Australia's National
Science Agency

Pathways to Net Zero Emissions – An Australian Perspective on Rapid Decarbonisation

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Foreword

Australia has made a commitment to get to net zero by 2050 – a goal requiring the effort of every single Australian. Eyes are on the business sector to accelerate its efforts and lead the way for the rest of the country. How to move faster to deliver a cleaner, sustainable and strong economy is the question on every business leader's mind.

CSIRO's new report *Pathways to Net Zero Emissions – An Australian Perspective on Rapid Decarbonisation* could not be more timely. Now is the time to take a comprehensive look at the opportunities, risks and challenges associated with decarbonisation, and outline achievable, low emissions paths for each sector to drive greater decarbonisation ambition and action.

This unique report, funded by the Commonwealth Bank of Australia, takes the International Energy Agency's authoritative work on the technology, energy and investment needed to limit global warming to 1.5 degrees as a starting point and applies it to our uniquely Australian context – across key sectors of our economy, including electricity, building, transport, steel, aluminium, and cement.

The transformation required in our energy system is key, and one of the biggest shifts we will see in our lifetimes. The way forward is not going to be simple or easy. Dragging our feet will almost certainly result in more costly decarbonisation, increased risk of assets becoming stranded or impaired, greater sovereign risk, and the overall long-term competitiveness of our economy being severely hampered.

While the warning is serious, the report has an underlying message of optimism. There is a lot to gain on the path to net zero. It builds on the findings of CSIRO's Australian National Outlook report, which showed it's possible to get to net zero, while achieving economic growth.

There are immense opportunities to grow new and existing industries, and to provide essential goods and services for decarbonising other economies. These pathways will help Australian industry, financial institutions and governments shape the transition to net zero – guiding investment to mitigate climate change, seizing new opportunities and creating jobs in emerging industries.

We at CSIRO hope these pathways will help foster the insight, collaboration and optimism required for the business community to keep moving towards action – toward a productive and sustainable net zero future.

Peter Mayfield

Executive Director – Environment, Energy and Resources

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Acknowledgments

The work presented in this report has been funded by the Commonwealth Bank of Australia (CBA). The work has benefited from input from a wide range of sector expertise within CSIRO, the CBA, industry feedback and the input of several anonymous reviewers. The views expressed in this report are those of the authors' and do not necessarily represent the views of the CBA or other stakeholders consulted throughout this work.

Executive summary

Limiting global average warming to 1.5-degrees Celsius (1.5°C) by 2100 necessitates a rapid transformation of global economic and social systems that will leave no country unaffected. For Australia, the need to become more resilient to the physical impacts of climate change is accompanied by the opportunity to grow new and existing industries to provide essential goods and services for decarbonising economies.

The International Energy Agency (IEA) provides authoritative global analysis of technological, energy and investment needs for 1.5°C, but the IEA does not identify Australia's decarbonisation separately in its model. This analysis develops two potential future scenarios explicitly contextualised to an Australian setting:

- CSIRO Rapid Decarbonisation (**CRD**), based on a rapid but plausible decarbonisation pathway to net zero for Australia aligned with the IEA's NZE global 1.5°C carbon budget.
- CSIRO Stated Policies (**CSP**), based on stated policies internationally and within Australia, which projects a 2.6°C temperature increase by 2100.

These scenarios are developed to translate the IEA's widely referenced global scenarios (Net Zero Emissions by 2050 (NZE) and Stated Policies Scenario (STEPS)) (International Energy Agency, 2021) to an Australian context. Scenarios project a lowest cost transition required to remain below a given emissions budget, not a forecast of the most likely transition. Scenarios draw on reported emissions for Australia through 2020 and model the period 2021-2050. These scenarios aim to help Australian industry, financial institutions and governments facilitate the transition to net zero emissions by 2050. Consistent with the IEA's approach, we do not model the impacts of chronic or acute physical risks of climate change which are already emerging and grow substantially into the future (Garnaut 2008).

The opportunity presented by the transition to a low carbon economy is immense and lagging behind international decarbonisation would be a competitive disadvantage for Australia. Australia is increasingly exposed to regulatory risk, as exemplified by the proposed European Carbon Border Adjustment Mechanism (CBAM) (European Commission, 2021). Beyond mandatory schemes, markets and consumers are increasingly focused on value chain emissions and decarbonisation. The ability to produce goods and services at a lower carbon intensity than our international peers increasingly present a competitive advantage. Most critically, failing to decarbonise now will only make the inevitable task more challenging. The gap between Nationally Determined Contributions (NDCs) and the Paris Agreement temperature goals implies that further pressure for countries to strengthen their decarbonisation policy and investments is inevitable. Previous work by the Network for Greening the Financial System (NGFS) and CSIRO (NGFS, 2021; Whitten et al., 2022) shows clearly that delaying the transition will require faster and more costly decarbonisation, impair or strand assets, increase sovereign risk, and subsequently impact Australia's longer-term competitiveness.

With these considerations in mind, this report focuses primarily on the Australia-specific Net Zero Emissions scenario – CRD. Key findings from the CRD scenario are:

1. **Australia can use existing technologies to reduce emissions by 52% from 2020 levels by 2030. This requires net emissions to decline from 512 Mt CO_2-eq in 2020 to less than 246 Mt CO_2-eq in 2030.** Decarbonisation of the electricity sector, switching to low-carbon fuels, shifting demand, energy and material efficiency, reducing land clearing and promoting offsets such as tree growth all contribute to this path (Figure 1). Emissions fall most rapidly in the electricity sector, declining by 83% from 174 Mt CO_2-eq in 2020 to 29 Mt CO_2-eq in 2030, followed by the mining and transport sectors (Figure 1). Transition of the electricity sector to low emissions drives wider decarbonisation through electrification in the mining sector, and later across all sectors, enabling emission reductions even as production activity grows overall. Negative emissions due to land-based sequestration also increase to 76 Mt CO_2-eq per year by 2030. By contrast manufacturing (including heavy industry) and agricultural emissions only decline gradually, with agricultural emissions intensity reductions of 54% complicated by 80% growth in output by 2050.

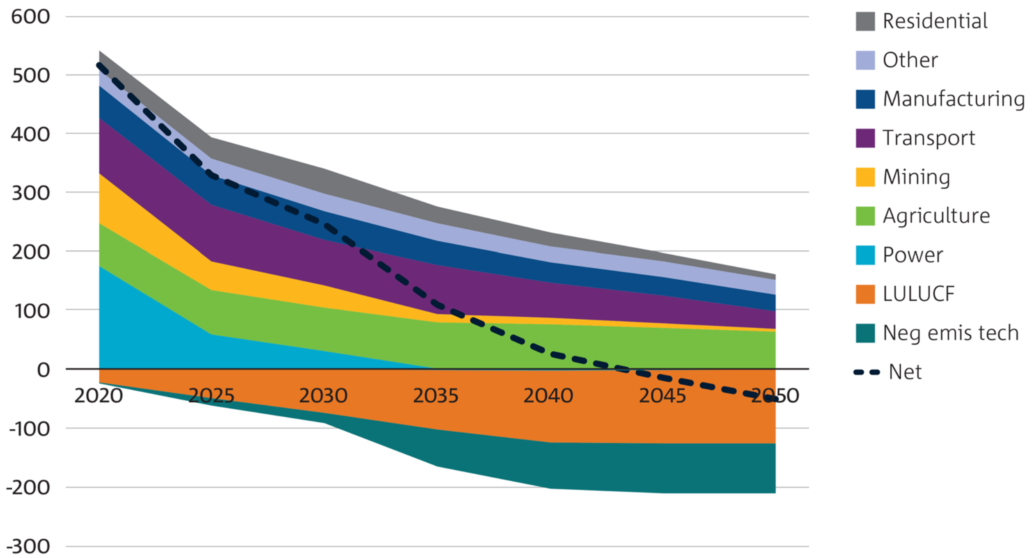

Figure 1 Australian gross emissions by sector in the CRD scenario

Note: Results shown for sectors individually identified in GTEM (commercial buildings not identified separately in GTEM).

2. **Electricity decarbonisation is the largest source of near-term abatement.** Total generation capacity increases substantially (Figure 2) alongside the share of national electricity consumption that is met by renewable sources tripling by 2030 (DCCEEW, 2022b). By 2030, solar photovoltaic (solar PV) and wind is projected to account for three quarters, or 94 TWh and 131 TWh respectively, of the nation's electricity generation. Short duration low-capacity storage (such as batteries) increases more than fivefold (to over 11 GW) and long duration high-capacity storage (pumped hydro) almost doubles. Fossil fuel use in the electricity sector falls from over 70% of total generation today to less than 10% by 2030 and is almost eliminated by 2040 except for gas peaking plants. Electricity decarbonisation drives down

emissions from energy use in housing and commercial buildings, mining (including mineral processing), and later in transport.

NEM POWER CAPACITY INSTALLATION BY TECHNOLOGIES IN THE CRD

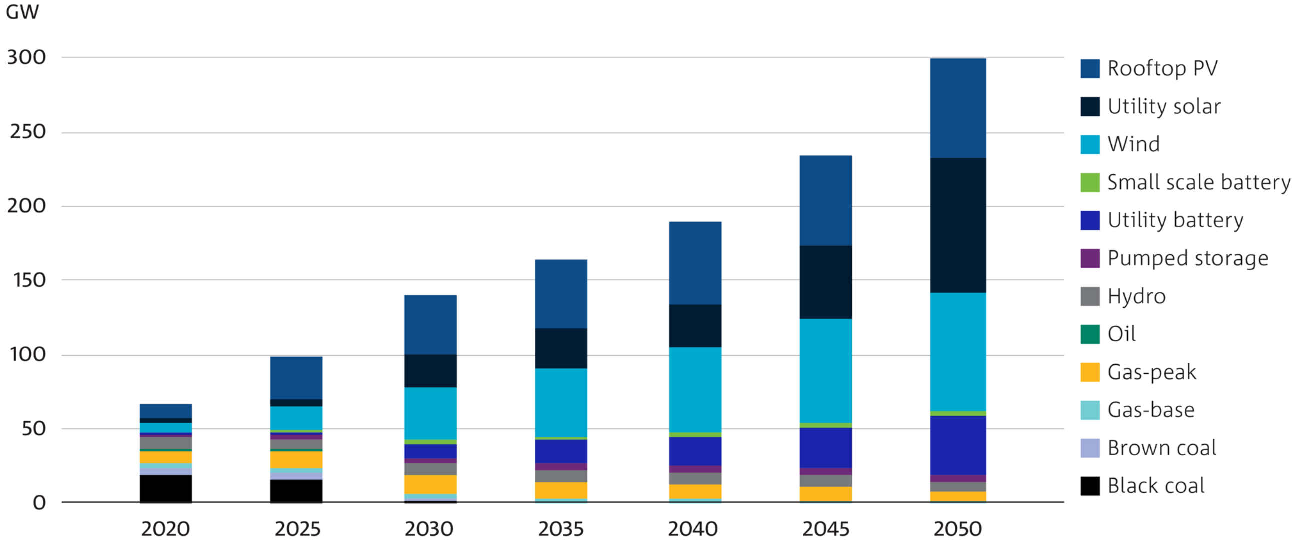

Figure 2 Electricity capacity installations by technology type for the CRD scenario

Source: AusTIMES

3. **The land and agriculture sector and new technologies will need to produce net negative emissions to support Australia's decarbonisation path. Total negative emissions grow to about 200 Mt CO_2 per year by 2040.** A reduction in land clearing, emerging solutions for reducing emissions from livestock, and sequestration in vegetation and soils all form part of the agricultural sector's decarbonisation pathway. The Agriculture, Forestry and Other Land Use (AFOLU) sector is a net emissions' sink by 2030 through avoiding land clearing and increasing sequestration in vegetation and soils. However, the agricultural sector remains a substantial emitter given the contribution of difficult-to-abate livestock in particular (Figure 1). Biological sequestration is projected to deliver 129 Mt CO_2 a year of negative emissions by 2050. Negative emissions technologies are projected to deliver a further 66 Mt CO_2 from non-specific direct air carbon capture and storage technologies (DACCS) and 18 Mt CO_2 from bioenergy with carbon capture and storage (BECCS).
4. **Residential and commercial building direct and energy emissions fall to less than 3 Mt per annum by 2050.** Half of all reductions in building emissions result from decarbonisation of the electricity sector. Improvements in heating and cooling efficiency achieved through new and rebuilt stock as well as some retrofitting account for around 25% of residential and 40% of commercial building improvements respectively. Fuel switching from gas to electricity and improved device efficiency make up the remaining improvements. All new houses are built and operated at high efficiency standards (including appliances) meaning sector emissions fall even while building stock grows by more than 50%.
5. **Transport decarbonisation requires different solutions for each transport mode.** Technologies in early stages of adoption in Australia need to become mainstream by the 2030s. Over the period to 2050, emissions from Australia's transport sectors reduce toward

zero. This occurs primarily due to electrification of the light vehicle fleet as adoption of electric vehicles (EVs) increases from less than 2% of Australian car sales to more than 55% by 2030. Decarbonisation of long distance and heavy transport accelerates through 2030-2040. As much as 56% of long-haul road transport is electrified by 2050 and the remainder uses low- or zero-emissions hydrogen. Shipping begins to decarbonise in the 2040s as hydrogen carriers and advanced biofuels become commercialised. Similarly, air transport begins to decarbonise with a move towards the use of biofuels.

6. **Beyond 2030, technologies currently in early development stages need to be in widespread commercial use to reach net zero emissions by 2050.** In 2050, one-third of emissions reductions come from technologies that are currently in early demonstration or prototype phases. Key among these technologies is low- or zero-emissions hydrogen and carbon capture, utilisation and storage (CCUS), and new feedstocks and catalysts, which are necessary to address hard-to-abate activities in manufacturing and transport. Domestic applications for green hydrogen spur production growth that reaches 200 PJ in 2050.
7. **Hard-to-abate industry sectors grow but can reduce their emissions intensity if early-stage technologies are commercialised at scale.** Continuing population growth in Australia, along with increasing demand for renewable energy generation and storage, drive the need for more infrastructure. This necessitates an increase in cement production of 27% by 2050 while emissions from the sector fall by 82% by 2050, with decarbonisation accelerating in the late 2030s. Iron ore follows a similar path with production increasing by 73% and emissions falling to almost zero by 2050 through electrification exploiting renewables. Even with direct reduction and electric arc furnaces, green hydrogen forms part of the steel industry’s critical path to decarbonisation, and carbon capture and storage (CCS) can assist with the decarbonisation of aluminium, cement, and steel. Investment in research, pilots and demonstration projects will play a critical part in enabling these technologies to be commercialised at scale.
8. **Fossil fuel exports decline significantly but Australia’s total mining exports by volume and value are projected to increase.** The implications are significant for Australia’s export markets. Australian coal production is projected to fall by 20% by 2030 and then more dramatically by 80% through 2050, with almost all remaining production being for metallurgical coal. Oil and gas production initially grows slightly through 2030 (by around 5% more than current levels) before falling by half and two-thirds, respectively, by 2050.

   However, non-fossil fuel mining continues to grow significantly. Production of iron ore increases by 73% from 2019 levels, and mining of other commodities grows by over 40%. In addition, increasing demand for solar PV and batteries drives demand for processed minerals such as rare earths, lithium, and cobalt. This presents a major economic opportunity for the Australian mining sector. It also means that decarbonising mining becomes even more important. It will be vital for significant innovation and investment to be made in low emissions mining across extraction, processing, and transport.
9. **Industrial decarbonisation will need nuanced policy support.** While the modelling results project a relatively smooth transition, other signals indicate this may not occur. Companies in hard-to-abate sectors will be relying on CCS, hydrogen, or offsets to prolong their longevity in a

low carbon future. A slower transition away from fossil fuels will necessitate greater decarbonisation from other sectors making an already challenging net zero outcome more difficult to achieve. These factors contribute to a risk that retirement of existing assets may occur faster than their low emissions replacements can be delivered. Nuanced policy design and regulation, and investment in new industries and technologies are key elements to supporting a smooth transition.

10. **Significant ongoing investment is needed, both in early-stage technologies and well-established infrastructure.** The modelling projects an additional $AU76 billion will need to be spent over the period 2020 to 2050 on electricity infrastructure across renewable energy, energy storage, and national to local transmission (Figure 3) including replacing our aging fossil fuel generation capacity. This excludes investment in developing complementary technologies, such as green hydrogen production, CCUS, and sustainable biofuels, which will all need investment at each point of research, development and commercialisation. De-risking this scale of investment suggests government investment policy may need to include a focus on removing barriers to private sector investment and facilitating innovative finance models to reduce or spread risk.

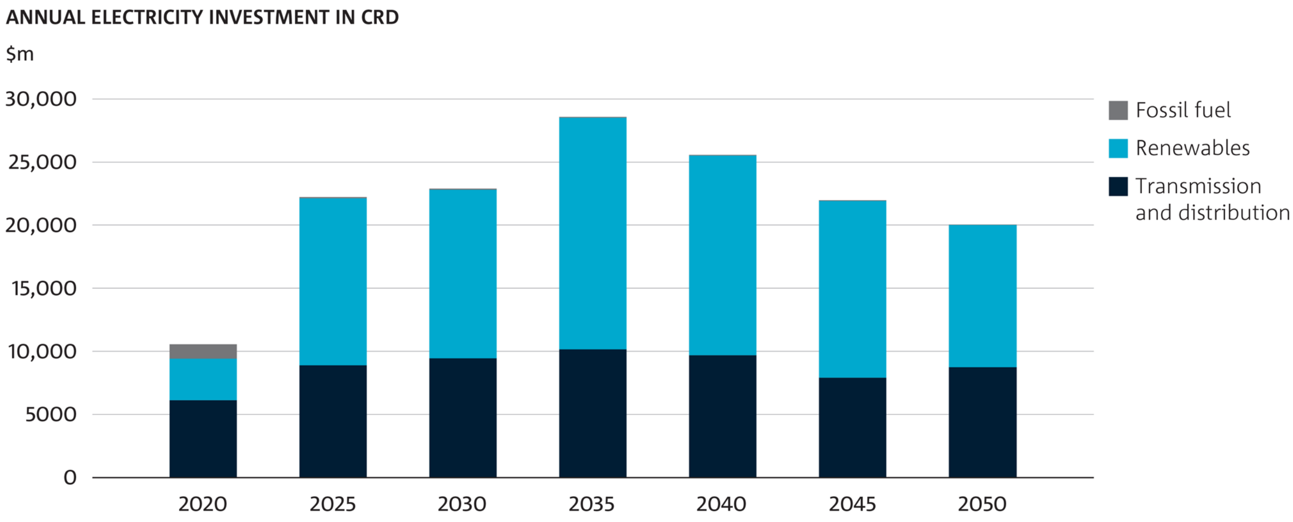

Figure 3 Annual electricity investment in the CRD scenario

Source: KPMG-EE

Modelling basis, sector engagement, and the CBA and CSIRO partnership

This work draws on IEA energy and sectoral pathways at the global level by incorporating these into CSIRO's Global Trade and Environment Model (GTEM). Two further models (KPMG's Energy and Environment model (KPMG-EE) and CSIRO and ClimateWorks' Australian TIMES (AusTIMES) model) were used to develop detailed technology pathways across energy, transport, buildings, steel, aluminium and cement. Australia's emissions (CO_2 plus non-CO_2) budget for the period reflects (i) the response by Australian sectors to the global CO_2 and non-CO_2 carbon prices, and (ii) assumptions regarding LULUCF (land use, land-use change and forestry) emissions and carbon removal technologies. Feedback on the detailed sector-by-sector pathways was obtained through consultation with a range of industry experts to assist in calibrating to the Australian context. A detailed agriculture sector pathway is planned for the future. Modelling has been completed by CSIRO as an independent subject matter expert and primary authors of this report.

This work has been funded by the Commonwealth Bank of Australia (CBA) to contribute to our collective understanding of potential decarbonisation pathways for Australia, consistent with limiting global warming to 1.5°C above pre-industrial levels. In addition to providing funding for this work, CBA facilitated stakeholder consultation and reviewed the utility of this information for private sector target setting. We thank participants from the Electricity, Buildings, Transport, Iron and Steel, Aluminium and Cement sectors for their input.

The views expressed in this report are those of the authors' and do not necessarily represent the views of the CBA or other stakeholders consulted throughout this work.

Part I Introductory context

1 Introduction

1.1. Climate change and the imperative of addressing it

Greater action on climate change mitigation and adaptation will be essential in this decade to avoid lock-in and path dependency. Scientific consensus indicates that the path to achieve 1.5°C by 2100 (with no or low overshoot) is becoming increasingly challenging. The UN Environment Program Emissions Gap Report 2022 (UNEP, 2022) illustrates that not only are country pledges insufficient to achieve a 1.5°C path, but that action is lagging pledges and global emissions are yet to peak. The UNFCCC Global Stocktake reinforces that current NDCs are vastly insufficient and, if ambition is not increased (UNFCCC, 2022), very little of the global budget will remain beyond 2030 to achieve a 1.5°C or less than 2°C pathway.

A delayed transition will increase the risk of severe physical climate impacts. If emissions continue in line with the IEA 2021 STEPS scenario, the world can expect an increase in average global temperatures of around 2.6°C by 2100 (International Energy Agency, 2021). This will be experienced through accelerating and intensifying impacts from chronic (slow onset) and acute (extreme) physical risks (see box below: Impacts of climate change in Australia).

Impacts of global climate change in Australia

If countries' current emission reduction pledges are fulfilled, global temperatures are expected to be between 2.6°C and 2.9°C warmer than historic averages by 2100.[1] Global warming of this extent will result in accelerating and intensifying physical impacts in Australia (Australian Academy of Science, 2021). These include:

- Frequency of Summer temperature highs above 35°C more than doubling for Melbourne, Sydney and Brisbane and becoming the norm year-round in Darwin.
- Extreme fire days likely to double in number leading to a 30% increase in bushfire risk.
- Oceans will be far more acidic and absorb less oxygen. Even at 1.5-2°C warming, the complete loss of coral across the Great Barrier Reef is very likely.
- Up to a quarter of a million properties are at risk of coastal flooding due to sea level rise of 1m by 2100 as 1 in 100-year coastal flooding events become annual.
- Peak annual rainfall events could increase by 40% even as water availability is likely to decrease due to reduced total rainfall and higher water loss through evaporation and plant use.

Recent trends support these future projections, with an increase in the frequency and severity of major bushfires and flooding experienced in the past 20 years.

[1] IEA World Energy Outlook 2021 and https://climateactiontracker.org/global/temperatures/

In this scenario some climate impacts would be irreversible over human timescales even if emissions were to reach net zero or net negative in the latter half of the century. This includes sea levels, which would be permanently about 1m higher by 2100. Biodiversity loss in certain areas will also not recover.

1.2. Implications of addressing climate change for Australia

The case for achieving the Paris Agreement goals and limiting physical climate impacts is clear. An accelerated transition to net zero (Figure 4) is needed along with a decoupling of emissions from economic activity. This will require a transformation of global economic and social systems which will leave no country unaffected. In Australia we are in the middle of rapid transformative change in the electricity sector, and other sectors will inevitably need to follow. This transformation is necessary for future climate liveability. The longer it takes for global economies to decarbonise the more challenging, costly and disorderly the transition will be (NGFS, 2022).

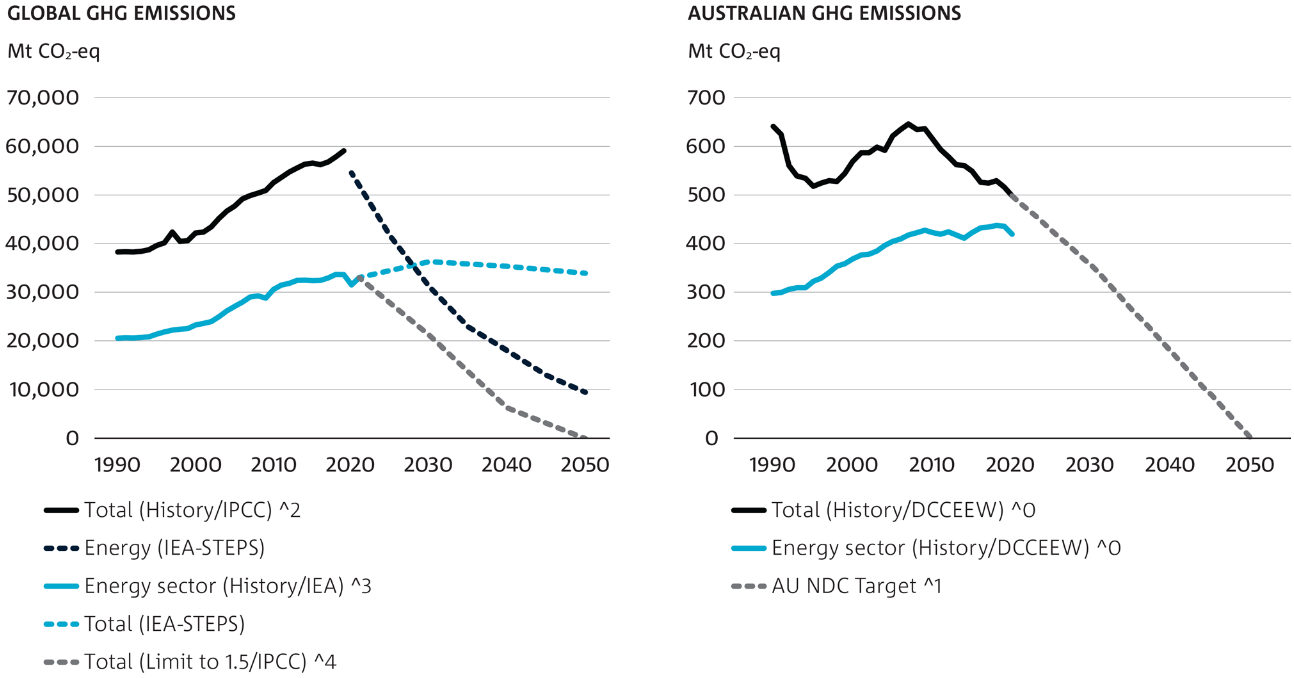

Figure 4 Total and energy sector breakdown of global and Australian greenhouse gas emissions since 1990

Note: The above figure represents total and energy-sector breakdown of global and Australian greenhouse gas emissions since 1990; and reduction pathways for the global emissions from the IEA NZE and STEPS scenarios. The linear pathways for Australian emissions reductions are based on the Australian Nationally Determined Contribution and a pathway to net zero by 2050 rather than consistency with a global 1.5˚C emissions budget. Energy sector includes all sources of energy across stationary energy such as electricity and heating, transport and fugitive emissions from fuel).

Source: ^0 Paris Agreement inventory_31-10-2022_14-54-30 in DEE (2020);[2] ^1 DISER (2022b); ^2 Lamb, W.F. (2022); ^3 Global energy-related CO_2 emissions in the Stated Policies, Sustainable Development and Net Zero scenarios, 1990-2050, IEA, Paris;[3] ^4 Kriegler et al. (2022).

[2] https://www.greenhouseaccounts.climatechange.gov.au/

[3] https://www.iea.org/data-and-statistics/charts/global-energy-related-co2-emissions-in-the-stated-policies-sustainable-development-and-net-zero-scenarios-1990-2050. IEA. License: CC BY 4.0

Australia's role in the value chain will influence its decarbonisation path. Australia is highly exposed to global trade and our emissions-intensive exports are vulnerable to the transition plans of global economies. However, this is coupled with new opportunities to provide essential goods and services for decarbonising economies such as critical minerals and green hydrogen. Our ability to capitalise on these opportunities, and the green premium they attract, will be enhanced by our ability to produce and transport them at low to zero emissions intensity. Failing to do so is likely to create competitive disadvantage via, carbon border adjustments policies, discounted pricing, and increased dependence on offsets. In addition, the scale of offsets required to support the global transition (3.2 Gt per annum by 2050 in the CRD scenario) means they are likely to become more expensive over time as cheaper options are exhausted. Both biological and technical sequestration solutions will have a role to play in addressing hard-to-abate emissions sources. However, given the inevitable need to move beyond net zero to net negative, it is imperative that offsets don't become a substitute for decarbonisation action.

A mix of considered policy architecture (incentives and regulations), technological advancement, and public and private investment will be required to drive Australia to net zero. The CRD modelling in this report estimates an increase of $AU76 billion in investment over CSP across renewables, transmission and other technology in the electricity sector will be required from now to 2050 to drive the transition. Australia's policy settings are evolving: the federal government legislated a target to reduce emissions by 43% by 2030 from a 2005 baseline (DISER, 2022b),[4] and changes to the Safeguard Mechanism have been implemented along with other supporting policies.[5] Australia's indicative 2030 national target (354 Mt CO_2-eq) still falls short of the average global emissions reduction needed by 2030 as do the announced pledges for most countries (International Energy Agency, 2021b). That is, the Intergovernmental Panel on Climate Change (IPCC) indicates that global CO_2 emissions need to decline by 43% from 2019 levels by 2030 for a likely chance of limiting global warming to 1.5°C with no or limited overshoot.[6] Advanced economies are widely expected to decarbonise more rapidly than developing economies in the IEA modelling (International Energy Agency, 2021b). Australia's 43% reduction on 2005 emissions NDC target translates to a 32% reduction on 2020. Figure 5 compares the 2030 NDC and IPCC 1.5°C targets with our modelling. Our Australian emissions outcome at 2030 (245 Mt CO_2-eq) is more stringent than both the NDC and global average IPCC 1.5°C targets and represents a 52% reduction by 2030 relative to 2020.[7]

[4] https://www.aph.gov.au/Parliamentary_Business/Bills_Legislation/Bills_Search_Results/Result?bId=r6885

[5] https://consult.dcceew.gov.au/safeguard-mechanism-reform-consultation

[6] https://www.ipcc.ch/sr15/chapter/spm/ - Emissions Pathways and System Transition Consistent with 1.5°C

[7] For reference a 52% emissions reduction on 2020 emissions equates to 61% on 2005 emissions as a point target (DISER, 2022b).

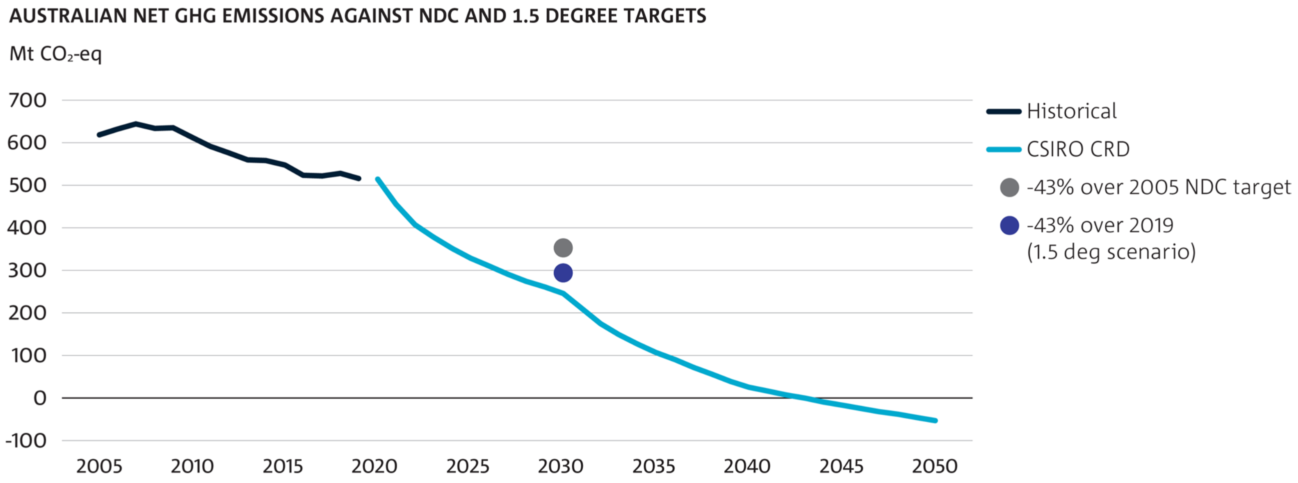

Figure 5 Comparison of the CRD path for Australian GHG emissions and the stated Nationally Determined Contribution (NDC) target

Source: Historical data sourced from DCCEEW;[8] The NDC target can be found in Australia's Nationally Determined Contribution: Communication 2022 (DISER, 2022b). The -43% over 2019 (1.5 deg scenario) is sourced from IPCC (2022).

1.3. Overview of modelling approach and alignment with IEA scenarios

The modelling framework applied in this work is designed to tailor the IEA's Net Zero Emissions (NZE) and Stated Policies Scenario (STEPS) to an Australian context in order to explore the implications for the Australian economy and sectors. The IEA's scenarios were tailored to create, respectively, the CSIRO Rapid Decarbonisation (CRD) and CSIRO Stated Policies (CSP) scenarios. While two scenarios were modelled, this report focuses primarily on the results of the CRD scenario with the intent to outline achievable, low emissions paths for each sector to drive greater decarbonisation ambition and action. In common with the IEA approach, we do not model the impacts of chronic or acute physical risks of climate change on productivity (labour and other factors of production), damage to physical infrastructure and health effects (Figure 6). These effects are already beginning to be experienced across the world but are expected to be much larger beyond the 2050 end of the modelled period. This is an area that will require increased attention in the future to identify the full range of benefits from rapid decarbonisation to be compared against the costs.

The approach nests three levels of models from global to sectoral to derive contextualised Australian outputs:

- CSIRO's Global Trade and Environment Model (GTEM), a computable general equilibrium (CGE) model, is used to model the global macroeconomic impacts in each scenario and explores how they influence Australia through globalisation and trade.
- KPMG's Energy and Environment model (KPMG-EE), a CGE model calibrated to Australia's industry sectors and current account balance, applies the global implications to Australia and provides insights into impacts on specific economic sectors.

[8] https://www.greenhouseaccounts.climatechange.gov.au/

- CSIRO and ClimateWorks' Australian TIMES model (AusTIMES, Reedman et al., 2018) provides a representation of the national energy sector based on least cost energy, emissions and technology pathways and complements the sectoral view provided by KPMG-EE.

Physical risks and costs of a warming climate

Chronic
Changing ambient climate conditions

Acute
Extreme weather events

Transition risks and costs along a net zero pathway

Policy and regulatory changes

Technological innovation

Social adaptation and consumer preferences

Liability risks

Stakeholder litigation

Regulatory enforcement

Legal liability

Direct damage to assets or property, health etc.

Not included:
- Productivity / health impacts
- Property damage
- Lower asset values
- Defaults on loans
- Increased insurance claims

Adjustment to a low-carbon economy

Included: Impacts on pricing, demand, energy, labour and trade; stranded assets

Not included: Supply chain disruption, defaults by businesses and households

Not considering or responding to climate change impacts

Not included:
- Business disruption resulting from litigation
- Penalties resulting from regulatory enforcement or litigation

Notes: Impacts will increase beyond 2050 with costs larger the slower the transition to net zero.

Notes: Delayed (net zero beyond 2050) or disorderly transition will incur additional transition costs not included in model.

Notes: A disorderly, delayed transition likely to impose higher liability risks than an orderly transition.

Figure 6 Which climate change risks and costs are included in this model?

Source: Adapted from Figure 2, Prudential Practice Guide: CPG 229 Climate Change Financial Risks, 2021, APRA.[9, 10]

Figure 58 in Appendix A provides an overview of the interrelationship between the International Energy Agency's (2021b) World Energy Outlook 2021 data and results and the modelling approach applied in this study. In this study we use the IEA results to constrain a global integrated assessment model (GTEM) to generate global trade and investment flows and a shadow carbon price. GTEM outputs together with Australia-specific technology and macroeconomic settings are then used to generate downscaled sectoral growth paths for the Australian economy. Finally, these sectoral growth paths, along with trade and carbon prices are implemented in the AusTIMES model to identify sectoral emission paths and technology transitions. Feedback on the transition trajectories from industry and domain experts were used to adjust these to ensure that they represent plausible future paths towards net zero in each sector. The KPMG-EE energy intensity paths were adjusted based on the initial AusTIMES results and then re-run in AusTIMES to produce consistent results across the two models.

[9] https://www.apra.gov.au/climate-change-financial-risks) and NGFS Climate Scenarios for Central Banks and Supervisors, June 2021

[10] https://www.ngfs.net/sites/default/files/medias/documents/ngfs_climate_scenarios_phase2_june2021.pdf

Key points of difference between this report's CRD scenario and the International Energy Agency's (2021b) World Energy Outlook 2021 include:

- The decarbonisation of the electricity sector in Australia is calibrated to the Australian Energy Market Operators' (AEMO) Progressive Change and Strong Electrification Scenarios, which are specifically calibrated to Australia's asset mix and projected lifespan. In particular, each of the coal generation capacity and gas generation capacity results from AEMO's Integrated System Plan (ISP) scenarios in each of the four largest states (Qld, NSW, Vic, WA) were imposed as minimum capacity requirements in the corresponding CRD or CSP scenarios. Furthermore, the generation capacity factors of onshore wind turbines for each year in the AusTIMES model were scaled to approximately match the average (post-curtailment) generation capacity factors implied by the capacity and generation results from the ISP scenarios.
- The decarbonisation of Australia's transport sector is calibrated to the current fleet structure and projected retirement dates and also reflects policy differences such as emission standards and incentives to purchase electric vehicles prevalent across many advanced economies.
- Building stock and carbon trajectories are specific to our understanding of the residential and commercial building stock in Australia in CRD, which in particular reflect a differing climatic environment and mix of heating and air conditioning needs relative to similar economies in the IEA modelling.
- Detailed industry calibration for steel, aluminium and cement reflects the Australian asset mix.
- There are also a range of areas where the GTEM and KPMG-EE models provide more detail on the Australian economy including sectoral resolution (such as the large mining sector in Australia), current account balance, and the role of transport given the large distances between population centres in Australia.

