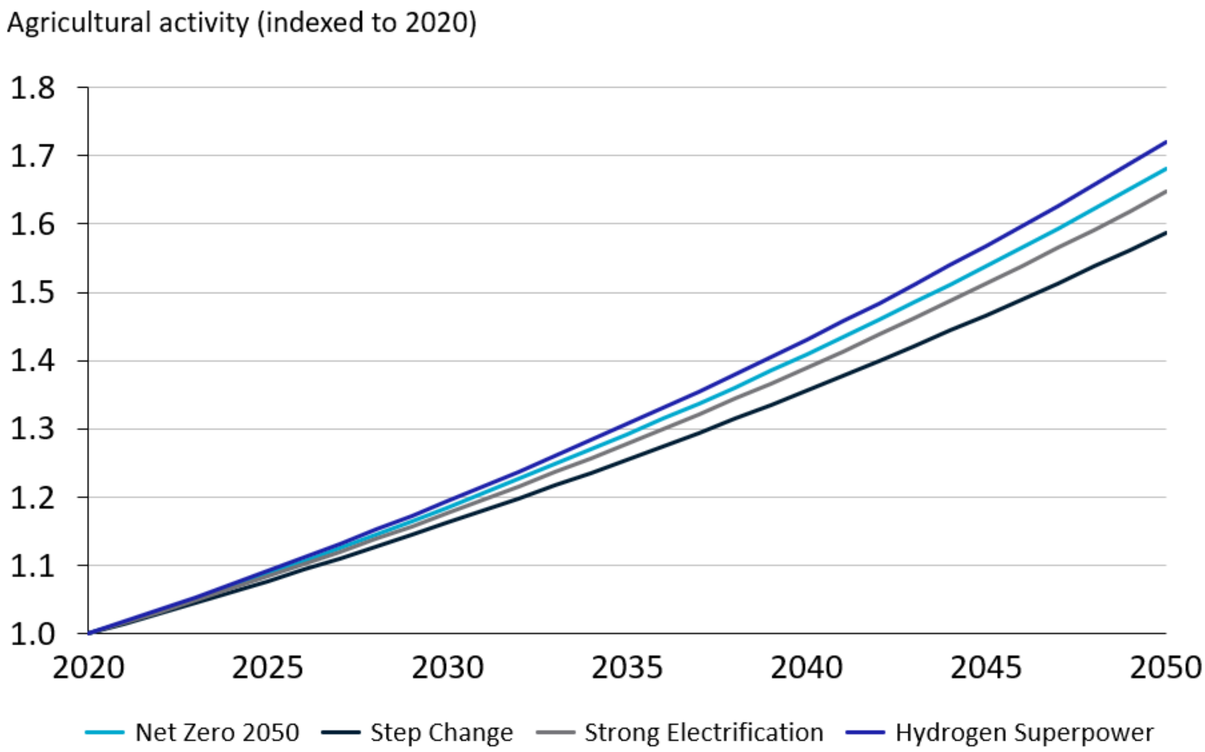


Figure 2-4: Agricultural baseline activity projection for the four scenarios in the NEM

2.2.2.5 Transport

As noted in Section 1.8, adoption modelling of alternative vehicles (plug-in hybrid electric vehicles, battery electric vehicles, and fuel cell electric vehicles using hydrogen) has been conducted by CSIRO, under a separate consultancy, in parallel to the multi-sector energy modelling. The varying inputs be scenario are outlined below (Table 2-8). For more detail, please refer to Graham and Havas (2021).

Table 2-8: Transport sector inputs that vary by scenario

Model Input Assumptions	Net Zero 2050	Step Change	Hydrogen Superpower	Strong Electrification
Economic growth and population outlook	Moderate	Moderate	High	High
Energy efficiency improvement	Moderate	High	High	High
Battery Electric Vehicle (BEV) uptake	Moderate	High	High	High
BEV charging time switch to coordinated dynamic charging by 2030	Moderate	High	Moderate/High	High
Internal Combustion Engine (ICE) vehicle availability	New ICE vehicles unavailable beyond 2050	New ICE vehicles unavailable beyond 2040	New ICE vehicles unavailable beyond 2035	New ICE vehicles unavailable beyond 2035
ICE retirement	Deregistered from 2055	Deregistered from 2050	Deregistered from 2045	Deregistered from 2045

Road user charges	2.5c/km from 2025	2.5c/km from 2030	2.5c/km from 2035	2.5c/km from 2035
Biofuel production costs*	2030: $76.4/GJ 2040: $75.7/GJ 2050: $75.7/GJ	2030: $69.2/GJ 2040: $63.7/GJ 2050: $63.5/GJ	2030: $59.5/GJ 2040: $49.1/GJ 2050: $48.8/GJ	2030: $59.5/GJ 2040: $49.1/GJ 2050: $48.8/GJ

Note: BEV: Battery Electric Vehicle; ICE: Internal Combustion Engine

*CSIRO estimates based on EIA (2020)

Economic and population growth impacts both passenger and freight transport demand across road and non-road transport. Demand projections by transport segment are consistent with Graham and Havas (2021). The uptake of alternative vehicle technologies by scenario is an input into AusTIMES for the multi-sector modelling. The assumptions impacting this potential uptake are documented in Graham and Havas (2021).

Non-road transport

The non-road transport consists of domestic aviation, domestic shipping, rail and other transport (i.e., transport related services from Division I). Similar to road transport, fuel consumption is dominated by oil-derived liquid fuels namely diesel (rail freight, shipping), kerosene (aviation), fuel oil (shipping) and gasoline (general aviation, recreational boating). Decarbonisation options include biodiesel, bio-synthetic paraffinic kerosene (sustainable jet fuel) and electrification. Hydrogen or ammonia are potentially other options for some segments of non-road transport (shipping, rail) but these options were not included in this modelling.

Until recently, the main option considered for decarbonising aviation is sustainable jet fuel which is a drop-in fuel for existing turbine aircraft currently using kerosene. This fuel can be blended with kerosene up to 100% based on numerous successful trials over the last two decades. Previously, aviation was not considered a candidate for electrification due to range limitations and weight considerations. However, with further improvements in battery technology, the success of electric-based drone technology in non-passenger applications and the continued proliferation of transport-on-demand business models in cities, electrification of aviation is considered to be more plausible. Currently, delivery models being considered are diverse and include; hybrids (single electric engine added to aircraft with other conventional propulsion), pure electric with modified air frame, vertical aero propeller / helicopter designs, hydrogen fuel aircraft designs and electric on-ground taxiing power. However, it is unclear if any of these designs could replace some long-haul aviation. It is more likely to be adopted for shorter route aviation.

The electrification of shipping is not commonly considered. This is because shipping already has access to some of the lowest cost liquid fuels available and potentially the range limitation of electricity. In addition, their diesel engines are more easily adaptable to alternatives such as natural gas and hydrogen (not modelled). As a result, CSIRO does not include electrification of marine transport in our projections.

The electricity consumption projections for passenger rail are similar to the projected rail passenger demand in Graham and Havas (2021). This is estimated by multiplying the extrapolated trend in rail energy requirements per passenger kilometre. For rail freight and aviation electrification, CSIRO estimates the total overall energy demand for each non-road transport sector before estimating the electricity demand for each non-road sector in accordance to the assumptions outlined in Table 2-9. The adopted assumptions is a subjective assessment of potential technology readiness for the non-road sector based on the scenario narratives.

Table 2-9: Rail freight and aviation electrification assumptions

Scenario	Electrification commencement date		Maximum share by 2050
	Rail freight	Aviation	%
Net Zero 2050	2035	2030	7
Step Change	2035	2030	10
Hydrogen Superpower	2030	2027	20
Strong Electrification	2030	2027	20

There are several transport sector assumptions that do not vary by scenario. These are listed in Table 2-10.

Table 2-10: Transport sector inputs that do not vary by scenario

Model input assumptions	**Data sources**
Energy balance	*Australian Energy Statistics (DISER, 2020b)*
Vehicle stock, scrapping rate	*ABS Catalogue No. 9309.0 - Motor Vehicle Census, Australia, 31 Jan 2020* (ABS, 2020a)
Average vehicle kilometres travelled	*ABS Catalogue No. 9208.0 - Survey of Motor Vehicle Use, Australia, 12 months ended 30 June 2020*(ABS, 2020b)
GHG emission factors	*National Greenhouse Accounts Factors* (DoEE, 2017)
Maintenance costs	ATAP (2016); RACQ (2018)
Registration, insurance costs	State/territory government websites
ICE vehicle fuel efficiency improvements	Graham and Havas (2021)
Retail fuel price components	Australian Institute of Petroleum
Fuel excise rates	Australian Taxation Office
Subsidies	Current policies on stamp duty, registration exemptions or direct financing retained until 2030
Biofuel mandates	NSW - *Biofuel (Ethanol Content) Act 2007*, historical take-up of ethanol and biodiesel is from the *Office of Fair Trading*. QLD - The *Liquid Fuel Supply (Ethanol and Other Biofuels Mandate) Amendment Act 2015*
Biofuel availability	Maximum amount of bioenergy available from lignocellulosic feedstocks that can be sent to biomass to liquids (BTL) processes. 2030: 674 PJ; 2050: 776 PJ*

*CSIRO estimates

2.2.3 Carbon budgets and emission targets

Carbon budgets consistent with each scenario narrative, with the exception of Net Zero 2050, are provided in Table 2-11. These were determined by selecting a global carbon budget that most closely aligned with the relevant global emissions and temperature outcome for each scenario, and converting this into a carbon budget for Australia following the methodology described in Section 1.6.

Table 2-11: Carbon budget and emission target assumptions by scenario

Model Input Assumptions	**Net Zero 2050**	**Step Change**	**Hydrogen Superpower**	**Strong Electrification**
Global emissions outcome	Broadly consistent with limiting global warming to 2.6°C above pre-industrial levels.	67% chance of limiting global warming to Less than 2°C above pre-industrial levels, with no temperature overshoot.	50% chance of limiting global warming to 1.5°C above pre-industrial levels, with no temperature overshoot.	50% chance of limiting global warming to 1.5°C above pre-industrial levels, with no temperature overshoot.
Global carbon budget from IPCC (Rogeli et al. 2018)	*No explicit carbon budget considered for this scenario; however an emissions trajectory*	830 Gt CO_2	580 Gt CO_2	580 Gt CO_2

(CO_2-only; from 1/1/2018)	*constraint was applied that results in cumulative emissions for Australia of 9.65 Gt CO_2-e from 2021-50.*			
Carbon budget for Australia **(from 1/1/2021)**		6.531 Gt CO_2-e	3.537 Gt CO_2-e	3.537 Gt CO_2-e
Decarbonisation target/s	Consistent with Australia's *Paris Agreement* NDC (26-28% reduction on 2005 levels by 2030) Economy-wide net zero emissions by 2050	Emissions fall below Australia's *Paris Agreement* NDC (26-28% reduction on 2005 levels by 2030) Economy-wide net zero emissions by 2050	Emissions fall below Australia's *Paris Agreement* NDC (26-28% reduction on 2005 levels by 2030) Economy-wide net zero emissions by or before 2050	Emissions fall below Australia's *Paris Agreement* NDC (26-28% reduction on 2005 levels by 2030) Economy-wide net zero emissions by or before 2050

The Net Zero 2050 scenario was not modelled to meet an explicit carbon budget, instead a specific emissions trajectory was supplied by AEMO for this scenario based on the NDC target for 2030 and gradually accelerating towards the net zero target by 2050. This trajectory is shown in Figure 2-5, and was used as a constraint for the Net Zero 2050 scenario.

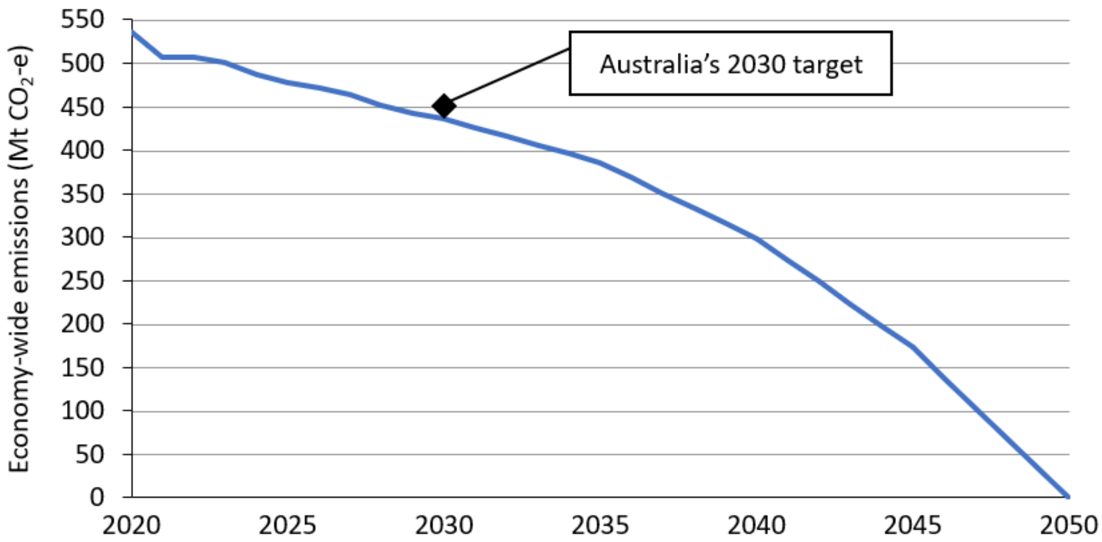


Figure 2-5: Net Zero 2050 imposed net emissions trajectory, with Australia's current NDC under the Paris Agreement marked (median of 26-28% reduction on 2005 levels by 2030). Note the acceleration in the emissions trajectory post-2030.

Specific long-term emissions targets for each scenario are also set. For Net Zero 2050 and Step Change, this includes a target of net zero economy-wide emissions by 2050. Step Change includes the additional constraint of keeping within a less-than 2°C carbon budget. In the case of the stronger emissions reduction scenarios, Hydrogen Superpower and the Strong Electrification sensitivity, no specific net zero constraint is applied, but it is expected that the 1.5°C carbon budget will see net zero emissions achieved earlier than 2050. As a result, Step Change, Hydrogen Superpower and Strong Electrification are designed to be consistent with the goals of the Paris Agreement.

Explicit in Net Zero 2050 and implicit in all other scenarios is the assumption that Australia will achieve or over-achieve its current Nationally Determined Contribution (NDC) under the Paris Agreement, to reduce emissions by 26-28% on 2005 levels by 2030. The trajectory for Net Zero

2050 (Figure 2-5) is designed in such a way that this 2030 target is met with minimal margin, followed by a significant increase in pace of decarbonisation to meet net zero emissions in 2050. For all other scenarios, and carbon budgets selected, it is expected that the other scenarios will exceed this target.

2.2.4 Land-based emissions sequestration

Table 2-12: Land-based emissions sequestration assumptions by scenario

Model Input Assumptions	Net Zero 2050	Step Change	Hydrogen Superpower	Strong Electrification
Land-based emissions sequestration approach	An imposed carbon sequestration trajectory is constructed according to the following constraints: - Carbon sequestration in 2050 is equivalent to Step Change levels. - Carbon sequestration uptake is delayed to 2030 - Carbon sequestration uptake does not exceed allowable LUTO carbon forestry planting rate (0.75 Mha/yr)	Maximum LUTO carbon sequestration trajectory (Figure 1-2) is scaled down to the level required to meet net zero emissions by 2050 after modelling iterations in the other sectors, and uptake rate is scaled down to the level required to meet scenario emissions budget.	Maximum LUTO carbon sequestration trajectory (Figure 1-2) is scaled down to the level required to meet the scenario emissions budget after modelling iterations in the other sectors. After the net zero point until 2050, carbon sequestration reduces to the minimum level required to offset residual emissions.	Maximum LUTO carbon sequestration trajectory (Figure 1-2) is scaled down to the level required to meet the scenario emissions budget after modelling iterations in the other sectors. After the net zero point until 2050, carbon sequestration reduces to the minimum level required to offset residual emissions.

As discussed in Section 1.7, these trajectories can be interpreted broadly as the amount of sequestration required through other land-based methods, which may include but is not limited to the strict definition of carbon forestry implied in the LUTO modelling. However, the use of forestry to represent this sector provides a clear cost-profile.

Sequestration from carbon forestry is an exogenous assumption determined for each scenario by the amount of sequestration actually required to offset residual emissions in the economy to achieve each scenario's carbon budget, and/or reach net zero emissions by 2050 (see section 1.7 for details), with an upper constraint determined by LUTO.

The specific assumptions applied for each scenario are detailed in Table 2-12. For the 1.5-degree scenarios, Strong Electrification and Hydrogen Superpower, it is assumed that only the amount of land-based sequestration needed to keep economy-wide emissions within the carbon budget, and to maintain net zero emissions would be deployed. The maximum allowable sequestration trajectory was scaled downward to achieve this objective. For Step Change, a similar approach was applied where land-based sequestration uptake was scaled downwards to match residual emissions (therefore achieving net zero emissions) by 2050. The projected uptake rate of land-based sequestration was adjusted downwards in order to exactly meet the carbon budget for that scenario.

As the Net Zero 2050 scenario was modelled by imposing the emissions trajectory in Figure 2-5, the portion of this that would be met by land-based sequestration had to be assumed exogenously. This was determined by scaling the maximum allowable trajectory to achieve an end-point that, through iteration, was found to lead to a feasible modelling outcome. The final endpoint of ~140 Mt/yr was found to be similar to the scenario with the next-closest temperature outcome, Step Change. Additionally, through iteration, it was determined that it was appropriate to delay the onset of land-based sequestration until 2030, in alignment with the relatively slow change in the imposed emissions trajectory up to this point. The final land-based sequestration trajectory is shown in Figure 2-6. The trajectory is shown in the context of the other sequestration outcomes in the results section.