These assumptions contribute to differences between the outputs of this work and IEA's 2021 NZE results (validated through a comparison with IEA results see Table 1):

- Global fossil fuel consumption is projected to be higher in both 2030 and 2050, of coal consumption is slightly higher in both 2030 and 2050, than the IEA projects.
- Negative emissions technologies are higher than the IEA and consistent with IPCC and NGFS usage (International Energy Agency, 2021a; Pathak et al, 2022).[11]
- This modelling produces lower initial global carbon prices than the IEA's range for advanced economies.
- Carbon prices in 2050 are projected to be higher than IEA advanced economies range noting that these will only apply to small remaining emissions.
- The modelled budgets for CO_2 align with IEA. This work also includes non-CO_2 emissions budgets consistent with the IPCC and the current Australian carbon budget.

The Technical Supplement in Appendix A contains additional information about the method and assumptions used for this modelling. Note that this modelling builds on the International Energy Agency's (2021b) World Energy Outlook 2021 rather than the more recently available World Energy Outlook 2022 (International Energy Agency, 2022) because of the lead time required to develop and validate the models. The key differences across the two models result from the disruption to world energy markets due to Russia's invasion of the Ukraine. The consequence of this disruption sees an increase in current (2022) fossil fuel demand in the World Energy Outlook 2022 (International Energy Agency, 2022), which is anticipated to moderate over time. This shift would make the achievement of net zero by 2050 under the 2022 analysis slightly more difficult than under the 2021 analysis. Furthermore, the IEA identifies that the bulk of energy investment continues to be in green energy – supporting the transition to net zero.

[11] NGFS Climate scenarios Data Set (3.4) [Data set]

Table 1 Comparison of CRD metrics to IEA and other benchmarks

Category	Output	Units	Period	Region	CSIRO	Benchmark	Source	Difference relative to benchmark (%)
Emissions and policy	CO_2 budget	Gt CO_2	2020 – 2050	Global	500	500	IEA	0%
	Non-CO_2 budget	Gt CO_2-eq	2020 – 2050	Global	326	331, 330, 323	IPCC6 WGIII REN, 1.5 5th, and 1.5 95th (Fig SPM.5)	-2%, -1%, 1%
	Emissions reductions	%	2020 – 2030	Australia	52	32	Australia NDC 2022	20%
	Real carbon price	US$2019 / ton	2030, 2050	Global	38, 345	130, 250	IEA NZE (Adv. Econ.)	-70%, 38%
Fossil fuels	Fossil fuel use	EJ	2030, 2050	Global	374, 147	338, 120	IEA (Fig 3.2)	11%, 22%
	Coal use	EJ	2030, 2050	Global	82, 19	72, 17	IEA (Fig 3.2)	13%, 12%
Power	Low-carbon (renewables + nuclear) share	% of generation	2030, 2050	Global	72, 99	75, 100	IEA (Fig 3.10)	-4%, -0.5%
	Electricity demand	TWh x 1000	2030, 2050	Global	36, 69	37, 71	IEA (Fig 3.9)	-3.0%, -2.5%

Source: IEA - Net Zero by 2050: A Roadmap for the Global Energy Sector (IEA, 2021); CCA - Reducing Australia's Greenhouse Gas Emissions – Targets and Progress Review Final Report (Climate Change Authority, 2014); IPCC6 - Sixth Assessment, Working Group III, Summary for Policy Makers Figure SPM.5 associated data (IPCC, 2022); NDC - Australia's Nationally Determined Contribution Update Communication 2022 (DISER, 2022b).

1.4. Carbon budget assumptions

The IEA scenarios form a common global reference point for many organisations and jurisdictions seeking to understand a decarbonisation path for the energy and industrial processes sectors. As a primary producing economy, Australia plays a key part in the value chains of these industries and will be influenced by the global decarbonisation path. This project seeks to demonstrate those international impacts, while also outlining achievable, low emissions paths for Australia's key economic sectors to drive greater decarbonisation ambition, action, and investment. To inform decarbonisation planning in the public and private sector, this report sets out quantitative paths for Australia's key sectors.

In translating this work to an Australian context, we have aligned our global carbon budget with the IEA's NZE scenario, which was based on a global net CO_2 budget of 500 Gt over 2020-2050. This budget comprises 460 Gt of energy and industrial process CO_2 emissions and 40 Gt of CO_2 emissions from AFOLU. The IEA 2021 NZE scenario is structured to limit the global temperature rise to 1.5°C (with a 50% likelihood and no overshoot). We also apply a non-CO_2 budget consistent with the IPCC 6th assessment report REN scenario.[12] Together these give a combined (CO_2 plus non-CO_2) emissions budget of 826 Gt CO_2-eq through 2050. We individually meet the budgets for CO_2 and non-CO_2 gases in our modelling.[13]

The global results are downscaled to Australia as follows. The global CO_2 and non-CO_2 carbon prices generated within the model apply to CO_2 and non-CO_2 emissions in Australia and other

[12] The non-CO_2 budget comprises three main non-CO_2 gas categories: CH_4, N_2O and F-gases. The non-CO_2 budget (in CO_2 equivalent terms) is 196.2 Gt CO_2-eq for CH_4, 88.4 Gt CO_2-eq for N_2O and 41.4 Gt CO_2-eq for F-gases (totalling 326 Gt CO_2-eq over 2020-2050).

[13] The CO_2 and non-CO_2 budgets are targeted via two shadow prices in GTEM; one that applies to CO_2 and another that applies to the three non-CO_2 gases.

regions once they are converted into local CO_2 and non-CO_2 prices.[14] The CO_2 and non-CO_2 prices then determine reductions in CO_2 and non-CO_2 emissions excluding any assumptions regarding LULUCF (land use, land-use change and forestry) emissions and carbon removal technologies. Using the existing literature and expert judgement we apply assumptions on the growth of LULUCF emissions (limited to -129 Mt CO_2/year by 2050)[15] and carbon removal technologies (limited to 84 Mt CO_2/year by 2050).[16] Taken together these assumptions give an Australian net emissions budget of 4.7 Gt CO_2-eq for 2020-2050.

It is helpful to place our emissions budget in the context of other work – see Table 2 for a summary. The 2014 Climate Change Authority (CCA) emissions budget was positioned at below 2°C at 6.3 Gt CO_2-eq over 2020-2050.[17] This budget is broadly consistent with Australian Net Zero Emissions projections from the Department of Industry, Science and Resources (DISER) (DISER, 2021a). The CCA's 6.3 Gt CO_2-eq budget falls within the range of estimates using the IPCC 1.5°C at 50% likelihood target with 500 Gt CO_2 remaining in 2020.[18]

Furthermore, our budget requires Australian emission reductions greater than the global average outlined by the IPCC as required for a likely chance of limiting global warming to 1.5°C with no or limited overshoot (noting the IEA scenarios suggest that advanced economies are expected to shoulder a greater emissions reduction load). This is clearly seen in Figure 10, where the Australian emissions reduction trajectory falls faster than the global 1.5°C trajectory. The CRD scenario models a 52% reduction by 2030 relative to 2020 – see Figure 5. Comparing global and Australian emissions reductions at 2050 provides a similar picture. The IPCC projects that global net CO_2-eq emissions need to fall by 86% relative to 2019; whereas the CRD projects that Australian net CO_2-eq emissions fall by 110% relative to 2020. Similarly, global net CO_2 emissions need to fall by 103% relative to 2019; in the CRD scenario Australian net CO_2 emissions fall by 143% relative to 2020. This confirms that our emissions budget is well within a 1.5°C scenario with no or limited overshoot.

[14] The global CO_2 and non-CO_2 prices are converted into regional CO_2 and non-CO_2 prices based on average consumer prices in each region.

[15] The LULUCF emissions assumptions are based on internal CSIRO modelling and are consistent with assumptions applied in Australian Government (2021).

[16] The modelling presented here assumes a more conservative role for carbon removal technologies than under the IEA's NZE 1.5°C scenario. That is, carbon removal technologies are projected to offset 5.1%, 35%, and 52.7% of Australia's gross emissions in 2030, 2040, and 2050 respectively, compared to 1.5%, 18.8% and 100% of global emissions in IEA's NZE scenario.

[17] The 2013 CCA budget was determined as 10.1 Gt CO_2-eq for the period 2013-2050. We adjust this by removing historical emissions up to 2019. This gives a budget of 6.3 Gt CO_2-eq over 2020-2050. The Australian Government's updated NDC references an indicative emissions budget for 2021-2030 corresponding to the 43% reduction on 2005 target as 4.4Gt CO_2-eq using a straight-line 2020-2030 trajectory as compared to a 3.3Gt CO_2-eq budget 2021-2030 in our modelling (DISER, 2022b).

[18] There is some debate about Australia's 'fair share' of global emissions. Various approaches have been applied to this challenge and the IPCC explicitly does not specify NDCs or define a mechanism for attributing a 'fair share'. The Australian Government describes its approach as "Achievement of Australia's 2030 and 2050 emissions reduction targets will contribute towards holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels" (DISER, 2022b).

Table 2 Comparison of Australian carbon budgets across various studies

Study	Time period	Temperature outcome	Carbon budget over 2020-2050 (all gases)
Climate Change Authority (2014)	2020-2050	<2.0°C	6.3 Gt
CRD scenario in this report	2020-2050	1.5°C	4.7 Gt
Reedman et al. (2022) Hydrogen Export scenario	2021-2050	1.5°C	3.4 Gt
ClimateWorks Australia (2020) Decarbonisation Futures (50% chance)	2020-2050	1.5°C	4.1 Gt

We also note that others have applied more restrictive carbon budgets in recent work. Notably, Reedman et al. (2022) applies an Australian emissions budget of 3.4 Gt CO_2-eq over 2021-2050 (see AU MSM22 in bottom panel of Figure 66) in multi-sector analysis of Australia achieving very high levels of electrification and hydrogen production, including a higher capacity to expand exports of “green commodities” to global consumers. Unlike this work, Reedman et al. (2022) does not apply a global integrated assessment framework, and emissions reductions in Australia occur in the absence of explicit global decarbonisation. These methodological differences mean that the Australian emission budgets are not directly comparable across reports.

This work does not seek to replicate or provide a view on business-as-usual emissions under current policy settings. Instead, it aims to illustrate a path to net zero which may need to be steered and accelerated using existing and new policy measures. Further information about the method and assumptions used is provided in section 1.3 and the Technical Supplement in Appendix A

Part II Results

2 An IEA aligned net-zero roadmap for Australia

2.1 Australia's emissions composition and profile towards net-zero

Based on the IEA's global carbon budget consistent with 1.5°C (500 Gt CO_2 and an additional 326 of non-CO_2 GHG emissions between 2020 and 2050, see section 1.4), global gross CO_2-eq emissions will need to be reduced by 27% (CO_2 by 41%) by 2030 and 66% (CO_2 by 86%) by 2050. Similarly, in Australia our CRD carbon budget implies gross CO_2-eq emissions will need to be reduced by approximately 37% (net CO_2-eq by 52%) by 2030 relative to 2020, and 71% (net CO_2-eq by 110%) by 2050. Globally and in Australia the reduction in CO_2 emissions will need to be sharper than non-CO_2 emissions given their long life in the atmosphere.[19]

The challenge of meeting these targets is illustrated in Figure 8. This figure includes current Australian Government sectoral emissions projections based on existing policy, which results in emissions reductions of 32% from a 2005 baseline by 2030 (DCCEEW, 2022a), along with the projected reduction of ~40% with additional measures currently in development or recently implemented. Australia's emissions (excluding LULUCF) grew rapidly from 1990 but have been on a downward trajectory since 2007 (Figure 8). This is primarily attributed to the extraordinary growth of renewable energy, at both grid and household scale, and the retirement of ageing coal fired power stations. However, more ambitious and systematic changes are needed by all industries to meet the targets identified. A substantial improvement in energy efficiency is projected along with fuel switching from fossil fuels to renewably generated electricity. Total electricity generated is projected to more than double in the CRD scenario (almost entirely generated from renewable sources), whilst fossil fuel usage is projected to fall by more than three quarters (Figure 9).

Reductions of existing emission sources will need to be coupled with low emissions growth of existing and new industries to meet the needs of a growing population and economy. Residual emissions will need to be offset by removals. Modelling of the CRD scenario projects that in Australia, offsets, of which 60% are nature-based removals, will exceed emissions by 33% by 2050. Australia has a high potential to draw on carbon offsets through cost-effective nature-based removals across Australia's large landmass (Figure 10).

[19] Note that all modelling baselines are 2020 because most of the statistical datasets on which the baselines rely take some time to collect, collate, review and make publicly available, leading to delays between the data currency and publication of these results. Hence, our results are calibrated to, and percentages calculated from, DISER (2021) emissions projections.

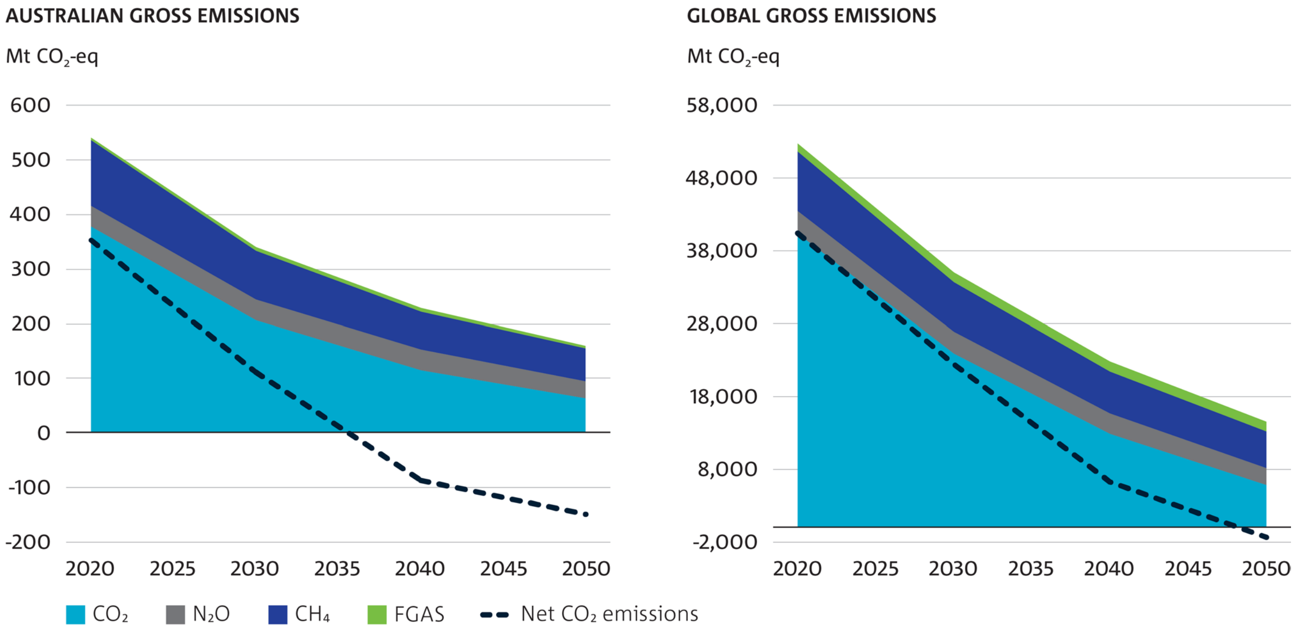

Figure 7 Australian and global gross emissions by gas and net CO_2 emissions in the CRD scenario

Source: GTEM

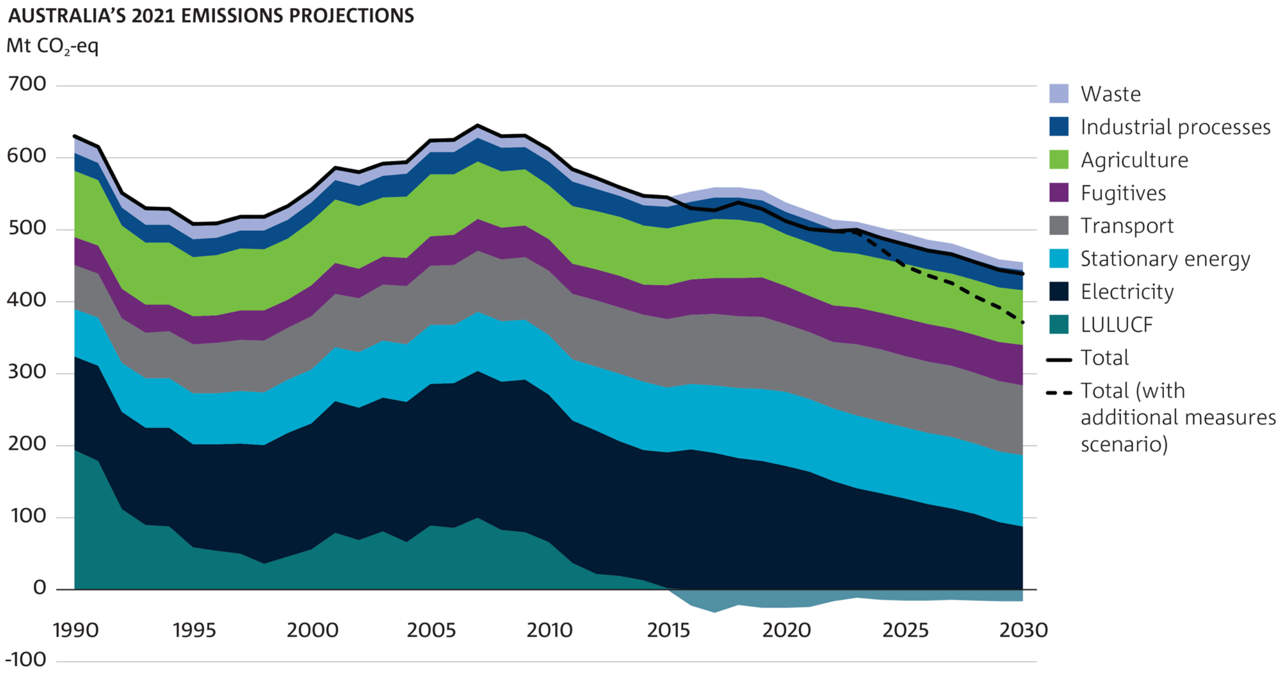

Figure 8 Australian Government GHG emissions by sector and energy carriers 1990 through 2021 and projected to 2030

Note: 2030 projected reductions are 32% on 2005 levels whilst target reductions are 43% and take into account 'with additional measures' recently implemented or in development.

Source: DCCEEW (2022a)

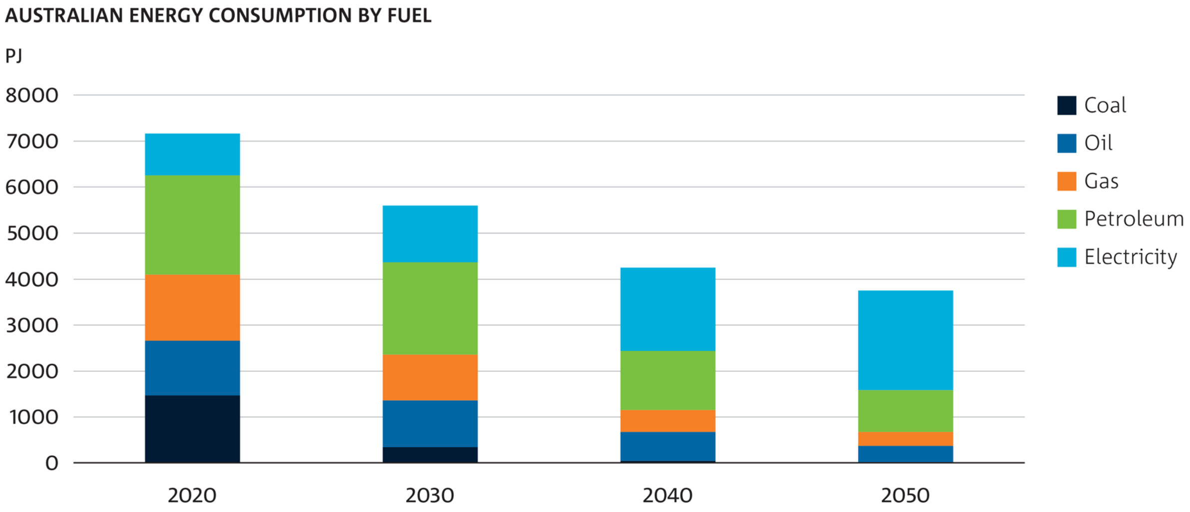

Figure 9 Australian energy consumption by fuel

Source: GTEM

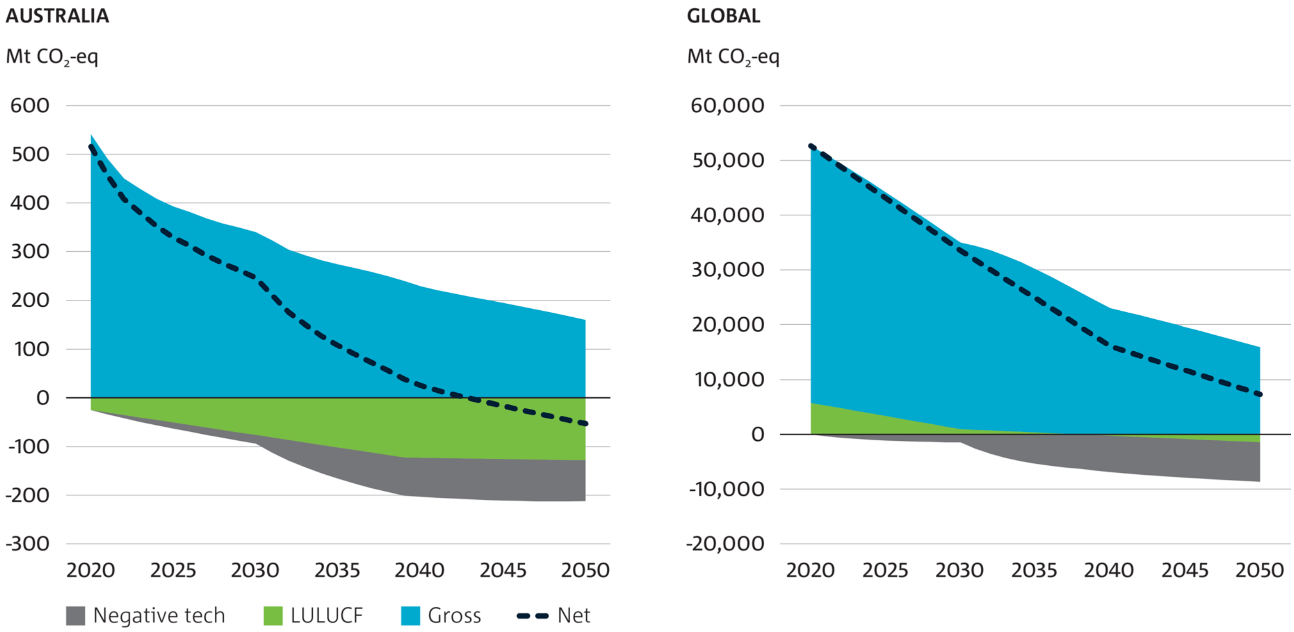

Figure 10 Australian and global net emissions by component in the CRD scenario

Source: GTEM

Comparable CRD trajectories for several major regions and large emitting nations are shown in Figure 11. There will be some sectoral and temporal variability in how decarbonisation plays out in practice, which is not reflected in the forward-looking modelling exercise (for example see Figure 8 showing variable historical data and smoother projections as an example). Exact trajectories will be influenced by policy drivers, cost, commercialisation rates, the emissions intensity of economic growth, and actions of those in the most emissions-intensive sectors. As the transition progresses, ongoing assessment of the carbon budget will continue to be a useful complement to point-in-time targets to ensure the transition is progressing at sufficient speed and scale.

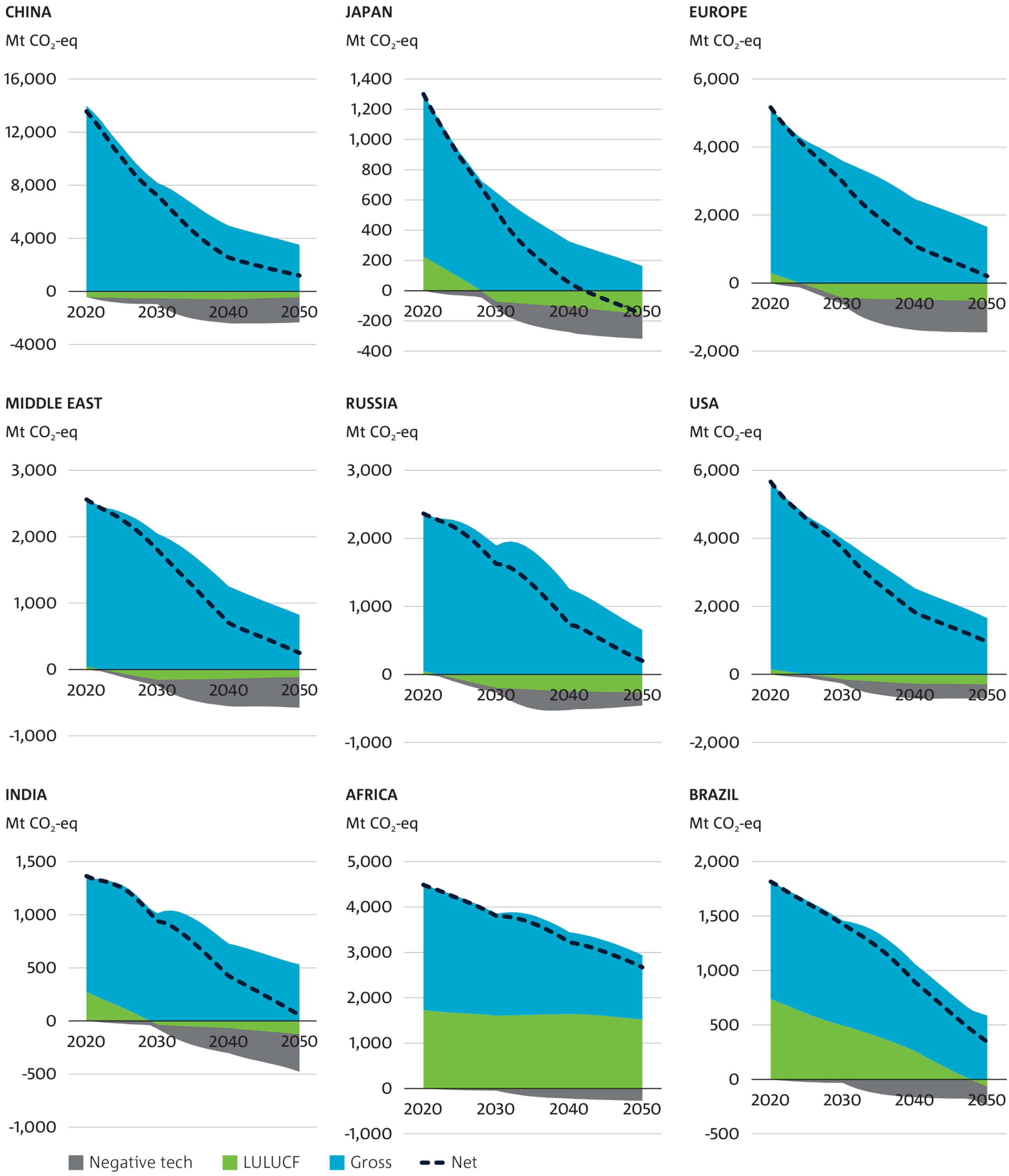

Figure 11 Regional net emissions by component in the CRD scenario

Note: Regional trajectories are based on model projections that account for carbon shadow prices required to achieve the global emissions budget and include potential for offsets and negative emissions. Hence, these paths may differ from nationally determined contributions.

Source: GTEM

2.2 Australia's sectoral emissions profile towards net zero

Analysis of sectoral emissions pathways indicates that the electricity sector has the greatest opportunity for decarbonisation in the 2020s (Figure 12). The mining sector begins to decarbonise in the mid-2020s. Investment in decarbonising the transport sector takes some time to reduce emissions, with its efficacy not apparent until around 2035. Building stock (not shown) gradually decarbonise through 2050. Initial reductions result from decarbonisation of the electricity sector and fuel switching (natural gas to low emissions electricity for space and water heating, and cooking), whilst replacement building stock impacts emissions across the modelled period. By the 2040s, hard-to-abate sources will need to be addressed. Significant investment in research, development, and commercialisation in the preceding two decades are anticipated to unlock some new technological solutions to address some hard-to-abate sources. The remaining emissions that cannot be avoided will need to be offset by either technological or biological sequestration. In the coming decades, it will also be critical for a net zero economy for new industries, growth and expansions to be designed at very low to zero emissions intensity.

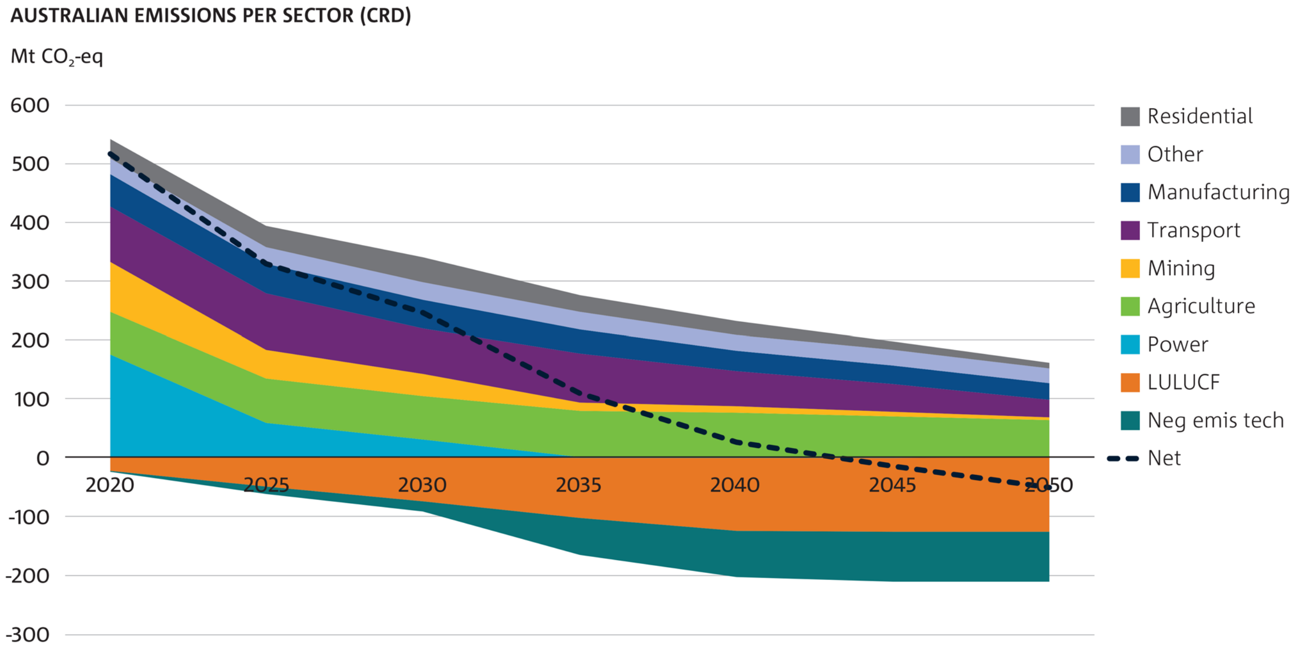

Figure 12 Australian emissions by sector in the CRD scenario

Source: GTEM

Economic shifts of this scale will require carbon emissions to incur cost, which can be delivered through a combination of a broad-based carbon price and other policy measures (the higher the price signal required the more likely both a carbon price ***and*** other policy measures will be needed).[20] Results of this modelling show the 'shadow carbon price', a proxy for the combined economic influence of any direct carbon price and complementary policy, increasing from $38/t CO_2-eq in 2030 to a high of $345/t CO_2-eq in 2050 (Figure 13). While this provides a representation of the potential cost of carbon in Australia, it is also important to recognise the influence of international policy. For example, the European Union's (EU) Carbon Border Adjustment

[20] Policies supporting emission reduction effectively incentivise industries and individuals in a similar way to a carbon price and can be considered to place a price on carbon that can be applied in scenario modelling exercises such as undertaken in this work. Carbon prices resulting from this model will differ from market prices, such as ACCUs in Australia because those prices are specific to the rules and requirements of the particular market, whereas the carbon 'shadow price' generated from the model represent average or equilibrium price effects across the entire economy.

Mechanism[21] will levy a carbon price on imports of iron, steel, cement, fertiliser, aluminium, and electricity beginning in 2023 with first payments in 2026. At current prices of EU carbon permits this would add more than AU$100/t CO_2-eq to the cost of exports. The United Kingdom (UK), Japan and Canada are also considering carbon tariffs to mitigate carbon price impacts on their local competitiveness.

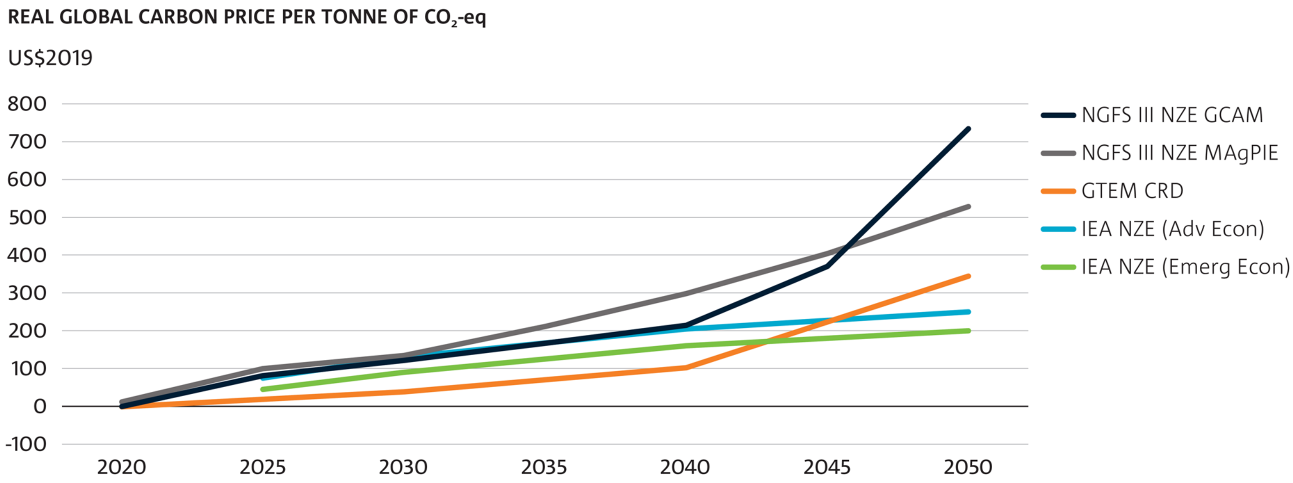

Figure 13 Comparison of the global carbon price profiles for CRD scenarios modelled by GTEM under this work with corresponding scenarios modelled within the IEA and NGFS (via their GCAM and MAgPIE approaches) $US/tonne

Source: IEA (2021a), Net Zero by 2050 (Table 2.2), IEA Paris https://www.iea.org/reports/net-zero-by-2050, License: CC BY 4.0; NGFS Climate Scenarios Data Set v3.4.[22]

Sectoral modelling focused on the high emissions sectors of the Australian economy (direct and indirect): power, buildings (residential and commercial), transport, steel (and iron ore mining), aluminium (including alumina refining and bauxite mining), and cement. These sectors produce around two thirds (66%) of Australia's emissions either directly or through consumption of energy. Detailed sectoral exploration of agriculture was excluded in this iteration. Other sectors of the Australian economy, such as services, construction, other industry including mining (other than iron ore and bauxite) and manufacturing (other than steel, aluminium and cement), water and waste, have been included holistically to understand economy-wide impacts but have not been a focus of this work.

There are several decarbonisation levers applicable across sectors. These include decarbonising electricity production, electrification, fuel switching, energy and material efficiency, reducing land clearing and promoting tree growth. Later in the modelled period CCUS and hydrogen begin to reduce hard-to-abate emissions sources. Negative emissions are assumed to come from land-based sources, and a conservative assumption has been made to constrain the role of geological and mineral storage to reflect their nascent state of development.

The following section highlights five key aspects for each sector: production and demand shifts, emissions, opportunities, risks, and implications.

[21] https://eur-lex.europa.eu/legal-content/en/TXT/?uri=CELEX:52021PC0564

[22] https://doi.org/10.5281/zenodo.7198430

Table 3 Australian emissions (Scope 1 and 2) by sector in the CRD scenario Mt CO_2-eq

Sector	2020	2030	2040	2050
Agriculture	72	75	75	62
Mining	85	37	11	5
Power	174	29	-3	-1
Transport	94	78	59	29
Manufacturing	55	48	35	29
Other	27	30	28	25
Residential	32	42	23	10
LULUCF	-25	-76	-123	-129
Negative emission technologies	0	-17	-80	-84
Net	514	246	25	-54

Source: GTEM model outputs

Notes: Sector splits in the Table above are according to International Standard Industrial Classification (ISIC). Later classifications in Section 3 use Australia and New Zealand Standard Industrial Classification (ANZSIC). Therefore, emissions calculated from GTEM and AusTIMES are not directly comparable nor do these data directly correspond to 2020 ANZSIC aligned reporting. 2020 data is targeted to the DISER (2021) reported emissions for Agriculture, Power, Transport and LULUCF. Other sectors are then derived using emissions intensity data from the GTAP data base (see Appendix A2.2). The calibration process leads to very small divergences in sectoral and overall emissions (514 vs 512 Mt) in 2021 from reported emissions.

3 Detailed IEA-aligned sectoral paths for Australia

In this section we describe downscaled sectoral paths for four high emission sectors in Australia: energy, buildings (commercial and residential), transport, and industry across steel, aluminium and cement. For these sectors and industries detailed analysis of the decarbonisation options and pathways have been undertaken considering both sector growth and technology options and tested with industry bodies where possible. Data in this section has been downscaled from the global and national modelling described above using AusTIMES and reflects the more detailed sectoral attribution available in this model. This approach exploits the greater sectoral detail for some industries in AusTIMES relative to GTEM and KPMG-EE. The difference in sectoral classification means that emissions data in AusTIMES is not always directly reconcilable with those in GTEM. Full details on the modelling process are provided in Appendix A: Technical Supplement.

3.1 Electricity

Emissions, production, and demand shifts

The electricity sector is critical to Australia's decarbonisation trajectory. Without its contribution our 2030 targets could not be achieved. To date, the decarbonisation of electricity generation has primarily been motivated by economic drivers. Over the last decade, Australia's oldest coal fired power stations have become less reliable and more costly to operate, which along with environmental concerns, has led to many operators to retire these assets before the end of their technical lives. This, coupled with the declining cost of renewable energy, has seen a substantial increase in new renewable capacity, with a continued increase in solar, wind, hydro and battery installations projected (AEMO, 2022). Cost drivers have also contributed to a strong uptake of solar PV at household level. More than one in four households now have rooftop solar PV installations.

These changes have introduced new challenges for the operation of electricity grids and markets. Security and stability risks are increasing. Solar and wind deliver intermittent supply, which is difficult to match with demand, making management of the electricity grid increasingly complex. While the uptake of renewable energy continues at pace, there is a risk that the market will not sufficiently incentivise investments in the other storage and transmission assets needed to maintain a reliable power grid at progressively deeper levels of renewable energy penetration. The ability of the complex regulatory framework to evolve appropriately to balance technical and commercial challenges along with the public good, is a key factor in the smoothness or otherwise of the transformation of the electricity system.

How these trends may play out differs across scenarios. The Australian Energy Market Operator's Integrated System Plan outlines various scenarios for grid decarbonisation (AEMO, 2022). Their scenarios have been referenced in the development of the CRD and CSP scenarios for Australia.

Figure 14 shows the CRD modelled outputs compared with AEMO's Strong Electrification scenario.[23]

In the CRD scenario, the increasing pace of electrification in transport and industry will substantially increase Australia's electricity needs as illustrated in Figure 14. Transmission and distribution requirements will rapidly increase. In contrast, CSP foresees a slower exit from coal generation capacity, with coal remaining part of the capacity mix until the mid-2040s, albeit with very low shares of generation post 2035 (see Table 5). The projected uptake of rooftop PV in the NEM in the CRD scenario is quantified in Table 4.

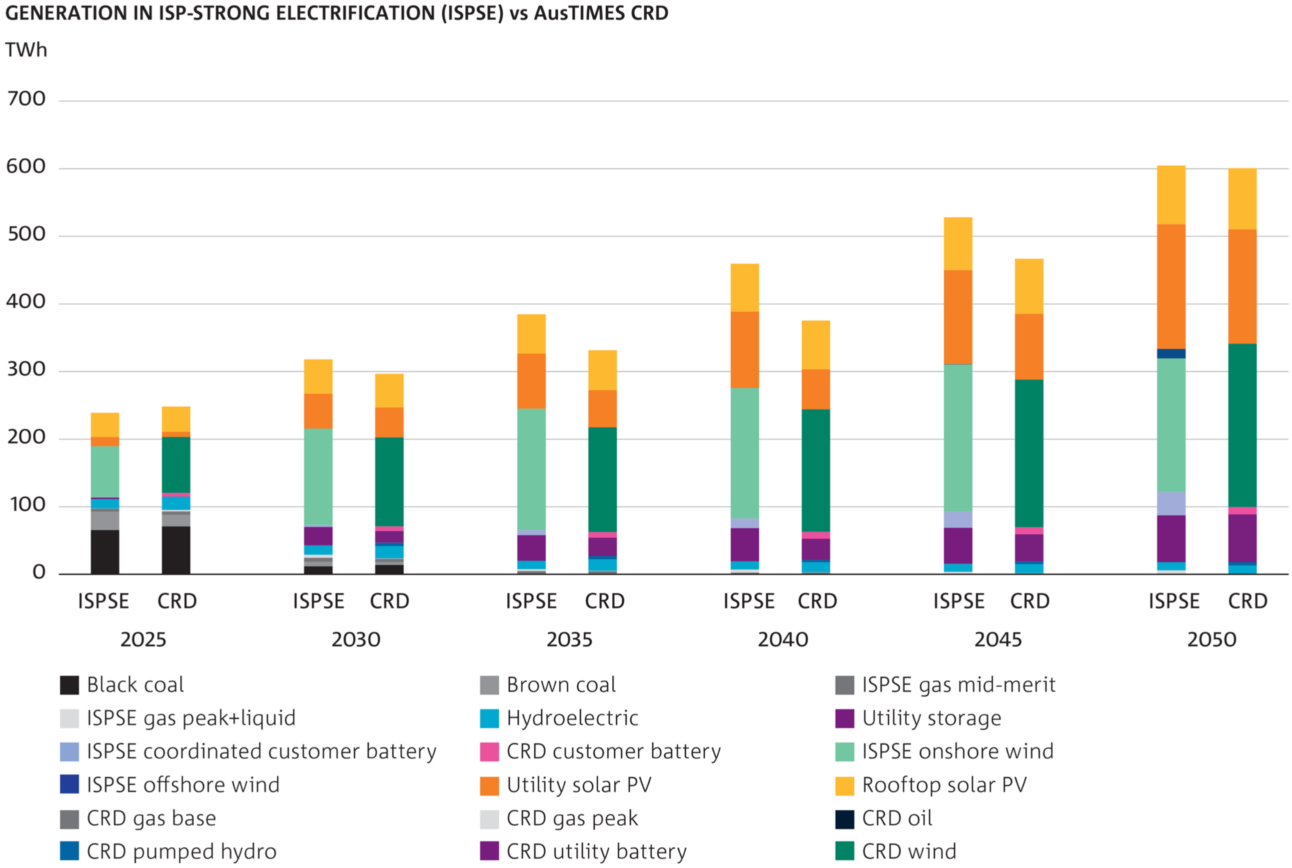

Figure 14 Generation in ISP-strong electrification vs AusTIMES CRD (TWh)

Note: Figure 14 reflects the National Electricity Market (NEM) which excludes Western Australia and the Northern Territory.

Source: AEMO (2022), AusTIMES

The CRD scenario reflects the expectation that 85% of Australia's coal fired generation capacity will need to close by 2030 (generating just 6.7% of total electricity) and the remainder will be closed by 2035. Renewable energy is projected to make up more than 90% of the power mix by 2030. To achieve this, almost all new capacity installed in the next decade would need to come from wind, solar and hydropower supported by increased storage capacity Figure 16). These

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[23] Note that the CRD and AEMO results are derived using different models and input settings. For example, sector electricity demand is derived from different models and the technology available in the models has minor differences. As such any direct comparison should be interpreted with caution.

changes will continue drive down the emissions intensity of electricity generation to zero by 2050 (Figure 15).

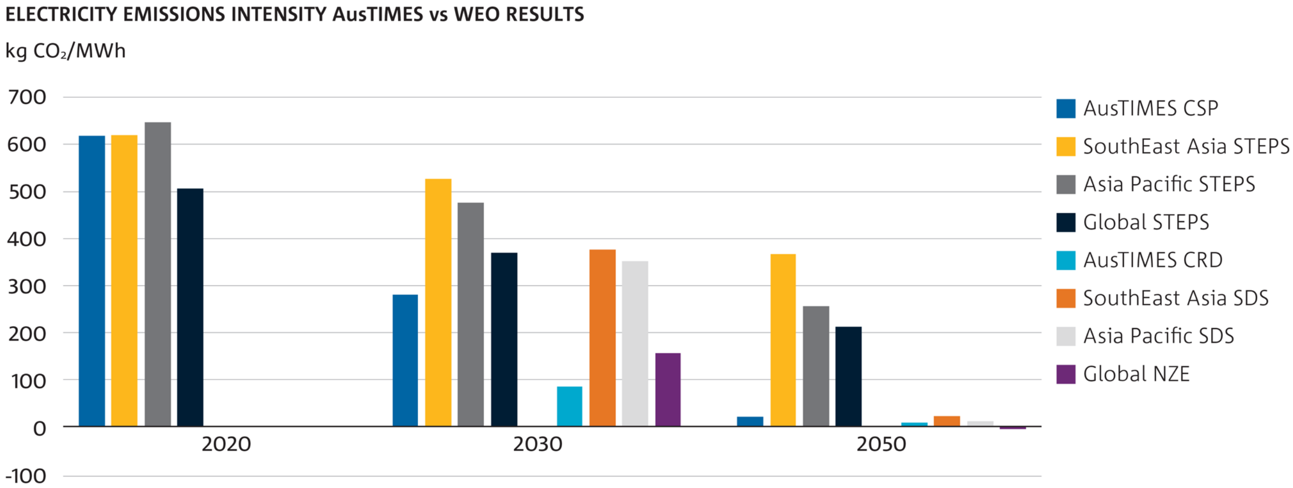

Figure 15 Electricity emission intensity for Australia in the CRD and CSP scenarios compared to South-east Asia and Asia Pacific regions

Source: AusTIMES (for Australia), IEA World Energy Outlook 2021 (for South-east Asia, Asia Pacific), IEA Net Zero by 2050 (for the World)

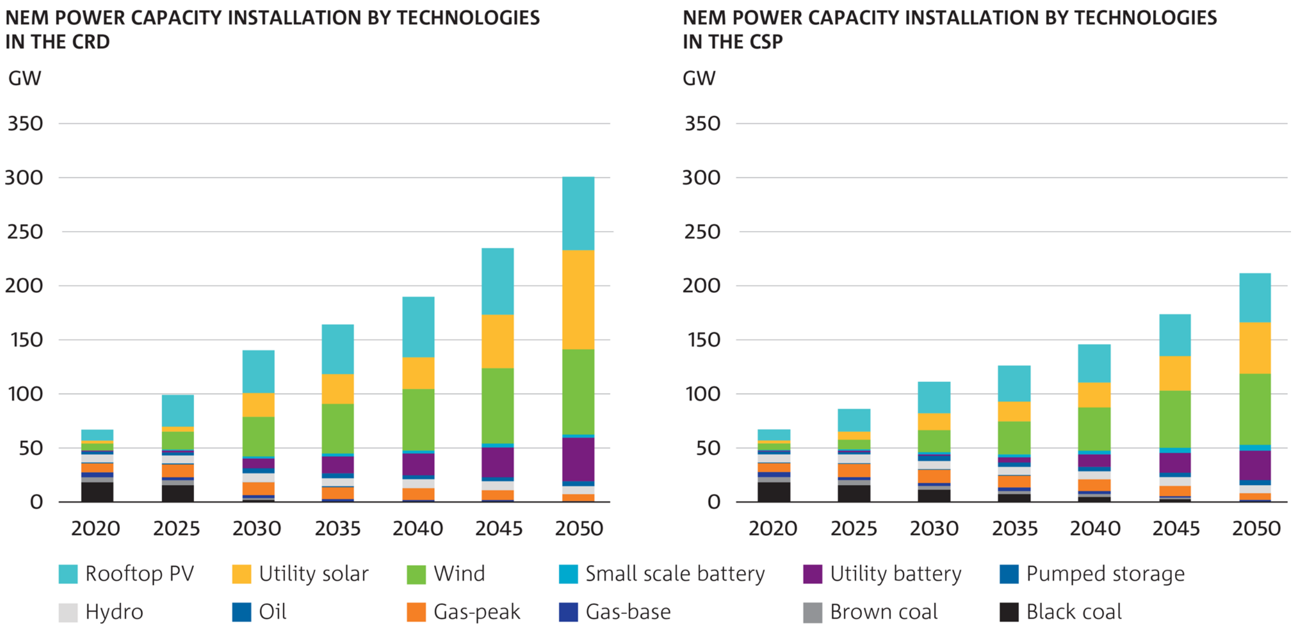

Figure 16 NEM power sector installed capacity by technology in the CRD and CSP scenarios

Note: The National Electricity Market excludes Western Australia and the Northern Territory.

Source: AusTIMES

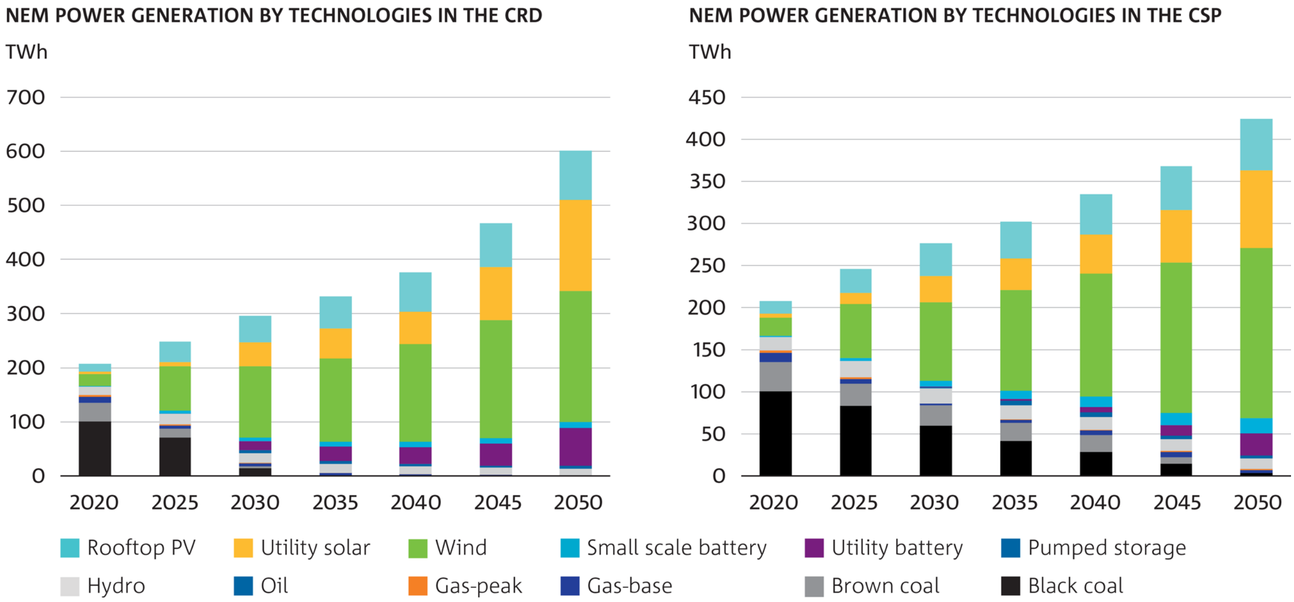

Figure 17 NEM electricity generation by technology in the CRD and CSP scenarios

Note: The National Electricity Market excludes Western Australia and the Northern Territory.

Source: AusTIMES

Opportunities, risks and challenges

Electrification, and the retirement of existing generation assets, provides continued opportunities to invest in renewable generation. Electrification also drives a need for energy efficiency without which electricity demand and consequent investment requirements will be even higher and more challenging. Lower costs, abundant renewable resources, a strong industry skills base, and commercial familiarity (particularly for solar PV and wind) contribute to making renewable energy an attractive investment as long as there is a stable and supportive regulatory regime and an ability to hedge electricity price risk. For organisations, renewable power purchase agreements can provide the additional benefits of longer-term price certainty and a decarbonised energy source. Export opportunities are also being explored directly and through use of electricity to produce hydrogen.

Investment will also be needed in the short and long duration storage needed for grid security and to firm variable renewable generation. Projects such as the Hornsdale Power Reserve[24] helped to validate the commercial benefits and prove the technical merits of grid scale batteries. The success of this project has seen increased interest in grid-scale battery storage, with an additional 1,856MW of battery storage (almost three times the existing installed capacity) committed and anticipated as at October 2022.[25] Increase interest at household level, and pilots of battery virtual power plants, may also increase deployment as costs fall. Both grid-scale and household investment are expected to support a net increase in jobs in construction and installation.

Long duration storage presents greater challenges. High capital costs, long lead times to develop, constraints on suitable locations (for technologies such as pumped hydropower), long payback and riskier cash flows make these a prohibitive investment for many actors. For projects to proceed,

[24] https://arena.gov.au/projects/hornsdale-power-reserve-upgrade/

[25] https://www.aemo.com.au/en/energy-systems/electricity/national-electricity-market-nem/nem-forecasting-and-planning/forecasting-and-planning-data/generation-information (AEMO, 2022) Accessed 10/11/2022

they may need to be significantly de-risked by public funding, such as taking first loss. Snowy Hydro 2.0 provides a current example of some of the challenges and risks faced by these projects (Snowy Hydro, 2022) whilst the Long-Term Energy Service Agreements in NSW represent one policy response.[26]

The logistical challenges of building sufficient generation assets, transmission infrastructure, and storage are also significant. Increasing pressure on strained supply chains may impact Australian ability to deploy the solutions needed on time and at sufficient scale. Increasing global demand and geographic concentration of supply could lead to scarcity, longer lead times, and low or inconsistent quality. These factors are anticipated to increase the costs of new construction whilst initiatives in other countries such as the demand and price effects of the Inflation Reduction Act, in the US further complicate investment decisions.

Growing electricity costs have been an ongoing challenge in Australia. The reverberation of the northern hemisphere energy crisis through international gas (and to a lesser extent thermal coal) markets has exacerbated already high prices. This coincided with the physical impacts of climate variability exacerbated by climate change, including recent flooding in eastern Australia, which impacted the supply and cost of coal for electricity generation. The culmination of these events resulted in an unprecedented suspension of the National Electricity Market (NEM) in June 2022. This is expected to continue to make fixed pricing, particularly for electricity retailers, increasingly complex, indicating that price challenges are far from solved.

Implications

Continued collaboration between all stakeholders (market operators, national agencies, state and federal government departments, and industry) will be important to plan for and underpin the transition. Clear and stable policy frameworks and defined geographies of focus (such as renewable energy zones) provide the signals needed by the private sector to de-risk investments and increase the scale and speed of deployment. However sufficient scale and speed will not be achieved by the private sector alone. The continued involvement of dedicated agencies is vital, including the Australian Renewable Energy Agency (ARENA)[27] to drive innovation and make early-stage investment, and the Clean Energy Finance Corporation (CEFC)[28] to support wider adoption of proven technologies. Dedicated funds, such as the Rewiring the Nation Fund, play an important role in deploying the large-scale investment required for the transition.

Energy affordability is expected to be an ongoing challenge for both businesses and households in the foreseeable future. Levers available to business include power purchase agreements and buying groups for longer term price certainty, behind the meter renewable energy generation, and battery storage as the costs decline.

The regulatory environment will also need to continue to evolve to manage technical and commercial challenges. Aspects such as demand response and orchestration of distributed energy resources will be vital to enabling greater shares of variable generation within the energy mix. In

[26] https://www.energyco.nsw.gov.au/industry/long-term-energy-service-agreements/

[27] https://arena.gov.au/

[28] https://www.cefc.com.au/

time this may provide greater opportunities for businesses and households to participate and share in the benefits of the modernised electricity grid.

ELECTRICITY SECTOR EMISSIONS INTENSITY IN THE CRD SCENARIO

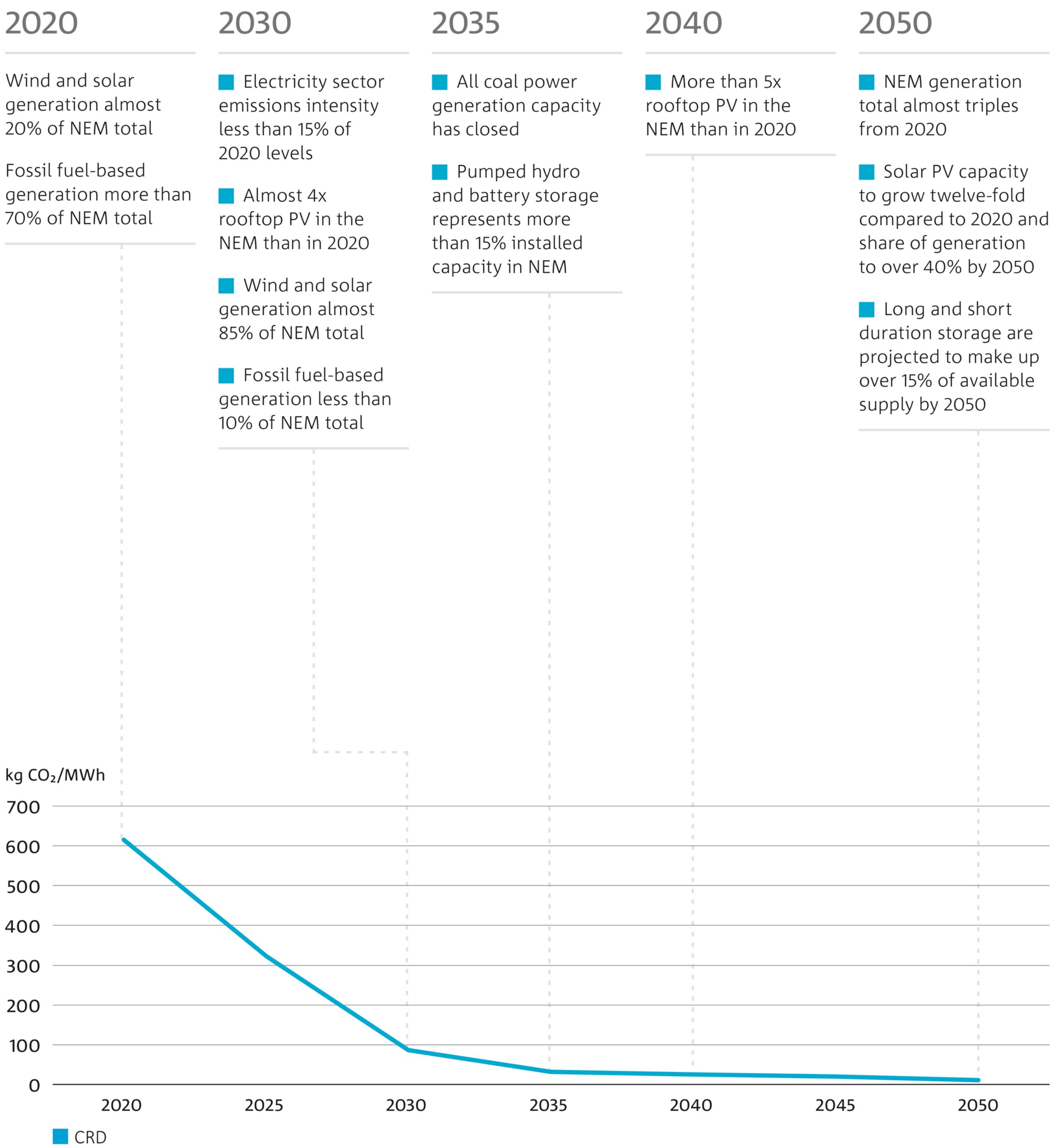

Figure 18 Summary of key transition milestones - Electricity

Table 4 Key CRD milestones for distributed PV in the NEM

	2020	2030	2040	2050
Installed capacity (GW)	10.3	39.4	55.2	67.9
Generation% (TWh)	15.4%	28.1%	29.1%	22.6%

Note: The National Electricity Market (NEM) excludes Western Australia and the Northern Territory

Source: AusTIMES model output based on Graham and Havas (2021)

Table 5 Key CRD generation milestones in the NEM by decade[29]

	2020	2030	2040	2050
Generation total (TWh)	206	267	331	514
Renewables capacity (GW)	27.2	105.5	148.8	245.0
Renewable generation share (% of TWh)	27.6%	91.1%	99.1%	99.9%
Wind and solar generation share (% of TWh)	19.8%	84.4%	94.6%	97.5%
Coal generation share (% of TWh)	65.7%	6.7%	0.0%	0.0%
Gas generation share (% of TWh)	6.6%	2.2%	0.9%	0.1%

Note: The National Electricity Market (NEM) excludes Western Australia and the Northern Territory
Source: AusTIMES

3.2 Buildings (commercial and residential)

Emissions and demand shifts

Emissions from the operation of commercial and residential buildings currently make up 95 Mt CO_2-eq of Australia's total (50 Mt residential and 45 Mt commercial).[30] Key emissions sources include gas (for water heating, space heating and cooking) and non-renewable electricity. At present, the vast majority of building emissions in Australia are indirect, from electricity, with relatively little gas heating outside of some areas in the south (primarily Melbourne). The design of the existing building stock means that many of our commercial and residential buildings are poorly built for their conditions with drafts, poor insulation, poor solar orientation and insufficient shade contributing to energy loss and excessive energy use. Schemes such as the National Australian Built Environment Rating System (NABERS) have encouraged some retrofit to existing commercial buildings to improve their energy use. Note that this discussion does not consider embodied carbon in building materials, although this is an important source of emissions. Nor does it include increased electricity consumption due to charging electric vehicles – this is covered in the transport sector modelling, discussed in section 3.3. Table 26 in the Appendix lists some additional quantitative assumptions and sources for the building sector results.

Electricity made up 58% of energy consumption by buildings in 2020 and is projected to increase to more than 85% by 2050 in the CRD scenario. Approximately 30% of detached homes in the NEM

[29] Table 5 incorporates the electricity generated by wind and solar that is stored in batteries or pumped hydro, whereas Figure 16 reports the power directly delivered in order to supply consumers by technology.

[30] Note that the classification of emissions from the operation of buildings in AusTIMES does not directly map to the classification of emissions by sector in GTEM. The former classification collects together the emissions created by the inputs used to operate buildings and assigns them to buildings. The latter classification attributes the emissions created by the inputs used to operate buildings to the sectors that produce those inputs.

now have rooftop solar (AEMO, 2022). In the CRD scenario this would need to increase to 47% by 2030, equivalent to almost 3000 additional homes fitted with rooftop solar per week. Where this is not suitable or cost effective, this renewable share of household electricity consumption is anticipated to come from the grid.

Overall, the CRD scenario projects a reduction in emissions from residential buildings to 9 Mt CO_2-eq (18% of 2020 emissions) by 2030 and 0.7 Mt (1.4% of 2020 emissions) by 2050 (remaining emissions shown by the black part of the bars in Figure 19). In addition to renewable energy, this decarbonisation will be achieved through shifts in the construction and design of new buildings to improve their thermal (space heating and cooling) energy efficiency and switching from gas to electricity for space heating, hot water, and cooking. Residential building thermal efficiency will need to increase by 15% on average by 2050, to be achieved through the two-thirds of 2050 residential building stock which will have been built since 2020, almost all to meet a seven-star rating under the Nationwide House Energy Rating Scheme (NatHERS).[31]

The changes in this sector will only result in a modest increase in energy consumption overall, with growth in building stock mostly offset by improvements to both building thermal energy efficiency and in hot water, lighting and other appliances (device efficiency). Electrification in the housing sector will see the contribution of electricity to total energy consumption increase from 49% in 2020 to 58% by 2030 (and 62% by 2050).

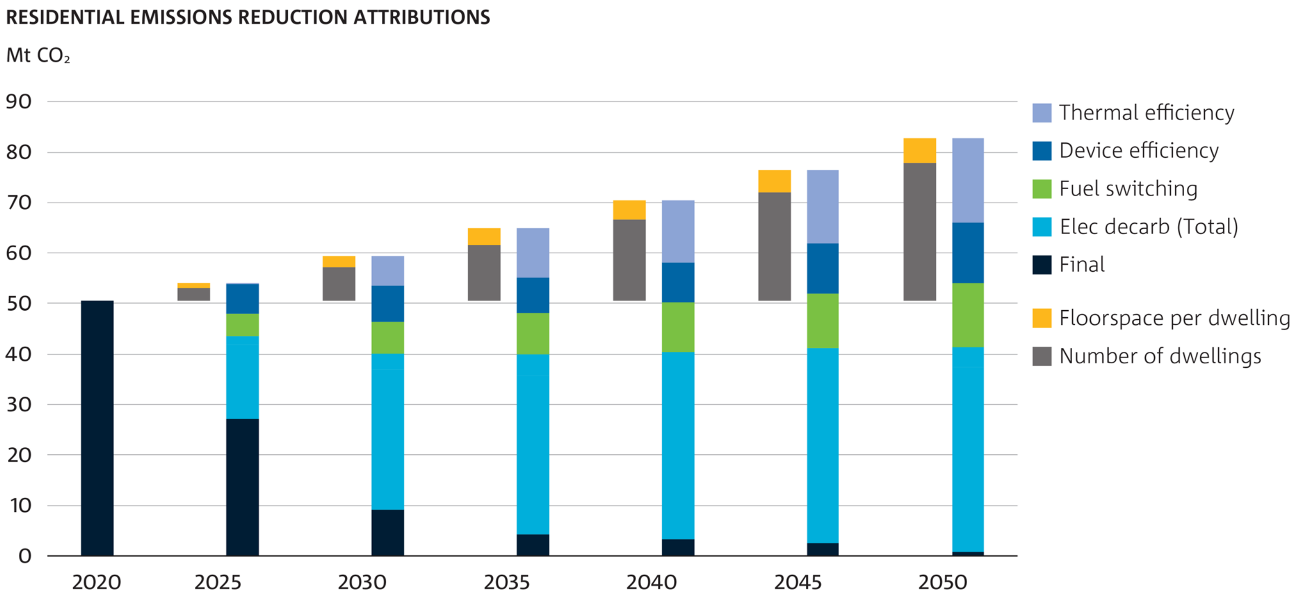

Figure 19 Residential emissions reduction attributions in the CRD scenario

Note: The black column segments indicate unabated emissions from residential buildings, and from 2025 onwards, the left yellow+dark grey column indicates the breakdown of additional (but abated) emissions increases due to growth in number and size of buildings; and the right column shows how that abatement is achieved.

Source: AusTIMES

The CRD scenario projects a similar reduction in emissions from commercial buildings to 8.8 Mt (20% of 2020 emissions) by 2030 and 1.5 Mt (3.4%) by 2050 (remaining emissions shown by the

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[31] See https://www.nathers.gov.au/

black part of the bars in Figure 20. Again, decarbonisation results from improvements to the energy efficiency of new buildings and a switch from gas to electricity for space heating, hot water, and cooking (details in Table 6). Almost half of 2050 commercial floorspace is projected to be built after 2020 to higher energy efficiency standards). The remainder of improvements result from renewal and modifications to existing stock.

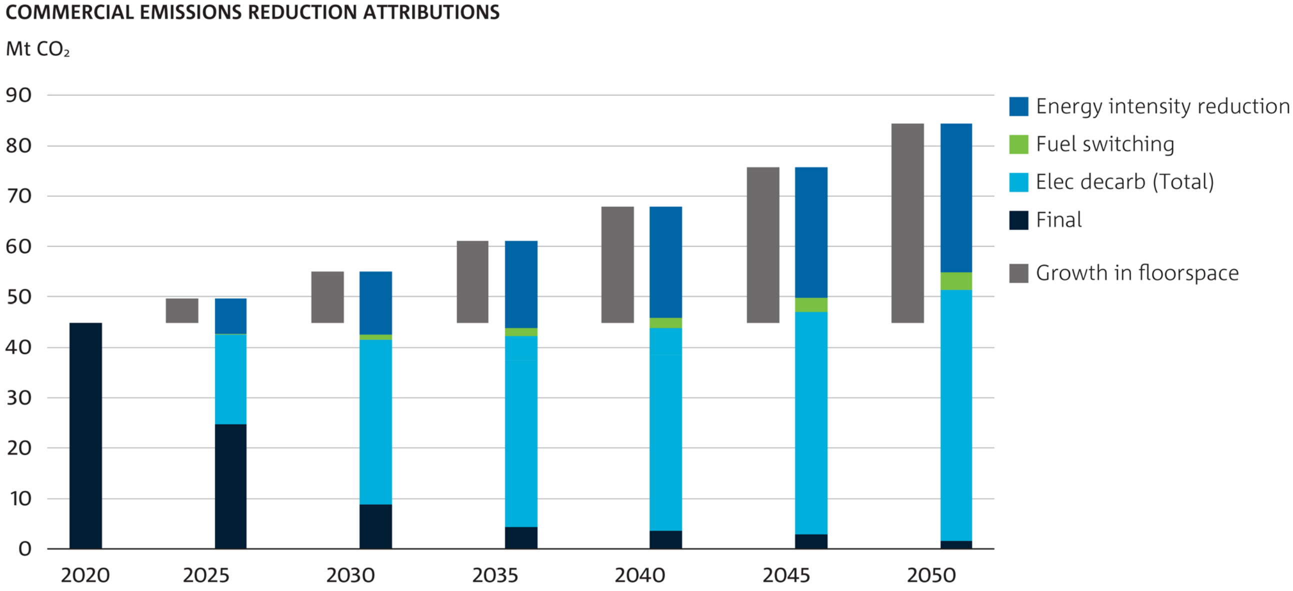


Figure 20 Commercial emissions reduction attributions in the CRD scenario

Source: AusTIMES

In the CSP scenario, the uptake of rooftop solar is slightly lower. The reduction in emissions intensity of electricity generation, fuel switching, and the improvements in the energy efficiency of appliances all occur more slowly than in the CRD. This contributes to a reduction in emissions from commercial and residential buildings to just less than 20 Mt (19% of 2020 emissions) by 2030 and 2.3 Mt (2.3%) by 2050 (see Figure 21 and Table 27). Emissions intensity results appear in Figure 22 (and Table 28).

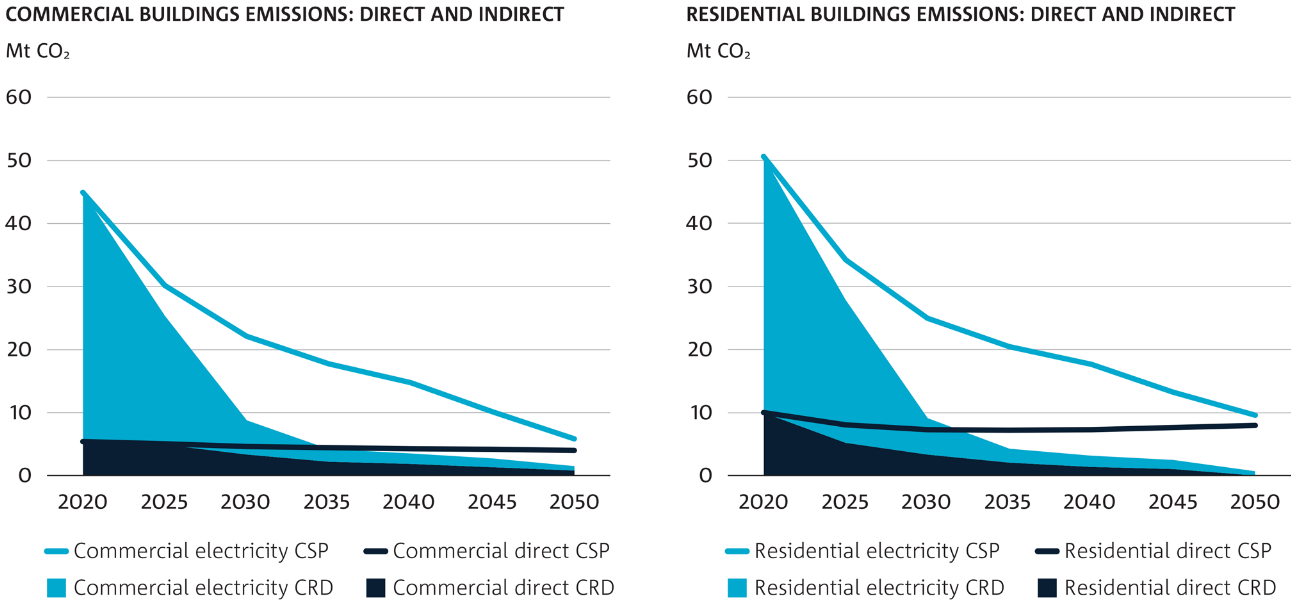


Figure 21 Commercial and residential building emissions in the CRD and CSP scenarios

Source: AusTIMES

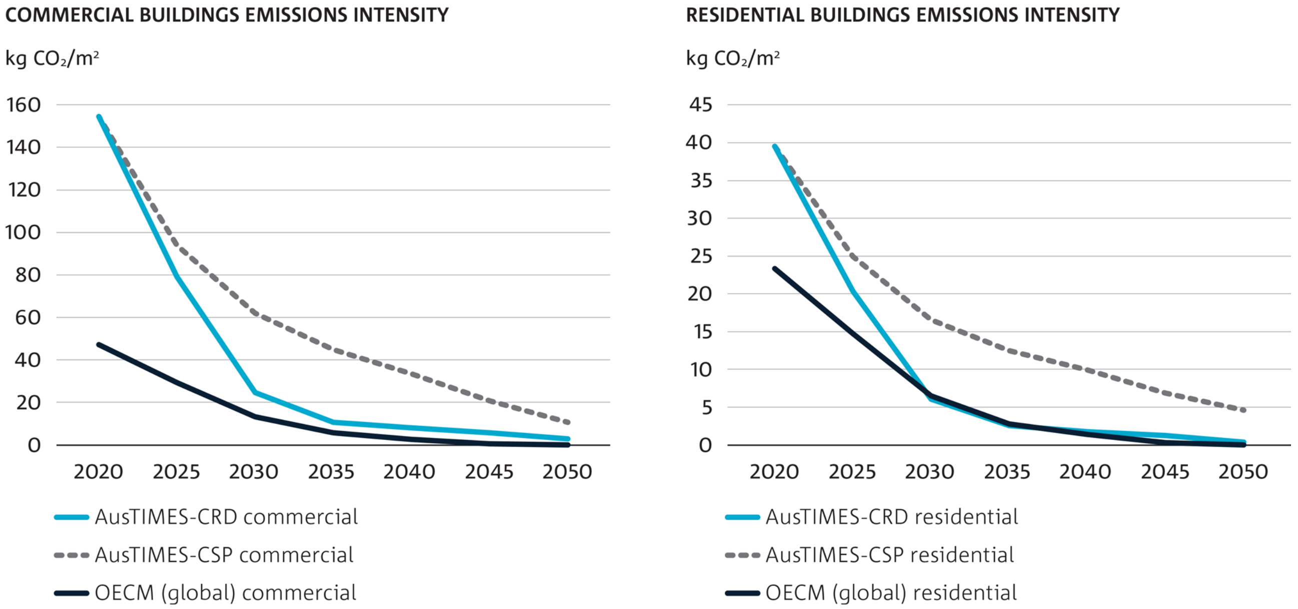


Figure 22 Building emissions intensity (per unit floorspace) for the CRD and CSP scenarios

Source: AusTIMES for emissions, Australian Bureau of Statistics for average floorspace per household in 2020 (165m^2), NatHERS data (CSIRO, 2022) for ratio of household living area to total floorspace (75%), Teske et al. (2020) for OECM data series

Table 6 Key milestones in residential building electrification (% fuel use – PJ)

	2020	2030	2040	2050
Space conditioning (Heating and cooling)	35%	53%	62%	70%
Water heating	58%	78%	87%	100%
Cooking	56%	62%	84%	100%

Limitations in attribution of roof-top solar to self-consumption versus export

AusTIMES does not provide detailed roof-top photovoltaic (RTPV) production and end-user consumption disaggregated by individual customer and hour of day. The detail does not support representation of RTPV exported by a customer and imported by another customer in the same sector or exported at one point in time and imported by the same customer at a different time within in the same aggregated time slice. As a consequence, it is not possible to accurately split RTPV production between self-consumption and grid export, but only to calculate an upper bound on self-consumption. Correspondingly it is not possible accurately distinguish emissions avoided from emissions abated by RTPV and hence to accurately attribute avoided emissions to each individual (residential or commercial) sector. In Figure 19 and Figure 20 above RTPV from both the residential and commercial sectors are attributed entirely to reduction in average electricity emissions generation intensity rather than accounted for as a reduction in (net) electricity demand. If avoided emissions due to RTPV self-consumption were accurately accounted for, the emissions intensity of electricity consumed in each of the residential and commercial sectors (and hence also scope 2 emissions) would be slightly lower.