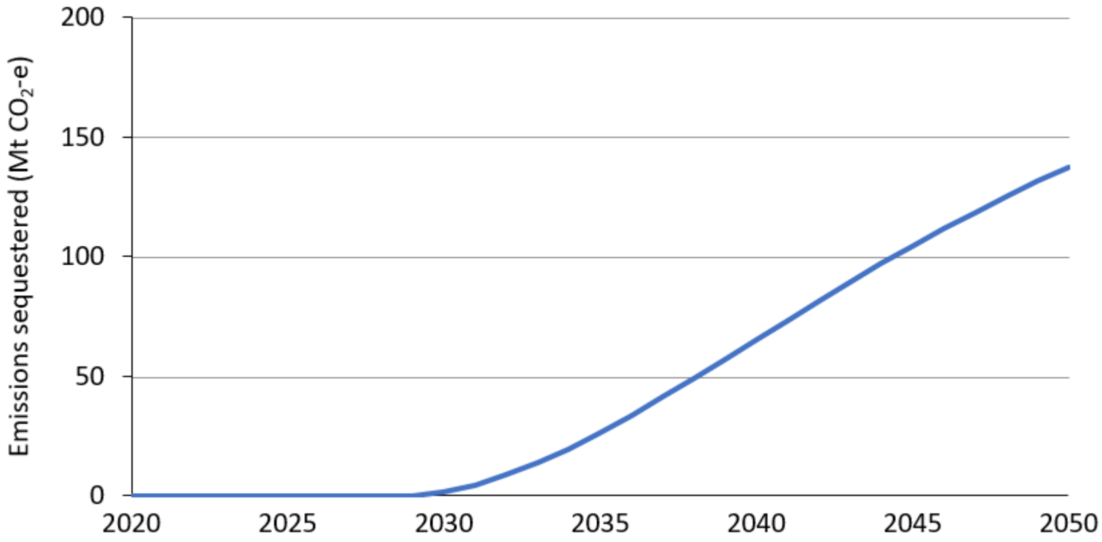


Figure 2-6: Final exogenously-applied land-based emissions sequestration trajectory for Net Zero 2050

2.2.5 Hydrogen production and export

As outlined in Section 1.2, there are five hydrogen production pathways specified in AusTIMES:

- Proton exchange membrane (PEM) electrolysis;
- Alkaline electrolysis (AE)
- Steam methane reforming (SMR)
- SMR with carbon and storage (CCS), and;
- Coal gasification with CCS.

Based on the demand for hydrogen which is a combination of exogenous inputs (e.g. export demand for hydrogen or demand for hydrogen-based DRI steel[7]) and endogenous outcomes (e.g., optimal uptake of fuel cell vehicles in road transport; hydrogen reciprocating engines in the

[7] Based on an assumption of 50Mtpa national green steel production by 2050, following an uptake curve aligned to the Targeted Deployment scenario from Australia's National Hydrogen Strategy.

electricity sector; least cost fuel switching in buildings, some industry subsectors and non-road transport), AusTIMES optimised investment in production capacity and operation to deliver hydrogen to end-users at least cost (including emissions costs).

Cost and performance data for non-electrolyser production pathways were initially developed in the *National Hydrogen Strategy* and these have been subsequently updated in the *Technology Investment Roadmap* process led by DISER. Cost and performance data for electrolyser production pathways are broadly consistent with GenCost2021 (see Figure 2-7 for the PEM cost projections), although the differences between the scenarios was expanded to better account for uncertainty and to differentiate across the scenarios.

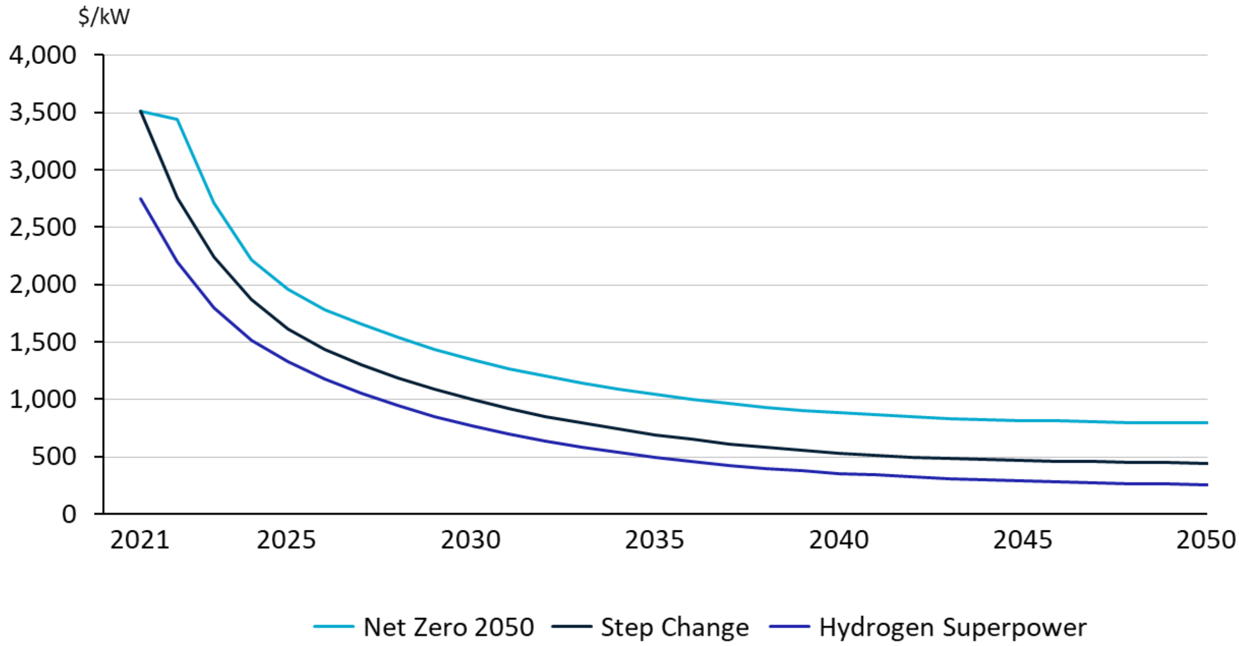
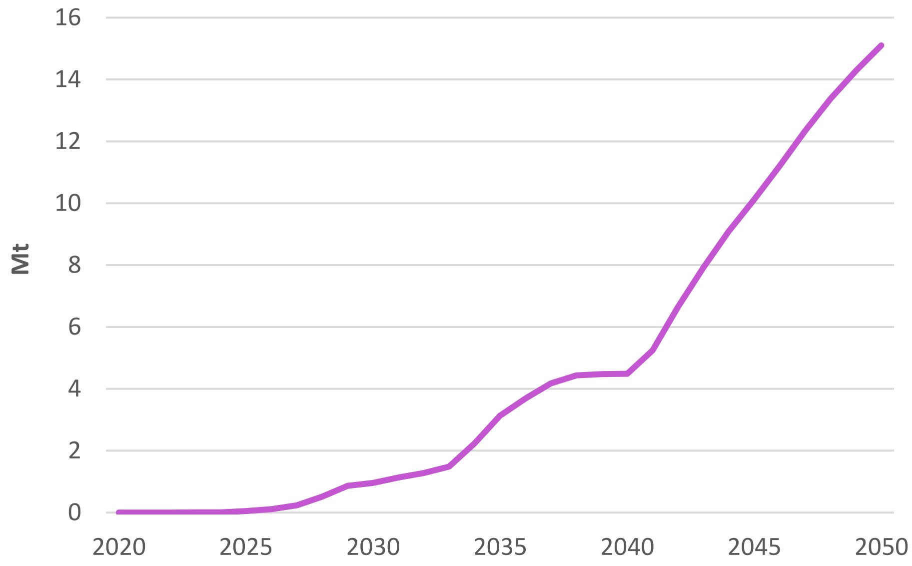


Figure 2-7: Electrolyser capital costs by scenario (note Step Change electrolyser costs were also used for Strong Electrification, but only to meet transport demand)

For the Hydrogen Superpower scenario, a key exogenous input is the external demand for the export of hydrogen. The current estimate for this scenario is a gradual increase to 4.5 Mt by 2040 and then accelerated increase to around 15.1 Mt by 2050 (Figure 2-8).



Source: https://aemo.com.au/-/media/files/electricity/nem/planning_and_forecasting/inputs-assumptions-methodologies/2021/draft-2021-22-inputs-and-assumptions-workbook.xlsx?la=en

Figure 2-8: Hydrogen export demand, NEM, Hydrogen Superpower scenario

3 Projection results

3.1 Underlying electricity demand

Contrary to trends in recent years, underlying electricity demand in the NEM is expected to increase over the projection period in all scenarios (Figure 3-1:). Underlying demand here refers to end-use demand for all sectors, which can be met by either grid or off-grid electricity, before the impacts of any DER technology is considered. The lowest underlying electricity demand is projected in the Net Zero 2050 and Step Change scenarios, reaching 446 TWh and 398 TWh by 2050 respectively, as these scenarios have the lowest population and economic growth. Despite strong energy efficiency uptake in Step Change, growth in final electricity demand remains significant as the energy efficiency is counter-balanced by higher electrification uptake relative to Net Zero 2050. In Net Zero 2050, there is an uptick in electricity demand in the last few years when electrification ramps up, resulting in underlying demand increasing from 290 TWh (2040) to 446 TWh (2050), higher than Step Change. High levels of electrification contribute to Strong Electrification demand sitting above Net Zero 2050 and Step Change at 464 TWh by 2050.The growth in electricity demand is most notable in Hydrogen Superpower, where the high growth in electricity-intensive industries and significant production of hydrogen from electrolysis results in an electricity demand of 1,063 TWh by 2050; over 2.3 times higher than the scenario with next highest demand (the Strong Electrification sensitivity) and over five times the current NEM's electricity demand.

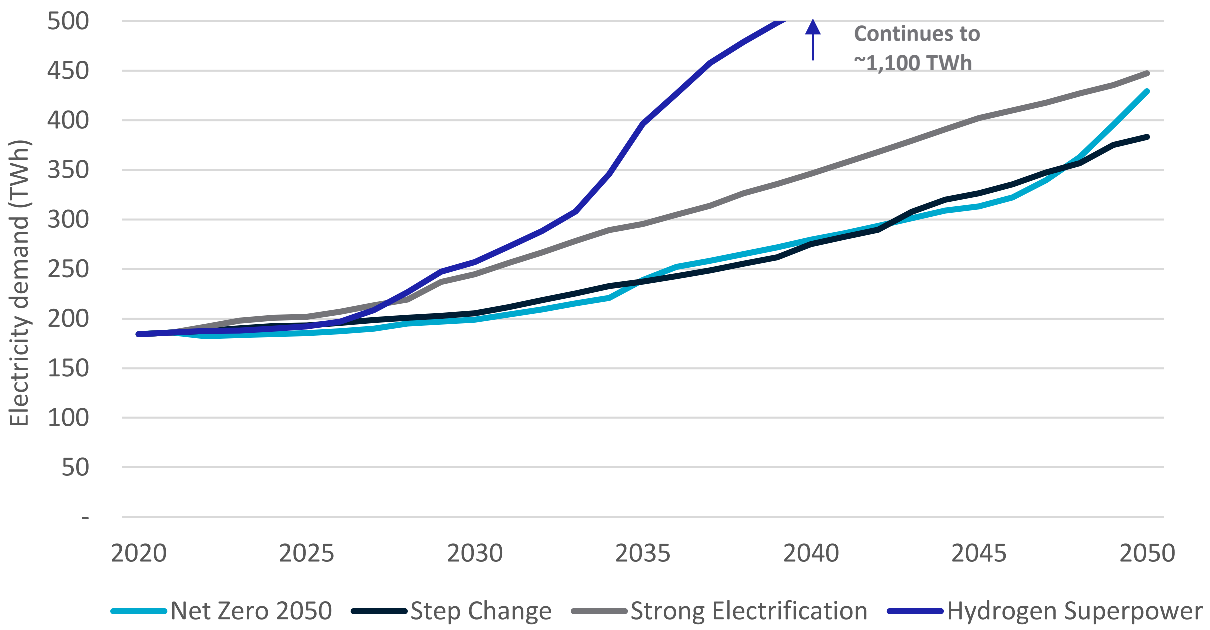


Figure 3-1: Projected electricity demand from the end-use sectors including hydrogen production for the NEM region

Detailed demand results by sector for each scenario are shown in Figure 3-2 (note difference in scale for Hydrogen Superpower). All scenarios except for the Strong Electrification sensitivity demonstrate relative similarities in the first decade. However, this breakdown also highlights some of the unique characteristics for each scenario. For instance, industrial demand demonstrates particularly strong growth in Strong Electrification and Hydrogen Superpower (150% and 140% respectively from 2020-2050), followed by Net Zero 2050 and Step Change (116% and 56% respectively). The relative impact of the inclusion of hydrogen production on NEM demand can also be seen in Net Zero 2050 and Step Change (where it is relatively modest), and in Hydrogen Superpower (where it is the largest component of demand growth).

The final demand shown in these figures is influenced by a range of determinants, including energy efficiency and electrification uptake. More discussion on these issues are outlined in Section 3.5.

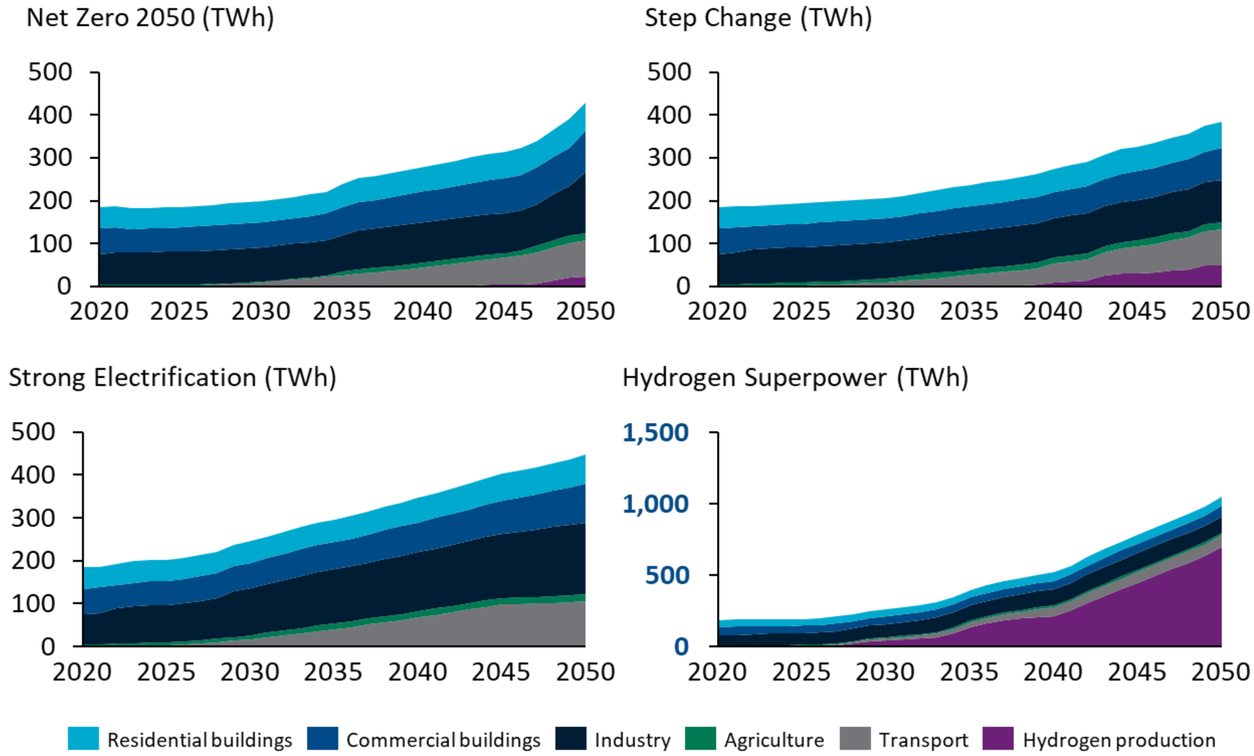


Figure 3-2: Detailed electricity demand split by sector for the NEM (note difference in scale for Hydrogen Superpower)

3.2 Underlying gas demand

While there is a large focus on electricity sector implications in this report, implications for other fuels in the economy, including natural gas and hydrogen, were also modelled. Figure 3-3: shows total demand for natural gas and hydrogen in end-use sectors in the four scenarios.

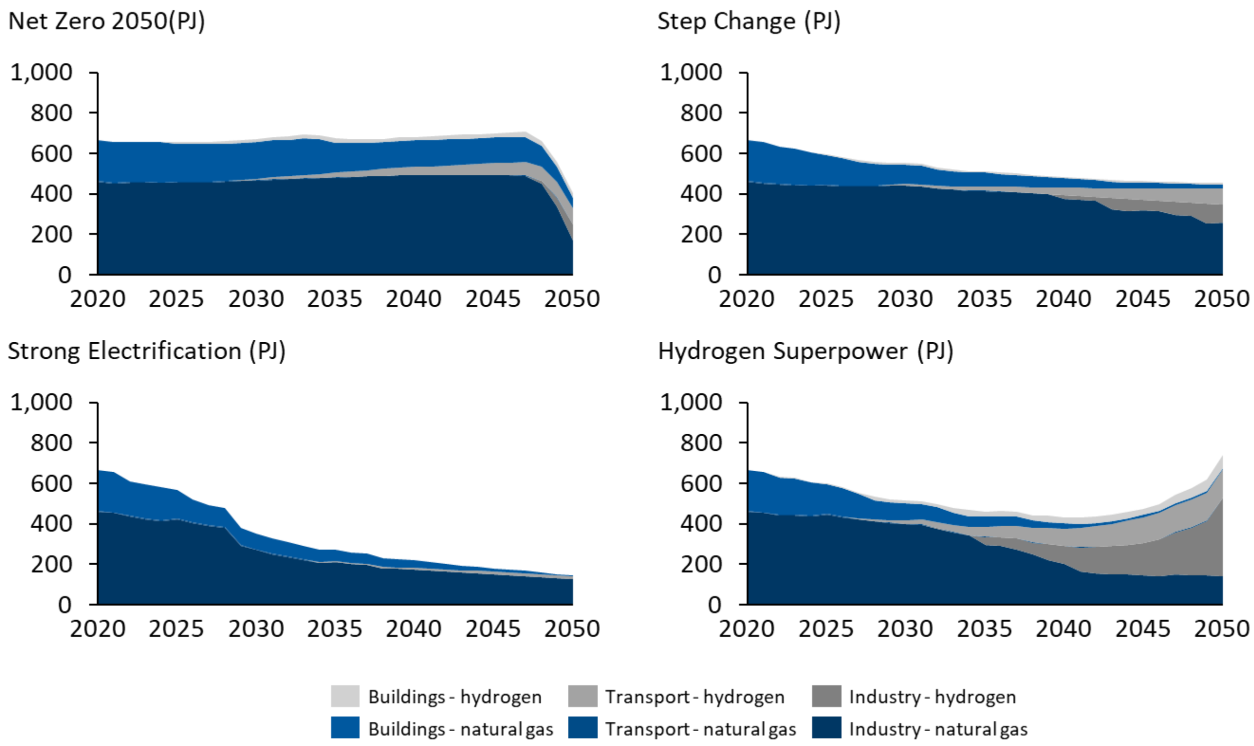


Figure 3-3: Detailed gas demand (natural gas and hydrogen) split by end-use sector for NEM states. Hydrogen Superpower data excludes hydrogen produced for export.

In the Net Zero 2050 scenario, current trends in gas demand broadly persist until about 2035, where there is an overall slight decline in line with increasing electrification as the economy begins to transition towards net zero. From 2045-2050 very significant changes are seen, with overall gas use declining across all sectors, but particularly sharply in industry. This decline is driven by a sharp uptick in electrification, rather than any decrease in industrial activity. Some additional hydrogen is deployed to replace natural gas, particularly in industry. There is gradual growth in hydrogen demand from the transport sector throughout the projection period.

Overall gas demand also declines under the Step Change scenario. However, this occurs much more gradually, in line with the higher climate ambition of this scenario and more steady progress towards net zero emissions that begins from the start of the projection period. This steady progress combined with reductions in hydrogen electrolyser costs means that hydrogen has a stronger role in displacing natural gas, particularly in industry, from around 2040. The decline in gas is more prominent in buildings compared to industry, which is due to the lower barriers to electrification in that sector.

The Hydrogen Superpower scenario and Strong Electrification sensitivity share a common level of climate ambition and many other common assumptions (see Section 2.2). However, the outcome for gas demand is very different between the two. In Hydrogen Superpower, the weaker push to electrify leads to higher demand for natural gas into the 2030s, at which point a large amount of gas use begins to switch to hydrogen, supported by reductions in electrolysis costs. Hydrogen demand grows further, exceeding baseline natural gas demand, in order to support new green steel industries and uptake of hydrogen in the transport sector. By comparison, low-cost hydrogen is not available in the Strong Electrification scenario, and we see the strongest decline in overall gas use from any scenario (78% from 2020-2050), with the majority being replaced by electricity.

It should be noted that these results are based on economic fuel-switching decisions by the model on the basis of fuel costs. There is no explicit representation of the assets and costs associated with gas production, transmission and distribution in the model. Infrastructure costs may be a limiting factor that determines whether it is viable to maintain small amounts of natural gas and/or hydrogen supply via pipelines in the context of high uptake of electrification.

3.3 Emissions

Net emissions across all scenarios are shown in Figure 3-4, alongside the median point of the federal government's NDC under the Paris Agreement (26-28% reduction on 2005 levels by 2030; DISER 2021), and most recent government emissions projections (DISER 2020a). All scenarios show the NDC is expected to be achieved, with emissions falling below government projections. Largely, this is driven by lower emissions in the electricity sector, which is expected to steadily decarbonise under all scenarios, driven by competitive costs in renewables. Note also the difference in starting point between these projections and those modelled by the government, which is due to different modelling approaches applied to a common base year in the past (2019).

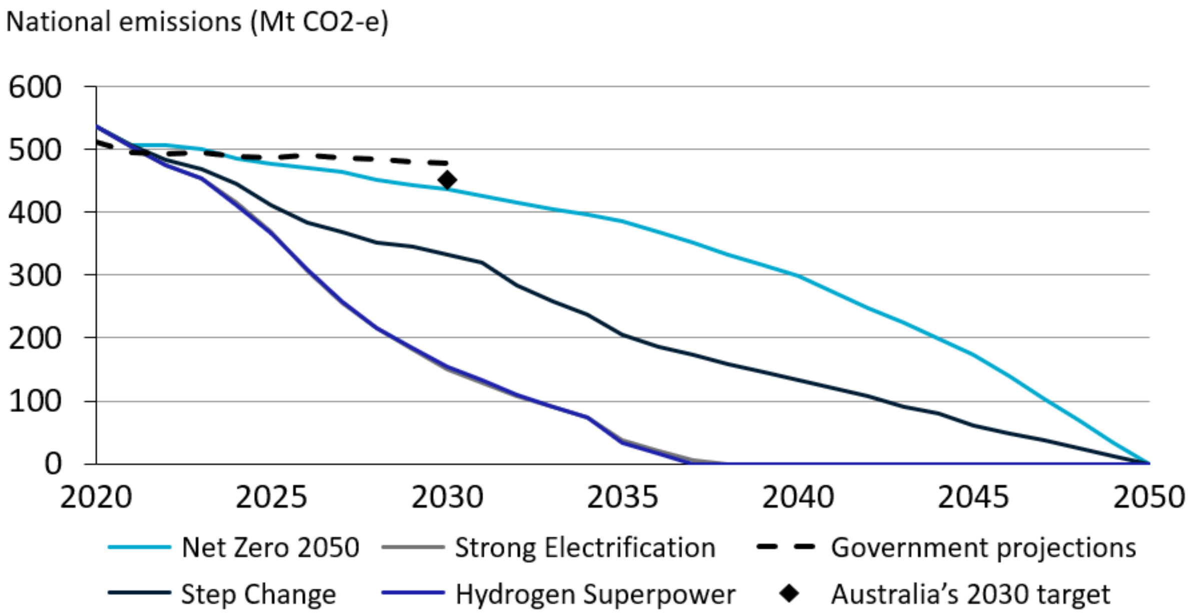


Figure 3-4: National net emissions in the four scenarios, compared to emissions projections (DISER 2020a) and Australia's 2030 target submitted under the Paris Agreement (median of 26-28% reduction on 2005 levels by 2030; DISER 2021). Note the emissions trajectory for Strong Electrification and Hydrogen Superpower follow a very similar shape and are difficult to differentiate.

With the exception of Net Zero 2050, these emissions trajectories are the product of residual economy-wide emissions from the modelled sectors, and exogenously-applied carbon forestry trajectories (see section 2.2.4 and 3.7). For the Net Zero 2050 scenario, the emissions trajectory was imposed as an input, broadly aligned with current policy settings as detailed in Section 2.2.3.

The difference in carbon budgets between the 1.5-degree scenarios (Hydrogen Superpower and the Strong Electrification sensitivity) and the below 2-degree scenario (Step Change) drives the difference between these scenarios, including the point when net zero emissions is reached. The 1.5-degree scenarios, Hydrogen Superpower and the Strong Electrification sensitivity, reaches this by 2036-37, while Step Change reaches this by 2050. It is expected that net zero emissions would occur earlier in Australia, and other advanced economies, compared to the global net zero emissions likely to be reached in a 2°C or 1.5°C scenario. For example, the IEA's 1.5-degree roadmap sees global net zero emissions reached by 2050, and the Sustainable Development Scenario (between 1.5-2 degrees) sees global net zero emissions reached by 2070 (IEA 2020; 2021).

Cumulative emissions from 2021-2050 in the three carbon budget-driven scenarios match those carbon budgets exactly (6.531 Mt CO_2-e in Step Change, and 3.537 Mt in Hydrogen Superpower/Strong Electrification). The applied emissions trajectory in the Net Zero 2050 scenario results in cumulative emissions of 9.65 Mt CO_2-e, which if considered under the carbon budget approach in Section 1.6, exceeds the level of ambition required to limit warming to 2.6°C.

3.4 Electricity generation

Historically, coal-fired generation has dominated the electricity generation mix in the NEM. Despite the historical dominance of non-renewable centralised electricity generation, there has recently been significant growth in the deployment of distributed rooftop solar photovoltaic (PV) systems, especially on residential buildings, followed by large-scale renewable generation (primarily wind and solar). Due to falling technology costs, renewable targets and decarbonisation goals, renewables deployment is expected to accelerate coinciding with an ageing coal-fired generation fleet.

Under all four scenarios, the projected generation mix shows significant change for the NEM from its current level of around 67% of coal-fired generation (Figure 3-5). Falling costs of renewable generation and storage technologies, an ageing coal generation fleet, and the cost competitiveness of electrification in a future with strong emissions reduction targets are the key drivers to an increasing share of variable renewable energy (VRE), mainly in the form of utility-scale solar PV and wind farms over the projection period.

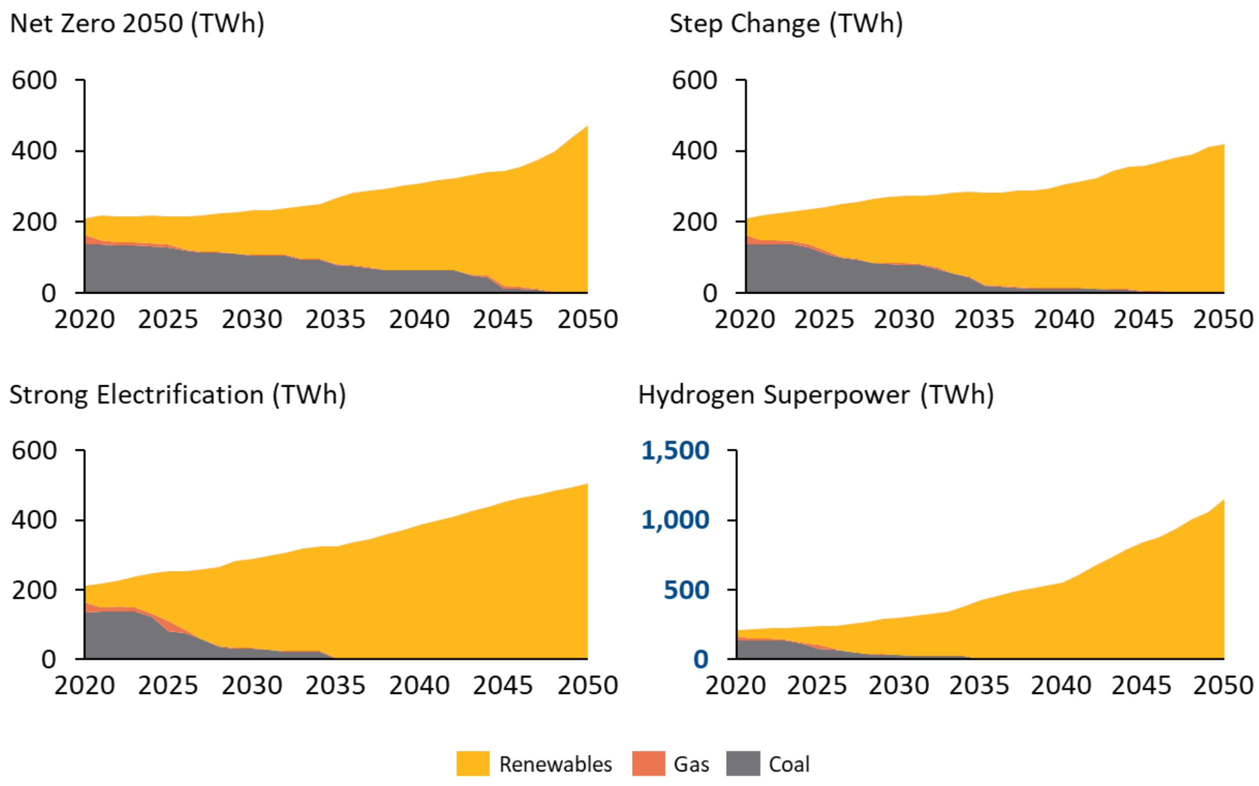


Figure 3-5: Electricity generation mix for the NEM regions (note difference in scale for Hydrogen Superpower)

In Net Zero 2050, moderate growth in demand in conjunction with state renewable energy targets (QRET, TRET, VRET and *NSW Electricity Infrastructure Roadmap*) transitions the NEM away from coal-fired generation to an increasing share of VRE, mainly in the form of utility-scale solar PV and onshore wind farms. As the share of VRE increases over time, there is an increasing need for dispatchable storage (pumped hydro and batteries) to maintain system balance.

This transition is accelerated across the other three scenarios with a more rapid reduction in coal-fired generation. The proportion of coal-fired generation declines over time, with it phased out the earliest in the Strong Electrification and Hydrogen Superpower scenarios (around 2035). Some coal generation remains until the late 2040s in Step Change scenario but the output is minimal, and this may be forced to close earlier than has been modelled due to minimum run levels. This pattern is also observed in the Net Zero 2050 scenario. This supply transformation results in the decline of electricity sector emissions in the NEM (Figure 3-6) from current levels of around 136 Mt to minimal emissions in all scenarios. Small amounts of gas-fired generation remain, an important complement to storage technologies to firm renewable energy resources, resulting in some emissions even late in the horizon. The Step Change scenario has a more gradual reduction in emissions because of greater gas-fired generation but still reaches low carbon emission levels around 2035.

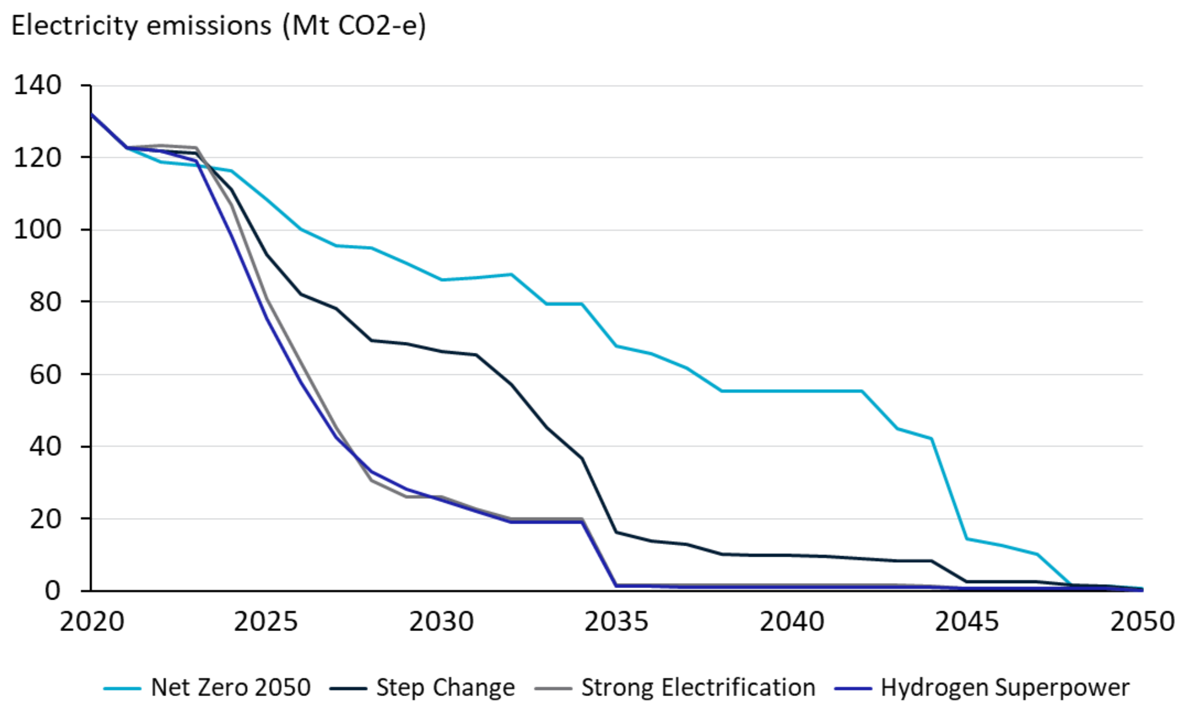


Figure 3-6: Electricity grid emissions for the NEM

3.5 End-use sectors

Outcomes in the end-use sectors including residential buildings, commercial buildings, industry, agriculture and transport determine the underlying demand for electricity in each scenario. This section discusses the key modelling outcomes from these sectors.

3.5.1 Energy efficiency and electrification

Demand in the end-use sectors is influenced by a range of determinants, including energy efficiency and electrification uptake. Figure 3- shows the final uptake of electrification by scenario, while Figure 3-8 shows the final uptake of energy efficiency improvements. Electrification is the highest in Strong Electrification, reaching 224 TWh by 2050, driven by the highest level of emissions reduction targets, without strong cost reductions in alternative energy sources. Net Zero 2050 reflects the current trend of electrification rates, steadily increasing over the years and ramping up post-2030, reaching an endpoint of 194 TWh in 2050 when decarbonisation efforts accelerate to reach economy-wide net zero emissions. The rapid increase in the late 2040s reflects a strong, deferred push towards net zero with a short time left to implement other decarbonisation options.

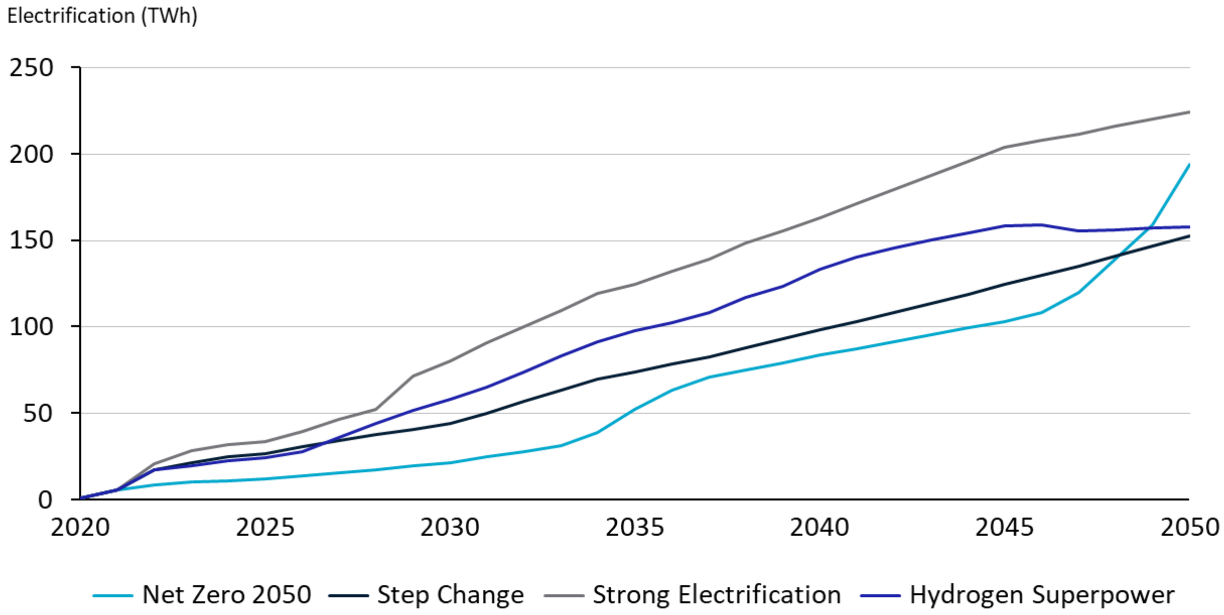


Figure 3-7: Electrification of all end-use sectors (including Transport) in the NEM

Energy efficiency uptake is the highest in the Hydrogen Superpower scenario (972 PJ by 2050), followed closely by Step Change scenario (958 PJ by 2050), due to the strong focus on high energy productivity. Although barriers to energy efficiency are higher in Hydrogen Superpower (as proxied by hurdle rates on energy efficiency technologies, see Table 2-4 to Table 2-7), it is also the scenario with the highest population and economic growth, leading to higher baseline energy demand and more opportunities for energy efficiency improvements. The Net Zero 2050 scenario shows the lowest uptake of energy efficiency improvements (679 PJ by 2050), due to the lower incentives for uptake in earlier years, and the fact that once strong decarbonisation is required between 2040-2050, and the electricity grid is largely decarbonised, energy efficiency does not offer as effective a means of decarbonisation as electrification.