Opportunities, risks and challenges

Many of the opportunities to decarbonise in this sector impose upfront costs to consumers although savings accrue over the opportunities' total operating lives. An increase in rooftop generation and storage provides an opportunity for greater energy independence for consumers but also increases challenges for grid stability. Furthermore, without schemes for renters and low-income households to participate it may also exacerbate inequities.

Many of the retrofit opportunities are already commercially available. These include heat pumps, solar water heating, and electric or induction stoves. Some behaviour change will be required on the part of consumers to take up these options (noting that load shifting, or similar options are not modelled). Some consumers may face barriers to access opportunities with high upfront and lower operating cost. Building codes may need to be strengthened to mandate uptake, and failure to do so could limit the pace of decarbonisation. There will also be hard limits to retrofitting some older buildings.

Both retrofits and new builds will flow through to increased economic activity for the construction sector and trades. However, this sector will compete with others for materials and skilled labour and supply challenges may be a constraint.

The physical risks of climate change will also impact this sector in ways which are not fully considered in this analysis. Many of the design and retrofit opportunities will be vital to improve the resilience of buildings and their occupants to extreme heat. However, the impacts of extreme events such as flooding, cyclones and bushfires, and the insurability of buildings against these impacts, may cause economic strain to households and communities in vulnerable locations.

Implications

Building standards have an important role to play in setting out current and changing expectations for new buildings and retrofitting existing building stock (note for example the seven-star rating of new building stock included in the modelling). Stronger standards for tenanted buildings could be transformational to reduce cost and inequities and mitigate some of the physical impacts of climate change on vulnerable households. Government initiatives could include subsidies for electric appliances or phase-out of gas appliances at point of sale. Beyond mandates, there is a role for advocacy through industry associations and building designers to increase awareness and adoption of technologies which are less familiar to consumers. Banks could also play a role by providing lower interest sustainable loans for measures that reduce the emissions profile and increase the adaptive capacity of owner-occupied and tenanted buildings.

BUILDING SECTOR EMISSIONS IN THE CRD SCENARIO

2020

Building operation makes up about 18% of total emissions

Existing building stock have poor energy efficiency

One third of detached homes have rooftop solar

Half of water heating and cooking are electrified

Electricity makes up half of household energy

About one third of space heating is electrified

2030

- Emissions from commercial buildings at 20% of 2020 levels
- Half of detached homes have rooftop solar, or 3000 more homes fitted each week
- Emissions from residential buildings at 18% of 2020 levels
- Electrification of residential buildings means the fraction of electricity making up total energy consumption increases to 58% (from 49% in 2020)

2050

- Emissions from commercial buildings at 3.4% of 2020 levels
- Almost half of commercial floorspace is now built to higher energy efficiency standards
- Emissions from residential buildings at 1.4% of 2020 levels
- Two thirds of residential buildings built at higher energy efficiency rating (since 2020)
- Further electrification of residential buildings sees the fraction of electricity making up total energy consumption increase to 62% (from 49% in 2020)
- Water heating and cooking are 100% electrified for residential buildings

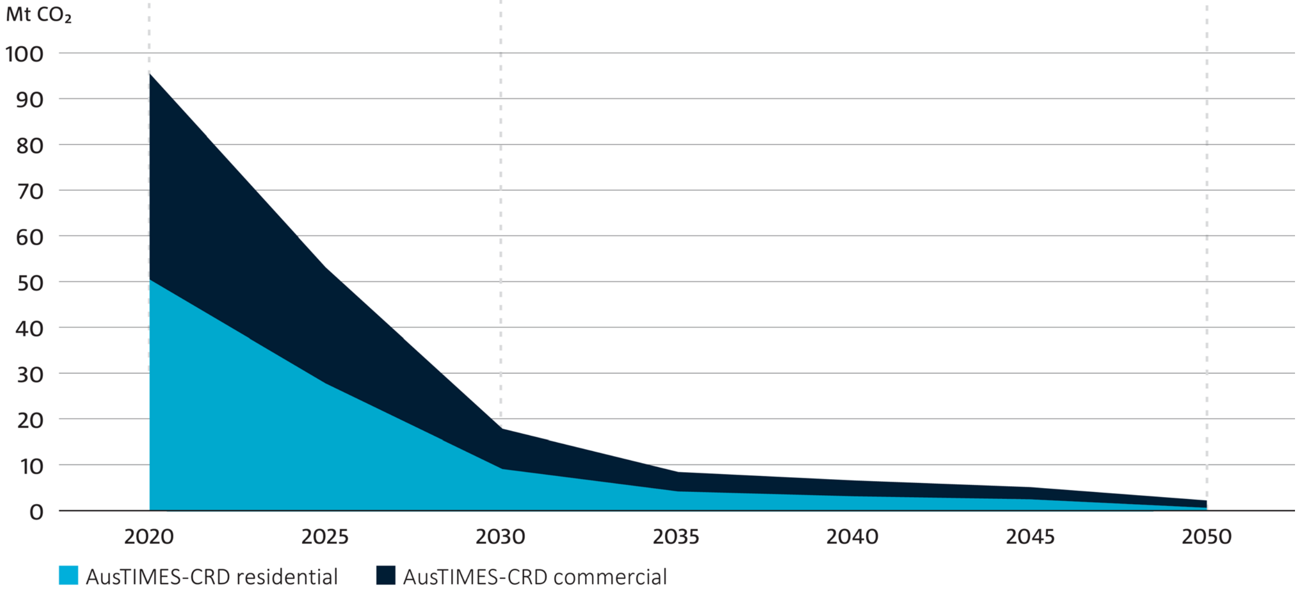


Figure 23 Summary of key transition milestones – Residential and commercial buildings

3.3 Transport

Emissions, production and demand shifts

Emissions from transport are Australia's third largest source, making up 19% of emissions in 2021.[32] Road transport is the most material category and within this subsector light vehicle transport has the greatest opportunity for near-term decarbonisation (See Figure 28 and Table 29). Key levers for reducing emissions include electrifying transport, improving energy efficiency, behavioural change and switching to lower emissions mobility such as public transit, walking and cycling.

Australia lags other countries in terms of transport decarbonisation policy. Australia has recently committed to fuel efficiency standards for light vehicles with policy currently in the design stage. The Australian Capital Territory (ACT) has announced a ban on sales of internal combustion engine (ICE) light vehicles by 2035,[33] but similar commitments are yet to be made federally or by other states and territories. Preferential supply of electric vehicles to other countries with fuel efficiency standards is currently contributing to insufficient supply in Australia to meet growing demand.

Investment in charging infrastructure has been made through a mixture of public and private sources. Fast charge network infrastructure along Australia's key national transport routes will be vital to increase uptake of electric vehicles.

The CRD scenario assumes that the sale of ICE vehicles ends after 2035. Electrical vehicles prices are expected to decline and reach cost parity with new ICE vehicles from 2030. This accelerates their uptake (Figure 29). Greater investment in charging infrastructure through this period also facilitates accelerated uptake. By 2030, the modelling shows that 23% of light vehicles on road are electric vehicles and by 2040 this increases further to 73%. This differs from the CSP scenario which projects that the sale of ICE vehicles will not end until after 2050 and the share of electric vehicles within the light vehicle fleet will be only 45% in 2040. All road vehicle emissions are close to zero by 2045 in the CRD scenario, while in the CSP has road vehicle emissions do not reach zero until after 2050 (Figure 24 and Figure 25). As elsewhere model outputs are used for 2020 to avoid COVID bias to emissions data.

[32] https://www.dcceew.gov.au/sites/default/files/documents/nggi-quarterly-update-december-2021.pdf,see Figure 4, p9.

[33] https://www.climatechoices.act.gov.au/__data/assets/pdf_file/0006/2038497/2022_ZEV_Strategy.pdf

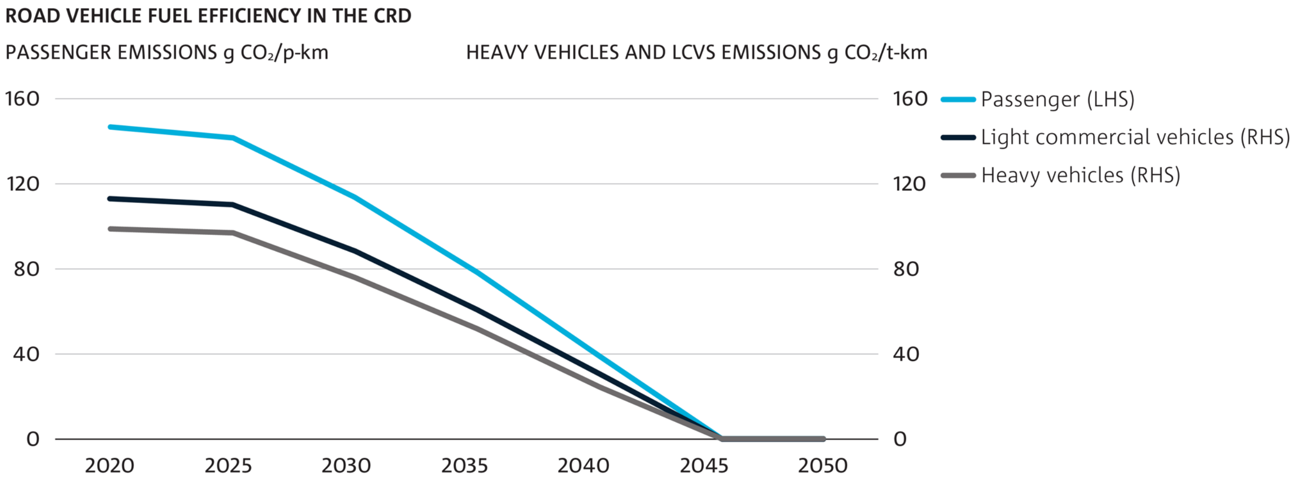


Figure 24 Road vehicle fuel efficiency in the CRD scenario[34]

Source: AusTIMES

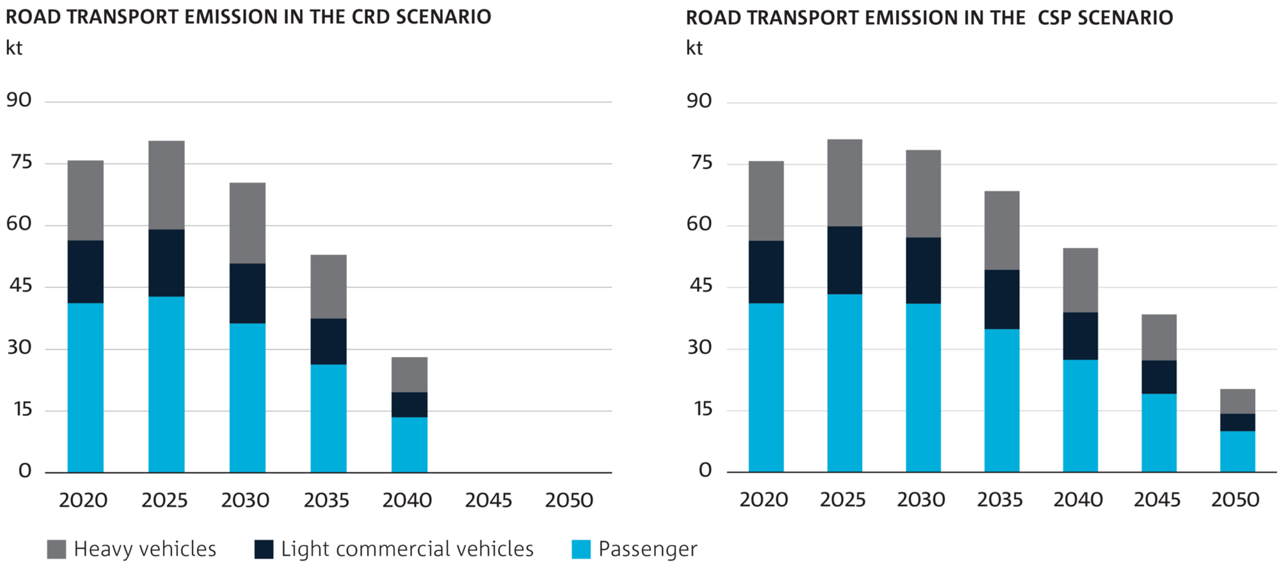


Figure 25 Road transport vehicles combustion emissions in the CRD and CSP scenarios

Source: AusTIMES model outputs

[34] Freight tonnage emissions intensity of light commercial vehicles is calculated assuming 2.5 t-km per v-km (10% of light commercial vehicle v-km services are assumed to provide freight transport). Passenger emissions intensity of passenger vehicles is calculated assuming 1.7 p-km per v-km (90% of light commercial vehicle v-km services are assumed to provide passenger transport).

New car sales

The light vehicle transport sector could take many paths along the journey to electrification. The modelling of the CRD scenario for this report has 59% of light vehicles sold in Australia are electric by 2030, and this share increases to 95% by 2040-2050. The remainder transition to hydrogen fuel cell technology. In the CSP scenario uptake is assumed to be slower and corresponds to 35%, 73% and 96% of light vehicle sales in 2030, 2040, and 2050 respectively. (See Figure 29, Figure 30, and Table 7)

In exploring transport road transport in Australia judgement has been applied to reflect Australian expectations and policy settings across equivalent vehicle segments to the IEA modelling. These shares will vary as Australia introduces additional policy measures and progresses toward its 2030 targets and beyond.

The electrification of heavy vehicles (rigid trucks and articulated trucks) is also made much more difficult by cost, charging infrastructure and other regulatory barriers, such as curfews and weight limits on heavy vehicles. There are currently few electric heavy vehicles models available in Australia. Changes to regulatory requirements would assist by aligning our vehicle standards with international counterparts (ATA-EVC, 2022). Hydrogen fuel cell vehicles are another option with longer range and a faster fill time than electric alternatives. However, their commercialisation is even more nascent, and a large infrastructure network would also be required to enable their adoption in Australia. In the CRD scenario the emissions intensity of heavy vehicle transport falls from 100g CO_2-eq /t-km in 2020 to zero in 2050.

Rail transport in Australia is not anticipated to decarbonise as quickly as road transport. Projections based on the CRD scenario suggest that the share of rail transport using electricity approximately doubles by 2050 from 12% in 2020, and biofuels substitute more than half of liquid fuel use. Regenerative braking can reduce emissions from short distance passenger transport. Battery electric trains and hydrogen fuel cells are emerging options to displace the existing diesel fleet. However, long asset and infrastructure lifespans and few commercially available options, especially for freight, mean that uptake will be slow (see Figure 29).

The shipping industry relies heavily on fossil fuels in the forms of heavy fuel oil and diesel. Travel distances, cargo requirements, long asset lifespans, and lack of retrofit alternatives create challenges to decarbonisation, which is why the sector is considered hard-to-abate. The International Maritime Organisation (IMO) has been working to steward the decarbonisation of the sector and has set targets to reduce shipping emissions intensity by 40% by 2030 and reduce absolute emissions by 50% by 2050 (IMO, 2019) (relative to 2008 levels).

In the short term, methanol can be used in low concentration blends (up to 20%) in existing engines to reduce emissions intensity (ARENA, 2021). Some commercial vessels currently use LNG, but this provides minimal emissions benefits and is incompatible with the reductions required under a 1.5°C pathway. Other options for new fleets include ammonia, hydrogen, and 100% biofuels. All options come with challenges including energy density of fuels, energy losses in conversion, supply chain challenges, commercial availability of vessels, port infrastructure requirements, and cost. The production methods of alternative fuels also need to be considered, with electrolysis and renewable energy use providing a least emission but highest cost pathway for ammonia and hydrogen (see section 4.4). Biomass faces challenges of availability, cost and competition with other sectors (see section 4.1).

The CRD scenario assumes Australian domestic (i.e., coastal) shipping progresses as per the IEA modelling for global shipping, decarbonising via energy efficiency and substitution of existing fuels with low carbon alternatives. The emissions intensities of global shipping and aviation fuel use decrease by 2050 to, 15% and 21% of their 2020 levels respectively (Figure 26). The CSP scenario assumes a slower uptake of lower emissions intensity fuels, so that by 2050 the emissions intensity in shipping and aviation remains at 91% and 93% of 2020 levels.

Currently there are no zero emissions alternatives to aviation fuels that can be deployed at scale. Options for fuel switching include electrification and green hydrogen (for short distance small passenger aircraft) and sustainable aviation fuel (SAF) for long haul flights (West and Curry, 2022). Electrified, hydrogen, and hybrid options are under development. Small quantities of SAF and hydrogen are being produced at a significant cost premium. The same barriers that apply for hydrogen and biofuels impact the viability of these decarbonisation options. Emissions that could not be reduced by either new technologies or demand reductions would need to be offset (see section 4.2).

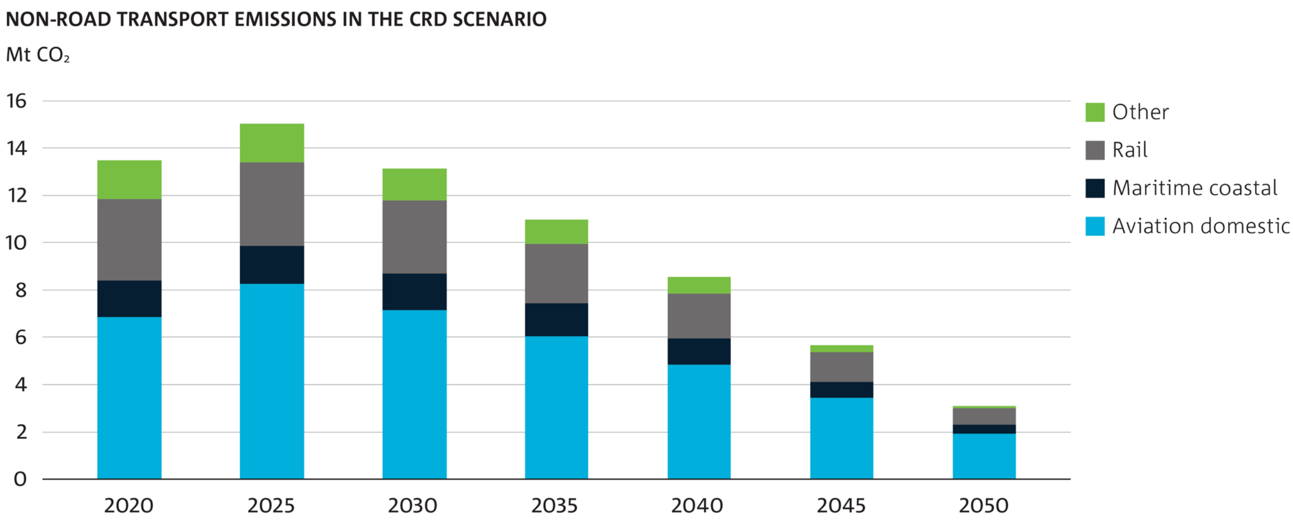


Figure 26 Non-road vehicle combustion emissions by transport mode in the CRD scenario

Source: AusTIMES model outputs

The modelling assumes that domestic shipping and aviation demand will increase in line with economic growth rate projections, but international shipping and aviation fuel use will increase in line with historical growth. The emissions intensity of shipping and aviation fuel differs substantially by scenario, taken from IEA Net Zero by 2050 (IEA, 2021). In shipping, energy efficiency is expected to reduce the demand for fuel, and emissions intensity in both shipping and aviation is reduced, owing to the use of advanced biofuels and fuels derived from low emissions hydrogen (IEA 2021, p61).

Opportunities, risks and challenges

For households and small businesses electric vehicles are projected to deliver cost savings on an upfront and operating basis over the long term, and fuel costs that are less volatile. The large share of rooftop solar may help to accelerate the uptake up of electric vehicles as the upfront costs fall, and householders look to better utilise their generated electricity. Heavily populated areas will experience reduced air pollution as a co-benefit.

Lack of interoperability of charging networks could present a barrier if not considered and addressed. The availability of raw materials and manufacturing capacity to build new charging networks, as well as the electric vehicles themselves, may constrain the speed of adoption.

Other commercial and passenger transport modes (heavy road vehicles, rail, shipping and aviation) all feature expensive, long-lived assets, which are challenging to decarbonise. These industries are also low margin, making cost a barrier to uptake for new technology options. To decarbonise these sectors the cost of transport may need to rise significantly. For aviation this could mean less discretionary travel, and for the rest of the modes this may be passed through as higher cost of goods in other economic sectors. The International Renewable Energy Agency (IRENA) underscores the potential for high emissions lock-in in these sectors: "*considering the average age of the existing vessel fleet and the technical lifetime of large and very large vessels, i.e., 25-30 years, the development of new vessel designs, and engines needs to happen between 2025 and 2030. Indeed, the vessels to be deployed in the next five to ten years will characterise energy demand and carbon emissions by 2050.*" (IRENA, 2021)

Implications

Policy measures can hasten Australia's transition away from ICE for light vehicles which is slow compared to other advanced economies (Figure 29). The proposed introduction of fuel efficiency standards could provide confidence to electric vehicle suppliers that there will be a stable market for their product. This would encourage a greater variety of vehicles and increased competition helping to reduce the upfront cost. It may also influence decision making by those consumers seeking to hold their vehicle for the long term or wanting certainty of a strong second-hand market. Banks can play a role here by either issuing lower interest loans for electric vehicles or by phasing out financing of ICE vehicles.[35]

Heavy road vehicles, shipping and aviation are likely to require more substantial innovation. Concessional loans could be an option for heavy road vehicle owners to encourage a switch. Some incentivisation may also come from downstream customers who are increasingly focusing on value chain emissions and may be prepared to pay a premium for low-emissions transport. Shipping, aviation and long distance and heavy rail require significant investment in research and development, and potentially complimentary policy or subsidies to accelerate adoption. Shorter distance and passenger rail requires investment in electrical infrastructure. Swift intervention may be needed to avoid high emissions lock-in and reduce the risk of stranded assets in this sector.

The intractable challenge of biofuels, particularly for aviation, will need to be addressed. Utilisation of agricultural wastes and algae are options that do not require virgin biomass and would not compete with other agricultural uses. Significant investment would need to be made in processes and systems to allow these to be efficiently generated at scale and transported (at low emissions intensity) to their point of use. Additional research, government investment, and incentives be needed to surmount these hurdles.

[35] https://bankaust.com.au/about-us/why-us/ev-transition-ending-fossil-fuel-car-loans-2025

DOMESTIC TRANSPORT SECTOR EMISSIONS IN THE CRD SCENARIO

2020

Australia lags other jurisdictions in fuel efficiency standards

The transport sector is Australia's 3rd largest emissions source making up 19%

EVs make up 2% of new car sales

2030

EVs make up 23% of passenger and LCVs on the road

EVs reach cost parity with new internal combustion vehicles

EVs make up more than half of new car sales

2035

The sale of new internal combustion engine vehicles has ended

2040

Shipping decarbonisation via hydrogen and biofuels has begun

Air transport has begun to decarbonise via biofuels

EVs make up 73% of passenger and LCVs on the road

2050

All heavy road transport is a mix of electric and hydrogen (by 2045)

More than 90% of road vehicles are electric by 2045

Shipping and air transport emissions intensity is less than 10% of 2020

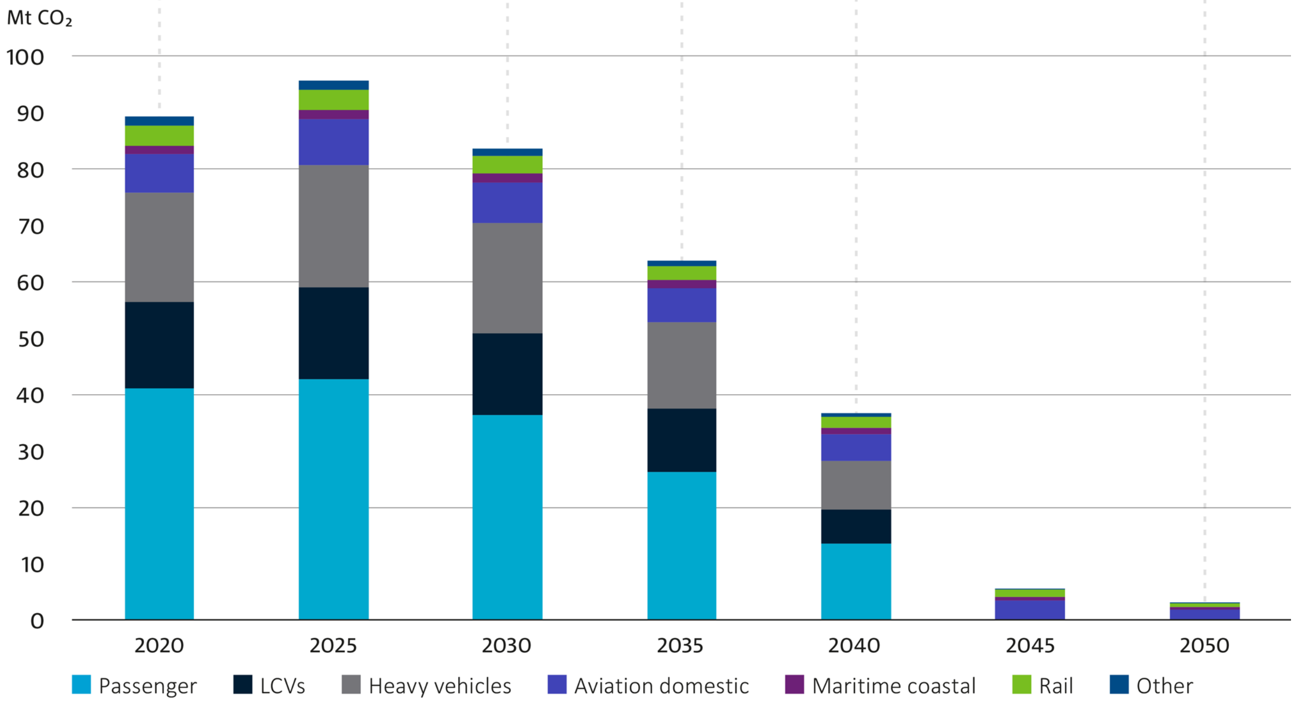


Figure 27 Summary of key transition milestone – Transport

ROAD TRANSPORT BY FUEL TYPE IN THE CRD SCENARIO

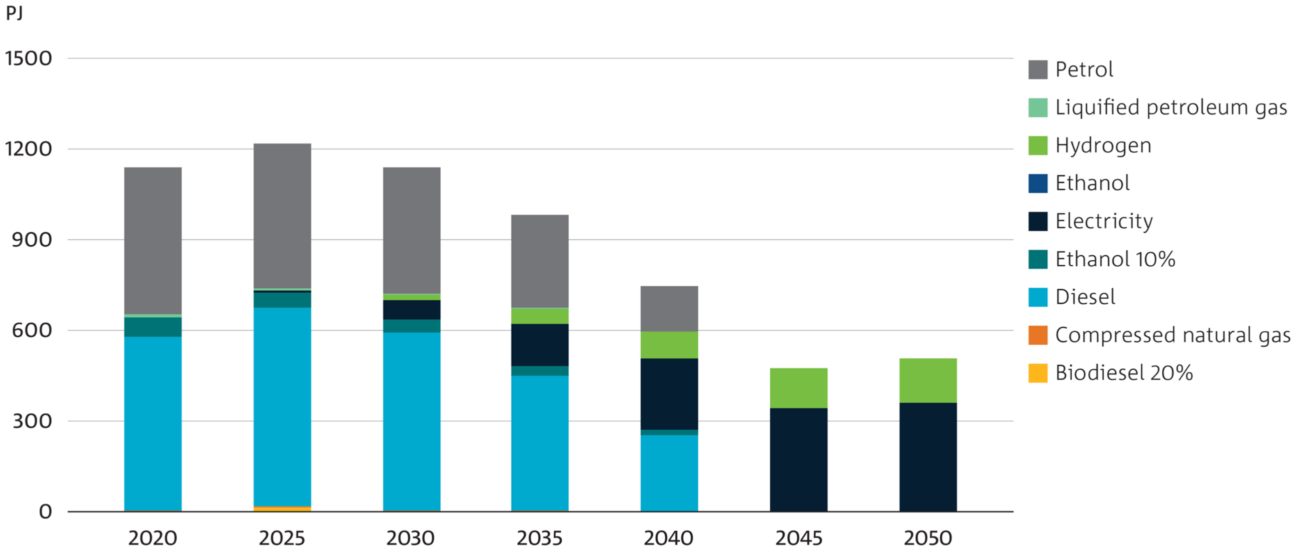


Figure 28 Road transport fuel use in the CRD scenario

Source: AusTIMES

NEW ROAD VEHICLES NUMBERS BY TECHNOLOGY IN THE CRD

NEW ROAD VEHICLES NUMBERS BY TECHNOLOGY IN THE CSP

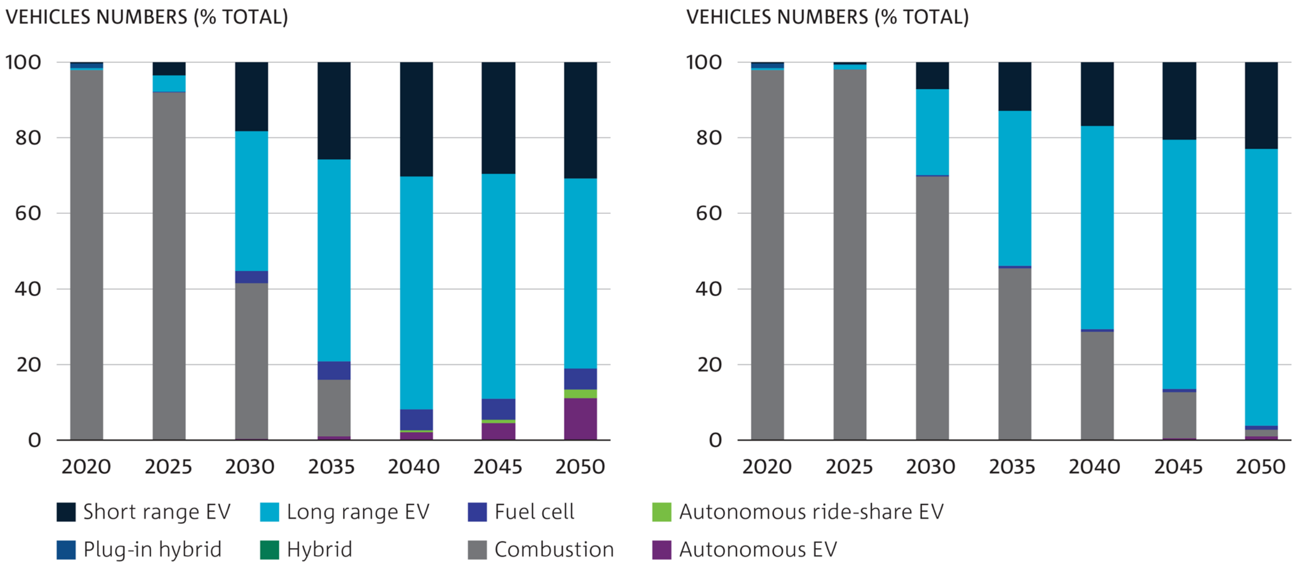


Figure 29 New road vehicles market share (vehicle count) by technology in CRD and CSP scenarios

Source: AusTIMES

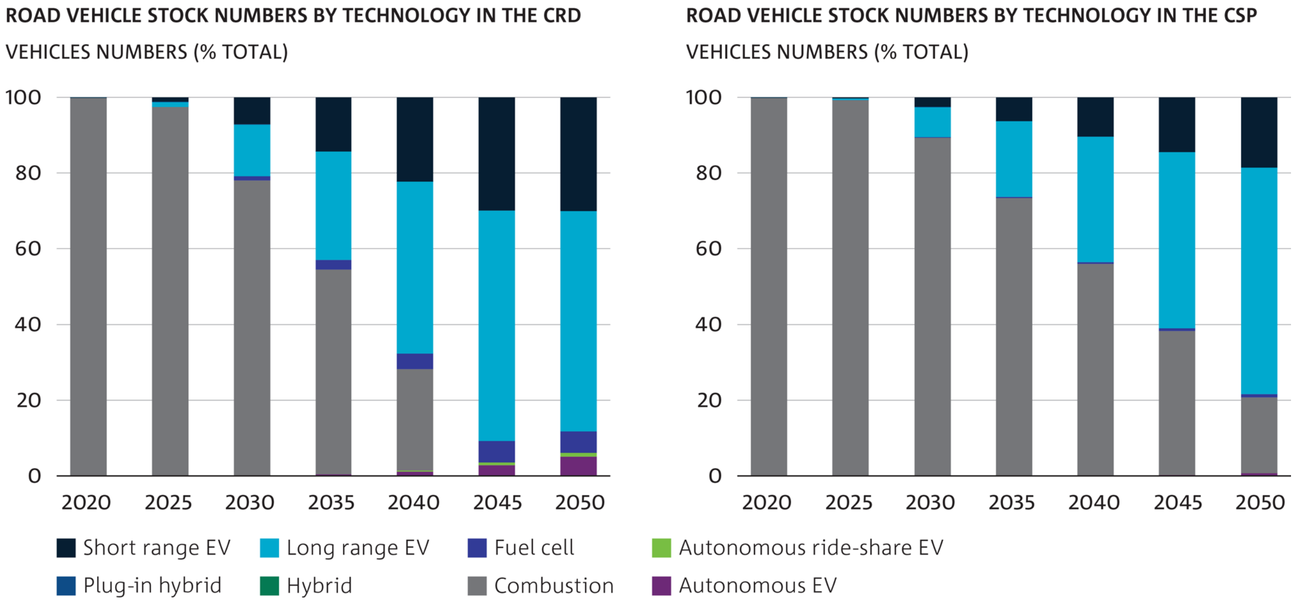


Figure 30 Road transport vehicle market share (vehicle count) by technology in the CRD and CSP scenarios

Source: AusTIMES

Table 7 Key decarbonisation percentages of new sales (vehicle count) by road transport type by decade for the CRD scenario.

	2020	2030	2040	2050
Combustion	98%	41%	0%	0%
Hybrid	0%	0%	0%	0%
Plug-in hybrid	1%	0%	0%	0%
Long range EV	1%	37%	61%	50%
Short range EV	0%	18%	30%	31%
Autonomous EV	0%	0%	2%	11%
Autonomous ride-share EV	0%	0%	1%	2%
Fuel cell	0%	3%	6%	6%

Source: AusTIMES

3.4 Industry

While the implications for steel, cement, aluminium are discussed separately, they have been grouped for efficiency into a single section as the decarbonisation options are similar.

Several sectors face substantial obstacles to achieving full decarbonisation with current technologies. Production processes using fossil fuels as a catalyst or feedstock, such as iron ore reduction and cement manufacture are particularly vulnerable. High temperature heating applications such as alumina refining and cement production present electrification challenges. These three sectors are the largest emitting industry sectors in Australia and are the focus of this section. Figure 32 depicts the growth in each sector as projected by the national economic model (see also Table 8). Note that the significant majority of iron ore and bauxite produced in Australia is exported rather than processed domestically, so the scale of Australian alumina, aluminium and steel production is small in comparison.

We note that the macro-scale energy system model employed for this work is more suited to projecting broad trends rather than investment decisions at the scale of individual production plant. In reality, investment in (and closure of) production capacity in each of the three sectors, aluminium, iron and steel, and cement, is lumpy (that is, the minimum scale of new production is large relative to existing production capacity in each Australian state), and future market demand is uncertain. Commercial considerations in practice would include an assessment of the credibility of global demand expectations, and also the expected cost competitiveness of domestic production relative to international peers at the time of the investment decision. The implication for the projections shown below is that a smoother transition is shown than may be practicable as plants close and new plants are brought on-line.

HEAVY INDUSTRY SECTOR EMISSIONS IN THE CRD SCENARIO

2020

In cement production, 84% comprises clinker

In alumina refining, more than two thirds fuel use is natural gas

In bauxite and iron ore mining, more than half fuel use is diesel

2030

In concrete, post-construction recarbonation is recognised

In alumina refining, mechanical vapour recompression technology encourages electrification fuel switching from natural gas

In bauxite and iron ore mining more than two-thirds fuel use is electricity or biofuel

2040

In cement production, some CO_2 capture by 2040

In steel refining, some production by direction Reduction Iron (hydrogen) electric arc furnace by 2040

In steel production, emissions intensity reduced by 22% on 2020 levels by 2040

Some aluminium smelting exploits inert anode technology

2050

In cement production, less than 61% is clinker

In Iron ore mining and cement production, hydrogen provides 10% or more of fuel used

For steel smelting, more than half of production is by Direction Reduction Iron (hydrogen) electric arc furnace

In alumina refining, fuel use is more than half electricity and less than a third natural gas

In bauxite and iron ore mining, use of diesel is eliminated

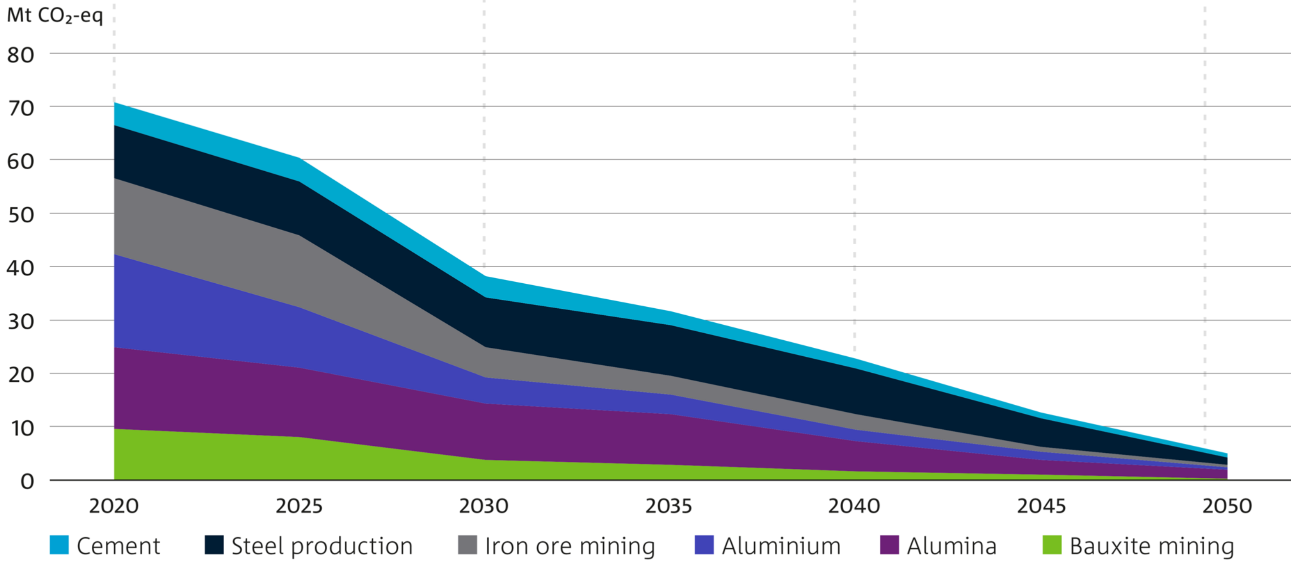


Figure 31 Summary of key transition milestones - Heavy industry

Bauxite, alumina, and aluminium

Emissions, production and demand shifts

Options for decarbonising bauxite mining are similar to those for other mining activities: fuel switching from diesel to electricity for haul trucks, machinery, and conveying and decarbonising the electricity supply (Figure 36). Low temperature heating in the digestion process also presents an electrification opportunity (ARENA, 2022). The calcining process used to produce alumina from bauxite requires very high temperatures commonly achieved by combusting coal or natural gas. This is a more challenging emissions source to abate. Feasibility studies are underway to investigate the suitability for hydrogen to displace fossil fuel sources in this process (Rio Tinto, 2022). Anodes used for aluminium smelting are also a hard-to-abate source for which alternatives are being investigated. Table 30 in the Appendix lists some additional quantitative assumptions and sources for the results of several industry sectors, including bauxite mining and alumina refining, with Table 31 specifically for the aluminium value chain.

Overall demand from this sector is fairly consistent through the period. Australian production is strongly influenced by global demand and consequently will be driven by Australia's relative price competitiveness across the value chain. In particular, refined product production (e.g., alumina, iron and steel) will reflect the relative prices of energy for Australian producers compared to international competition. Globally there is an expectation of increased demand for batteries, solar PV, and wind, all of which embody aluminium to some degree. The CRD scenario assumes initial increased demand is met by increased local production, and the potential for higher recycling rates for aluminium is a decarbonisation opportunity which is not fully captured in the modelling.

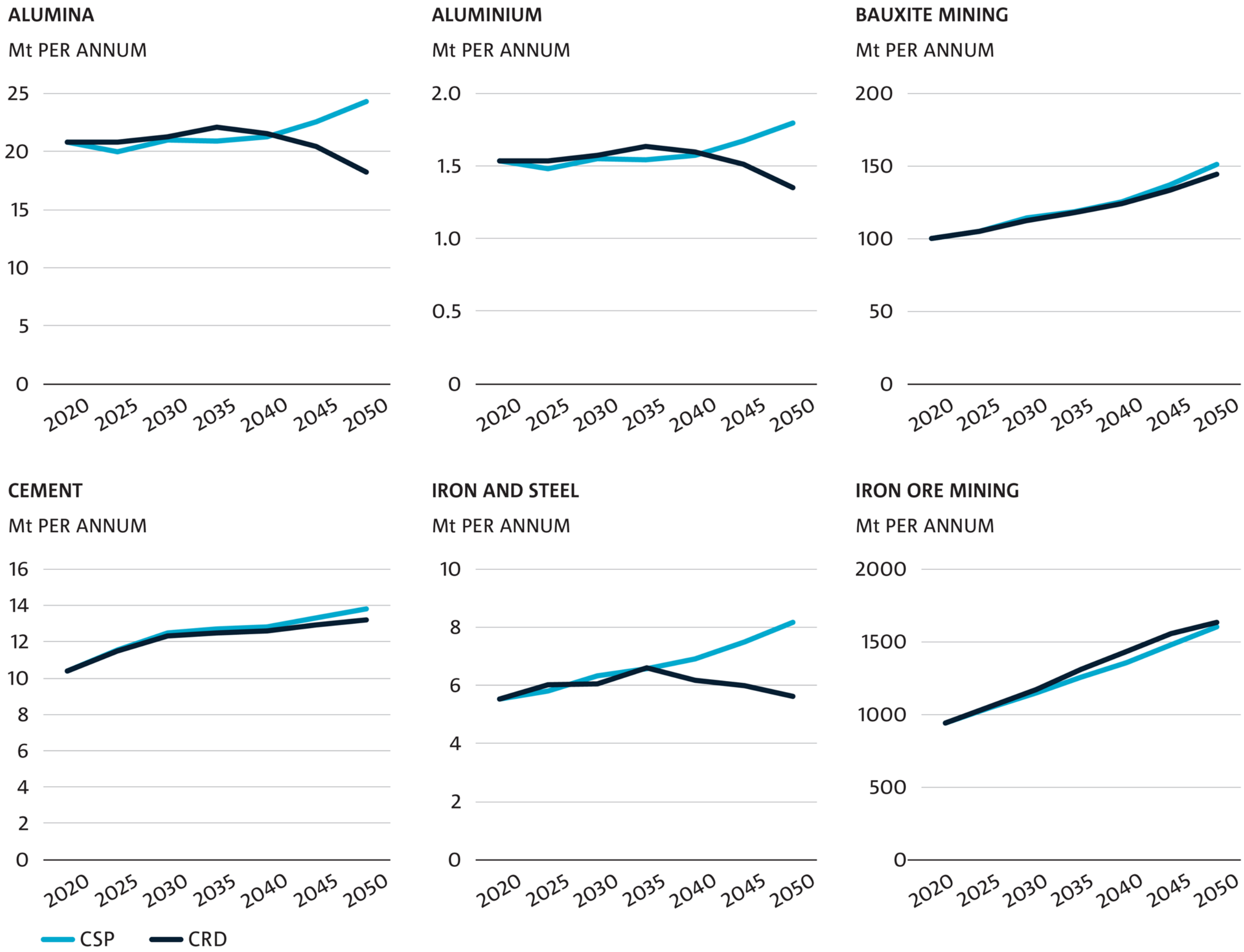


Figure 32 Industry sectors production (Australia) in the CRD and CSP scenarios

Source: KPMG-EE and AusTIMES

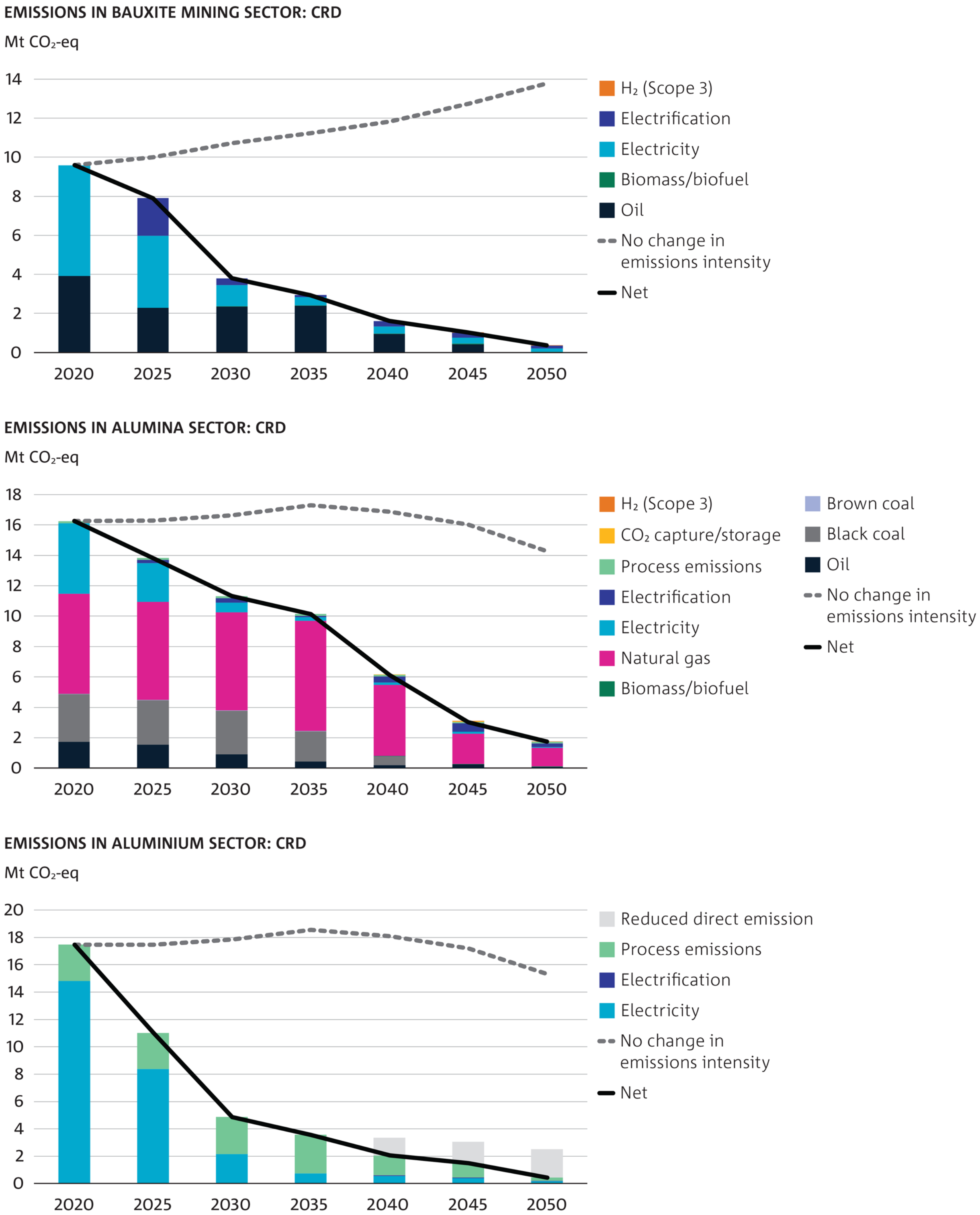


Figure 33 Emissions in the aluminium supply chain in the CRD scenario[36]

Note: "No change in emissions intensity" means emissions that otherwise would have occurred with no change in emissions from current intensities, given the projected change in production

Source: AusTIMES

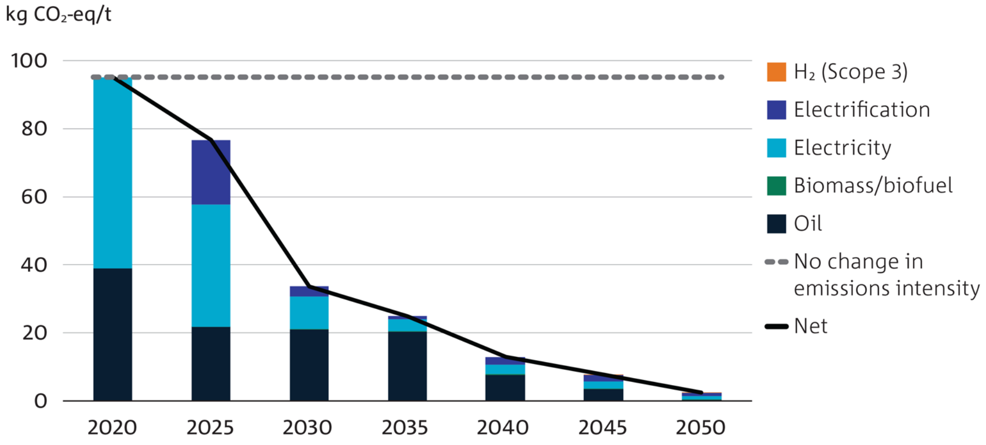
[36] Note that a limitation of the modelling framework is that it does not enforce a minimum scale of investment or minimum scale of plant shutdown (see Appendix A.2.3): investment and production are continuously scalable. Furthermore, the model does not currently track the stock of industrial production in the aluminium value chain. Where small increases or declines in national production are shown, this should be interpreted as a projection that there will be additional demand (in this case, global demand) for (Australian) product if it could be expanded or contracted across a continuous range. Because industrial production stock is not represented in these sectors, any new production capacity is implicitly assumed to have identical characteristics to the existing capacity.

In the CRD scenario (Figure 34, Figure 36), emissions from bauxite mining reduce through electrification, along with decarbonising electricity inputs. By 2030 diesel emissions are less than one quarter of 2020 levels, and by 2045 diesel use is fully displaced. This contrasts with the CSP scenario where diesel displacement occurs more slowly, and electrification and decarbonisation of the electricity supply also occurs more gradually.

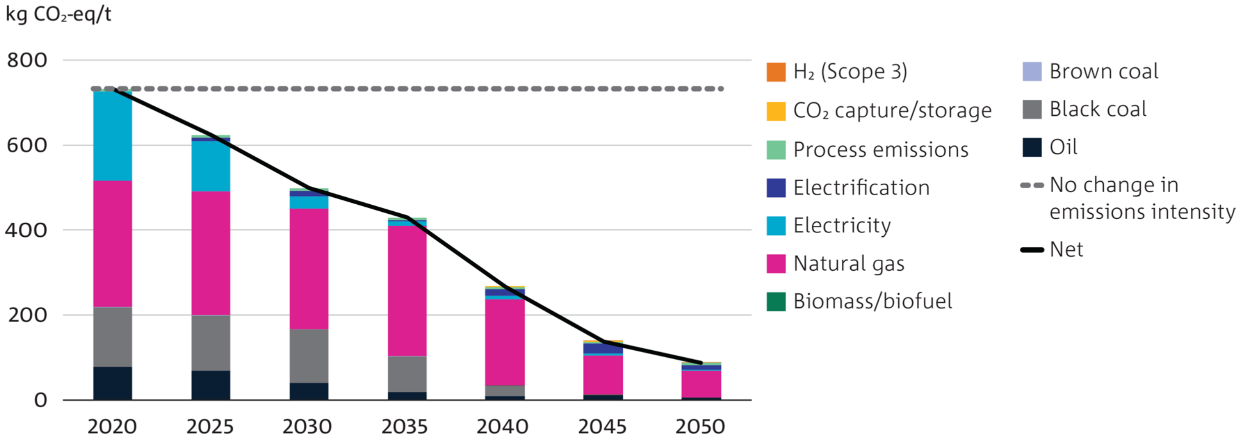
In the near term, the CRD scenario projects electrification and decarbonisation of electricity supply also contribute to reducing emissions from alumina production (Figure 34, Figure 37). However, the most material emissions sources, coal and natural gas for high temperature heating, take longer to abate with substantial reductions occurring in 2040 and beyond. Studies and pilots occurring in the next five to ten years will determine whether these emissions reductions occur. In the CSP scenario, coal is displaced by natural gas rather than electrification, with emissions from natural gas remaining significant in 2050.

For aluminium production, decarbonising existing electricity supply provides short-term reduction opportunities in the CRD scenario. Process emissions have few currently feasible reduction options. Innovation, such as development and trial of inert anodes, will be needed before process emissions can be significantly reduced from 2040 onwards (Figure 34, Figure 37). The implementation of inert anode technology in aluminium smelting necessitates the additional consumption of electricity (see Figure 36), although this is assumed to be offset by ongoing improvements in process energy efficiency to 11kWh/kg by 2050 (Matthews et al., 2020). CSP assumes that decarbonisation of the electricity supply occurs more slowly, and energy efficiency improves only to 12.5kWh/kg.

EMISSIONS INTENSITY IN BAUXITE MINING SECTOR: CRD



EMISSIONS INTENSITY IN ALUMINA SECTOR: CRD



EMISSIONS INTENSITY IN ALUMINIUM SECTOR: CRD

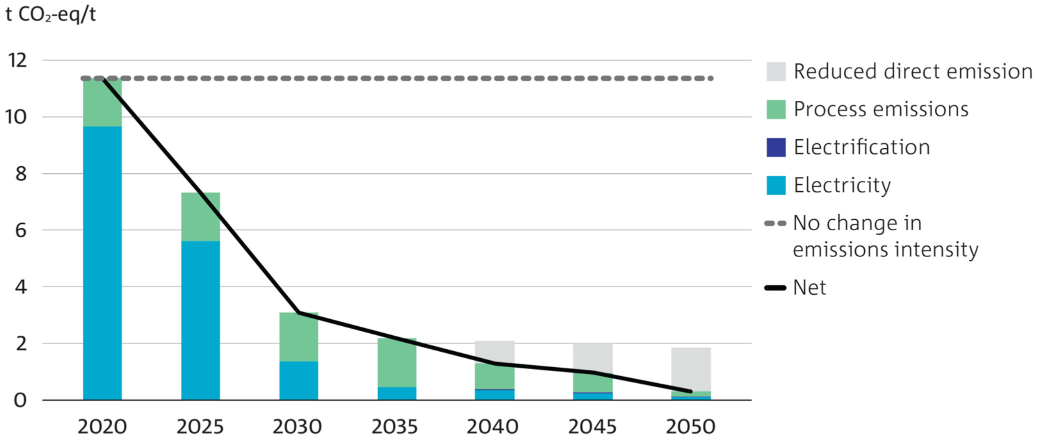


Figure 34 Emissions intensity in the aluminium supply chain in the CRD scenario

Source: AusTIMES

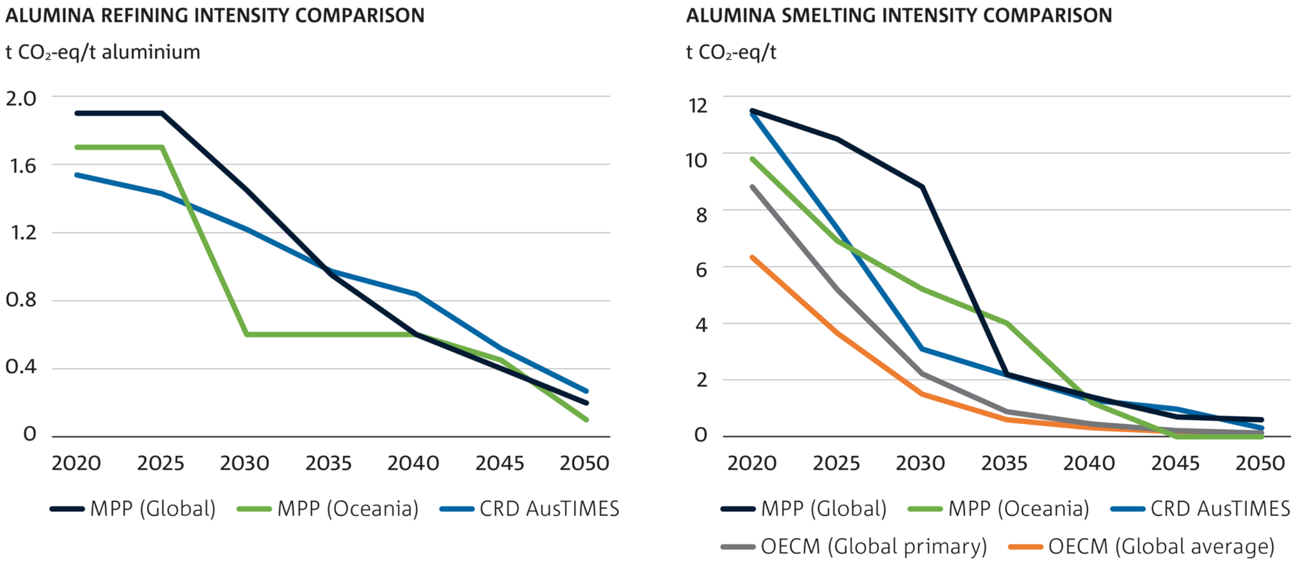


Figure 35 Emissions intensity in the aluminium supply chain, benchmark sources compared to AusTIMES in the CRD scenario

Source: Teske et al. (2020), Mission Possible Partnership (2022), AusTIMES, and CSIRO analysis

Opportunities, risks and challenges

Smelters connected to the NEM have an opportunity to participate in demand response by curtailing loads in periods of high demand and price. This could generate cost savings from reduced energy consumption in periods of high pricing and create an additional revenue stream. Renewable power purchase agreements to decarbonise electricity supply could be an opportunity to lock in longer-term price certainty for stable and predictable loads. Australia has an opportunity to leverage its renewable energy resources to produce aluminium at lower emissions intensity than international competitors. As demand for green metals (a metal with lowest total life cycle carbon emissions per useful life cycle) (Lord et al., 2019) increases this could attract a price premium.

The technical challenge to abate high temperature heating emissions and process emissions for this sector should not be underappreciated. Significant investment in research, development and pilots along with industry collaboration will be needed to commercialise decarbonisation measures. Additionally, green hydrogen industry may contribute to decarbonisation of the alumina production process. In such a case, hydrogen would need to be produced in co-located facilities or transport infrastructure will need to be established.

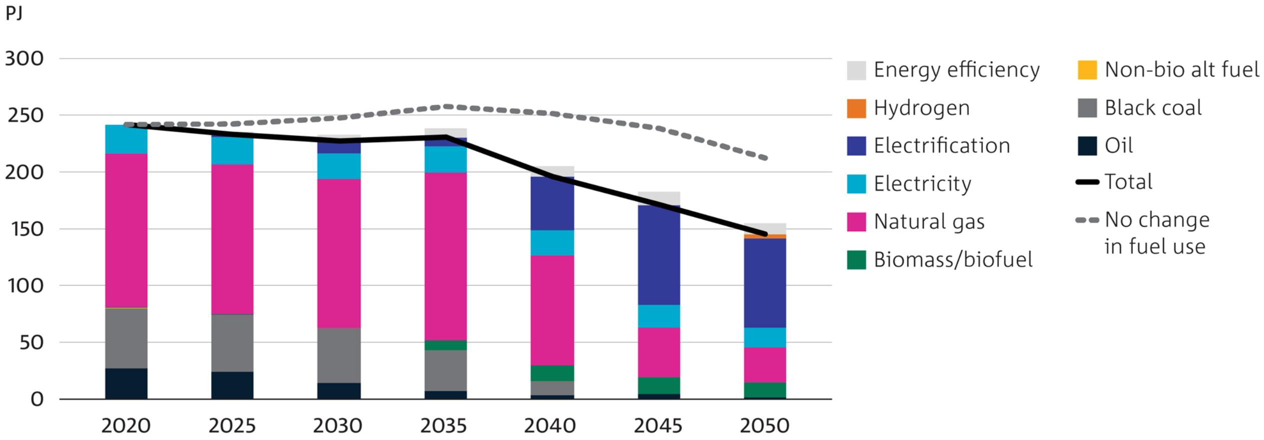
Implications

The bauxite, alumina and aluminium sectors are very cost sensitive which may inhibit their ability to invest in research and development and decarbonisation measures with long-term pay-back. A material rise in costs without adequate protections could see Australia lose market share to overseas producers. This could have a knock-on impact to the rest of the industry. At the same time, failure to make these investments also exposes the industry to higher costs. Aluminium will be a sector covered under the EU CBAM, which will see the sector having to pay an EU-equivalent carbon price on scope 1 emissions. Although this incentive may be low for the EU alone (less than 1% of Australia's aluminium exports are sold into the EU)[37] the use of border adjustment schemes could become more ubiquitous, with the UK, Japan and Canada currently considering similar schemes. This, along with pending changes to the Safeguard Mechanism baselines, creates a financial incentive to electrify material scope 1 sources (diesel, natural gas, and coal).

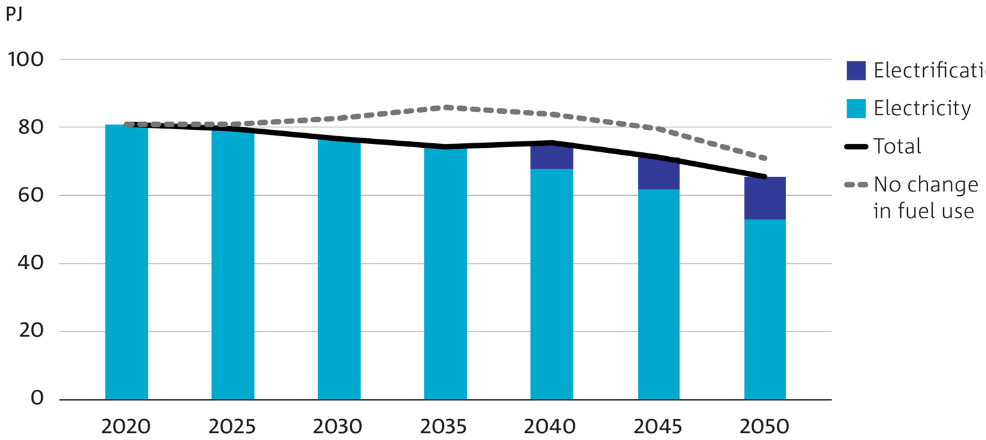
Without a near term payback for research and pilots, the finance sector's willingness, and the industry's ability to make significant investment may be constrained. Government funding, such as through ARENA's low emissions metals focus area, could play an important role in decarbonising hard-to-abate sources in this sector.

[37] https://cdn.aigroup.com.au/Reports/2021/CBAM_summary.pdf

FUEL USE IN AUSTRALIAN ALUMINA SECTOR: CRD



FUEL USE IN AUSTRALIAN ALUMINIUM SECTOR: CRD



FUEL USE IN AUSTRALIAN BAUXITE MINING SECTOR: CRD

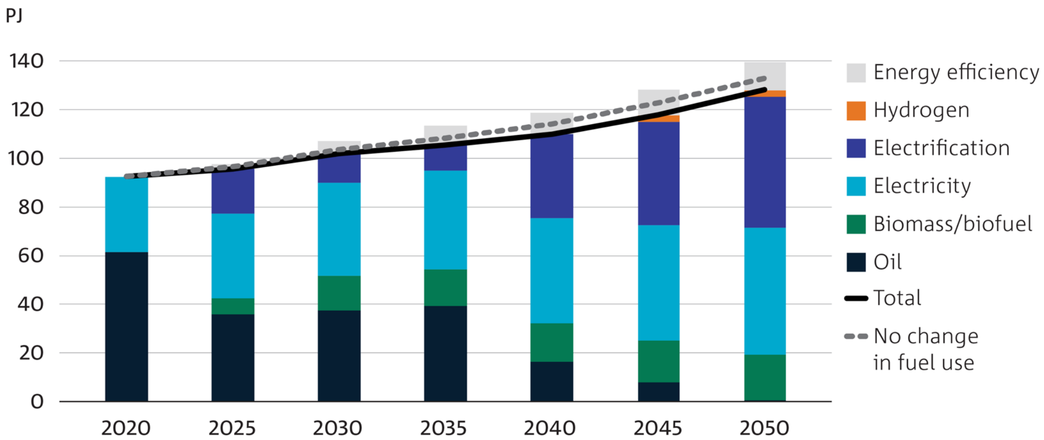


Figure 36 Fuel use in the aluminium supply chain in the CRD scenario[38]

Source: AusTIMES

[38] "Energy Efficiency" refers to a reduction in fuel use intensity owing to investment in more energy efficient production processes using the same fuel. It does not include changes in fuel use intensity from changing the production process resulting in fuel switching.

Cement

Emissions, production and demand shifts

Cement production involves quarrying and crushing raw materials, heating them in a kiln with additives to produce clinker, then grinding and mixing the clinker with gypsum and limestone. Most of the industry's emissions arise from the production of clinker, a portion of which is imported into Australia meaning that its production emissions are not included in this analysis. Clinker production has the dual decarbonisation challenge of requiring very high heat and producing carbon dioxide as a by-product. To address the high heat challenge, some of the gas and coal consumed could be replaced with biomass, hydrogen, or other alternative fuels (such as those derived from solid waste). Electric kilns may also be an option in the long term. However, in the CRD scenario complete displacement will not be achieved by 2050 (Figure 38). Table 32 and Table 33 in the Appendix lists some additional quantitative assumptions and sources for the cement sector, with Table 30 also listing some relevant sources.

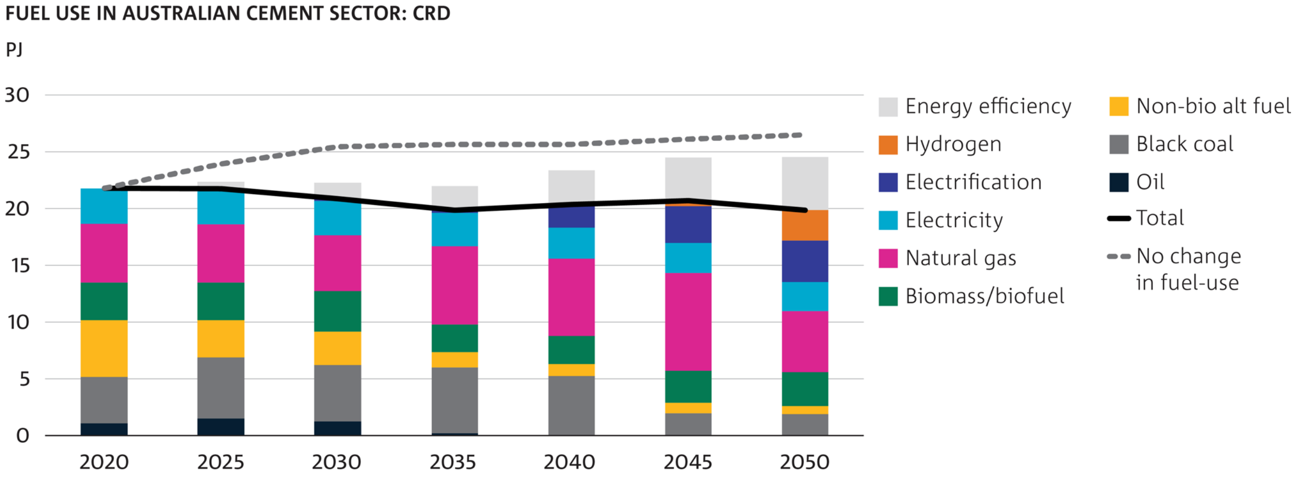


Figure 37 Fuel use in the cement sector in the CRD scenario

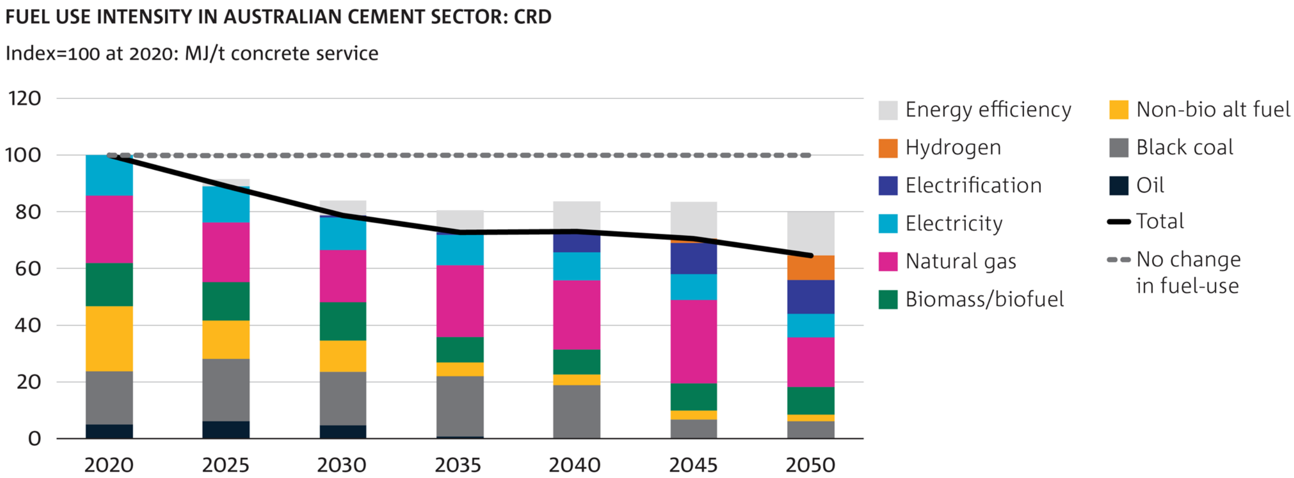


Figure 38 Fuel use intensity in the Australian cement sector in the CRD scenario

Source: AusTIMES

To address cement process emissions, carbon capture will need to be deployed post 2035 (Figure 39). This increases the energy intensity of production as carbon capture requires additional energy (assumed in the modelling to be provided by electrification). Direct capture of carbon dioxide from relatively pure gas streams has been identified as a key technology for decarbonising cement production. These technologies are currently at the demonstration stage in this sector and will take some time and innovation to achieve market maturity (IEA 2021a).

For other emissions sources, there are opportunities to reduce the emissions intensity of cement by displacing some of the clinker with other additives (supplementary cementitious materials (SCMs) such as slag and fly ash). Electrification options to displace diesel (such as for transport and quarrying machinery) are expected to become more commercially available and cost effective over time. There are immediate opportunities to decarbonise electricity use for sources which are already electrified.