The detailed trends of the uptake of energy efficiency and electrification in each end-use sector will be discussed in the following sections.

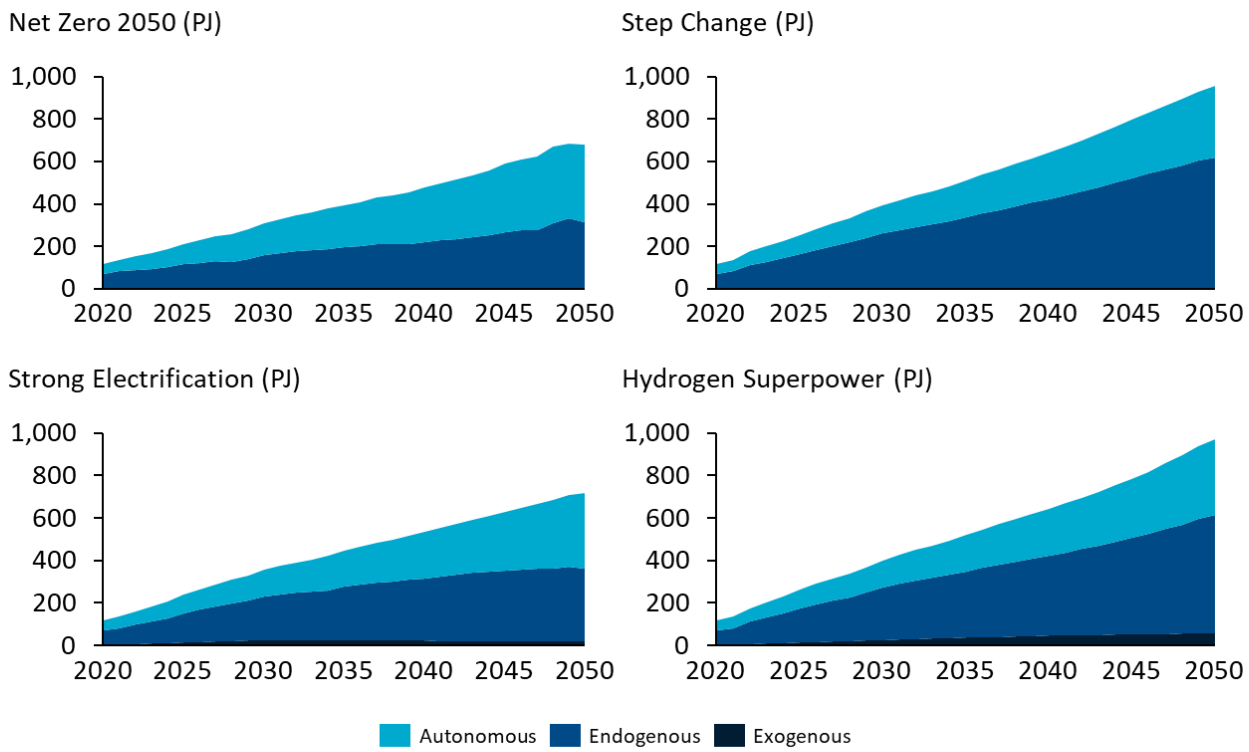


Figure 3-8: Breakdown of energy efficiency gains by type for all end-use sectors except Transport, and all fuel types.

3.5.2 Residential buildings

The mix of fuels in the total energy consumption for residential buildings is shown in Figure 3-9. Note that the total energy consumption represents the net energy consumed after considering energy efficiency, electrification and hydrogen uptake. The underlying baseline demand before these effects is driven by the population projections shown in Figure 2-1 and discussed in Section 2.2.2.1.

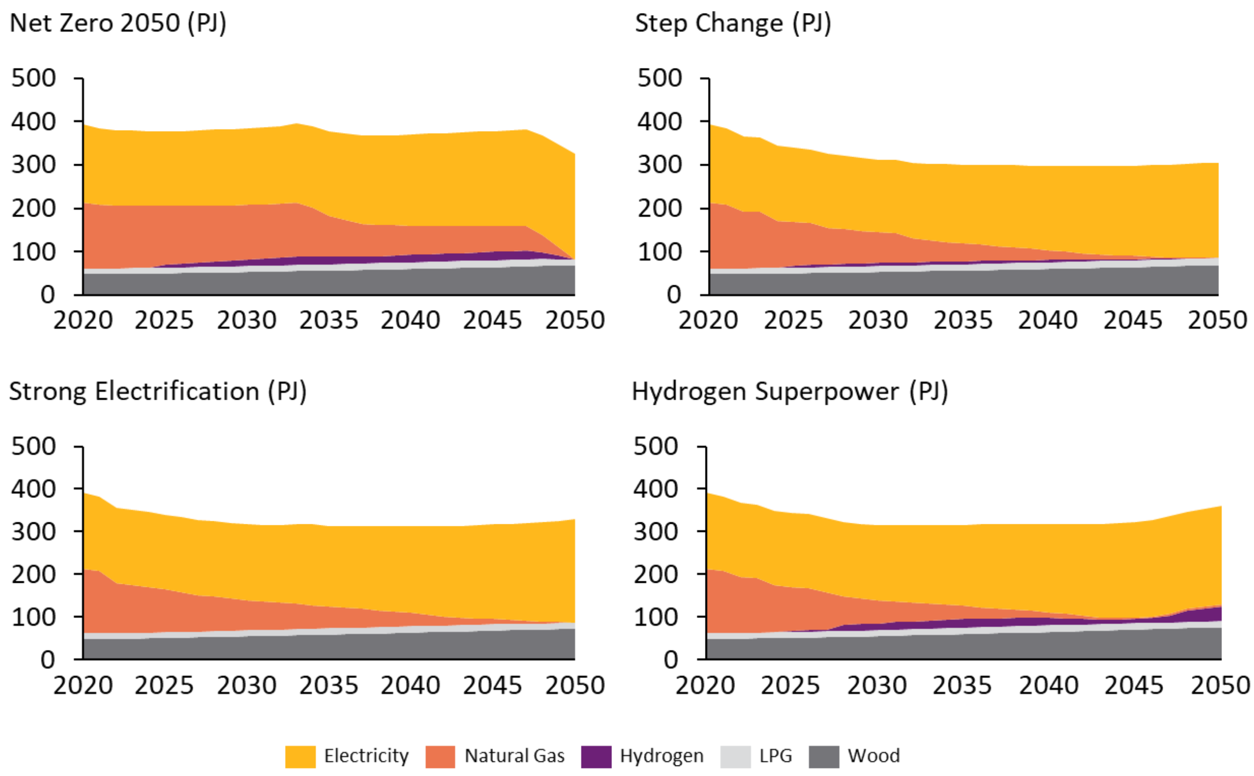


Figure 3-9: Fuel share in residential buildings across the four scenarios

Similar trends are seen across most scenarios, where gradual fuel switching from natural gas to electricity leads to a growing proportion of electricity consumption (most significant in the Strong Electrification sensitivity where it reaches 74% by 2050). The relative impact of hydrogen as a residential fuel blended in natural gas pipelines can be seen in all scenarios except Strong Electrification, although in both Net Zero and Step Change, the residential consumption of gas (natural gas or hydrogen) is entirely displaced by 2050. However, it should be noted that the modelling here does not consider costs associated with maintaining gas distribution networks, which would be an important consideration in determining the economic feasibility of maintaining blended gas networks alongside electrification.

In Hydrogen Superpower where the cost of hydrogen production becomes competitive with electricity because of the booming hydrogen export industry, a higher proportion of hydrogen is blended in pipelines to service gas appliances. By the mid-2030s, substantial portions of the gas distribution network have been converted to 100% hydrogen. By 2050, residential hydrogen consumption remains, making up 10% of energy demand, yet there is no natural gas consumption. As gas appliances are generally less efficient than their electrical counterparts, the total energy consumption is visibly higher than the other scenarios in the last few years.

A relatively stable fuel mix can be seen in Net Zero 2050 from 2020-2035 due to lower levels of electrification. Continuing decarbonisation of the electricity grid post-2035 allows for electrification to become more economical, resulting in a ramp-up of uptake in the following years, reaching 57% of energy demand by 2040. Similar trend is observed closer to 2050 when economy-wide effort is required to achieve net zero emissions by 2050, at which point electricity reaches 75% of energy demand.

Total energy consumption in Net Zero 2050 remains relatively stable across the time horizon (until the last few years), reducing by 4% from 2020-2045, representing a lower energy efficiency uptake and reduced fuel switching compared with the other scenarios. Strong population growth drives relatively strong demand in Hydrogen Superpower and Strong Electrification, while the minimal difference in residential energy consumption between these scenarios (360 PJ and 330 PJ by 2050 respectively) is mainly due to slightly higher energy efficiency gains assumed for the Hydrogen Superpower scenario.

Residential energy consumption from wood does not have conversion pathways implemented in AusTIMES, and simply grows with population. It is also important to note that while wood is a notable provider of energy, it is also highly inefficient when compared with electricity; fuel-switching to electricity would only represent a small increase in electricity consumption. Wood also provides services with unconsidered externalities that may support continued consumption, and is also assumed to be a net zero emission energy source.

3.5.3 Commercial buildings

The mix of fuels in the total energy consumption for commercial buildings is shown in Figure 3-10. Note that the total energy consumption represents the net energy consumed after considering energy efficiency, electrification and hydrogen uptake. The underlying baseline demand before these effects is driven by the floorspace projections shown in Figure 2-2 and discussed in Section 2.2.2.2.

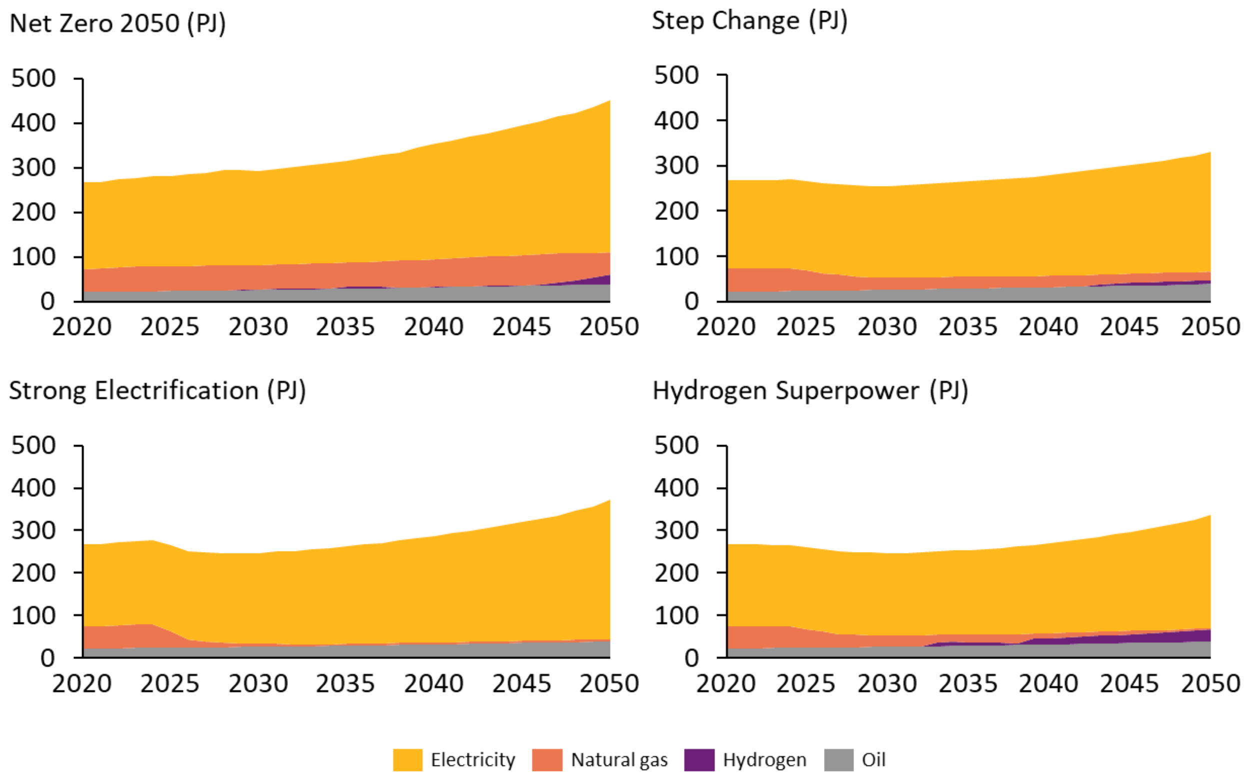


Figure 3-10: Fuel share in commercial buildings across the four scenarios

As commercial buildings are already predominantly electrified, the potential for further electrification in commercial buildings is relatively small and energy efficiency is largely responsible for the difference in total energy consumption between scenarios. As a result, scenarios with strong efficiency gains, such as Step Change and Hydrogen Superpower, have significantly lower energy demand growth (24% and 26% respectively), when compared against Net Zero 2050 and to a lesser degree Strong Electrification (68% and 39% respectively). The low uptake of energy efficiency in Strong Electrification is partially compensated by efficiency gains through higher electrification.

Switching from natural gas to electricity is most significant in Strong Electrification (where electricity comprises 88% of energy demand by 2050) and to lesser extents in the other scenarios. Similar to residential buildings, the relative impact of hydrogen blended in natural gas pipelines can be seen in all scenarios except Strong Electrification. However, the commercial sector differs from the residential sector in that an ongoing role for hydrogen and natural gas continues past 2050. The impact of hydrogen is the most pronounced in Hydrogen Superpower where the rapidly growing hydrogen export industry drives down the cost of hydrogen production and results in most gas distribution pipelines in commercial areas converting to 100% hydrogen – consistent with the residential sector. Hydrogen makes up 8% of commercial energy demand by 2050 in this scenario.

3.5.4 Industry and Agriculture

The mix of fuels in the total energy consumption for the industrial and agricultural sectors is shown in Figure 3-11. Note that the total energy consumption represents the net energy consumed after considering the effects of energy efficiency, electrification, bioenergy and hydrogen uptake. The underlying baseline demand before these effects is driven by the activity projections shown in Figure 2-3 and Figure 2-4, and discussed in Sections 2.2.2.3 and 2.2.2.4.

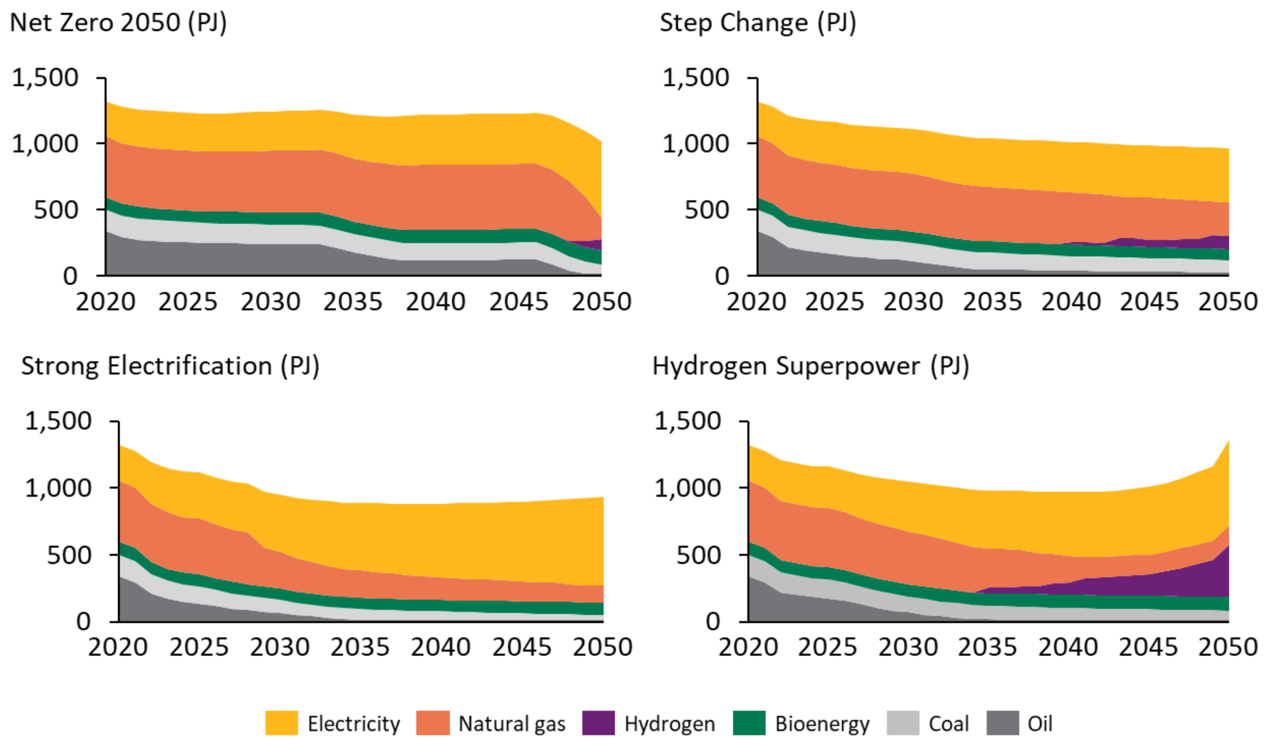


Figure 3-11: Fuel share in industry across the four scenarios

In all scenarios, oil demand shows the steepest decline amongst all industrial fuels. This is largely due to its high emissions intensity combined with relatively high cost, which makes it the most economical fuel to substitute through electrification or energy efficiency under any emissions reduction incentive. This is followed by the replacement of coal and natural gas, although there are some limits to the degree these can be removed due to proportions of fuel that are being used as feedstock or reductants. Industrial consumption of bioenergy is present in all scenarios, and sees modest growth consistent with expansion of existing industries; but, on an economy-wide scale, this is relatively minor when compared with electrification. In the later years of the projection period, hydrogen plays a role in displacing some natural gas use in the scenarios where it is featured, as it becomes cost-competitive against other fuels. In certain subsectors, such as chemical manufacturing, hydrogen can be used to replace natural gas that would otherwise be used as a feedstock to produce ammonia.