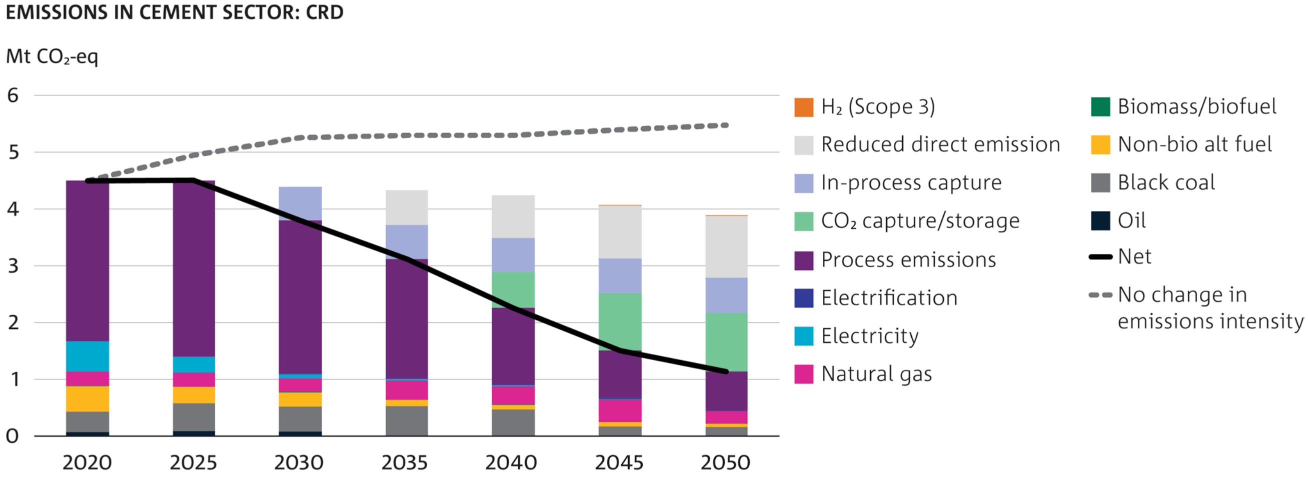


Figure 39 Emissions in cement sector in the CRD scenario[39]

Note: "No change in emissions intensity" means emissions that otherwise would have occurred with no change in emissions from current intensities, given the projected change in production

Source: AusTIMES

The CRD projects growth in the demand for cement and concrete as we transition to a low carbon economy. Over the period to 2050 demand is projected to grow by 27% relative to 2020 levels. This will come from industries such as electricity (for wind power, hydropower, and new electricity infrastructure), construction (for built environment and transport), and mining. The CSP scenario projects slightly higher growth of 33% relative to 2020 levels.

[39] This excludes emissions from imported clinker.

EMISSIONS INTENSITY IN CEMENT SECTOR: CRD

Index=100 at 2020: kg CO_2-eq/t concrete service

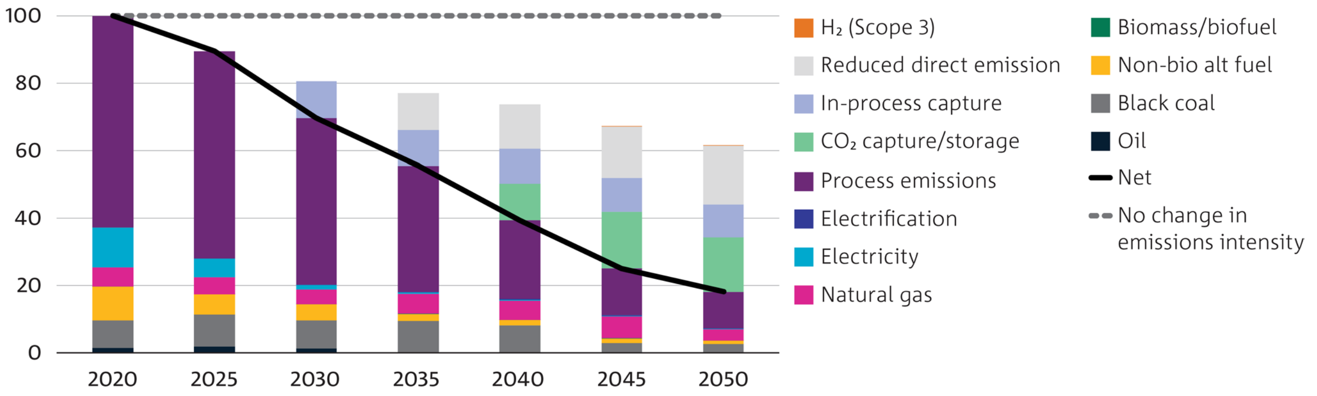


Figure 40 Emission intensity in cement sector in the CRD scenario in terms of construction service requirements[40]

Source: AusTIMES

Opportunities, risks and challenges

Similar to the aluminium sector, decarbonising the electricity supply of a cement production facility will reduce the emissions intensity of production and to secure longer term power price certainty (if done through a renewable power purchase agreement). Companies producing cement at a lower emissions intensity to competitors may also be able to sell at a price premium and reduce the impact of domestic and international carbon pricing (see Bauxite, alumina, and aluminium section).

Options to displace natural gas and coal all have technical or commercial challenges. Green hydrogen is in its infancy but is being trialled for similar high heat applications (see Bauxite, alumina, and aluminium section). For biomass, biofuels and other alternative fuels scale and consistency of supply may be hurdles to broader uptake. Competition for biofuels from other hard-to-abate industries, such as aviation, is likely to be high (see Transport section 3.3).

The production of carbon dioxide arises from the reaction in the clinker production process and is unavoidable. This will remain a hard-to-abate source which either needs to be captured (and used or stored) or offset. Investment in carbon capture, use and storage will be important to address the different needs and technical challenges to this sector. Research suggests that there are some opportunities for circularity in the production process, where captured carbon dioxide could be mineralised and used within a supplementary cementitious material (SCM).[41]

[40] This excludes emissions from imported clinker and cement, and is based on an assumption of cement demand in 2019-2020 of 11.7 Mt. To show potential emissions reductions from all reduction levers in VDZ (2020), including reduced concrete requirements in the construction sector and reduced cement requirements in concrete, the intensity here is expressed as an index in terms of emissions per unit of concrete service demand. Projections assume domestic clinker production remains the same proportion of total clinker requirements as initial year and cement imports remain as the same proportion of total demand. For intensities expressed in terms of tonnes of cement, and corresponding adjustment factors, see p121.

[41] https://www.nature.com/articles/s43247-022-00390-0

Implications

Opportunities in this sector are characterised by lower technology readiness. There are several barriers to investment in research and development:

- Low profit margins in the industry reduce its ability to invest in projects with uncertain outcomes or long payback periods.
- Nascent markets for green products.
- Low willingness to invest by the finance sector in early research, development, and pilots particularly when the commercial benefit is uncertain.

These barriers could slow the decarbonisation progress for this industry and limit international competitiveness in a low carbon economy. To address some of these barriers government incentives or co-investment may be required.

Upcoming changes to the Safeguard Mechanism, and international carbon boarder adjustment schemes, may increase costs but could also act as a financial incentive to decarbonise material scope 1 sources (natural gas and coal). A material rise in costs without adequate protections could see Australia lose market share to overseas producers. This could have a knock-on impact to the rest of the industry.

Iron ore, iron and steel

Emissions, production and demand shifts

Emissions from the mining of iron ore arise primarily from electricity use and diesel consumed in haul trucks, heavy machinery, and transport. Decarbonisation opportunities include electric haul trucks, hybrid diesel-electric with trolley assist, and hydrogen fuel cell trucks. Electric conveying is feasible and in-pit crushing provides opportunities to reduce material movement. For transport between mine and port large miners are trialling battery electric trains with regenerative drives.[42] All these opportunities require a low emissions energy source. For grid-connected mines opportunities exist now to decarbonise electricity. Renewable power purchase agreements are becoming more widely used. For mines not connected to a national grid which generate their own power or receive power directly from third party generators, decarbonising electricity presents an operational challenge. Storage and load shifting may be required, and the path to decarbonisation will be more costly. Mines needing hydrogen to displace fossil fuels will need a low to zero emissions source so that the emissions benefit of doing so is retained. New mines and expansions have the opportunity, and the imperative given their long operating lives, to design for net zero.

In the steelmaking process, the most material emissions sources come from metallurgical coal (used in blast furnaces for its chemical properties and to generate heat) and carbon dioxide (produced as a by-product of the reduction process). Hydrogen and biomass could be used to reduce emissions intensity but cannot fully displace metallurgical coal in the typical blast furnace and basic oxygen furnace production process. CCUS comes with challenges which need to be surmounted (see section 4.2) to reduce the emissions output from existing assets.

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[42] Including Fortescue (https://www.fmgl.com.au/in-the-news/media-releases/2022/09/20/fortescue-announces-execution-plan-for-industry-leading-decarbonisation) and BHP (https://www.bhp.com/-/media/documents/media/reports-and-presentations/2022/221003_waiospeeches.pdf)

A less emissions intensive, and less commonly used, process involves directly reducing the iron ore (using natural gas or hydrogen as an input) and then producing steel in an electric arc furnace. If green hydrogen is used this has the potential to produce steel at low emissions intensity. Australia faces challenges given most iron ore produced in Australia is not suited to this process (see challenges and opportunities section below).

Other options to reduce the emissions intensity of the sector is to increase steel recycling using electric arc furnaces which can produce steel at much lower emissions intensity than primary production. Scrap steel is an important input into basic oxygen furnaces and electric arc furnaces for producing steel from iron ore. Availability is one of the key challenges of greater utilisation of scrap steel as it is typically used in long life applications (such as transport, infrastructure and buildings).

The CRD scenario projects Australian steel production will increase over the period to 2035 before declining. This is driven initially by economic activity and population growth before relative cost pressures see some production moving offshore. In iron ore mining, electrification and decarbonisation of electricity enable significant emissions reduction. Hydrogen plays a minor role. The fuel mix in the CSP scenario follows a similar path to CRD (Figure 41, Figure 42) although electrification occurs slightly earlier and faster in the CSP scenario, the resultant emissions reduction is less vigorous as the emissions intensity of the electricity sector is higher in that scenario. Table 34 and Table 35 in the Appendix lists some additional quantitative assumptions and sources for the iron and steel value chain.

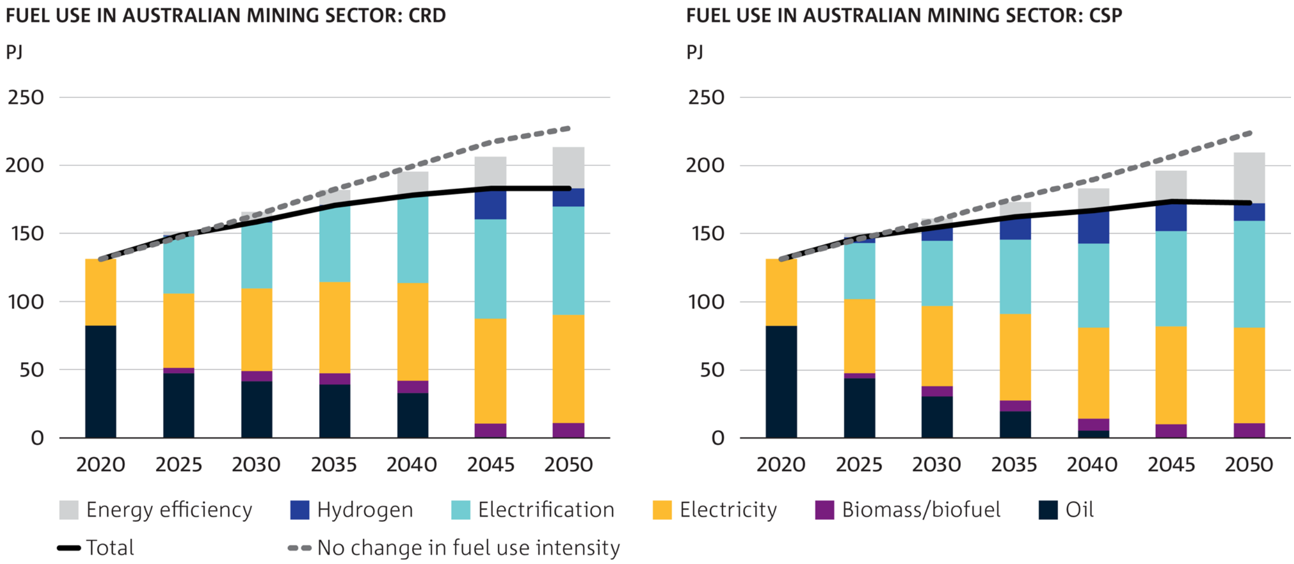

Figure 41 Fuel use in Australian iron ore mining sector in the CRD and CSP scenarios

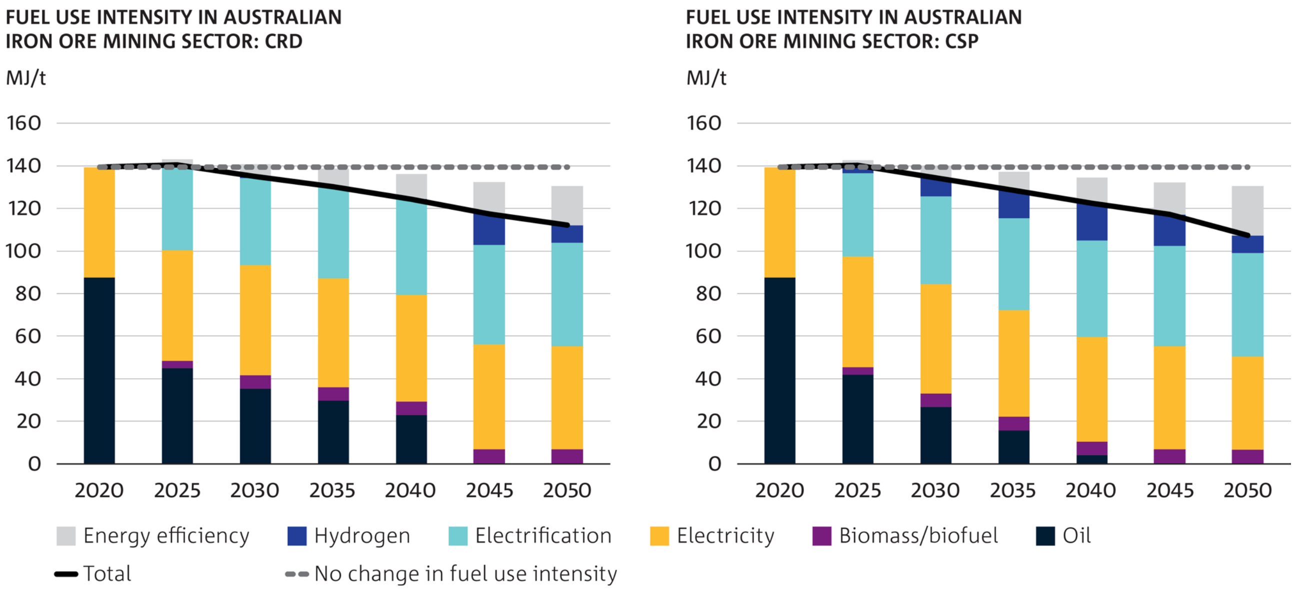

Figure 42 Fuel use intensity in Australian iron ore mining sector in the CRD and CSP scenarios

Source: AusTIMES

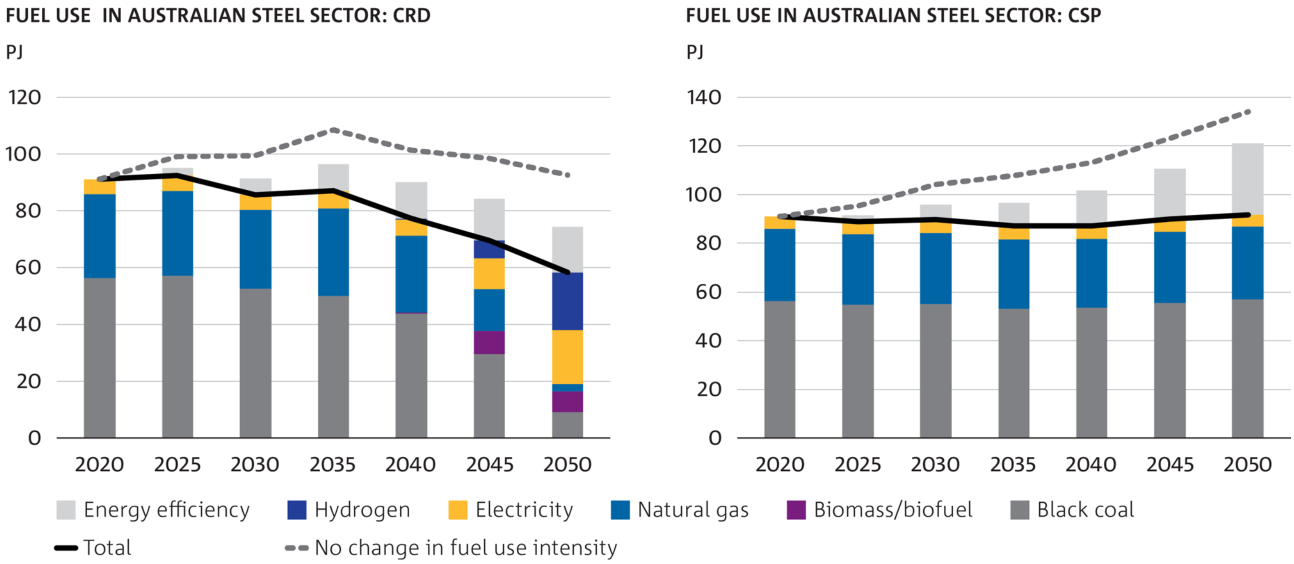

Figure 43 Fuel use in Australian steel sectors in the CRD and CSP scenarios

Source: AusTIMES

In steel production processes decarbonisation is relatively incremental in the near term. Some reductions are projected from increased efficiency and low emissions electricity consumption. Over the long term the modelling assumes a greater use of electric arc furnaces using scrap or direct reduced iron with green hydrogen as an input. This delivers deeper decarbonisation from 2040 onwards (Figure 45, Figure 48).

The relatively small production quantity of Direct Reduction Iron (H_2)-EAF projected in 2040 in the CRD scenario (Figure 46) is a consequence of the AusTIMES model structure, which tracks the capital stock, but also permits incremental capital investment and assumes perfect forecasting of demand (provided by KPMG-EE). Hence the projected production results are indicative only.

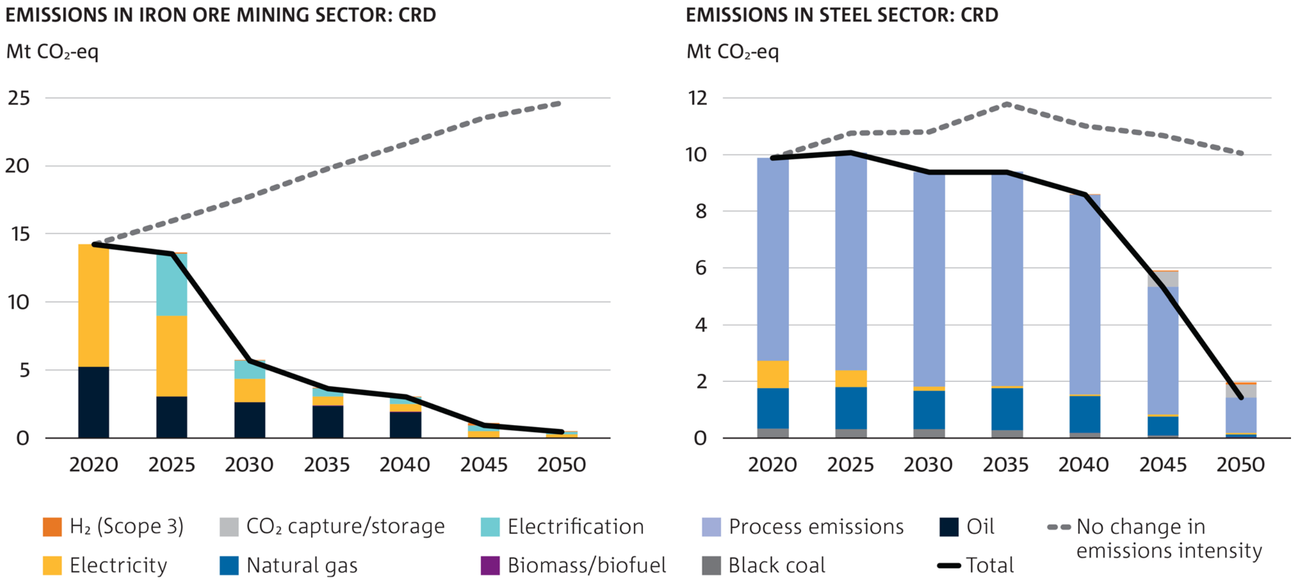

Figure 44 Emissions in the iron and steel sector in the CRD scenario

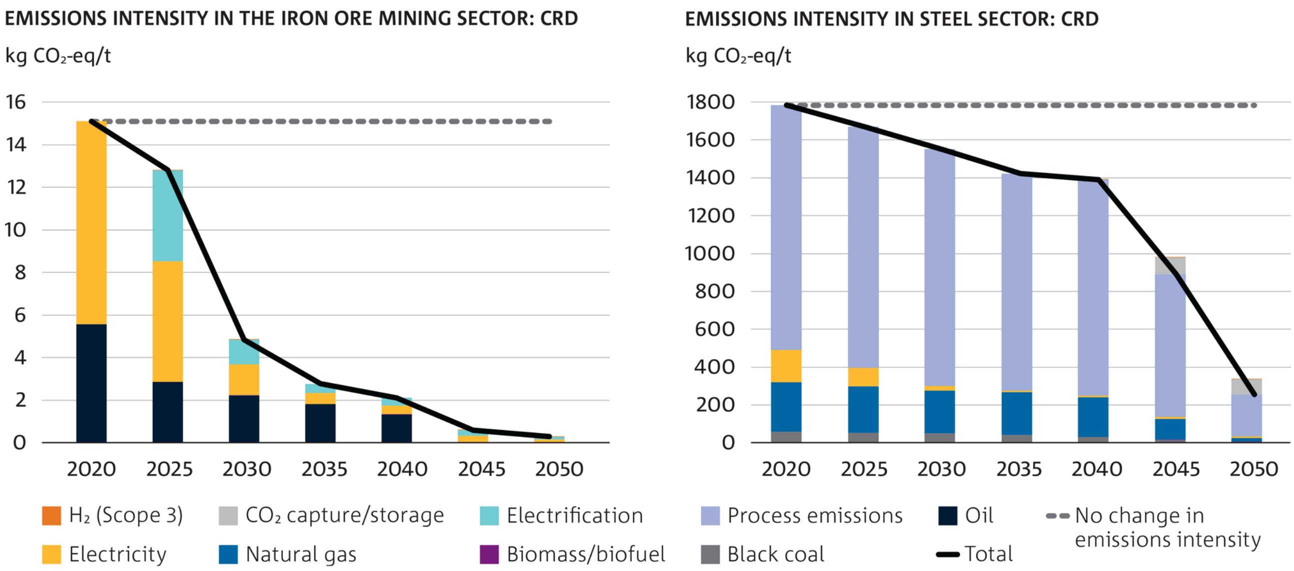

Figure 45 Emissions intensity in the iron and steel sectors in the CRD scenario

Source: AusTIMES

Opportunities, risks and challenges

Iron ore mines are long life assets and those developed now are likely to still be operational in 2050. In this context planning for net zero for new developments and expansions will be vital to avoid more costly decarbonisation later. An increase in net zero commitments in the mining sector more broadly demonstrates a recognition of these risks and opportunities. As demand for green steel grows and value chain emissions become more important, low emissions producers are likely to find it easier to obtain finance, may be able to attract a green premium for their products, and will avoid carbon penalties. All producers may find themselves with higher expectations associated with the traceability of emissions and other environmental and social impacts in their value chain. An increasingly stringent and non-stationary legislative environment should be anticipated such as ongoing increases to environmental licence requirements.

Mines and smelters have the opportunity to lock in low emissions electricity supplies and longer-term price certainty through renewable power purchase agreements. However, the technical challenge to abate process emissions for this sector should not be underappreciated. Significant investment in research, development, and pilots along with industry collaboration is underway to commercialise decarbonisation measures. Green hydrogen could play a role in displacing a portion of existing gas use but comes with some challenges which need to be surmounted (see alternative fuels in section 4.4).

Australia faces the additional challenge that the majority of iron ore produced is unsuitable for current methods of green steel production. As the sector transitions, Australia will either need to shift production towards ore suited to direct reduction iron, of which there are substantial deposits, or identify low emissions technology suited to the majority of iron ore produced by Australia (ClimateWorks Centre and Climate KIC Australia 2023). The research path is attractive because of the high iron content of most ore currently produced by Australia relative to that suited to direct reduction iron.

At a whole of economy level there is an opportunity to onshore more steel production to leverage our national renewable energy resources and produce steel at lower emissions intensity than international competitors. Greater vertical integration could create more jobs in smelting and manufacturing. Doing so would require Australian energy and other costs of production to be more competitive globally than our key competitors.

Implications

Demand for green steel is likely to grow from manufacturers, vehicle manufacturers and other downstream purchasers. However, decarbonisation opportunities are fairly limited for existing furnaces. Deeper emissions reduction is likely to need new electric arc furnaces and greater recovery and utilisation of scrap. In the longer term this could impair or strand blast and basic oxygen furnace assets. There is also the potential for carbon pricing (either domestic or international) to materially impact this sector given near term scope 1 decarbonisation opportunities are limited (see Bauxite, alumina, and aluminium in section 3.4).

Even with direct reduction and electric arc furnaces, green hydrogen will be part of the industry's critical path to decarbonisation. It will be crucial to avoid high emissions lock-in in the hydrogen industry as it forms (see 4.4).

Without a near term payback for research and pilots, the finance sector's willingness, and the industry's ability to make significant investment may be constrained. Government funding, such as through ARENA's low emissions metals focus area, could play an important role in decarbonising hard-to-abate sources in this sector.

PRODUCTION IN AUSTRALIAN STEEL SECTOR: CRD SCENARIO

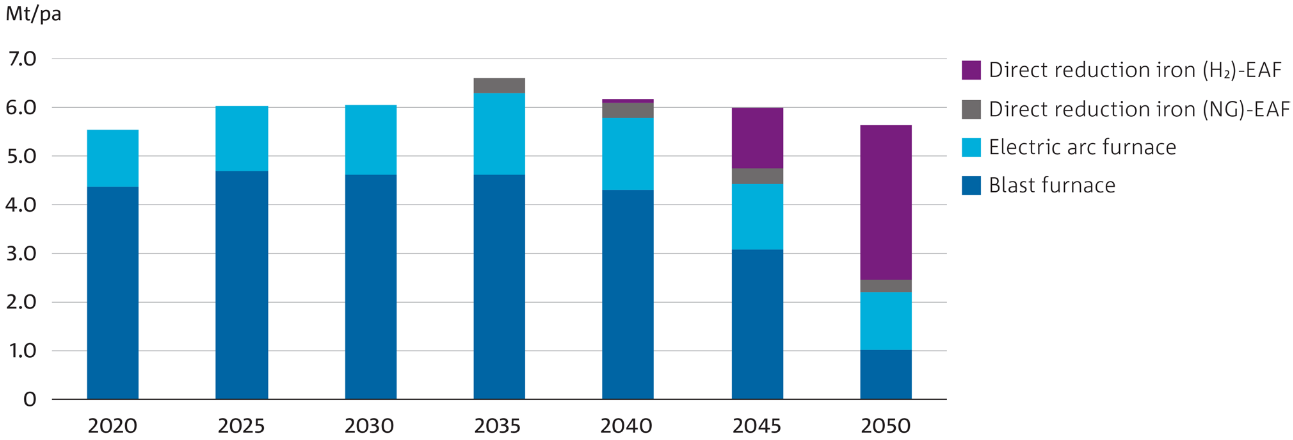

Figure 46 Steel production by process in the CRD scenario[43]

Source: AusTIMES

[43] Note that a limitation of the modelling framework is that it is scalable rather than depending on either investment in plant over time or conversely plant closure to reduce production. That is, the model does not enforce a production change aligned with minimum plant size (see Appendix A.2.3). Where only small increases in production are shown in 2035 and 2040 with new production processes, this should be interpreted as an expectation that these production processes would be cost competitive relative to the alternatives for *new* investment at scale.

Table 8 Low-carbon energy use milestones by industry type by decade

		2020	2030	2040	2050
Mining	Electricity	35.5%	60.9%	66.5%	82.9%
	Hydrogen	0.0%	1.1%	1.7%	8.7%
Alumina production	Electricity	10.5%	14.6%	35.2%	66.2%
	Hydrogen	0.0%	0.0%	0.0%	2.6%
Steel production	Electricity	5.8%	6.2%	7.7%	31.6%
	Hydrogen	0.0%	0.0%	0.6%	35.3%
Cement production	Electricity	14.3%	15.5%	24.7%	31.3%
	Hydrogen	0.0%	0.0%	0.0%	9.4%
Total industry	**Electricity**	**18.9%**	**26.5%**	**34.0%**	**70.8%**
	Hydrogen	**0.0%**	**0.1%**	**0.2%**	**3.1%**

4 Wider sectoral implications of CRD for Australia

In this section we provide a more detailed picture of the CRD transition across sectors likely to be directly and indirectly impacted. Detailed analyses of technology options and pathways were not undertaken within these sectors. These results are drawn from the CRD (and to a lesser extent) CSP scenarios using the approach described in Appendix A Technical Supplement. Note that we are focused on the direct economy impacts of a net zero transition and do not include the chronic and acute costs of climate change (see Figure 6, Section 1).

4.1 Agriculture, forestry and other land-use (AFOLU)

Emissions, production and demand shifts

Australia's agriculture sector encompasses livestock (primarily sheep, beef, and dairy cattle), fisheries, grains, fibres, and other biomaterials. Domestically we produce about 90% of our food needs (Ridoutt et al., 2017) and the sector also forms a valuable export industry. Most forestry production is from plantations with a small share from native forest.[44]

Australian agricultural production is modelled to increase by around 80% by 2050. At the same time agricultural emission intensity is projected to fall by over half (54%) meaning that sectoral emissions only decline by 14%. Most agricultural emissions (90%) are methane (CH_4) (from livestock and nitrous oxide (N_2O), (mainly from fertiliser use). Comparison of results with other modelling exercises is complicated due to the different assumptions around sectoral growth and innovation efficacy. Note also that limited industry engagement was undertaken in modelling changes in the agricultural sector. However, we note that our results are broadly similar to recent Australian Government modelling (Australian Government, 2021) and others who suggest that approximately halving emissions intensity is possible by 2050 while larger reductions in methane emissions from livestock are necessary to reduce sectoral emissions further. The CSP scenario projects a slower uptake of agricultural emission reduction measures and fewer carbon credits than in CRD.

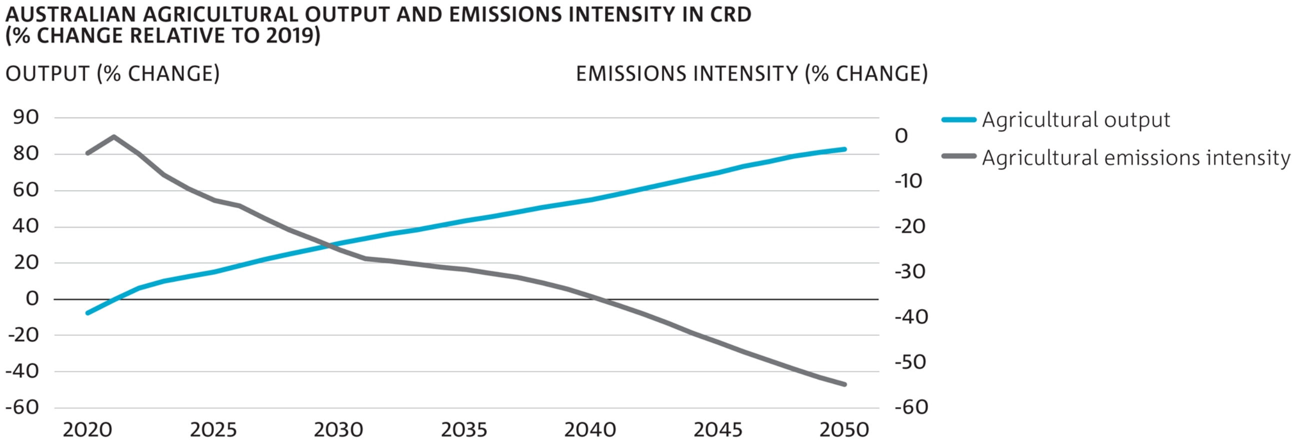

Figure 47 Australian agricultural output and emissions intensity in the CRD scenario

[44] https://www.agriculture.gov.au/abares/products/insights/snapshot-of-australias-forest-industry#log-harvest

This is a complex sector: many parts of the agriculture, forestry and landuse (AFOLU) sector can be either an emissions' sink or source depending on how they are managed. For example, land clearing (for development, agriculture, and forestry harvest) increase emissions, whilst avoided clearing and improved forest management reduce emissions. Overall, these practices currently deliver substantial negative emissions (relative to Australia's baseline). Sinks from vegetation and vegetation or fire management projects, though small overall, have generated more than half of the Australian Carbon Credit Units (ACCU) issued to date (noting many landuse, landuse change and forestry (LULUCF) activities measured in the National Greenhouse Accounts result in sinks that may not result in ACCU generation).[45]

Enteric methane emissions from livestock are a key hard-to-abate source in this sector. While opportunities exist to reduce the emissions intensity of livestock production (such as through immunisations and change in feed) greater decarbonisation may depend on reducing red meat consumption.

In aggregate, the overall AFOLU sector, encompassing both agriculture and LULUCF, moves from being a net emissions source to a net carbon equivalent sink by 2030 through increasing sequestration in vegetation and soils. Tree-planting and other forms of agricultural behaviour are modelled as sequestering around 3 Gt CO_2-eq from 2020 to 2050. The large increase in agricultural carbon sequestration is not projected to have a substantial impact on production as the majority of these are projected to be generated from marginally productive lands or in ways that complement productivity (Australian Government 2021). Some caution should be exercised in how this positive story is interpreted because a non-trivial portion of sequestered carbon may be sold as carbon credits (via ACCUs) to buyers outside the sector (which if subtracted could imply agriculture remains a net positive emissions source).

Future work is needed to refine this analysis as modelling does not capture the physical climate impacts to this sector, which include changes in rainfall patterns, increases in average temperature and temperature extremes, and rising sea levels. These impacts have the potential to decrease agricultural productivity and nutritional value and increase costs. The modelling also does not capture potential changes in consumer preferences, such as greater demand for plant-based alternatives or cultured meats. Reducing waste through behaviour change and improved waste utilisation using circular systems has also not been captured.

Opportunities, risks and challenges

Australia has world leading research capability in reducing agricultural emissions and effective translation of research to industry could accelerate sectoral decarbonisation. Even with these measures, agriculture is anticipated to become one of the largest sources of residual emissions, increasing from 14% in 2020 to 39% of gross emissions in 2050.

Australia's significant land mass, including degraded and marginal land, provides an opportunity to offset land use emissions through afforestation and reforestation. Creating carbon offsets from vegetation and soils can provide an additional revenue stream for farmers and can often be

[45] https://www.cleanenergyregulator.gov.au/maps/Pages/erf-projects/index.html

undertaken in a way which complements existing practice, utilises marginal parcels and supports natural capital.

However, there are complex measurement, tracing, and carbon accounting challenges as the sector navigates to net zero. Double counting can easily arise and is often poorly understood (for example by selling an offset certificate and still claiming the benefit). These factors expose the unwary or unscrupulous to risks of greenwashing if diligence is not applied. Hence the importance the recent review into the integrity of the Australian Carbon Credit Units (ACCU) scheme which found the overall approach was sound, as well as identifying continual improvements to protect integrity into the future.[46]

Implications

Innovation will help to reduce emissions but will be insufficient for the agricultural sector to reach net zero. A combination of demand side changes (to preferences and diets) and supply-side changes (for efficiency, waste and circularity) will be required. Residual emissions will need to be offset. On-farm vegetation, soil or biogas projects could be a complementary way for some of this abatement to be delivered. Strong land use regulation at state and territory level is also needed to prevent avoidable deforestation and retain the biodiversity value of established ecosystems.

The physical impacts of climate change on this sector could be substantial if not mitigated. There is potential for some locations to become less viable for farming. This could include locations where livestock would be vulnerable to changes in heat and humidity outside their levels of tolerance, or where rainfall patterns may make cropping and irrigation needs too high and expensive to maintain viability. This is an area where further modelling is required.

4.2 Negative emissions

Emissions, production and demand shifts

Negative emissions result from technologies that remove carbon dioxide and either use or store it. Storage may be biological (in vegetation and soils, see previous section), geological (such as underground storage in oil and gas reservoirs), and in mineral form (such as through mineral carbonation, which accelerates weathering of rocks to sequester carbon dioxide).

Many of these technologies are nascent but are projected to form a substantive part of the net zero story. The modelling of the CRD scenario assumes a conservative role for negative emissions projecting total annual negative emissions of 7.2 Gt CO_2 per annum globally by 2050 (comprising 5.8 Gt CO_2 from non-specific technology such as DACCS and 1.4 Gt CO_2 from BECCS). Of this Australia is projected to capture 84 Mt CO_2 by 2050 (comprising 66 Mt CO_2 from non-specific technology including DACCS and 18 Mt CO_2 from BECCS) (see Table 9). Potential measures include CCS to assist with the decarbonisation of some hard-to-abate sources in the aluminium, cement, and steel sectors. In this capacity CCS plays a role in reducing emissions from these sectors but does not contribute to negative emissions.

[46] https://www.dcceew.gov.au/climate-change/emissions-reduction/independent-review-accus

This contrasts to the IEA's net zero roadmap which projects that 7.6 Gt CO_2 per annum will be captured globally by 2050 and 95% of that will be permanently stored.[47] The IEA's analysis also includes a role for DACCS and BECCS. The role of BECCS in Australia is anticipated to be limited, due to the high cost of BECCS compared with renewable energy. Interest in DACCs is growing and IEA analysis suggests it will form part of global decarbonization pathways.[48] Early-stage research, studies and business case development are underway, with the IEA suggesting that costs could fall to under \$100US/tCO_2, though CSIRO's research suggests DACCs will take time to become established with Australian projects in early stages of development (Fitch et al., 2022).[49]

Opportunities, risks and challenges

The IPCC emphasises that "*the deployment of carbon dioxide removal (CRD) to counterbalance hard-to-abate residual emissions is unavoidable if net zero CO_2 or GHG emissions are to be achieved*" (IPCC, 2022). New industries will emerge for those options which prove to be successful.