Fuel use in Net Zero 2050 remains reasonably stable through to the 2040s, which is mainly driven by relatively modest electrification and energy efficiency. Note that this reflects an overall reduction in energy intensity alongside continued industrial growth. Energy intensity (and final consumption) is driven downwards in the final few years (-17% from 2045-2050) due to an increase in electrification, and the realisation of associated energy efficiency benefits.

Both Step Change and Strong Electrification scenarios see a gradual decline in overall fuel demand; -27% and -29% from 2020-2050 respectively, driven by varying industrial activity assumptions combined with strong energy intensity reductions. Specifically, strong energy efficiency assumptions adopted in the Step Change scenario and higher levels of electrification, with associated efficiency benefits, in the Strong Electrification sensitivity, outweigh the effect of industrial activity growth on energy demand. Total energy demand in Strong Electrification plateaus at approximately 900 PJ from approximately 2035-2050, after the majority of oil consumption is electrified and opportunity for further electrification decreases.

While the Hydrogen Superpower scenario sees a declining trend in energy use up to 2035 (-26% on 2020 levels), demand increases across the rest of the projection period (38% from 2035-2050). This is largely attributable to the growth of a new hydrogen-based steelmaking industry, but also to overall higher industrial growth assumptions when compared with the Strong Electrification scenario, albeit slightly diminished by uptake of energy efficiency and associated energy efficiency benefits from electrification and switching to hydrogen.

Industrial use of hydrogen is most prominent in Hydrogen Superpower, driven by a combination of growth in hydrogen-based steelmaking, and an increased use in other end use sectors substituting natural gas use to hydrogen – largely driven by a fall in the relative cost of hydrogen in this scenario and its high availability to be deployed across industry in this scenario. In the Step Change scenario, a modest level of hydrogen uptake is seen beyond 2040 (reaching 94 PJ by 2050), representing an amount of fuel that is economical to shift without requiring substantial equipment upgrades in industry.

In the Net Zero 2050 scenario, only a very small uptake of hydrogen is seen in the final few years; 79 PJ by 2050. This late uptake is due to the assumption that higher hydrogen production costs persist longer in the Net Zero 2050 scenario than Step Change and Hydrogen Superpower. There is also less incentive to switch away from natural gas as the emissions trajectory across most of the projection period is higher than other scenarios. This hydrogen demand is likely making use of electrolysers that have already been deployed to produce hydrogen for buildings – which declines along a similar timeframe. The Strong Electrification sensitivity does not consider hydrogen impacts in this sector.

Results from agriculture are included in Appendix A. Agricultural trends mostly follow the results discussed for the rest of industry above. This includes a high level of electrification, given that the present fuel mix of agriculture is dominated by oil use. It is assumed that this largely represents electrification of farm machinery. Examples of electric farm machinery are already becoming available in the market, with electric tractors available from companies such as John Deere and Fendt, with current uptake being led in the US and UK (see White 2016, Fendt 2017 and National Farmers Union 2019).

3.5.5 Transport

The projected fuel consumption for transport in the NEM is shown in Appendix A. At the beginning of the projection period, most of the 1120 PJ energy consumption in 2020 is oil derived fuels of petrol and diesel in road transport (light and heavy vehicles) and kerosene in domestic aviation. The biofuel consumption is mainly low-blend ethanol (E10) in some Eastern states with a small amount of biodiesel consumption due to mandates in NSW and QLD (see Table 2-10). Similarly, there is modest liquefied petroleum gas (LPG) consumption in petrol ICE vehicles converted after market, although this consumption declines over time as its attractiveness diminishes due to announced increases in excise rates on LPG. Continued growth of demand for transport results in peak fuel use in the late 2020s in all scenarios. However, as non-ICE drivetrains (i.e., hybrid, plug-in hybrid, and electric) continue to reduce in upfront costs, these vehicles become more economic and there is a switch away from oil consumption. This dynamic is most pronounced in the Strong Electrification scenario.

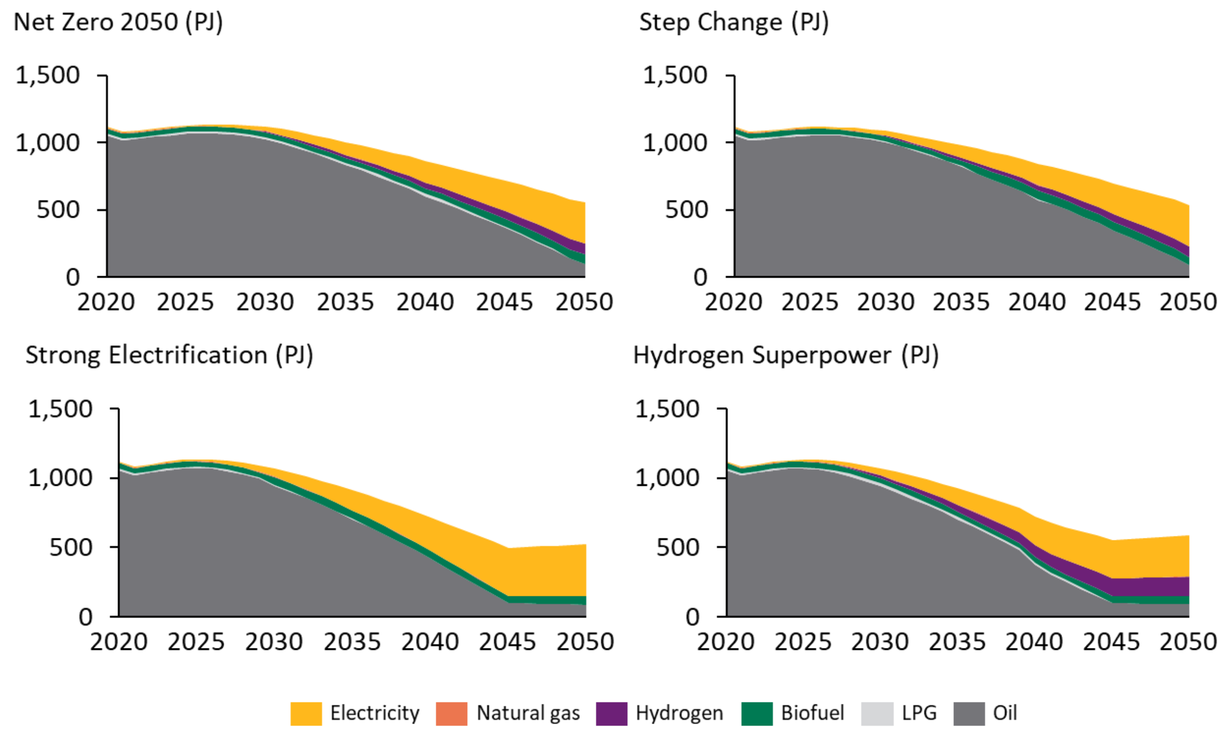


Figure 3-12: Fuel share in transport (both road and non-road) across the four scenarios

The electrification of road transport (and to a lesser extent rail and aviation) accelerates the decline in the overall level of fuel use, reflecting the greater efficiency of the electric drivetrain to deliver more kilometres per unit of energy. Informed by earlier work (Graham and Havas, 2021), this acceleration occurs in the mid-2030s as electric vehicles dominate new vehicle sales with ICE vehicles unavailable beyond 2035 in Strong Electrification and Hydrogen Superpower and 2040 in the Step Change scenario. Dependent on vehicle size, electricity displaces over 3 times the same volume of liquid fuel to deliver vehicle kilometres (around 0.7MJ/km of electricity compared to around 2.5MJ/km for liquid fuelled medium sized car).

In the mid to late 2020s, at around the time electric vehicles are beginning to increase their share of sales, hydrogen fuel cell vehicles are also assumed to increase their sales from their current near zero vehicle stock. Fuel cell vehicles will be able to benefit from some co-learning in their costs since fuel cell electric vehicles and battery electric vehicles both use an electric drive-train, just with a different fuel storage and conversion step (i.e. with a hydrogen storage vessel and fuel cell replacing the battery components). Under our assumptions, fuel cell vehicles remain a much smaller share of the fleet than electric vehicles, at least in part due to availability of refuelling stations. However, the projected volume of hydrogen consumption is still quite high because their main area of adoption is in road trucks. Since each truck will consume many more times the fuel of a passenger car per year, the required volume of hydrogen demanded by the truck fleet is still substantial. Another reason for the greater hydrogen volume is that hydrogen fuel cell vehicles are not as energy efficient, requiring around twice the equivalent energy content per kilometre compared to electricity.

The flattening out of fuel consumption from 2045 onwards in the Strong Electrification and Hydrogen Superpower scenarios reflects the deregistration of ICE vehicles from that year and a stable mix of vehicle-types across the various transport sectors.

The moderate increase in biofuel consumption in the long-term reflects increased uptake in domestic aviation of bio-derived jet fuel as a ‘drop-in’ fuel for kerosene in existing turbine aircraft.

3.6 Hydrogen demand and production

Hydrogen demand features in all scenarios, and is particularly high in Hydrogen Superpower due to large hydrogen production capacity driven by cost-effective electrolysers powered by renewables. By contrast, the Strong Electrification scenario sees minimal cost reductions and only considers hydrogen consumption in the transport sector. Total demand for hydrogen across the relevant scenarios is shown in Figure 3-13. The earliest uptake of hydrogen across all scenarios is seen in pipeline gas (assuming that hydrogen is mixed with natural gas that is delivered to buildings) and as a transport fuel. These represent two of the lowest-cost applications for hydrogen that can be available in the near-term. In later years (post-2045 in the Net Zero 2050 scenario, post-2040 in Step Change scenario and post-2035 in Hydrogen Superpower scenario), the uptake of hydrogen is also seen in industry, which represents hydrogen replacing some natural gas demand for industrial heating, and as a direct chemical feedstock (e.g. for ammonia production).

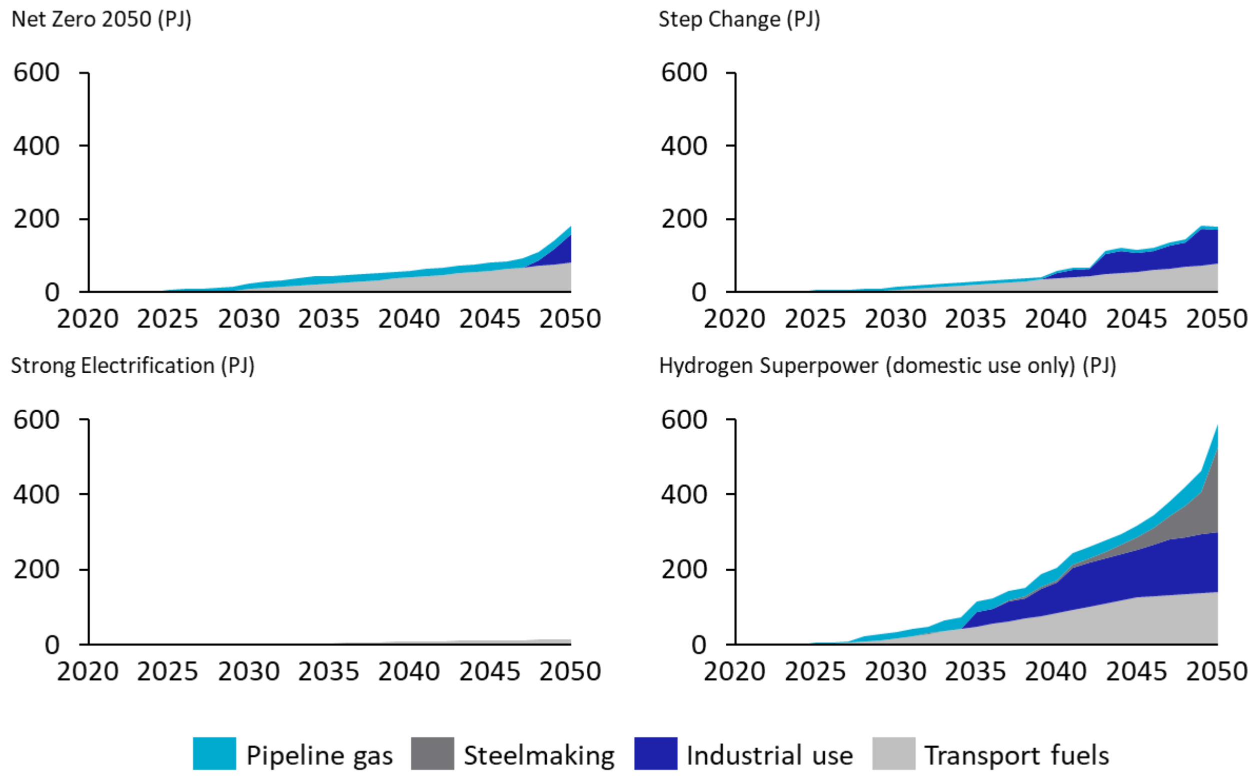


Figure 3-13: Demand for hydrogen across the four scenarios for the NEM

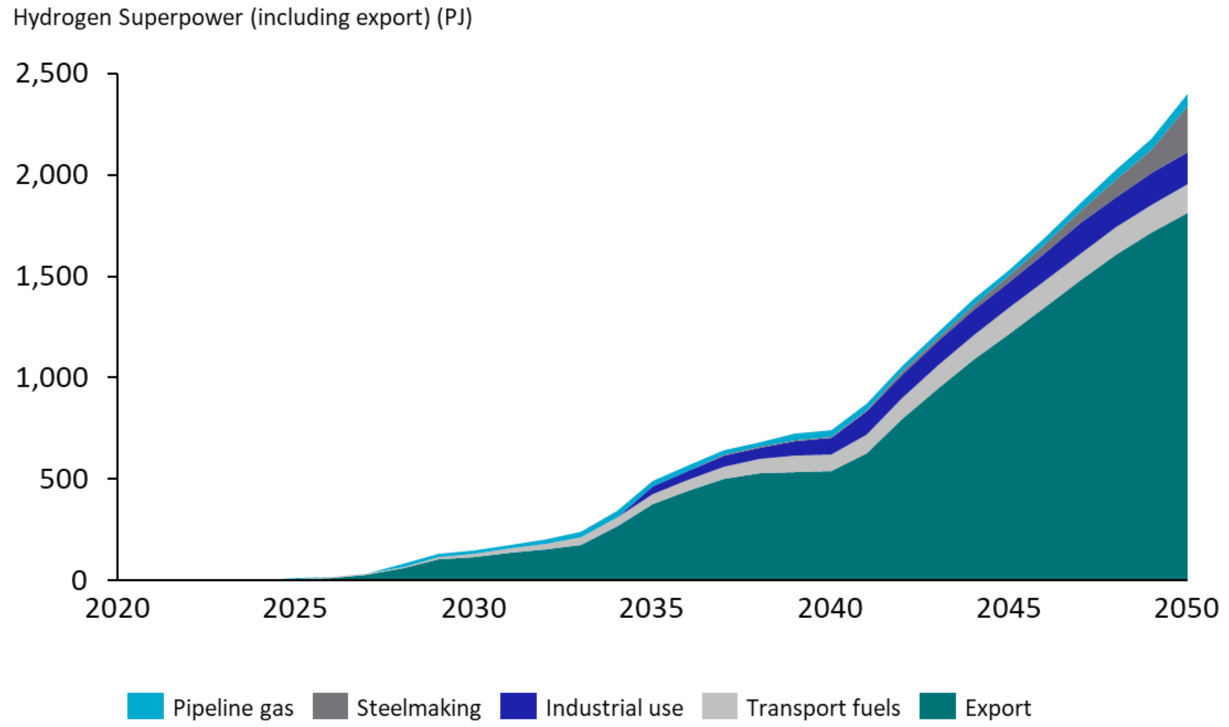


Figure 3-14: Demand for hydrogen in Hydrogen Superpower (including export)

Hydrogen superpower features two additional demands for hydrogen: one for hydrogen-based steelmaking, which follows the assumption of 50 Mtpa steel production nationally by 2050 (see section 2.2.2.3), and another for hydrogen exports, based on the assumption that Australia's competitive advantage in low-cost green hydrogen production allows it to capture significant new global energy export opportunities of a similar scale to the most ambitious scenario reported in

Australia's National Hydrogen Strategy (Deloitte, 2019) (see Section 2.2.5). Collectively, these additional demands raise the hydrogen demand in this scenario by nearly four-fold compared to domestic demand by 2050.

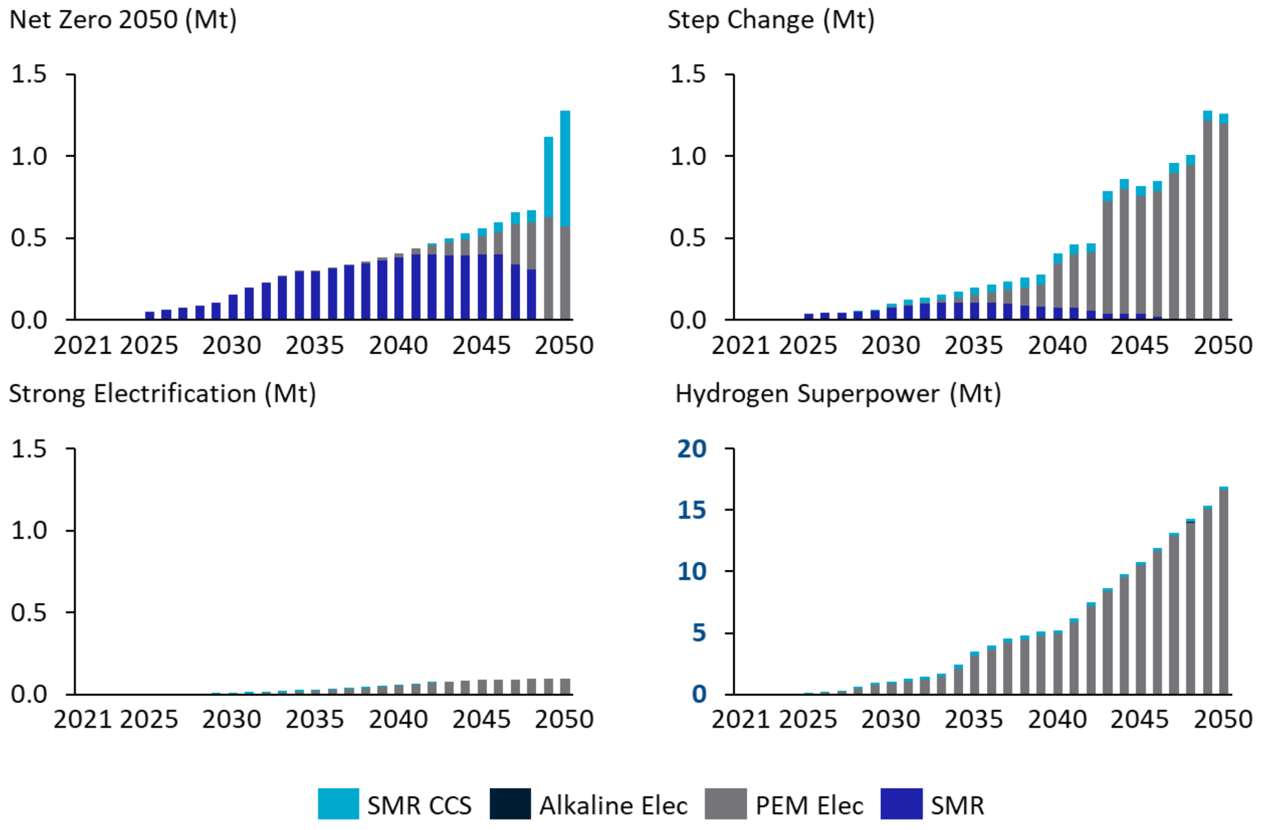


Figure 3-15: Hydrogen production by process for the NEM (note difference in scale for Hydrogen Superpower)

Figure 3-15 shows the production process used to produce hydrogen in the four scenarios, respectively. There are five possible hydrogen production pathways that were considered: steam methane reforming (SMR); SMR with carbon capture and storage (CCS); coal gasification with CCS; alkaline electrolysis, and; proton exchange membrane (PEM) electrolysis. The modelling framework optimises the production process and location of the hydrogen production as part of the least cost optimisation for each of the scenarios. However, there is a requirement that in the Hydrogen Superpower scenario, any hydrogen export or DRI steel exports are produced from renewable electricity.

It is observed that early in the Net Zero 2050 and Step Change scenarios, SMR is the lower-cost production process. In fact, in Net Zero 2050, Victoria's hydrogen production is entirely produced from SMR (either standalone or with CCS). However, as the need to reduce emissions becomes more stringent, PEM electrolysis and SMR with CCS produce the bulk of the hydrogen. In contrast, in the Strong Electrification and Hydrogen Superpower scenarios, the rapid decarbonisation of the electricity means that PEM electrolysis is the preferred production pathway in the near- and long-term with SMR with CCS having a minor role.

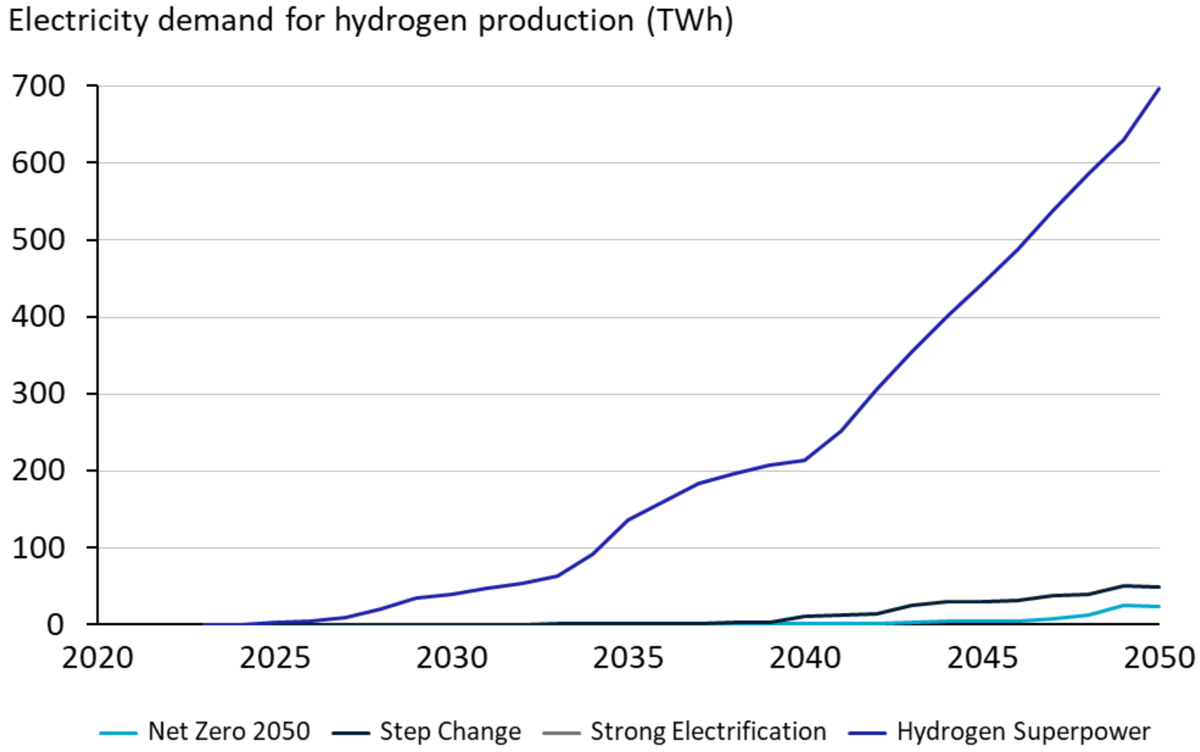


Figure 3-16: NEM electricity demand required for hydrogen production in the four scenarios. Note that electricity demand for hydrogen production in Strong Electrification is negligible, given the minimal demand for hydrogen in that scenario.

The amount of electricity consumed to produce hydrogen across each scenario is shown in Figure 3-16. This is a product of both the underlying hydrogen demand in each scenario, and the proportion of that demand that is supplied by electrolyser pathways (AE or PEM). Electricity demand for hydrogen is very small in Strong Electrification, where underlying hydrogen demand is not considered outside transport. Net Zero 2050 and Step Change scenarios feature a demand of 23 TWh and 49 TWh respectively, but by far the biggest impact is seen in Hydrogen Superpower, where hydrogen production leads to an additional 697 TWh electricity demand by 2050.

3.7 Carbon Sequestration

Two means of emissions sequestration were considered in these scenarios: Sequestration via carbon capture & storage (CCS) and via land-based methods, modelled as carbon forestry[8]. The total uptake of these technologies by scenario is shown in Figure 3-18. Although CCS is available in the electricity generation sector, it does not see uptake in these scenarios on the basis of not being cost-competitive. However, small amounts of CCS are assumed to be deployed in industry to target hard-to-abate emissions, largely non-energy related. One hydrogen production pathway available is steam methane reforming (SMR) with CCS, and this also sees small levels of uptake, particularly in Hydrogen Superpower where the larger demand for hydrogen leads to increased

[8] No allowance for international trading was considered

production via all cost-effective pathways.

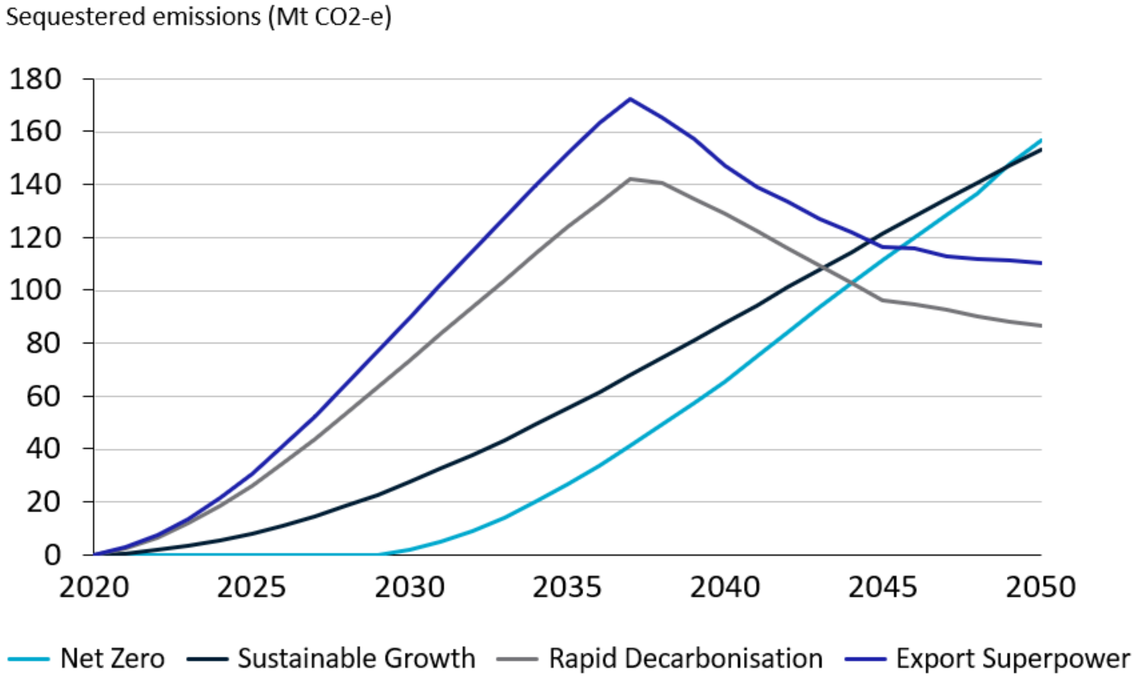


Figure 3-17: Emission sequestration trajectories for each scenario, incorporating both land-based sequestration and CCS, in Mt CO_2-e

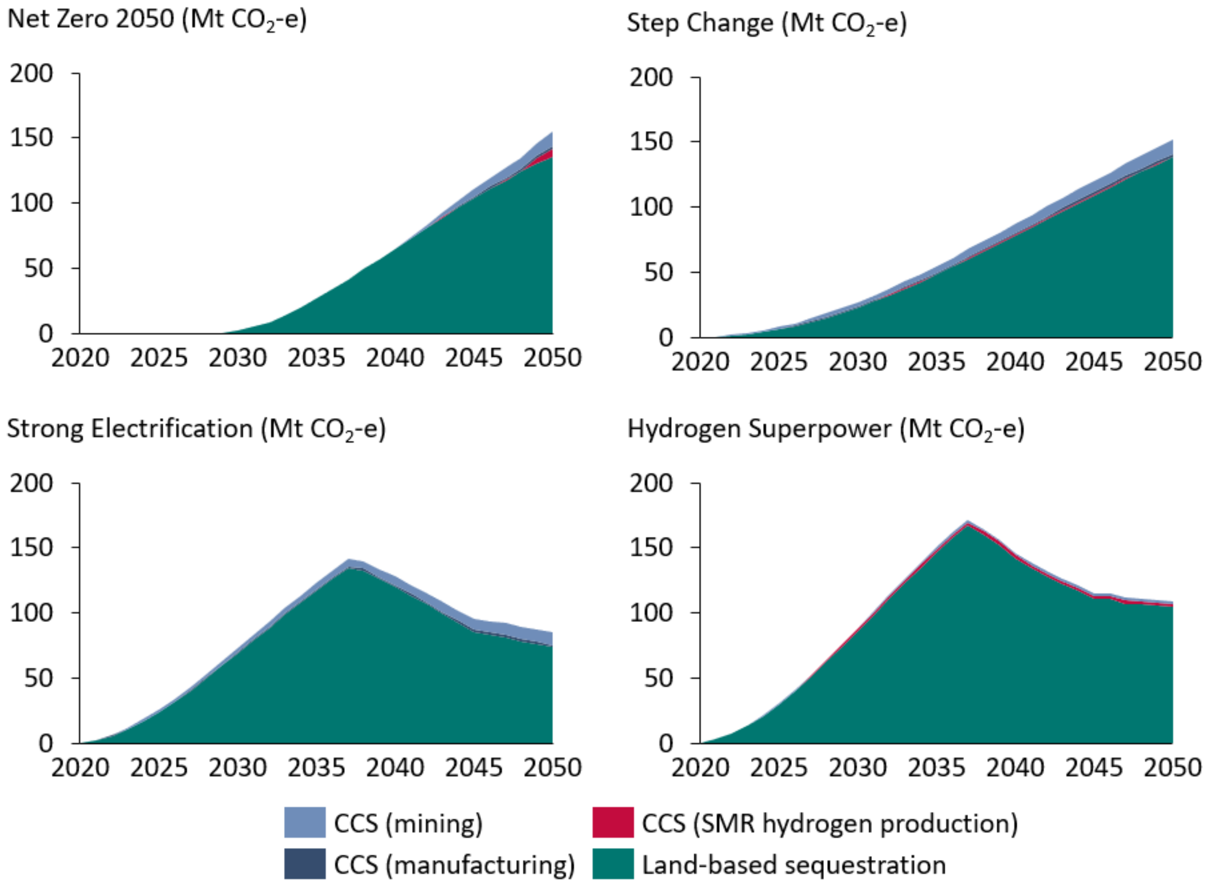


Figure 3-18: Total GHG emissions sequestered in each scenario, showing the relative components from land-based sequestration and three applications of CCS

As detailed in Section 1.7 and 2.2.4, carbon forestry trajectories, used as a proxy for land-based sequestration potential, for each scenario are calculated as an exogenous sequestration trajectory, based on modelled outcomes from CSIRO's LUTO model. Net Zero 2050 and Step Change scenarios achieve close to 140 Mt CO_2-e/year sequestration by 2050, with the key difference being a delayed onset of carbon forestry until 2030 in the Net Zero 2050 scenario, which is reflective of the overall emissions trajectory that sees only incremental change in this first decade. The 1.5-degree scenarios (Strong Electrification and Hydrogen Superpower) have significantly higher levels of carbon forestry earlier in the modelling horizon. The carbon forestry peaks at above 136 Mt CO_2-e/year (Strong Electrification) and 168 Mt CO_2-e/year (Hydrogen Superpower) in 2037. This peak occurs due to the fact that both scenarios are optimised to meet their respective carbon budgets. After economy-wide net emissions reach zero, the amount of sequestration that is needed from carbon forestry declines over time, remaining equal to the amount of residual emissions left from other sectors of the economy.

In practice, this decline could represent actual reductions in carbon forestry sequestration from a number of drivers if policy incentives are scaled down. Alternatively, carbon forestry could continue to exist in order to support international trade in carbon offsets, supporting countries that do not achieve net zero emissions by 2036. Carbon accounting practices mean that this sequestration would not be included in Australia's net emissions trajectory.

State-level carbon forestry outcomes have been provided in the full dataset to AEMO, and are based on the proportions of plantings in each state from the original maximum LUTO carbon forestry results. These state shares are largely determined by the amount of suitable land that was considered in each state, and the economic potential of carbon forestry against other land uses. In general, there is a strong weighting towards carbon forestry activities occurring in Queensland and New South Wales. Given the limitations of the LUTO modelling (see Section 1.7), and the fact that this sequestration curve could be interpreted to include other, non-modelled land-based sequestration methods, state-based results should be taken as indicative only. Additionally, state-based carbon forestry sequestration reflects only the amount of physical plantings in each state. It is probable that states will continue to implement policies to achieve net zero emissions at a state level. Such policies may allow for the purchase of carbon offsets from other states (as is the case in Victoria's current legislation; DELWP 2017), which would mean that the actual accounted carbon sequestration levels may be distributed differently amongst the states.

Appendix A: Structural detail of AusTIMES model

A.1 Electricity sector

In the TIMES framework, the power (electricity) sector is a transformation sector that converts forms of primary energy (i.e., coal, natural gas, renewable resources) into electricity that is a derived demand of the end-use sectors (see Section A.2). An advantage of the TIMES model is that different spatial and temporal scales can be implemented in different sectors. The electricity sector in AusTIMES has the following features:

- Electricity demand aggregated to 16 load blocks reflecting seasonal and time of day variation across the year
- 19 transmission zones: 16 zones in the National Electricity Market (NEM)[9]; South-West Interconnected System (SWIS); North-West Interconnected System (NWIS); and Darwin Katherine Interconnected System (DKIS)
- Existing generators mapped to transmission zone at the unit-level (thermal and hydro) or farm-level (wind, solar)
- Renewable resource availability at Renewable Energy Zone (REZ) spatial resolution for solar, on- and off-shore wind and tidal resources and sub-state (polygon) spatial resolution for geothermal and wave resources in the NEM
- Trade in electricity between NEM regions subject to interconnector limits
- 31 new electricity generation and storage technologies: black coal pulverised fuel; black coal with CO2 capture and sequestration (CCS); brown coal pulverised fuel; brown coal with CCS; combined cycle gas turbine (CCGT); open-cycle gas turbine (OCGT); gas CCGT with CCS; gas reciprocating engine; biomass; biomass with CCS; pumped storage hydro (PSH) with 4 hours storage (PSH4); PSH with 8 hours of storage (PSH8); PSH with 12 hours of storage (PSH12); PSH with 24 hours of storage (PSH24); PSH with 48 hours of storage (PSH48); onshore wind; offshore wind; large-scale single-axis tracking solar photovoltaic (PV); Concentrating Solar Thermal with 8 hours storage; residential rooftop solar PV; commercial rooftop solar PV; hot fractured rocks (enhanced geothermal); conventional geothermal; wave; tidal; hydrogen reciprocating engine; diesel reciprocating engine; small modular nuclear reactor; battery with 2 hours of storage; battery with 4 hours of storage; battery with 8 hours of storage.
- Current policies: national Large-scale Renewable Energy Target (LRET); Queensland Renewable Energy Target (QRET), Tasmania Renewable Energy Target (TRET); Victoria Renewable Energy Target (VRET); Small-scale renewable energy scheme; NSW Energy Security Target; NSW Electricity Infrastructure Roadmap.