The IEA identifies that innovation will be needed across the DACCs value chain for large-scale projects to proceed and to overcome the lack of success to date. [48,50] In Australia there is huge potential with our abundant land resources and geological storage potential.[51] As with other nascent technologies, investment in research, trials and commercial pilots in the next five-to-ten years will be crucial to enable their roll out in the following decades.

Sequestration in vegetation is relatively well established and there is an opportunity to grow this sector subject to overcoming challenges in measurement to ensure the emissions reductions claimed have been achieved (see previous section).

Implications

Negative emissions are projected to form a key element of decarbonization – forming the 'net' element of net zero. There are risks if nations, jurisdictions, and companies pursue an offset dominant strategy in lieu of feasible decarbonisation options because this will delay the transition towards zero (but not necessarily net zero) emissions. Furthermore, current technology focused on land-based projects which sequester emissions for shorter periods than geological or mineral storage and have a higher risk of reversal. Delaying decarbonisation will increase the disorderly nature of the transition, the likelihood that it will be globally uncoordinated, and the speed and cost of future emissions reduction as offsets become less available and more expensive. This is more likely to impair or strand assets, impact Australia's longer-term competitiveness, and increase sovereign risk.

Building negative emissions into net zero pathways will require offsets with higher permanence and lower risk of reversal will become increasingly important to meet global decarbonisation objectives. Developing permanent storage options will require investment into technologies which

[47] https://iea.blob.core.windows.net/assets/deebef5d-0c34-4539-9d0c-10b13d840027/NetZeroby2050-ARoadmapfortheGlobalEnergySector_CORR.pdf pg. 79

[48] https://www.iea.org/reports/direct-air-capture-2022

[49] https://www.csiro.au/en/research/environmental-impacts/emissions/carbon-sequestration-potential

[50] https://www.sciencedirect.com/science/article/pii/S030142152100416X

[51] https://iea.blob.core.windows.net/assets/deebef5d-0c34-4539-9d0c-10b13d840027/NetZeroby2050-ARoadmapfortheGlobalEnergySector_CORR.pdf pg. 79

have a high capital outlay and risk of technical and commercial failure. Government investment has a role to play to establish viability. Commercial interest is growing in demonstration projects for both geological and mineral storage.[52] This modelling highlights a need for negative emissions technologies to reduce emissions from alumina, cement and steel production. By contrast, negative emissions technologies in hydrogen (e.g., steam methane reforming and CCUS) and electricity generation (e.g., gas with CCUS or BECCS) are projected to be immaterial in Australia as other more cost effective and technologically feasible decarbonisation options are available.

Table 9 Australian negative emissions milestones by decade (in units of Mt CO_2)

Technology type	2020	2030	2040	2050
LULUCF	25	76	123	128
BECCS	0	3	17	18
DACCS	0	14	63	66

Source: GTEM

4.3 Finance sector

Demand shifts

The global investment required to achieve net zero runs into the trillions of dollars. This excludes capital needed to respond and adapt to the physical impacts of climate change. The IEA's NZE scenario, projects between $US2 and $US2.5 trillion will be needed globally per annum for electricity sector transition alone, comprising about half of the total capital investment needed to achieve NZE.[53] The CRD modelling in this report estimates an additional $AU76 billion in investment over the existing trajectory in the CSP will be required in Australia from now to 2050 to shift the electricity sector transition. This represents a relatively modest difference in total investment in the electricity sector between CRD and CSP ($713 billion as compared to $637 billion).[54] Note that our modelling covers electricity as a sector of the economy inclusive of household and small business investments in rooftop solar, local distribution, and investments in areas outside the national electricity market such as Western Australia, which AEMO does not. Nevertheless, our modelling results are proportionately similar to AEMO modelling which suggests that the cost of replacing obsolete existing technology is also substantive (AEMO 2022). For example, the AEMO Integrated System Plan modelling suggests investment requirements under both 'progressive change' and 'step change' will require between $350 and $400 billion to be invested between 2023 and 2050 (AEMO 2022) with much of the debate around the optimal system configuration and generation mix rather than the overall cost. Our modelling suggests CRD generation investment requirements of $437 billion (Figure 48) noting again that this does also

[52] https://www.minister.industry.gov.au/ministers/taylor/media-releases/412-million-new-investment-carbon-capture-projects

[53] https://iea.blob.core.windows.net/assets/deebef5d-0c34-4539-9d0c-10b13d840027/NetZeroby2050-ARoadmapfortheGlobalEnergySector_CORR.pdf pg81

[54] CRD generation mix is broadly in-line with the AEMO's 'Strong Electrification' scenario whilst CSP generation mix is broadly in-line with 'Progressive Change'. The investment modelling in this report encompasses the electricity sector inclusive of local transmission and distribution whereas AEMO modelling relates only to utility scale generation and major new interconnectors in the national electricity market.

include generation in WA and NT along with rooftop solar, whilst AEMO modelling is limited to utility scale electricity generation and major interconnectors within the national electricity market in the eastern states. The modest difference in investment under different scenarios in both models is because the electricity sector transition to net zero is closely aligned with much of Australia's coal generation plant reaching the end of viable operating life and the cheapest replacement options involve a mix of renewable technologies alongside network and storage augmentation.

An important complicating factor, both in identifying a relevant business as usual case, and in structural shifts to new export industries, is the extent to which electrification of other sectors such as transport and heavy industry or the growth of a hydrogen sector would occur irrespective of the net zero transition and require a substantive growth in system capacity. For example, our modelled CRD scenario is closer to the 'strong electrification' scenario modelled by AEMO, which corresponds to significant growth in electricity demand. Were the transition to result in more modest electricity demand investment needs would be lower.

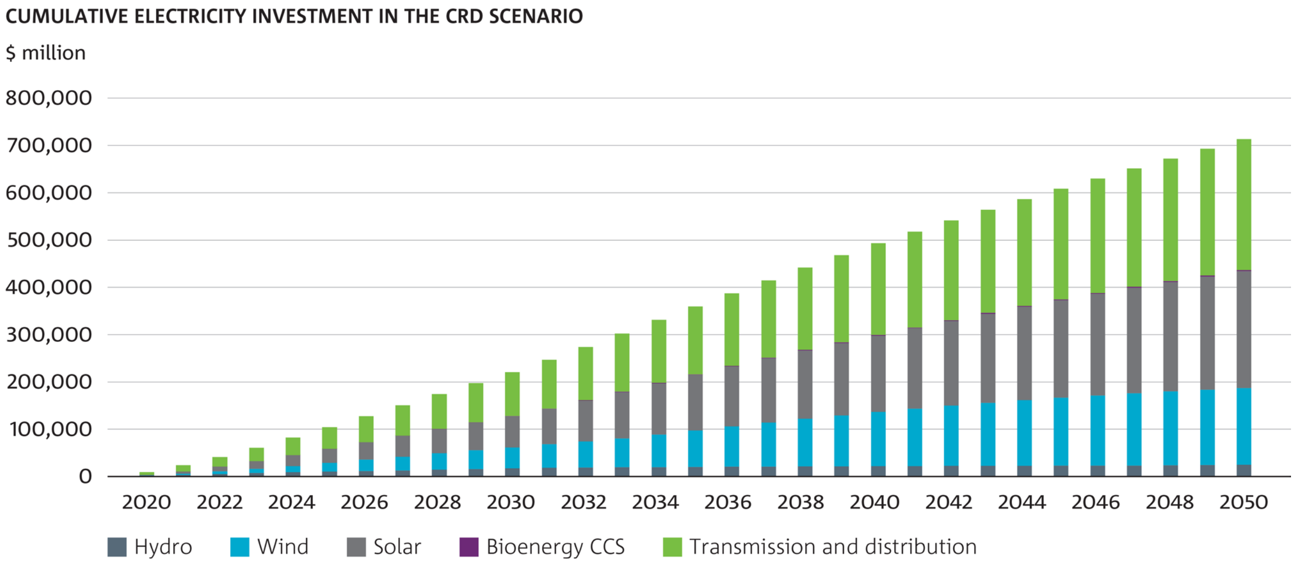

Figure 48 Cumulative electricity investment in the CRD scenario

Source: KPMG-EE

Opportunities, risks and challenges

A key challenge for the financial sector will be to adequately evaluate the risk of continuing with the status quo and to steer capital to where it is needed. There is an opportunity to drive greater decarbonisation within new and existing investments, such as creating financial incentives to support the achievement of sector-level emissions targets – which is one of the drivers of this analysis. For residential and small commercial buildings there are opportunities for banks to provide lower interest sustainable loans for measures which can reduce the emissions profile and increase the adaptive capacity for owner occupied and tenanted buildings.

Stakeholder pressure and an increasing focus on value chain impacts are also causing some investors and banks to reduce their exposure to high emissions activities.

The key challenge is the mismatch between investment opportunity and capital deployment arising partly from differences in scale and risk tolerance. Large institutional investors commonly seek high scale and low risk. Many have mandates (either regulated[55] or internally imposed) that restrict their ability to invest. In contrast, opportunities to invest in decarbonisation, particularly at pilot or demonstration phase, are often low scale and high risk. They may have long payback periods, uncertain cash flows, or even no immediate prospects of delivering a commercial return.

Capability is also a challenge. The growing interest in climate-related investment means that some finance professionals may find themselves with insufficient knowledge to evaluate the merits of technical proposals and advise on sustainable investments. Green growth in several industries has been rapid, causing an explosion of new market entrants. Diligence is needed when assessing the credibility and feasibility of investment opportunities. Data availability and integrity for sustainable investments can also be lacking. These issues impact the ability to benchmark investment performance and risk which undermines confidence in sustainable investments.

De-risking and scaling emerging technologies are key roles for Government. This may take several forms including taking first loss, providing some price certainty, or being a buyer of last resort. This involvement often enables private sector investors to participate within their risk tolerance. The role of clear and stable policy should also not be underestimated. This can help to provide some certainty for demand and enable markets for new technologies to emerge. This report outlines several priority sectors for de-risking investment in hard-to-abate sectors including aluminium, cement, negative emissions, heavy transport and aviation, and electricity infrastructure and storage. Some funding for these industries has already been allocated. ARENA and CEFC have and continue to play an instrumental role in commercialising new technologies and scaling their impact.

Implications

The scale of investment required in the transition may exceed the Government's capability or appetite to de-risk. This could result in a slow and disorderly transition. All of these things could lock the economy into a path dependency.[56] A vital part of the transition needs to be focused on facilitating and removing barriers to private sector investment and developing innovative finance models to reduce or spread risk.

4.4 Fuels and mineral resources

This section covers fossil fuels (energy coal, metallurgical coal, oil and gas), alternative fuels (hydrogen, biomass, and uranium) and mineral resources such lithium and cobalt.

[55] https://www.ato.gov.au/General/New-legislation/In-detail/Super/Super-Reforms---Your-Future,-Your-Super/

[56] https://www.ipcc.ch/report/ar6/wg2/downloads/report/IPCC_AR6_WGII_SummaryForPolicymakers.pdf

Fossil fuels

Emissions, production, and demand shifts

Coal, oil and gas, have historically played a critical role in Australia's economic prosperity. They currently make up more than 40% of our exports by value, generating over $200bn per annum.[57]

As the global economy decarbonises the outlook for these industries is rapidly shifting. Renewable energy, storage, and the electrification of transport will contribute to the near-term displacement of fossil fuels in Australia and other developed nations. The decarbonisation path for developing countries may be slower, and in some jurisdictions the demand for gas may temporarily increase in the period through 2040 as a lower emissions alternative to coal. Recent shifts in global demand and supply resulting from the invasion of the Ukraine by Russia, also complicate the near-term outlook for fossil fuels. Australia is not immune from these effects; gas prices have caused major disruption in the domestic energy market and substantial increases in coal and gas revenues.

PERCENTAGE CHANGE IN FOSSIL FUEL EXPORTS BY VOLUME COMPARED TO 2020

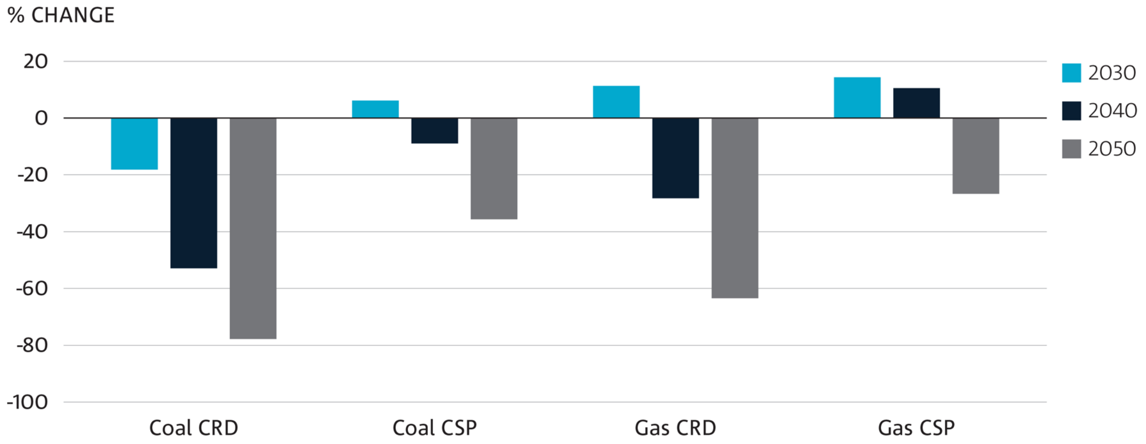

Figure 49 Percentage change in Australian fossil fuel exports by volume, CRD and CSP scenarios

In the CRD scenario, Australia's total coal production is projected to fall by 20% by 2030, 50% by 2040 and more than 75% by 2050. Demand for Australia's energy coal in particular, falls domestically and internationally. Domestic demand drops with the closure of coal fired power stations. Export demand falls as countries reduce their consumption and choose to use their own reserves. Remaining production in 2050 will be almost entirely metallurgical coal, a key input for steel production which is more difficult to displace. Australia's steel production capacity is small on a global scale and most of our metallurgical coal is exported. Innovative green steel production techniques are anticipated to reach commercialisation and begin to displace coal completely towards the end of the modelled period.

Natural gas has some commonalities with both energy and metallurgical coal. In some applications (including baseload and mid-merit electricity generation, space heating, and low to moderate industrial heating) natural gas can be more easily displaced. However, like metallurgical coal, gas is also used as a feedstock. In these applications it will be harder to displace in the near term.

[57] https://www.dfat.gov.au/publications/trade-and-investment/trade-and-investment-glance-2021#exports

Innovation in green hydrogen may open up options for longer term decarbonisation of these processes. The CRD scenario indicates Australia's natural gas production will peak before 2030 and then steadily decline by around one third by 2040 and almost two thirds by 2050. Internationally the shift away from gas is anticipated to occur more quickly for developed nations (such as Japan and South Korea) than it is for developing countries (such as China and India). The outlook for our liquified natural gas (LNG) export industry will be heavily influenced by how rapidly these shifts occur alongside the continuing shifts caused by recent market disruption.

In the CSP scenario key differentiators from CRD are:

- Slower rate of decline of coal production with a fall of just over a third (36% by 2050 compared to 2020 volumes)
- Gas production grows slightly through 2040 (peaking mid-2030s) before declining by just over a quarter (27%) compared to current levels by 2050.

Australia's oil exports, including crude and condensates, are dwarfed by our international counterparts and the majority of domestic oil consumption is imported. The decarbonisation path for this sector will be influenced in the near term by the electrification of light vehicle transport and the extent to which challenges to decarbonisation of other transport modes are overcome (see section 3.3).

Opportunities, risks and challenges

While there are near term opportunities for economic gain the risks and challenges to this sector are significant. Companies with significant fossil fuel revenues and reserves facing challenges to their social licence as climate litigation grows,[58] shareholder resolutions increase (Freeburn and Ramsay, 2021) and development conditions tighten (EPA, 2022). Investors are increasing their scrutiny of corporate emissions, net zero targets and transition plans.[59] Companies seeking to sell assets with direct or indirect exposure to fossil fuels (including Origin[60,61] and BHP[62]) have been unsuccessful or have sold at a loss. As the transition progresses, ongoing collaboration will be needed between organisations, governments, and communities to ensure a just transition. Companies who remain in the sector are relying on CCS and hydrogen to prolong their longevity in a low carbon future.

Beyond our borders, Australia will be heavily influenced by the decarbonisation pathways and policies of our trade partners.

Implications

The combination of these factors creates several material risks including that:

- Existing energy production, exploration or transportation assets may be impaired or stranded
- Fossil fuel alternatives will not be deployed at sufficient speed and scale to fill the gap

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[58] https://www.ashurst.com/en/news-and-insights/legal-updates/climate-change-litigation-risk-in-australia/

[59] https://www.bloomberg.com/news/articles/2021-11-09/cost-of-capital-widens-for-fossil-fuel-producers-green-insight?leadSource=uverify%20wall

[60] https://www.afr.com/politics/nsw-government-knocked-back-origin-offer-to-sell-eraring-power-plant-20220614-p5atln

[61] https://www.originenergy.com.au/about/investors-media/origin-to-divest-beetaloo-basin-interests-intends-to-exit-upstream-exploration-permits/

[62] https://www.afr.com/companies/mining/bhp-retains-mt-arthur-coal-mine-plans-earlier-closure-as-buyers-walk-20220616-p5au7e

- Energy users may face higher prices
- Economic impacts may cascade through local communities and into other critical sectors
- Challenges with CCS will not be resolved[63] limiting the decarbonisation path for residual emissions.

All or some of these could result in a disorderly transition in this sector. These challenges cannot be solved in isolation. Recognition of these risks by key stakeholders in the value chain, nuanced policy design and regulation, and government investment to help mobilise finance to new industries and technologies are key elements to guide the transition. However, slowing the transition from fossil fuels will necessitate greater decarbonisation from other sectors, making an already challenging path more difficult to achieve.

Alternative fuels

Emissions, production, and demand shifts

There is significant global interest in alternative fuels to displace traditional fossil fuel sources. In Australia, hydrogen is a key focus with many jurisdictions developing strategies for a local hydrogen industry. Uses being canvassed include blending hydrogen with natural gas for domestic pipeline use and exporting either liquified hydrogen, ammonia, or other carriers. If produced by electrolysis using renewable energy, a domestic hydrogen industry could facilitate faster decarbonisation of pipeline gas, heavy transport, and hard-to-abate industrial emissions sources. Several pilots are underway trialling hydrogen production, blending into natural gas pipelines, and export (Commonwealth of Australia, 2019).

Combusting biomass for energy, producing biogas from waste (landfill or wastewater), and liquid biofuels are other potential sources of alternative fuels. The ability to generate ACCUs has incentivised many landfill gas operators to capture and combust waste gases and opportunities remain to increase this uptake. Liquid biofuels and biomass for energy are more nascent. Key barriers include cost and the availability of biomass in consistent and large enough quantities to displace traditional fossil fuels. In virgin (rather than waste) form biomass also competes with food and other land use.

The modelling projects a growing role for hydrogen (Figure 50) and to a lesser extent alternative liquid fuels and biomass. The opportunity for hydrogen is much greater in CRD, to a level which implies the need for a domestic green hydrogen industry. This industry is projected to reach scale in the 2030s.[64] In the CSP scenario, the hydrogen industry size in 2050 is around a quarter of that projected in CRD.

[63] https://www.theguardian.com/environment/2022/jul/16/gas-giant-chevron-falls-further-behind-on-carbon-capture-targets-for-gorgon-gasfield

[64] The hydrogen production technology mix was projected using cost assumptions from Graham, Hayward, Foster and Havas (2021) suggesting that steam-methane reforming technology would prove more prevalent than electrolysis at first due to cost reasons, with CCS to minimise emissions, before electrolysis becomes dominant by the mid-2040s. The more recent capital cost estimates of electrolysis in Graham, Hayward, Foster and Havas (2022) are lower, suggesting (AEMO, 2022) that electrolysis would be the production method of choice from much earlier.

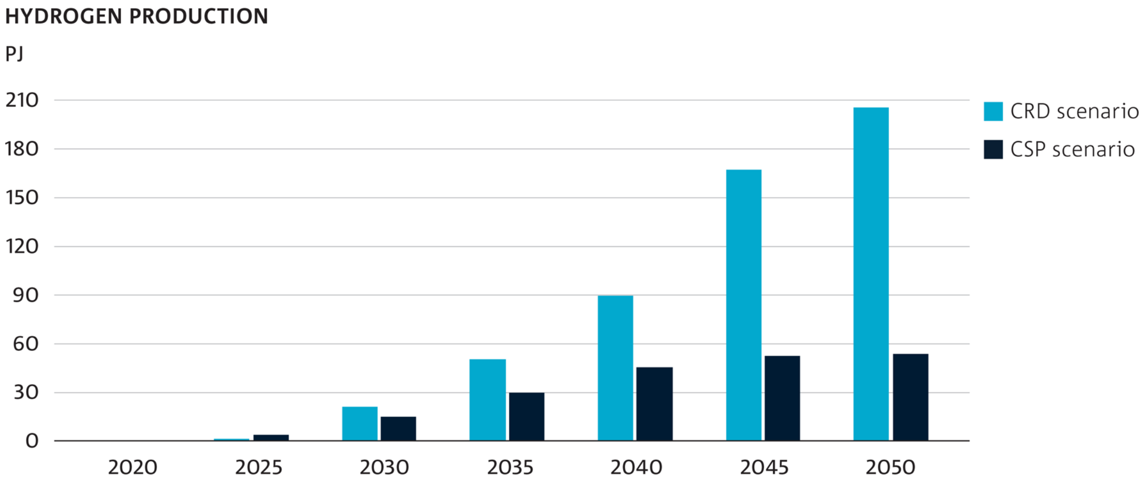


Figure 50 Hydrogen production in Australia in the CRD and CSP scenarios

Opportunities, risks and challenges

Australia is well placed to take advantage of growing global demand for zero emissions fuels. As an early mover, our expertise in designing, building and operating complex engineering projects and managing the processing and containment of volatile liquids and gases provides an advantage in building a new viable export industry to augment, and in time replace, our fossil fuel exports. A green hydrogen industry will allow us to make greater use of our renewable energy resources by consuming energy when it is plentiful and cheap. It would also support decarbonisation of other industries, such as aluminium, cement and steel.

However, to realise this potential, several technical and commercial barriers will need to be addressed. The cost of producing hydrogen using renewable energy is substantially higher than the cost of production using coal gasification and steam methane reforming. While blending into existing natural gas pipelines at low concentration (around 10% to 20%) (Bruce et al., 2018) is viable, higher concentrations would require replacement of end use equipment, such as domestic appliances, and new pipeline infrastructure. Coupled with the energy losses incurred when producing hydrogen (and sometimes also conversion at its destination) high-emissions production paths could result in a net increase, or marginal decrease, in emissions.

Other challenges include the lack of infrastructure for production and transport and the lack of market demand. Further complications arise from rapid international developments such as the Inflation Reduction Act in the USA. These developments mean Australia will need to move quickly to secure international capital and expertise or lose the possibility to capture early mover advantages.

Liquid biofuels are one of the very few options available to decarbonise aviation. In this context, the opportunity to service that industry is substantial if continuity of supply can be scaled and maintained without displacing other vital land use activities.

Implications

For hydrogen, it is crucial that policy makers, investors and participants remain mindful of the core objective of developing this new industry: to meet the growing domestic and international needs for zero emissions energy. It will be crucial to avoid high emissions lock-in as the industry forms. Due to our geographic isolation, the value chain emissions will also need to be considered, including how to minimise emissions associated with transport. Investment and pilots will need to continue to address key barriers: cost, infrastructure, and demand.

Biofuels are anticipated to be in strong demand to decarbonise aviation and potentially as substitutes for fossil fuels in heavy vehicle transportation and other chemical manufacturing processes. This will put increasing pressures on land use, including for food production and emissions sequestration in vegetation and soils. All these land uses are projected to increase in a low carbon future.

Mineral resources

Emissions, production, and demand shifts

The products needed for a low emissions economy, such as batteries, solar panels and electricity transmission infrastructure, will require more mineral resources including nickel, copper, lithium, and rare earths. Many of these minerals are abundant in Australia (DISER, 2022a).

Recycling and materials recovery is complex in many end use applications (CSIRO, 2021). In the CRD scenario global demand for critical minerals is project to increase substantially. The modelling anticipates that increased demand will be met primarily through increased production. Although our modelling does not specifically separate out critical minerals, other mining (in which they fall) is projected to increase in production by more than 50% and exports to nearly triple. This is a significant uplift when compared to the CSP scenario (Figure 51).

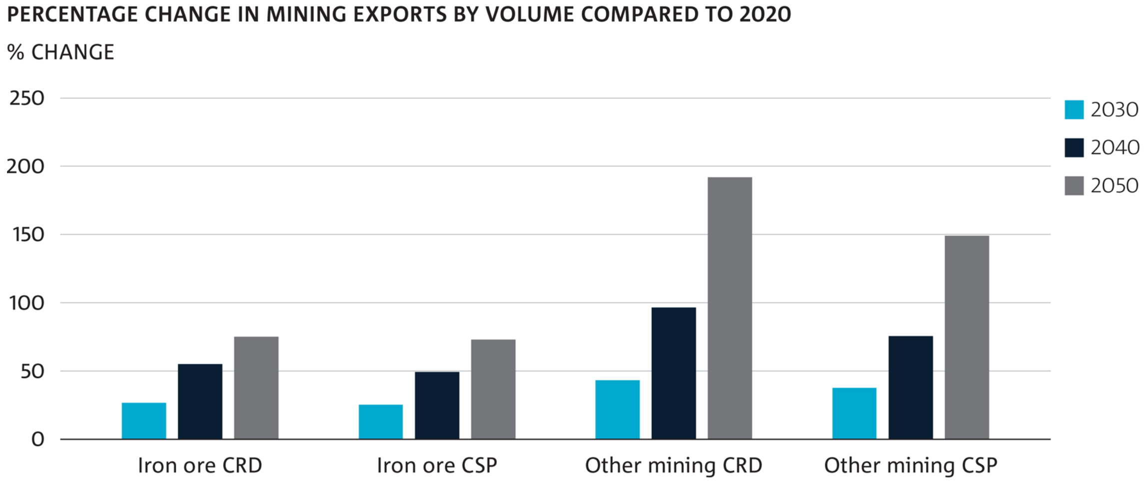


Figure 51 Percentage change in Australian mining exports by volume in the CRD and CSP scenarios

Opportunities, risks and challenges

The extraordinary global demand projected for critical minerals provides opportunities for Australia to leverage our mining and processing expertise to provide high quality resources to the world. Our stable geopolitical conditions, ability to provide continuity of supply, and low risk of forced labour are potential differentiators in the global market. However, our geographical distance from global markets, the emissions intensity of transport, and disruption to logistics chains (from physical climate impacts or other causes) may create challenges.

These critical minerals will need to be produced with low to zero emissions so that they do not undermine the environmental objectives of the end use products. Furthermore, many mineral projects are in remote locations and will need to build alternative power supply, adding to already substantial upfront capital costs and regulatory requirements. As value chain emissions become more important, low emissions producers are likely to find it easier to obtain finance, may be able to attract a green premium for their products, and will avoid carbon penalties. All producers may find themselves with higher expectations associated with the traceability of emissions and other environmental and social impacts in their value chain. An increasingly stringent and dynamic legislative environment should also be anticipated such as ongoing increases to environmental licence requirements.

Implications

An increase in net zero commitments in the mining sector more broadly demonstrates a recognition of these risks and opportunities. In this emerging subsector, the expected growth in new mines provide a critical opportunity to avoid lock-in by designing for net zero. Partially or fully electric mines and a decarbonised electricity supply are opportunities which are already achievable at design phase, particularly for mines with grid access. Process emissions will require step change innovation to decarbonise. The long lives of these operations and the importance of their end use products to global decarbonisation means that accelerating the uptake of opportunities for net zero mining will be a critical path activity for the transition.

5 Economywide transition implications for Australia

5.1 Economy and employment

The CRD transition generates both challenges and opportunities across the Australian economy as illustrated by the sectoral impacts detailed in the previous sections. This work highlights the potential for new export markets (for hydrogen and mineral resources) and opportunities for innovation (in new technologies and more efficient use of energy and materials). There are opportunities for cost reductions in electricity, light vehicle transport, and buildings. Other growth opportunities highlighted in this report but not captured in the modelling include vertical integration and onshoring of energy intensive activities to leverage Australia's renewable energy resources.

The transition also presents challenges to investment in decarbonisation required for the energy transition and to develop and grow new sectors. Downside risks not captured in the modelling include:

- More expensive energy from legacy fossil fuel use while these are being phased out, which flows through to increase costs for hard-to-abate sectors such as steel and cement.
- Loss of income and wealth in vulnerable communities within Australia and in developing countries.
- Potential skill shortages in burgeoning and complex industries and challenges in retraining and reskilling staff.

Our results suggest that growth in GDP will be strong during the current decade before moderating in the 2030s with some recovery in the 2040s (Figure 52). These results indicate that a transition to net zero does not substantially alter the likely economic growth trajectory for Australia. Note that the modelling approach is not designed to capture or replicate short-term variability across the economy that result from short term cyclical variation and sectoral economic frictions as the economy adjusts. Nor does the modelling capture the increased economic resilience of a low emissions economy, or the long-term benefits, mostly beyond the timeframe of this study, which would result from reduced climate change impacts if global actions to limit emissions are successful [See Figure 6 in Section 1]. Many of these positive impacts will be generated beyond 2050 whilst the costs of transition will be more immediate. This makes the trajectory shown in Figure 52 somewhat misleading as it reflects the economic pathway inclusive of the costs of transition under CRD, but does not show the growing future benefits, particularly beyond the 2050 modelling horizon, that would arise from limiting climate change.

Furthermore, there are other benefits of an early, managed transition in Australia. For example, irrespective of the net zero transition, our aging energy plants will need substantial investment over the next decade. Transitioning directly to renewables avoids locking in investment in long-lived high-carbon assets and thereby reduces the risk of asset stranding under a slower transition. Similarly, investment in energy efficiency in our residential and commercial building stock will reduce exposure to climate extremes and enhance resilience of individuals and communities. These types of benefits are inherently difficult to capture in modelling approaches yet offer tangible benefits from investing now over delay.

Despite the transition challenges facing Australia, modelling suggests that GDP growth in Australia will out-perform other advanced economies under the CRD scenario. European nations and Japan will be challenged by the conjunction of declining populations and a transition to net zero. Economic projections also suggest that Australia is likely to outperform the US and Canada as well as other major agricultural and mining exporters such as Brazil and Russia. Regions with stronger GDP growth than Australia are starting from a lower base and are concentrated in Asia (including India, China, Indonesia) and Africa (which is largely driven by ongoing population growth). Australia's ongoing GDP performance is also supported by a higher population growth rate than most other advanced economies.

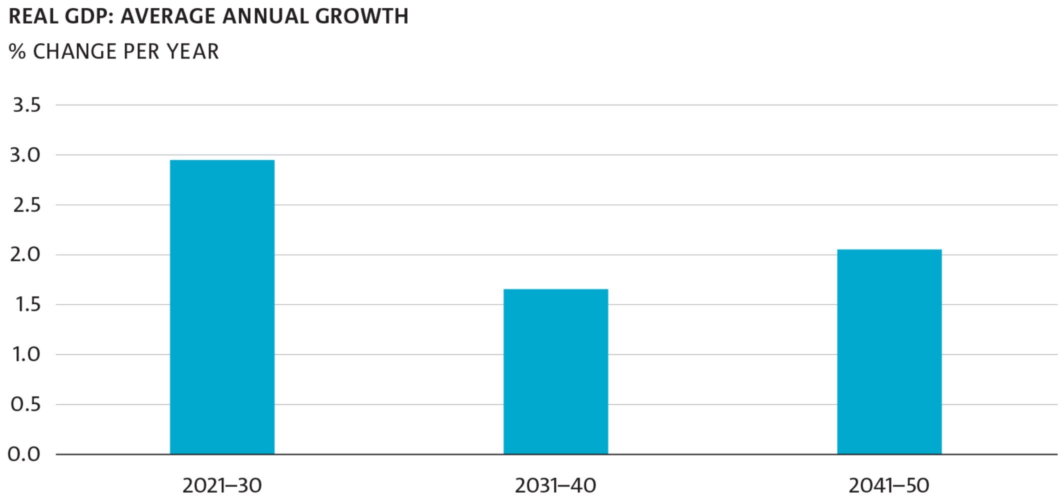


Figure 52 Decadal average Real GDP growth in the CRD scenario

Source: KPMG-EE

The growth in new and existing economic sectors will provide employment opportunities as the economy transitions. However, there will be a disproportionate impact on individuals who work in the most emissions-intensive sectors and the surrounding communities. The need to plan for a just transition of these industries has been well established.[65] Elements of successful transition include skills development, direct community investment, reframing community identity, and attracting low emissions industries to these regions.

Total employment is projected to grow over the short term before plateauing after 2031. The major shifts in employment in Australia are driven by a combination of demographics and population growth rather than the net zero transition. As shown in Figure 53, the input data, consistent with IEA scenarios, indicates Australia's population grows at a rate slightly above the global average. This generates a growing working-age population in Australia as reflected in employment throughout the model period. Some disruption to employment is inevitable because

[65] https://igcc.org.au/wp-content/uploads/2021/07/IGCC-Investors-role-in-an-Equitable-Transition-to-net-zero-emissions_FINAL-150720211-copy.pdf

of a change in balance of economic activity as the economy transitions to net zero (Figure 56). Even with support for a just transition, employment in fossil fuel sectors will decline and be replaced through growth elsewhere including other mining sectors, along with similar shifts from most emissions heavy parts of the economy into low emissions sectors.

The transition towards net zero may result in a lower terms of trade into the future for Australia as a result of a significant fall in the global prices of fossil fuels, which are Australia's largest exports. Terms of trade outcomes could shift were Australia to experience larger growth than modelled in other export sectors (e.g., transition metals, hydrogen). A similar effect would occur through growth of higher value exports that may draw on decarbonised energy sources, such as a shift toward greater onshore mineral processing than projected in this modelling. A more challenging possibility that compounds the risks to Australia is proceeding along a CSP decarbonisation trajectory whilst the rest of the world follows a rapid decarbonisation path, which may result in a range of trade penalties being imposed that exacerbate terms of trade challenges.

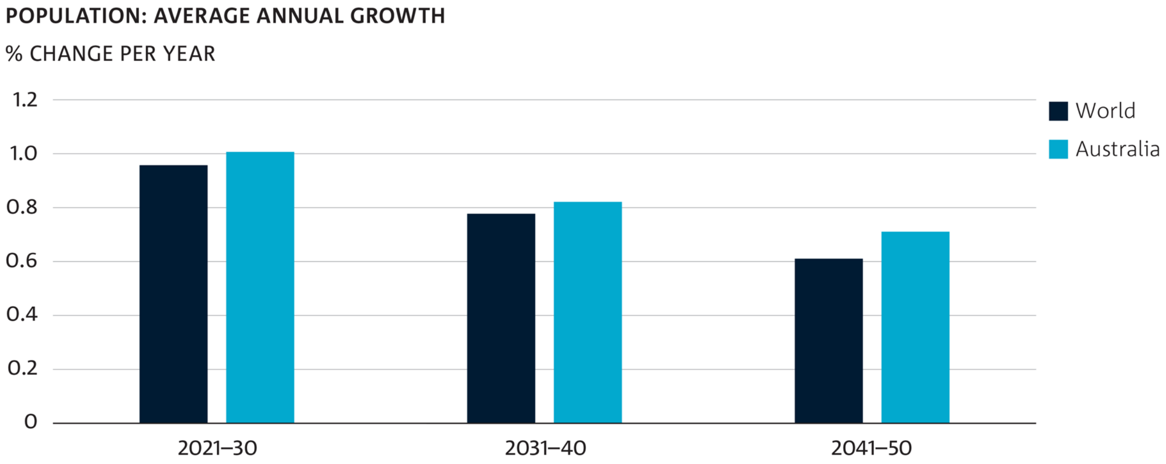


Figure 53 Decadal average Population growth in all scenarios

Source: KPMG-EE

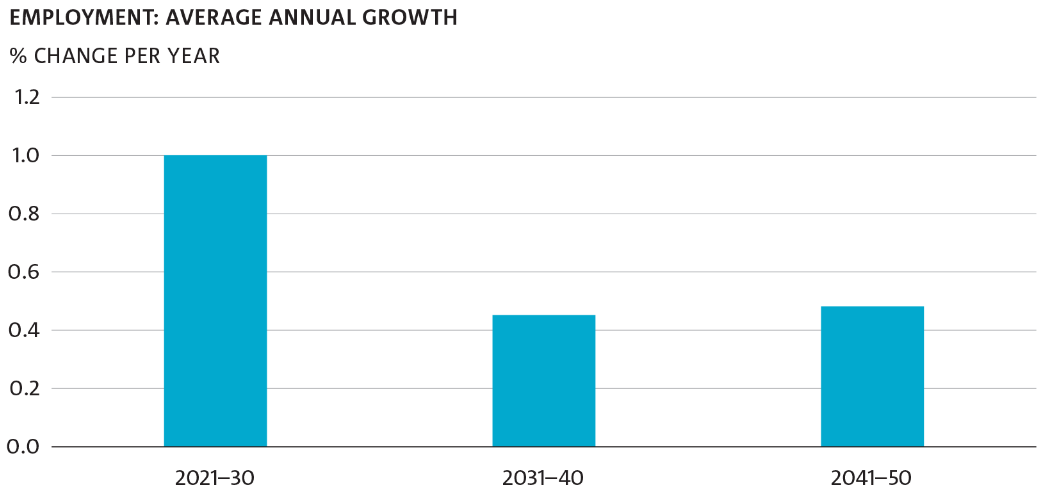


Figure 54 Decadal average Employment growth in the CRD scenario

Source: KPMG-EE

Export growth follows a similar trajectory to GDP resulting in substantial aggregate growth by 2050 (Figure 55). However, the mix of industry output changes over time, with a decline in world demand driving the large reductions in coal and gas production, (Figure 56) balanced by strong growth in iron ore and other mining, manufacturing including mineral processing, agriculture and services exports. The global and domestic energy sectors reflect the shape of the CRD transition. Increasing electrification drives initial growth in the electricity sector whilst improved energy efficiency and exit from fossil fuels eventually drives an overall decline in the total size of the energy sector inclusive of fossil fuels. Recent geopolitical events may support faster and larger growth in critical mineral exports (in both ore and processed form) to support net zero transitions. Similarly, a shift to a major export hydrogen industry (hydrogen superpower type scenarios) would grow exports more rapidly.