[9] The NEM zones reflect zones that were originally identified in AEMO's National Transmission Network Development Plan (NTNDP) publications, which has been replaced since 2018 with the Integrated System Plan (ISP).

A.2 End-use sectors

a) Residential buildings

The stock of buildings is sourced from the Residential Buildings Baseline Study (EnergyConsult, 2016), 2016 ABS *Census* data, 2016 ABS populations and dwellings projection, *Australian Energy Statistics*, and the *Low Carbon High Performance* report (CWA, 2016).

AusTIMES projects baseline energy consumption and can also implement a business-as-usual efficiency improvement (autonomous energy efficiency) at no cost, endogenous energy efficiency and electrification of technologies based on capital costs, technology-specific hurdle rates, equipment lifetime and fuel costs, if they are economically attractive when compared to the shadow carbon price. All assumptions on costs and savings are derived from the *Low Carbon High Performance report* (CWA, 2016). Hurdle rates for the endogenous technologies (represented as technology-specific discount rates) can be adjusted for different building types to reflect barriers inhibiting uptake of certain technologies. These technologies are not available to end-use service demands fulfilled by wood.

A significant discrepancy exists between the energy efficiency of market leading buildings and the worst performing buildings. Significant emissions abatement potential also exists in the development and implementation of innovative technology. Due to these, non-costed energy efficiency options can be imposed as exogenous decarbonisation options to capture the significant emissions abatement potential. Exogenous abatement potentials are derived from the *Decarbonisation Futures* report (Butler et al., 2020).

Hydrogen uptake in residential buildings is modelled as a category of fuel available for pipeline blending with natural gas. AusTIMES can make the decision to switch natural gas demand to hydrogen if it is economically attractive based on costs of fuels involved and the shadow carbon price. The fuel cost of hydrogen is determined through optimisation of investment in hydrogen production capacity and operation to deliver hydrogen to end-uses at least cost. Assuming hydrogen replaces natural gas with existing pipeline infrastructure, the capital cost of switching from natural gas to hydrogen technologies is not considered.

The residential building types, end-use service demands and fuel types are listed below (Table A-1).

Table A-1: Residential building types, end-use service demands and fuel types

Building types	End-use service demands	Fuel types
Detached (separate houses)	Space heating	Electricity
Semi-detached (townhouses, duplexes)	Space cooling	Natural gas
Apartments	Cooking	Hydrogen
	Water heating	LPG
	Appliances	Wood
	Lighting	

b) Commercial buildings

The stock of buildings is sourced from the *Commercial Buildings Baseline Study*, *Australian Energy Statistics*, and the *Low Carbon High Performance* report (CWA, 2016).

AusTIMES projects baseline energy consumption and can also implement a business-as-usual efficiency improvement (autonomous energy efficiency) at no cost, endogenous energy efficiency and electrification of technologies based on capital costs, technology-specific hurdle rates, equipment lifetime and fuel costs, if they are economically attractive when compared to the shadow carbon price. All assumptions on costs and savings are derived from the *Low Carbon High Performance* report (CWA ,2016). Hurdle rates for the endogenous technologies (represented as technology-specific discount rates) can be adjusted to reflect non-financial barriers and non-price uncertainties inhibiting uptake of certain technologies. Given uncertainties regarding specific technologies that utilise oil in commercial buildings (as reported in the Australian Energy Statistics), these technologies are not available to end-use service demands fulfilled by oil.

A significant discrepancy exists between the energy efficiency of market leading buildings and the worst performing buildings. Significant emissions abatement potential also exists in the development and implementation of innovative technology. Due to these, non-costed energy efficiency options can be imposed as exogenous decarbonisation options to capture the significant emissions abatement potential. Exogenous abatement potentials are derived from the *Decarbonisation Futures* report (Butler et al., 2020).

Hydrogen uptake in commercial buildings is modelled as a category of fuel available for pipeline blending with natural gas. AusTIMES can make the decision to switch natural gas demand to hydrogen if it is economically attractive based on costs of fuels involved and the shadow carbon price. The fuel cost of hydrogen is determined through optimisation of investment in hydrogen production capacity and operation to deliver hydrogen to end-uses at least cost. Assuming hydrogen replaces natural gas with existing pipeline infrastructure, the capital cost of switching from natural gas to hydrogen technologies is not considered.

The commercial building types, end-use service demands and fuel types are listed below Table A-2).

Table A-2: Commercial building types, end-use service demands and fuel types

Building types	End-use service demands	Fuel types
Hospital	Space heating	Electricity
Hotel	Space cooling	Natural gas
Law court	Water heating	Oil
Office	Appliances	Hydrogen
Public building	Lighting	
Retail	Equipment	
Supermarket		
School		
Tertiary		
Data centre		
Aged care		

c) Industry

Energy use in industry is significant and therefore is disaggregated into a number of sub-sectors. The mapping of AusTIMES to ANZSIC industry subsectors is displayed below (Table A-3).

Table A-3: Mapping of AusTIMES to ANZSIC industry subsectors

Aus-TIMES subsector (industry)	ANZSIC (2006) codes	ANZSIC Division
Industry - Coal mining	6	Division B
Industry - Oil mining	7	Division B
Industry - Gas mining	7	Division B
Industry - Iron ore mining	801	Division B
Industry - Other non-ferrous metal ores mining	0803, 0804, 0805, 0806, 0807, 0809	Division B
Industry - Other mining	9	Division B
Industry - Meat products	111	Division C
Industry - Other food and drink products	112, 113, 114, 115, 116, 117, 118, 119	Division C
Industry - Textiles, clothing and footwear	13	Division C
Industry - Wood products	14	Division C
Industry - Paper products	15	Division C
Industry - Printing and publishing	16	Division C
Industry - Petroleum refinery	17	Division C
Industry - Other chemicals	181, 182, 183, 185, 189	Division C
Industry - Rubber and plastic products	19	Division C
Industry - Non-metallic construction materials (not cement)	201, 202, 209	Division C
Industry - Cement	203	Division C
Industry - Iron and steel - Blast furnace	211	Division C
Industry - Iron and steel - Electric arc furnace	211	Division C
Industry - Alumina	2131	Division C
Industry - Aluminium	2132	Division C
Industry - Other non-ferrous metals	2133, 2139	Division C
Industry - Other metal products	212, 214, 22	Division C
Industry - Motor vehicles and parts	231	Division C
Industry - Other manufacturing products	239, 24, 25	Division C
Industry - Gas supply	27	Division D
Industry - Water supply	28	Division D
Industry - Construction services	30, 31, 32	Division E

Baseline energy use is disaggregated by subsector and fuel type (oil, bioenergy, black coal, brown coal, natural gas, electricity, hydrogen).

AusTIMES can implement a business-as-usual efficiency improvement (autonomous energy efficiency) at no cost, endogenous energy efficiency and electrification of technologies based on capital costs, technology-specific hurdle rates, equipment lifetime and fuel costs, if they are economically attractive when compared to the shadow carbon price. Assumptions on costs and savings are derived from the *Deep Decarbonisation Pathways Project* (CWA, ANU, CSIRO and CoPS, 2014) and *Industrial Energy Efficiency Data Analysis Project* (CWA, 2013). The total electrification allowed can be limited to reflect the levels expected in the scenarios.

In addition to these endogenous actions, exogenous (externally researched, calculated and respected by the model) abatement solutions can reduce emissions through any one of the following mechanisms: adjusting emission intensity, energy intensity or activity levels. The specific levels of these exogenous abatement solutions in a given scenario is informed by the scenario narratives. Exogenous abatement potentials are derived from the *Decarbonisation Futures* report (Butler et al., 2020).

Hydrogen uptake in industry is implemented endogenously to service end-uses through pipeline blending with natural gas. In this case, similar to natural gas, hydrogen is a category of fuel available to these end uses. AusTIMES can make the decision to switch natural gas demand to hydrogen if it is economically attractive based on costs of fuels involved and the shadow carbon price. The fuel cost of hydrogen is determined through optimisation of investment in hydrogen production capacity and operation to deliver hydrogen to end-uses at least cost. Assuming hydrogen replaces natural gas with existing pipeline infrastructure, the capital cost of switching from natural gas to hydrogen technologies is not considered.

Hydrogen use in industry is also modelled exogenously to meet the demand of hydrogen for the emerging green steel industry, based on an assumption of 50Mtpa national green steel production by 2050, following an uptake curve aligned to the Targeted Deployment scenario from Australia's National Hydrogen Strategy.

d) Agriculture

The agriculture sector is represented in AusTIMES as a subset of industry. Energy use in agriculture is minimal although non-energy emissions are significant. The mapping of AusTIMES to ANZSIC industry subsectors is displayed below (Table A-4).

Table A-4: Mapping of AusTIMES to ANZSIC agriculture subsectors

Aus-TIMES subsector (agriculture)	ANZSIC (2006) codes	ANZSIC Division
Agriculture - Sheep and cattle	0141, 0142, 0143, 0144	Division A
Agriculture - Dairy	16	Division A
Agriculture - Other animals	017, 018, 019	Division A
Agriculture - Grains	0145, 0146, 0149, 015	Division A
Agriculture - Other agriculture	011, 012, 013	Division A
Agriculture - Agricultural services and fishing	02, 04, 052	Division A
Forestry - Forestry and logging	03, 051	Division A

Agriculture activity growth forecasts were developed through the *Pathway to Deep Decarbonisation Project* (CWA, ANU, CSIRO and CoPS, 2014), drawing on results of CGE analysis by the Centre of Policy Studies at Victoria University. CWA hosts the ongoing multi-year initiative Land Use Futures, which focuses specifically on the Agriculture sector.

Similar to the structure for Industry described above, AusTIMES can implement endogenous energy efficiency improvements, electrification of energy use and endogenous hydrogen uptake. However, the key abatement mechanism in this sector comes from exogenous abatement solutions that reduce emissions through emission intensity. The specific levels of these exogenous abatement solutions in a given scenario is informed by the scenario narratives. Exogenous abatement potentials are derived from the *Decarbonisation Futures* report (Butler et al., 2020).

e) Transport

The transport sector is a significant and growing component of Australia's greenhouse gas emissions. AusTIMES has a very detailed representation of road transport. The road transport segments, vehicle classes, and fuel categories are listed below (Table A-5).

Table A-5: Road transport segments, vehicle classes, and fuel categories

Market segments	Vehicle types	Fuels
Motorcycles **Small, medium and large passenger** **Small, medium and large light commercial vehicles** **Rigid trucks** **Articulated vehicles** **Buses**	Internal combustion engine Hybrid/internal combustion engine Plug-in Hybrid/internal combustion engine Short-range electric vehicle Long-range electric vehicle Autonomous long-range (private) electric vehicle Autonomous long-range (ride-share) electric vehicle Fuel cell electric vehicle	Petrol Diesel Liquefied Petroleum Gas (LPG) Compressed or Liquefied Natural gas Petrol with 10% ethanol blend (E10) Diesel with 20% biodiesel blend (B20) Ethanol Biodiesel Hydrogen Electricity

Key inputs are ABS data on vehicle stock (ABS, 2020a), average kilometres travelled (ABS, 2020b), BITRE (2019) and *Australian Energy Statistics* data (DISER, 2020b) on fuel use, NGA emission factors for fuel (DoEE, 2017), population/GSP projections, assumptions around future vehicle costs and efficiency improvements (Graham and Havas, 2021), oil price projections (IEA, 2020) and production costs on biofuels (see Table 2-8). The delivery price of electricity and hydrogen for road transport is endogenously determined within AusTIMES.

There is less detailed representation of non-road transport, implemented on a fuel basis. The market segments and fuel categories are listed below (Table A-6).

Table A-6: Non-road transport market segments and fuels

Market segments	Fuels
Rail	Diesel Electricity
Aviation – domestic **Aviation- international**	Avgas Kerosene Biofuel Electricity
Shipping – domestic **Shipping – international**	Diesel Petrol Fuel oil

Key inputs are BITRE (2019) and AES data (DISER, 2020b) on fuel use, NGA emission factors for fuel (DoEE, 2017), population/GSP projections, assumptions around activity and fuel efficiency improvements (Graham and Havas, 2021), oil price projections (IEA, 2020) and production costs on biofuels (see Table 2-8). The delivery price of hydrogen for rail and shipping is endogenously determined within AusTIMES.

Appendix B: Full carbon budget methodology

A carbon budget approach was used to assess our decarbonisation scenarios against particular temperature outcomes. The carbon budget approach use is an adapted version of that used in *Decarbonisation Futures*, which is in turn based on the method developed by Meinshausen (2019).

Global temperature rise is closely linked to the cumulative concentration of greenhouse gases in the atmosphere. The IPCC (Rogeli et al. 2018) has published global carbon budgets consistent with particular global temperature outcomes, which represent the cumulative amount of carbon dioxide that can be emitted above a particular baseline before a given temperature outcome is reached (Table B-1). These carbon budgets involve inherent uncertainties, including:

- Actual historical emissions and warming since the period 1850-1900
- Transient climate response to cumulative emissions of carbon (TCRE) – the ratio of global average surface temperature change per unit CO_2 emitted. Uncertainties in this relationship are represented via percentiles – 33rd, 50th and 67th, interpreted as 33%, 50% and 67% chance of the cumulative emissions achieving a particular temperature rise respectively.
- Earth system feedbacks, including CO_2 that may be released through permafrost thawing.

Table B-1: Global carbon dioxide budgets from the IPCC Special Report on Global Warming of 1.5°C (from Rogeli et al. 2018)

Additional Warming since 2006–2015 [°C]*(1)	Approximate Warming since 1850–1900 [°C]*(1)	Remaining Carbon Budget (Excluding Additional Earth System Feedbacks*(5)) [$GtCO_2$ from 1.1.2018]*(2)			Key Uncertainties and Variations*(4)					
		Percentiles of TCRE *(3)			Earth System Feedbacks *(5)	Non-CO_2 scenario variation *(6)	Non-CO_2 forcing and response uncertainty	TCRE distribution uncertainty *(7)	Historical temperature uncertainty *(1)	Recent emissions uncertainty *(8)
		33rd	*50th*	*67th*	[$GtCO_2$]	[$GtCO_2$]	[$GtCO_2$]	[$GtCO_2$]	[$GtCO_2$]	[$GtCO_2$]
0.3		290	160	80						
0.4		530	350	230						
0.5		770	530	380						
0.53	**~1.5°C**	**840**	**580**	**420**	Budgets on the left are reduced by about –100 on centennial time scales	±250	–400 to +200	+100 to +200	±250	±20
0.6		1010	710	530						
0.63		1080	770	570						
0.7		1240	900	680						
0.78		1440	1040	800						
0.8		1480	1080	830						
0.9		1720	1260	980						
1		1960	1450	1130						
1.03	**~2°C**	2030	1500	1170						
1.1		2200	1630	1280						
1.13		2270	1690	1320						
1.2		2440	1820	1430						

1.5-degree and 2-degree climate scenarios typically show temperatures peaking between 2040-2060. Therefore, we consider the above and subsequent carbon budgets to be restricted from the baseline year to 2050, given that this reduces the chance of overshooting temperature levels (Meinshausen et al. 2018).

For the three scenarios that are constrained by temperature outcomes – Step Change, Hydrogen Superpower and the Strong Electrification sensitivity, an appropriate global carbon dioxide budget was selected from Table B-1 as documented in Table B-2.

Table B-2: Global carbon dioxide budgets from 2018 for the relevant scenarios in this report

Scenario	Temperature outcome and probability	Global budget (CO_2 only; from 2018)	Justification
Step Change	<2°C (67%)	830 Gt CO_2	67th percentile of '0.8' additional warming row from Table B-1
Hydrogen Superpower	1.5°C (50%)	580 Gt CO_2	50th percentile of '~1.5' additional warming row from Table B-1
Strong Electrification			

To align all assumptions with the approach used in Meinshausen (2019), it is necessary to adjust the start year of the carbon budget from a start year of 2018 to 2013. This is achieved by adding 200 Gt to each of the budgets (approximate global emissions between 2013-2017), resulting in the updated budgets in Table B-3. (Meinshausen, 2019).

Table B-3: Global carbon dioxide budgets from 2013 for the relevant scenarios in this report

Scenario	Temperature outcome and probability	Global budget (CO_2 only; from 2013)	Justification
Step Change	<2°C (67%)	1030 Gt CO_2	Add 200 Gt to budgets from Table B-2 representing global emissions from 2013-2017
Hydrogen Superpower	1.5°C (50%)	780 Gt CO_2	
Strong Electrification			

Next, 100 Gt emissions are subtracted from each budget. This represents the level of uncertainty in these budgets associated with various Earth system feedbacks. This results in the updated budgets in Table B-4.

Table B-4: Global carbon dioxide budgets from 2013 for the relevant scenarios in this report, after considering uncertainties from Earth system feedbacks

Scenario	Temperature outcome and probability	Global budget (CO_2 only; from 2013)	Justification
Step Change	<2°C (67%)	930 Gt CO_2	Subtract 100 Gt from budgets in Table B-3 representing uncertainty from Earth system feedbacks
Hydrogen Superpower	1.5°C (50%)	680 Gt CO_2	
Strong Electrification			

The carbon budgets provided in Table B-1 refer to temperature rise relative to an 1850-1900 baseline. However, it is useful to construct scenarios relevant to the Paris Agreement (UNFCCC 2015), which refers to a pre-industrial baseline. To account for this difference, we subtract an additional 180 $GtCO_2$ from all carbon budgets, which is based on an assumed additional warming of 0.1°C and the relative differences in warming levels under the 50th and 67th percentiles from Table B-1 and is consistent with Meinshausen et al. (2018). This results in the budgets in Table B-5.

Table B-5: Global carbon dioxide budgets from 2013 for the relevant scenarios in this report, adjusted to a pre-industrial baseline

Scenario	Temperature outcome and probability	Global budget (CO_2 only; from 2013)	Justification
Step Change	<2°C (67%)	750 Gt CO_2	Subtract 180 Gt from budgets in Table B-4 representing warming that already occurred from pre-industrial times until 1850-1900.
Hydrogen Superpower	1.5°C (50%)	500 Gt CO_2	
Strong Electrification			

Up to this point, carbon budgets apply to carbon dioxide only. For accurate comparison with our modelling outcomes, greenhouse gases other than carbon dioxide (for example nitrous oxide and methane) must be considered. We take an approach by Meinshausen (2019) that adjusts the carbon budget based on the relationship between cumulative carbon dioxide and cumulative (total) GHG emissions across scenarios from the IPCC Special Report on 1.5C scenario database, applying an uncertainty factor of ±100 $GtCO_2$-e (Figure B-1). The linear equation in Figure B-1 is applied to reach the final global carbon budgets (actually total GHG budgets) in Table B-6.

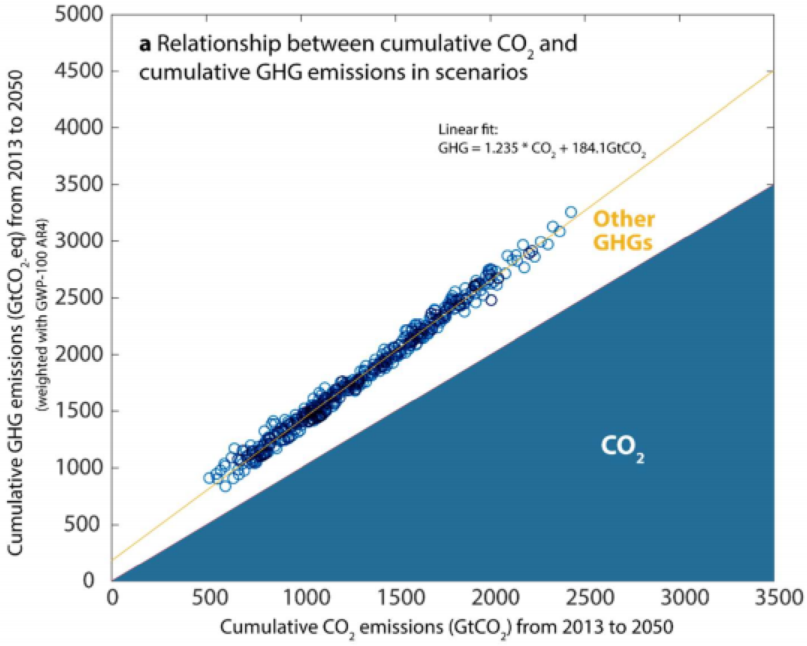


Figure B-1: Relationship between cumulative CO_2 and cumulative GHG emissions in 1.5°C scenarios. Used to convert a CO_2-only budget to a total GHG budget in units of CO_2-equivalent (from Meinshausen et al. 2018)

Table B-6: Global carbon budgets (applicable to all GHG emissions) from 2013 for the relevant scenarios in this report

<table>
<tr><th>Scenario</th><th>Temperature outcome and probability</th><th>Global budget (All GHGs; from 2013)</th><th>Justification</th></tr>
<tr><td>Step Change</td><td><2°C (67%)</td><td>1,110 Gt CO_2-e</td><td rowspan="3">Adjust budgets in Table B-5 using the linear fit $1.235 \times CO_2 + 184.1$
(From Figure B-1)</td></tr>
<tr><td>Hydrogen Superpower</td><td rowspan="2">1.5°C (50%)</td><td rowspan="2">802 Gt CO_2-e</td></tr>
<tr><td>Strong Electrification</td></tr>
</table>

There are a number of methods that can be used to determine Australia's 'fair share' of the global carbon budget based on different 'burden-sharing' approaches. Our chosen approach aligns to that used by the Garnaut Review (2008), adopted by the Climate Change Authority (2014) and validated by Meinshausen et al. (2018) that takes Australia's fair share to be 0.97% of the global carbon budget. Applying this percentage results in carbon budgets for Australia (from 2013) shown in Table B-7.

Table B-7: Australian carbon budgets (applicable to all GHG emissions) from 2013 for the relevant scenarios in this report

<table>
<tr><th>Scenario</th><th>Temperature outcome and probability</th><th>Australian budget (All GHGs; from 2013)</th><th>Justification</th></tr>
<tr><td>Step Change</td><td><2°C (67%)</td><td>10.770 Gt CO_2-e</td><td rowspan="3">Take 0.97% of the budgets in Table B-6, representing Australia’s ‘fair share’.</td></tr>
<tr><td>Hydrogen Superpower</td><td rowspan="2">1.5°C (50%)</td><td rowspan="2">7.776 Gt CO_2-e</td></tr>
<tr><td>Strong Electrification</td></tr>
</table>

Finally, to produce carbon budgets relevant to modelling outcomes, it is necessary to adjust the budget to begin from 2021. This is achieved by subtracting Australia’s emissions from 2013-2020 (4.239 Gt CO_2-e) to reach final national budgets from 2021-2050, in Table B-8. Sub-national carbon budgets (including for NEM-connected states) are not specifically considered. However, the cumulative emissions outcome for NEM-connected states can be considered an indication of the portion of this budget that those states could feasibly be constrained to in a given scenario.

Table B-8: Australian carbon budgets (applicable to all GHG emissions) from 2013 for the relevant scenarios in this report. These are the final budgets used to verify these scenarios against their targeted temperature outcomes

<table>
<tr><th>Scenario</th><th>Temperature outcome and probability</th><th>Australian budget (All GHGs; from 2021)</th><th>Justification</th></tr>
<tr><td>Step Change</td><td><2°C (67%)</td><td>6.531 Gt CO_2-e</td><td rowspan="3">Subtract 4.239 from the budgets in Table B-7, representing actual emissions from 2013-2020.</td></tr>
<tr><td>Hydrogen Superpower</td><td rowspan="2">1.5°C (50%)</td><td rowspan="2">3.537 Gt CO_2-e</td></tr>
<tr><td>Strong Electrification</td></tr>
</table>

Shortened forms

Abbreviation	Meaning
ABS	Australian Bureau of Statistics
ACCU	Australian Carbon Credit Unit
AE	Alkaline Electrolysis
AEMO	Australian Energy Market Operator
ANZSIC	Australian and New Zealand Standard Industrial Classification
AusTIMES	Australian TIMES
BEV	Battery Electric Vehicle
BTL	Biomass to Liquids
CCA	Climate Change Authority
CCGT	Combined Cycle Gas Turbine
CCS	Carbon Capture and Storage
CO_2-e	Carbon-dioxide equivalent
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CWA	ClimateWorks Australia
DER	Distributed energy resources
DISER	Department of Industry, Science, Energy and Resources
DoEE	Department of the Environment and Energy
DRI	Direct Reduced Iron
DSP	Demand Side Participation
EAF	Electric Arc Furnace
EE	Energy Efficiency
EFOM	Energy Flow Optimization Model
ERF	Emissions Reduction Fund
ETSAP	Energy Technology Systems Analysis Project
EV	Electric Vehicle
GDP	Gross Domestic Product
GHG	Greenhouse gas
GJ	Gigajoule
GSP	Gross State Product
Gt	Gigatonne
GVA	Gross Value Added
ICE	Internal Combustion Engine
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
ISP	Integrated System Plan
kW	Kilowatt

kWh	Kilowatt hour
LGC	Large-scale Generation Certificates
LRET	Large-scale Renewable Energy Target
LUTO	Land Use Trade-Offs
MARKAL	MARKet ALlocation
Mha	Million hectares
Mt	Million tonnes
MW	Megawatt
MWh	Megawatt hour
NDC	Nationally Determined Contribution
NEM	National Electricity Market
OCE	Office of the Chief Economist
PV	Photovoltaic
QRET	Queensland Renewable Energy Target
RCP	Representative Concentration Pathway
RET	Renewable Energy Target
REZ	Renewable Energy Zone
SGSC	Smart Grid Smart Cities
SMR	Steam Methane Reforming
SSP	Shared Socioeconomic Pathway
STC	Small-scale Technology Certificates
TIMES	The Integrated MARKAL-EFOM System
TRET	Tasmania Renewable Energy Target
UNFCCC	United Nations Framework Convention on Climate Change
VEEC	Victorian Energy Efficiency Certificate
VPP	Virtual Power Plant
VRE	Variable Renewable Energy
VRET	Victorian Renewable Energy Target

References

ATAP 2016. Australian Transport Assessment and Planning Guidelines: PV2 Road Parameter Values, Produced for the Department of Infrastructure and Regional Development, August, https://atap.gov.au/parameter-values/road-transport/files/pv2_road_parameter_values.pdf [accessed 14 September 2018].

Australian Bureau of Statistics 2020a. *Motor Vehicle Census, Australia, 31 Jan 2020, Catalogue No. 9309.0*. Australian Bureau of Statistics, Canberra.

Australian Bureau of Statistics 2020b. Survey of Motor Vehicle Use, Australia, 12 months ended 30 June 2020, Catalogue No. 9208.0. Australian Bureau of Statistics, Canberra.

Australian Energy Market Operator 2020, *AEMO virtual power plant demonstration: Knowledge sharing report #1*, AEMO.

Australian Energy Market Operator 2020, *2020 Inputs and Assumptions Workbook*, https://aemo.com.au/-/media/files/electricity/nem/planning_and_forecasting/inputs-assumptions-methodologies/2020/2020-inputs-and-assumptions-workbook-dec20.xlsx?la=en [accessed 21 March 2021]

Bureau of Infrastructure, Transport and Regional Economics 2019. Australian Infrastructure Statistics Yearbook 2019. Bureau of Infrastructure, Transport and Regional Economics, https://www.bitre.gov.au/sites/default/files/documents/BITRE_2019_YEARBOOK.pdf [accessed 21 March 2021]

Butler, C, Denis-Ryan, A, Graham, P, Kelly, R, Reedman, L, Stewart, I, Yankos, T 2020. *Decarbonisation Futures: Solutions, Actions and Benchmarks for a Net Zero Emissions Australia: Technical Report*. ClimateWorks Australia: Melbourne, https://www.climateworksaustralia.org/resource/decarbonisation-futures-solutions-actions-and-benchmarks-for-a-net-zero-emissions-australia/ [accessed 30 April 2020]

Campey, T, Bruce, S, Yankos, T, Hayward, J.A, Graham, P.W, Reedman, L.J, Brinsmead, T.S, and Deverell, J 2017. *Low Emissions Technology Roadmap*, Report No. EP167885, June, https://www.csiro.au/en/Do-business/Futures/Reports/Low-Emissions-Technology-Roadmap [accessed 21 March 2021]

Clean Energy Regulator 2018. Postcode data for small-scale installations. Clean Energy Regulator, updated periodically, http://www.cleanenergyregulator.gov.au/RET/Forms-and-resources/Postcode-data-for-small-scale-installations#historical-data [accessed 6 September 2018]

Climate Change Authority 2014. *Reducing Australia's Greenhouse Gas Emissions - Targets and Progress Review Final Report*, https://www.climatechangeauthority.gov.au/sites/default/files/2020-06/Target-Progress-Review/Targets%20and%20Progress%20Review%20Final%20Report.pdf [accessed 19 March 2021]

ClimateWorks Australia 2013. *Industrial Energy Efficiency Data Analysis Project: Executive Summary*, ClimateWorks Australia, https://www.climateworksaustralia.org/wp-content/uploads/2019/10/climateworks_dret_ieeda_factsheet_summary_20130521.pdf [accessed 21 March 2021]

ClimateWorks Australia, ANU, CSIRO and CoPS 2014. *Pathways to Deep Decarbonisation in 2050: How Australia can prosper in a low carbon world: Technical report*, ClimateWorks Australia, https://www.climateworksaustralia.org/wp-content/uploads/2014/09/climateworks_pdd2050_technicalreport_20140923-1.pdf [accessed 21 March 2021]

ClimateWorks Australia 2016. *Low Carbon. High Performance: Modelling Assumptions*, ClimateWorks Australia prepared for the Australian Sustainable Built Environment Council, https://www.asbec.asn.au/wordpress//wp-content/uploads/2016/05/160509-ClimateWorks-Low-Carbon-High-Performance-Modelling-Assumptions.pdf [accessed 21 March 2021]

Deloitte 2019. *Australian and Global Hydrogen Demand Growth Scenario Analysis*, Deloitte prepared for the COAG Energy Council National Hydrogen Strategy Taskforce, https://www2.deloitte.com/content/dam/Deloitte/au/Documents/future-of-cities/deloitte-au-australian-global-hydrogen-demand-growth-scenario-analysis-091219.pdf [accessed 23 March 2021]

Department of Industry, Science, Energy & Resources (DISER) 2020a. *Australia's emissions projections 2020*, December, https://www.industry.gov.au/data-and-publications/australias-emissions-projections-2020 [accessed 11 June 2021].

Department of Industry, Science, Energy & Resources (DISER) 2020b. *Australian Energy Update 2020*, October, https://www.energy.gov.au/publications/australian-energy-update-2020 [accessed 12 July 2021].

Department of Industry, Science, Energy & Resources (DISER) 2021. *International Climate Change Commitments*, https://www.industry.gov.au/policies-and-initiatives/australias-climate-change-strategies/international-climate-change-commitments [accessed 18 July 2021].

Department of the Environment and Energy 2017. *National Greenhouse Accounts Factors: Australia's National Greenhouse Accounts*. Department of the Environment and Energy, July, http://www.environment.gov.au/system/files/resources/5a169bfb-f417-4b00-9b70-6ba328ea8671/files/national-greenhouse-accounts-factors-july-2017.pdf [accessed 6 September 2018].

Department of the Environment and Energy 2019. *National Greenhouse Gas Inventory – Paris Agreement Inventory*, https://ageis.climatechange.gov.au/ [accessed 12 July 2021].

Department of the Environment, Land, Water and Planning (DELWP) 2017, *Climate Change Act 2017*, https://www.climatechange.vic.gov.au/legislation/climate-change-act-2017 [accessed 15 June 2021].

EIA 2020. *Assumptions to the Annual Energy Outlook: Liquid Fuels Module*. US Department of Energy, Washington DC.

EnergyConsult 2015. *Residential Energy Baseline Study: Australia*. Prepared for the Department of Industry and Science, August, https://www.energyrating.gov.au/sites/default/files/2020-06/report-residential-baseline-study-for-australia-2000-2030.pdf [accessed 21 March 2021]

Fendt 2017, *Fendt e100 Vario: The battery-powered compact tractor*, press release, https://www.fendt.com/int/fendt-e100-vario [accessed 11 June 2021]

Fishbone L and Abilock H 1981. 'MARKAL, a linear-programming model for energy systems analysis: Technical description of the BNL version.' *International Journal of Energy Research* 5 (4), 353-375.

Garnaut, R 2008. *The Garnaut Climate Change Review*, Cambridge University Press, accessed 18 March 2021, <http://www.garnautreview.org.au/2008-review.html>.

Graham, P 2021. Small-scale Solar and Battery Projections 2021, May, https://aemo.com.au/-/media/files/electricity/nem/planning_and_forecasting/inputs-assumptions-methodologies/2021/csiro-der-forecast-report.pdf?la=en [accessed 16 June 2021]

Graham, P, Hayward, J, Foster, J and Havas, L 2020. *GenCost 2020-21: consultation draft,* CSIRO, Australia.

Graham, P and Havas, L 2021. *Assumptions Report: Electric Vehicle Projections*, CSIRO, Australia.

Greening L and Bataille C (2009) Bottom-up Models of Energy: Across the Spectrum, in: Evans, J., Hunt, L.C. (eds), International Handbook on the Economics of Energy. Edward Elgar, Aldershot UK, pp. 257-284.

Hoffman K and Jorgenson D 1977. 'Economic and technological models for evaluation of energy policy.' *Bell Journal of Economics* 8 (2), 444-466.

International Energy Agency (IEA) 2020. World Energy Outlook 2020. International Energy Agency: Paris.

International Energy Agency (IEA) 2021. Net Zero by 2050: A Roadmap for the Global Energy Sector.

IPCC 2018. *Special report: Global Warming of 1.5° C*. <https://www.ipcc.ch/sr15/>

Manne A 1976. 'ETA: a model for energy technology assessment.' *Bell Journal of Economics* 7 (2), 379-406.

Meinshausen, M 2019. *Deriving a global 2013-2050 emission budget to stay below 1.5°C based on the IPCC special report on 1.5°C*, <https://www.climatechange.vic.gov.au/__data/assets/pdf_file/0018/421704/Deriving-a-1.5C-emissions-budget-for-Victoria.pdf>. [accessed 18 March 2021]

Meinshausen, M, Robiou Du Pont, Y and Talberg, A. 2018*, Greenhouse Gas Emissions Budgets for Victoria*, Briefing Paper for the Independent Expert Panel on Interim Targets, <https://www.climatechange.vic.gov.au/__data/assets/pdf_file/0016/421702/Greenhouse-Gas-Emissions-Budgets-for-Victoria.pdf>. [accessed 12 May 2021]

National Farmers Union 2019. *Electric tractors – your views revealed*, https://www.nfuonline.com/cross-sector/farm-business/energy-and-renewables/energy-and-renewables-news/electric-tractors-your-views-revealed/ [accessed 11 June 2021].

Pitt & Sherry 2012. Baseline Energy Consumption and Greenhouse Gas Emissions In Commercial Buildings in Australia, https://www.energy.gov.au/publications/baseline-energy-consumption-and-greenhouse-gas-emissions-commercial-buildings-australia [accessed 20 July 2021].

RACQ 2018. Private Vehicle Expenses 2018: The Costs of Owning a Car, Royal Automobile Club of Queensland, July, https://www.racq.com.au/cars-and-driving/cars/owning-and-maintaining-a-car/car-running-costs [accessed 14 September 2018]

Rogeli, J, Shindell, D, Jiang, K, Fifita, S, Forster, P, Ginzburg, V, Handa, C, Khesgi, H, Kobayashi, S, Kriegler, E, Mundaca, L, Seferian, R and Vilarino, MV 2018: Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development. In: *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty,* https://www.ipcc.ch/site/assets/uploads/sites/2/2019/05/SR15_Chapter2_Low_Res.pdf [accessed 10 June 2021]

UNFCCC 2015, Paris Agreement, https://unfccc.int/sites/default/files/english_paris_agreement.pdf [accessed 21 May 2021]

White, M 2016, *John Deere goes greener with new all-electric tractor*, https://www.aginnovators.org.au/news/john-deere-goes-greener-new-all-electric-tractor [accessed 11 June 2021]

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