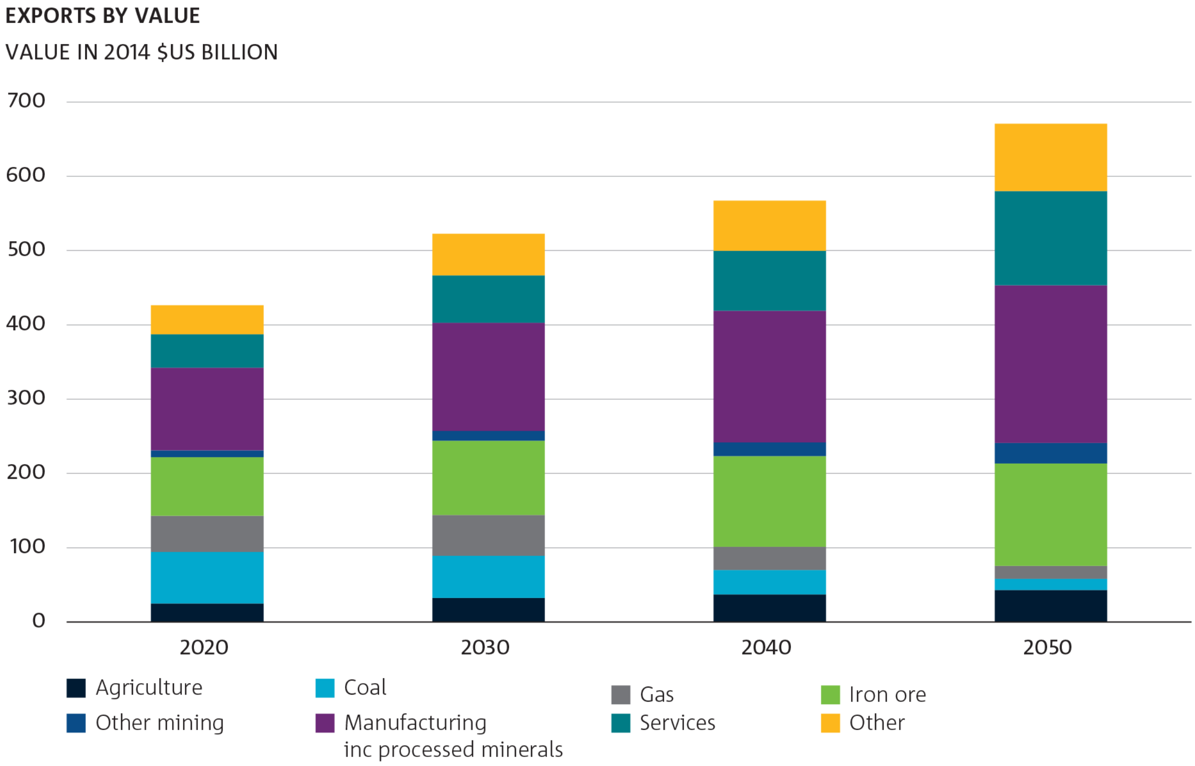


Figure 55 Australian exports by value in the CRD scenario

Source: KPMG-EE

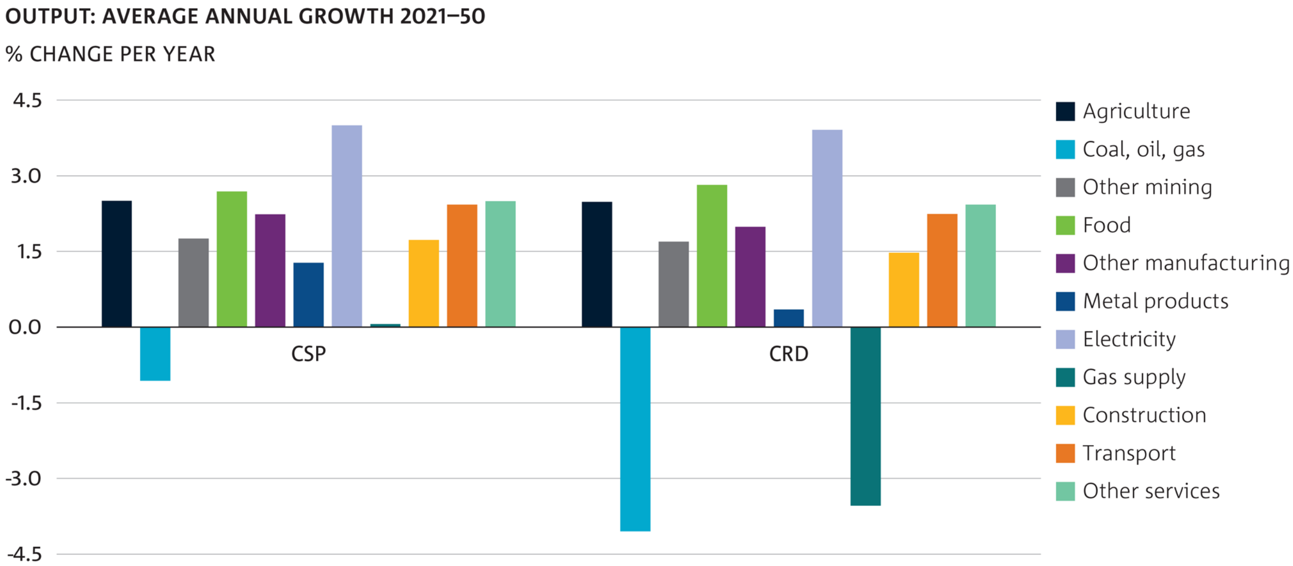


Figure 56 Change in industry sectoral output in the CSP and CRD scenarios

Source: KPMG-EE

5.2 Individuals

GDP per capita shifts reflect the influence of strong population growth on overall GDP (Figure 57) whilst household consumption grows more strongly than GDP. The effect on household consumption reflects a falling terms of trade as export prices fall under the CRD scenario. To maintain the same ratio of net foreign liabilities to GDP would require a higher saving rate (incompatible with the household consumption outcome) and higher export volumes. This less optimistic outlook for households emphasises the challenges of transitioning to net zero for individuals and households in Australia given the revenue earned from exporting coal and gas.

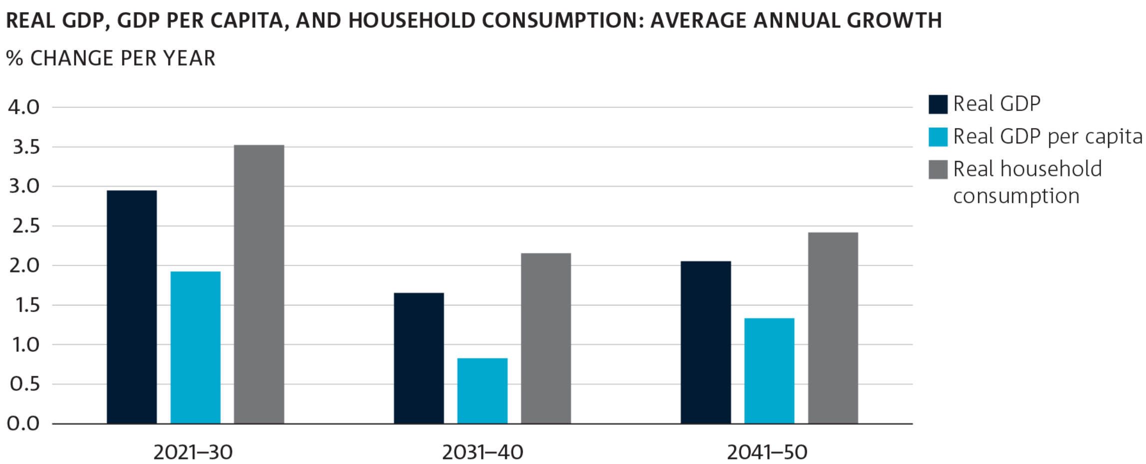


Figure 57 Decadal growth of Real GDP, GDP per capita and household consumption in the CRD scenario

Source: KPMG-EE

Energy affordability is expected to be an ongoing challenge for both businesses and households. Rising technology costs in some areas will also flow through to cost pressures for consumer goods.

These impacts will be disproportionately felt by lower income households. These households are also less able to invest in on-site renewable energy generation, due to high capital costs and lack of home ownership. Stronger standards for tenanted buildings could be transformational to reduce cost and inequities and mitigate the physical impacts of climate change on vulnerable households.

This modelling projects that individuals' behaviours will need to change to reduce the emissions intensity of residential buildings. Opportunities that have high upfront costs to achieve lower operating costs may make it more difficult for some consumers to switch as discussed in Section 3.

As a key trade partner of the Asia-Pacific region, Australia's responsibility also extends beyond our borders. By fostering regional partnerships and green growth corridors Australia can help bring prosperity to itself and the region. Lower income countries will also be faced with the competing priorities of securing energy access, alleviating poverty and solving other health and environmental challenges. This is likely to constrain their ability to mitigate and adapt to the impacts of climate change. Unlike in high-income countries, power and other industrial assets in emerging economies have more of their useful life remaining which creates hurdles for decommissioning these assets and switching to alternatives. Our role in helping our Asia-Pacific neighbours to finance the transition, adapt to the impacts of climate change, and share knowledge can help to alleviate some of these challenges.

5.3 Uncertainties

Australia can achieve the modelled reductions to 2030 based on measures that are already available. Decarbonisation of the electricity sector, rapid electrification, switching to low-carbon fuels, shifting demand, energy, and material efficiency, reducing land clearing, and promoting tree growth all contribute to this decarbonisation path. Some require behavioural change, such as in the buildings sector, which may need to be incentivised or influenced by Governments and industry bodies.

While the path to 2030 is relatively clear, the upfront investment costs are substantial and will require a large step up from investment from current levels. In the electricity and fossil fuel sectors, substantial investment will be needed to ensure replacement infrastructure is available to replace legacy assets that are retired or substantially decline in output (for example, electricity and fossil fuels). Mismatching the timing of retirements and replacement would result in a disorderly transition in these sectors without other interventions.

The pathway forward for decarbonisation technologies is not yet fully clear. Research, pilots, and private and public investment will be essential in the 2020s to enable new technologies to be commercialised in the 2030s and 2040s, drive deeper decarbonisation, and avoid adverse path dependency. Current barriers include lack of technological readiness, high costs, and uncertain demand profiles. Opportunities to decarbonise hard-to-abate sources (including in aviation, shipping, cement, and steel) have higher uncertainty in their feasibility, scale and timing of deployment.

Part III Appendices

Appendix A Technical Supplement

A.1 Additional detail on modelling scope and context

Scenario approaches, such as those explored in this research, are useful tools to explore aspects of an uncertain future, identify the types of economic transition required to restrict global emissions, and to explore the impacts of those transitions on sectors and communities. The IEA's World Energy Outlook 2021 encompassed three main scenarios (direct quote from the IEA World Energy Outlook 2021):

- **Net Zero Emissions by 2050 Scenario** (NZE), which sets out a narrow but achievable pathway for the global energy sector to achieve net zero CO_2 emissions by 2050.
- **Announced Pledges Scenario** (APS), which assumes that all climate commitments made by governments around the world, including NDCs and longer-term net zero targets, will be met in full and on time.
- **Stated Policies Scenario** (STEPS), which reflects current policy settings based on a sector-by-sector assessment of the specific policies that are in place, as well as those that have been announced by governments around the world.

The modelling framework implemented in this project was explicitly designed to tailor IEA's Net Zero Emissions (NZE) and Stated Policies Scenario (STEPS) to understand implications for the Australian economy and sectors. To do this we have developed two contextualised scenarios for Australia:

- CSIRO rapid decarbonisation (**CRD**) based on a rapid but plausible decarbonisation pathway to net zero for Australia within a global 1.5°C carbon budget.
- CSIRO stated policies (**CSP**) based on stated policies internationally and within Australia, which projects a 2.6°C temperature increase by 2100.

These scenarios represent three potential emissions trajectories and aligned economic trajectories at the global and Australian level. The scenarios can be viewed as archetypes of economic outcomes aligned with each emission path because there will be a range of economic paths available generating similar emission paths depending on policy settings and other factors. The IEA scenarios apply a consistent set of underpinning socioeconomic assumptions in order to better allow the implications of emissions pathways to be explored. IEA and those developed by CSIRO for Australia apply socioeconomic pathways similar to the shared socioeconomic pathway 2 (SSP2) (O'Neil et al., 2014), which is referred to as the 'middle of the road' pathway. IEA and CSIRO pathways assume moderate population and GDP growth. Some important implications of considering uncertainty when using the same overarching socioeconomic conditions are discussed in Box 1.

Box 1: Sources of uncertainty

All Integrated Assessment Model (IAM) projections of the coupled climate economic system, including those models adopted in this project, are subject to a range of uncertainties and limitations.

Uncertainty of socioeconomic settings – Projecting demographic and economic trends into the future is challenging, as they are highly interconnected, and changes in economic growth can have profound implications on population growth and vice versa. UN population projections have tended to overstate future growth, underestimating the decline in fertility rates observed over the past century. Nevertheless, these trends are not laws, and nothing ensures they will continue into the future. Furthermore, the future economic trajectories such as the Shared Socioeconomic Pathways or SSPs have generally been designed independently from climate change with the goal that they could be compatible with various climate change trajectories. As such, they do not explicitly consider potential climate change sensitivity and feedbacks to future economic growth, which may overstate future growth potential.

These same prescribed population trajectories are adopted across all scenarios, which does not capture any influence that changes to economic prosperity may have on population growth. Additionally, whilst we have corrected for near-term population implications of the COVID-19 event, the long-term implications on economic openness, migration patterns, and changes to the nature of work and productivity are still highly uncertain and not explicitly accounted for. The politics of climate action are also intertwined with socioeconomic pathways. Futures where there is faster growth spurred by technological development, for example, will face lower costs to mitigate climate, than futures where economic growth is stagnant or being driven by carbon-based technologies. Futures with increasing fragmentation (SSPs 4 and 5, for example) will present more challenging worlds for collective action and increase the risk of miscalculations and overshooting to achieve climate targets.

Uncertainty of manner to achieve emissions pathway – For given socioeconomic settings, there are potentially many combinations of technology mixes and/or CGE model parameters that achieve the same or similar emissions pathways; thus, increasing the uncertainty of the economic impact. The format of climate policy can have substantial impacts on the effectiveness of said policies, as well as the challenges of passing and implementing them, given domestic and international politics. A carbon tax with rebate, for example, may be an easier sell politically, even as a carbon tax whose revenue is used to subsidise greener technologies and practices could speed progress. Policies that further concentrate the cost of transition to specific sectors, for example, a removal of subsidies couple with clean standards or pollution pricing, may encourage more backlash than less coercive measures like emissions reduction credits, which are also likely to be slower to achieve emissions reductions.

Uncertainty of global and regional climate sensitivity – For a given emissions pathway the temperature response used in the CGE models is calibrated from complex physics-based models of the climate. Various climate models producing data for the International Climate Model Intercomparison Project (CMIP)[66] produce different global and local temperature responses. The spread in model results is such that there is significant overlap between each of the various emissions scenarios. The impact of climate change is summarised in an impact function based on changes to temperature, and therefore does not fully account for other changes caused by climate change, such as changing precipitation patterns or the effects of elevated CO_2, which can have profound sector-specific impacts.

Underestimate of economic volatility – economic modelling produces pathways that represent an average (or equilibrium) economic trajectory and are incapable of capturing recessions or booms in activity. The modelling assumes rational behaviour of the participants and that they act on all available information, neither of which are true in the real world. Additionally, this class of models cannot endogenously model structural change and societal transformations, which can radically change relationships between factors of production. These modelling limitations would contribute to increased volatility of the economic pathways, and as such the realised economic transitions will not be as smooth nor timely as the modelled ones.

Impact of natural variability – It is the total climate risk that is important to the banks and other institutions, not necessarily the risk decomposed into anthropogenic and natural. Whilst climate change is the dominant source of risk for multi-decadal timescales, within the first few years of the projections all scenarios exhibit similar climatic responses. As such, natural climate variability is the larger source of physical uncertainty in the early years.

It is also important to consider that the above sources of uncertainty are not independent and interact in non-trivial and complex ways.

Source: Whitten et al. (2022).

[66] https://www.wcrp-climate.org/wgcm-cmip

In this report we focus strongly on the results of the CRD scenario to outline plausible, achievable, low emissions paths for each sector to drive greater decarbonisation ambition and action.

A.2 Model framework and integration

A.2.1 The suite of models and how they fit together

In this analysis a multi-model approach has been tailored to downscale several IEA scenarios for an Australian context. The approach nested three levels of modelling from global to sectoral to derive contextualised Australian outputs:

- CSIRO's Global Trade and Environment Model (GTEM), a computable general equilibrium (CGE) model, is used to model the global macroeconomic impacts in each scenario and explores how they influence Australia through globalisation and trade
- KPMG's Energy and Environment model (KPMG-EE), a CGE model calibrated to Australia's industry sectors and current account balance, applies the global implications to the Australian economy and provides insights into impacts on specific economic sectors
- CSIRO and ClimateWorks' Australian TIMES (AusTIMES) model provides a view based on least cost energy, emissions and technology pathways and complements the sectoral view provided by KPMG-EE.

CSIRO's GTEM model[67] explores transitional risk impacts globally and how these influence Australia through international linkages and trade impacts. We consider how these global changes influence sectoral impacts on the Australian economy using the KPMG-EE model. In this exploration we focus only on the economic transition whilst disregarding the economic implications of chronic and acute physical hazards associated with climate change. Research suggests that both chronic and physical climate hazards will increase into the future and inclusion of these risks, particularly for the agricultural and construction sectors as well as some carbon removal activities such as afforestation and reforestation, will be an important area to focus on into the future. Finally, specific technology paths are explored for six high emission sectors (energy, transport, buildings, steel, aluminum, and cement) using AusTIMES. AusTIMES is calibrated to Australian sectoral starting technology mixes and is used to explore least cost sectoral paths consistent with emissions shadow prices and trading conditions (drawn from GTEM) and sectoral growth paths (drawn from KPMG-EE).

[67] https://research.csiro.au/foodglobalsecurity/data-and-tools/models/global-trade-and-environmental-model-gtem/ and as described in Cai et. al. (2015)

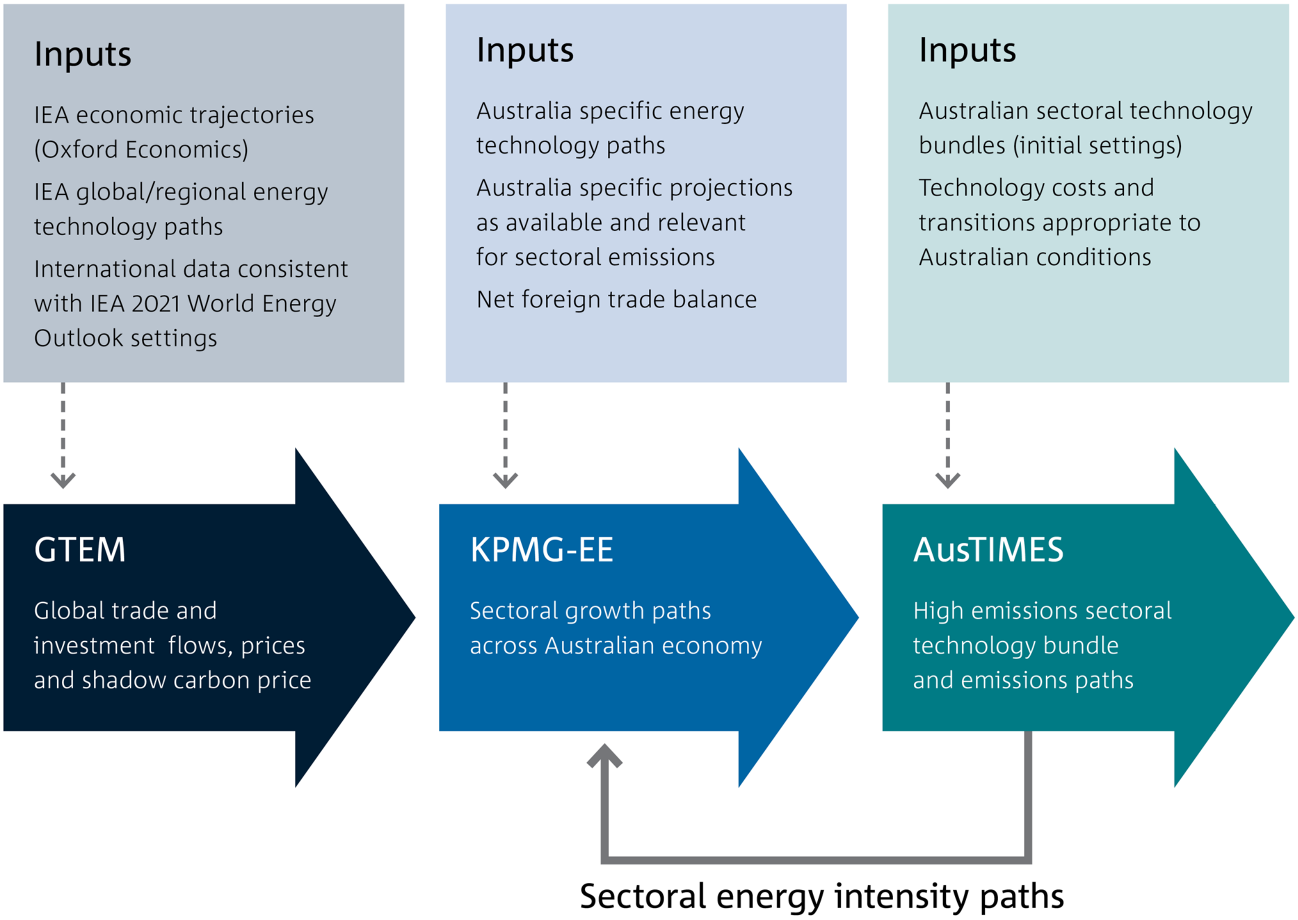


Figure 58 An overview of the interrelationship of input sources across the model suite

A.2.2 Integrated assessment models implemented

CSIRO Global Trade and Environment model

GTEM is a hybrid model that combines the top-down macroeconomic representation of a CGE model with the bottom-up engineering details of energy production along with a representation of greenhouse gas emissions by economic sector. The model features detailed accounting for global energy flows that are embedded in traded energy goods and offers a unified framework to analyse the energy-carbon-environment nexus. In this section we provide a summary of the relevant parts of the model whilst a detailed description of the model can be found in Cai et al. (2015).

In the GTEM model applied in this analysis the responses to emissions pathways occur through two mechanisms. Firstly, the speed of adjustment across technologies in the available bundle (effectively the elasticity of substitution across a known technology bundle). Secondly, the rate of price-induced technological innovation. A third feedback mechanism available in GTEM is the climate feedback from the emissions pathway, however, this mechanism is not activated in this analysis and not described further here. Each of these emission pathway responses are based on real world data and can be varied or constrained within the model, where required, to conform with other modelling such as the IEA model outputs, or to new or revised information or likely responses in the future.

Box 2: Description of how Integrated Assessment Models and Computable General Equilibrium Models Work

Integrated Assessment Models (IAM) attempt to represent the interactions between physical and economic systems. Human impact on the environment can fundamentally be understood as a product of three factors: population, affluence, and technology. From an energy and emissions perspective, affluence can be interpreted as energy consumed per person, and technology characterised by the amount of carbon emissions required to produce a unit of energy. Growing populations and levels of affluence increase the anthropogenic impact upon the environment. Advances in technology have the potential to modify the carbon footprint of human activities.

There are many IAMs in use, designed to explore different questions with varying degrees of representation of the economy, energy technologies, and land-use change, amongst other factors.[68] We apply a specific form of IAM called dynamic CGE models – which employ a more detailed focus on economic relationships – to simulate the global and domestic Australian economies. CGE models are quantitative economy-wide models comprised of a set of equations that describe how governments, firms, industrial sectors and households behave within an economy (or interacting economies), and how they could respond to changes in policy, technology, and availability of resources amongst other factors. The parameters in these equations are estimated based on historical economic statistics, observed behaviour, and economic theory. Typically, CGE models apply several key assumptions, including:

- Firms operate under conditions of perfect competition and are profit maximisers constrained by market prices and input costs.
- Households try to maximise the value of their real expenditures (utility) constrained by market prices, their income and preferences.
- Investors maximise their rates of return and this allows for the efficient allocation of capital across the economy.

The resources drawn from the environment and the impact of the climate on economic activity are also incorporated in the CGE framework adopted in GTEM, as illustrated for a given aggregate region in Figure 59. Each of the aggregate regions interacts with the other regions via trade and investment flows, and migration, as illustrated in Figure 60. All regions potentially contribute to global carbon (and non-carbon) emissions. These emissions influence the surface temperatures of each region via the greenhouse effect, which in turn influence economic activity via approximated chronic climate induced damages.

Finally, it is important to note that CGE models of any kind are not designed as predictive tools but are used to explore a plausible set of consistent economic and biophysical outcomes based on a series of prescribed assumptions of technological development, market behaviour and public policy.

Source: Whitten et al. (2022).

[68] An excellent introduction to IAMs is: https://www.carbonbrief.org/qa-how-integrated-assessment-models-are-used-to-study-climate-change

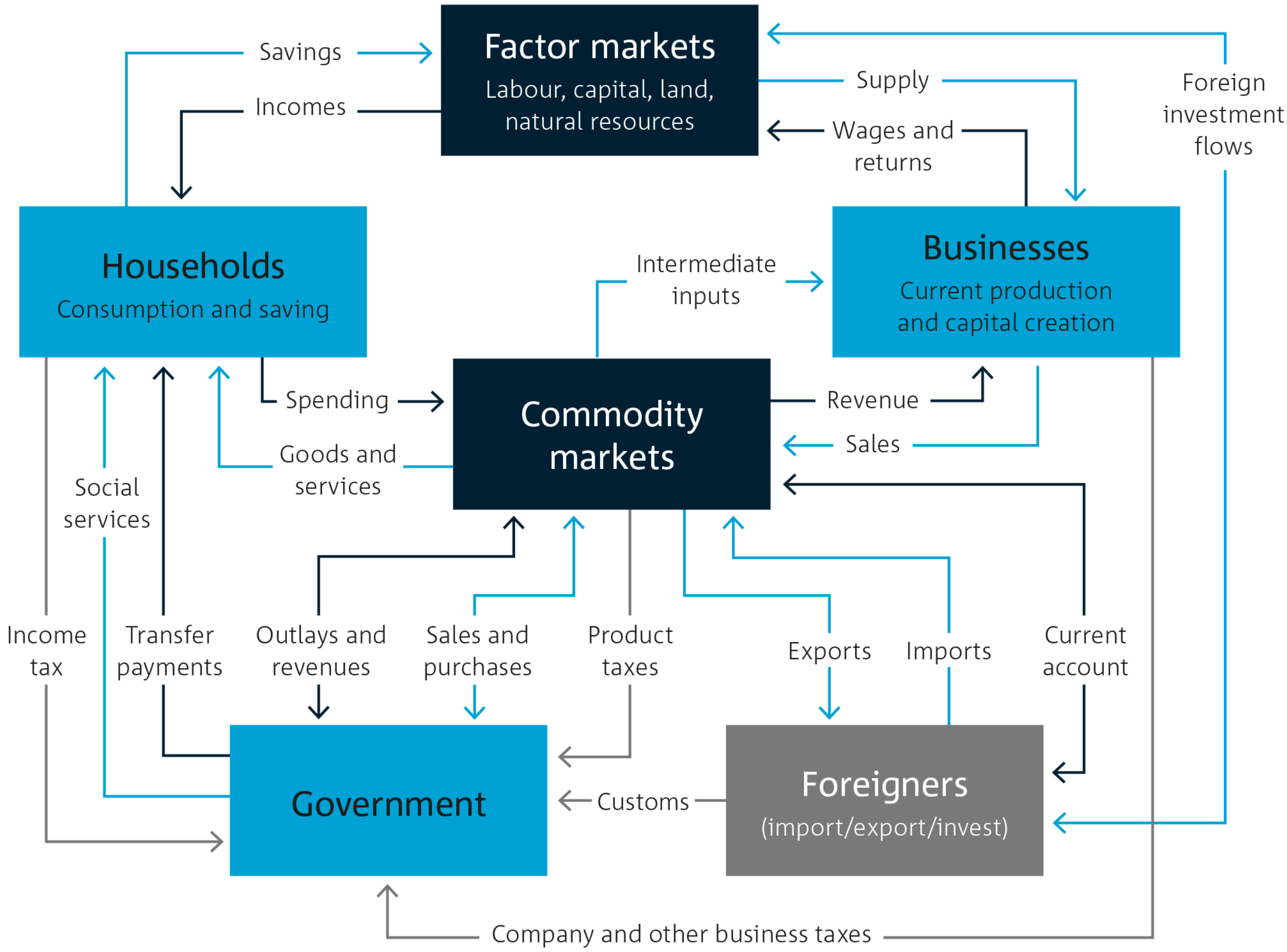


Figure 59 Interactions between agents within a given aggregate region in GTEM

Source: Whitten et al. (2022).

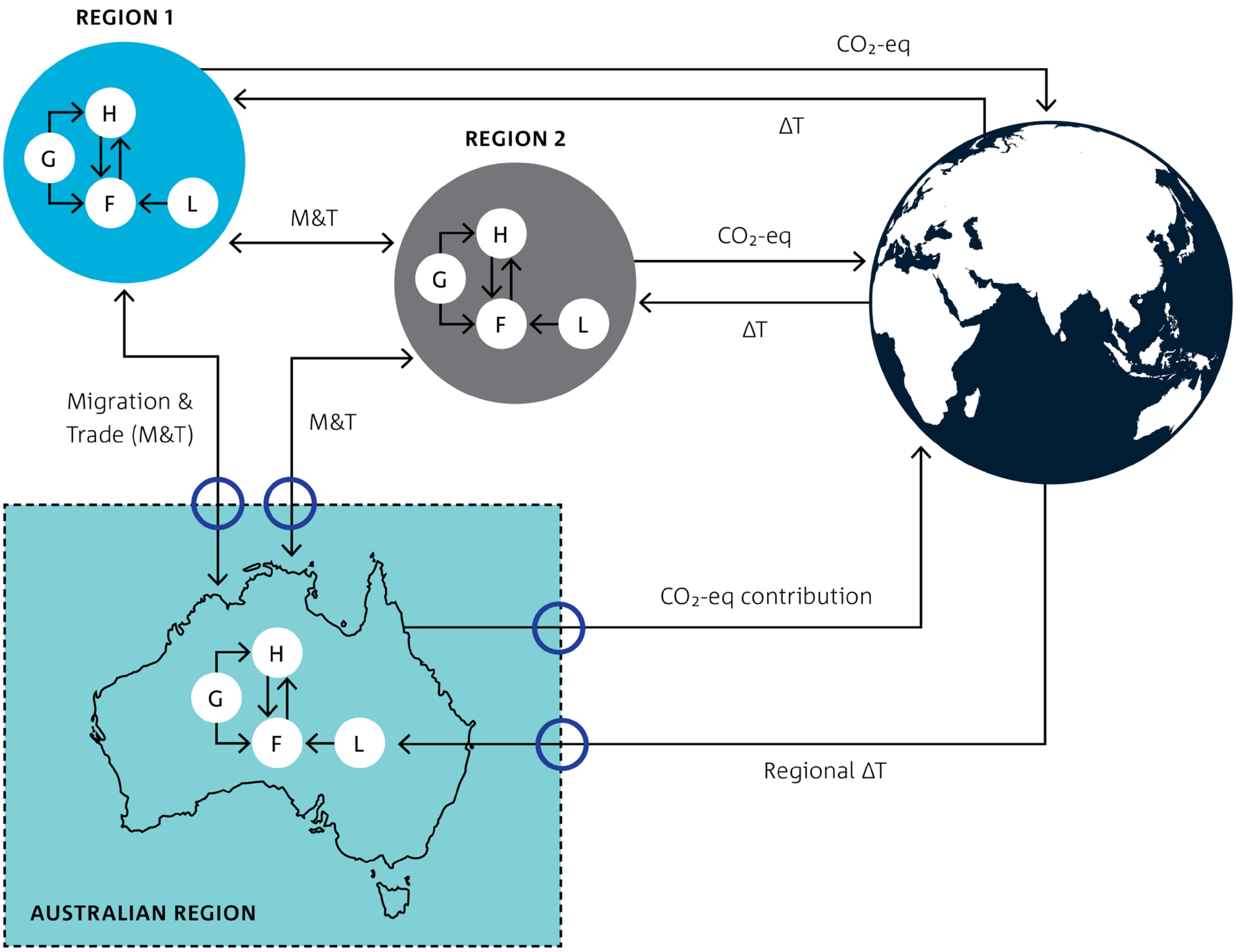


Figure 60 Interactions between the biophysical system (i.e., Earth), and aggregate regions

Note: Only 3 of the 20 regions are illustrated for clarity. Each region is comprised of representative agents for the government (G), firms (F), household (H) and tracks the harvesting of resources and land (L), temperature (ΔT) entering model via a productivity impact. The blue circles indicate where GTEM provides the boundary conditions for KPMG-EE.

Source: Whitten et al. (2021).

Firms and production

Technology bundle industries

Typically, CGE models represent production technologies across sectors using identical functional forms (e.g., constant elasticity of substitution (CES) technology) but differences exist in the relative use of factor and intermediate inputs; however, GTEM takes a different approach. In order to directly model the switch from fossil-fuel-based and carbon-intensive technologies to cleaner alternatives, GTEM distinguishes "technology bundle" (TB) industries from other industries. A technology bundle industry consists of a bundle of heterogeneous and competing technologies, and an assembling service that unifies products of all technologies into a homogeneous industrial output.

There are three TB industries in GTEM as implemented in this study: electricity, iron and steel, and land transport (i.e., road and rail transport). Here we focus on the treatment of electricity. Electricity generation accounts for a large fraction of greenhouse gas (GHG) emissions and plays an important role in carbon mitigation. The TB of the electricity industry has three emission-intensive technologies (coal, oil and gas), eight emission-free technologies (nuclear, hydro, wind, solar, biogas, other bioenergy, waste, and geothermal, wave and other renewables), and four carbon capture and storage technologies (coal, oil, gas, and bioenergy).

Figure 61 outlines the production structure of a typical TB industry. At the top of the production nest, the technology bundle and the assembling service are combined using Leontief technology, which is non-smooth and captures the rigidity of production in the presence of fixed or sunk costs and resource immobility. At the second level of the nest, the assembling service is a Leontief function of non-technology-specific intermediate inputs. The technology bundle is a modified CRESH (Constant Ratios of Elasticities of Substitution, Homothetic) function of different technologies. The modification adds a uniform adjustment factor that maintains the additivity (in volume terms) of all technologies in a single industrial output (e.g., electricity). The CRESH parameter controlling substitution across technologies is 0.8 in the electricity TB and 2 in the iron and steel TB and land transport TB. These parameter values are constant through time. Each technology is, in turn, a Leontief function of technology-specific factors of production (e.g., capital, labour) and (imported and domestic) intermediate inputs. Finally, intermediate inputs used by the assembling service and each technology are CES aggregates of domestic and imported goods. This means there is imperfect substitution between imported and domestic goods. The elasticities of substitution applied here are taken from the GTAP model (Aguiar et al., 2019).

Non-technology-bundle industries

Production within a non-TB industry also has a nested structure (Figure 62). At the top nest, industrial output is a Leontief function of a fuel-factor composite and other intermediate inputs. The fuel-factor composite is a Leontief or CES function of the fuel composite and the primary factor composite, allowing different levels of substitutability between fuel and other inputs. The fuel composite is a CRESH aggregate of coal, gas, petroleum, electricity and gas distribution. The CRESH inter-fuel substitution parameters are set to 0.2. This value falls within the range of the literature (Stern, 2012).

In contrast, the primary factor composite is a CES function of natural resources, land, labour and capital. Coal, gas, petroleum products, electricity and other intermediate inputs are, as before, CES aggregates of imported and domestic goods. The elasticities of substitution applied here are taken from the GTAP model (Aguiar et al., 2019).

The parameters follow Borrell and Hanslow (2004) in setting the inter-factor elasticities of substitution such that the long-term supply elasticities of coal, oil and gas are consistent with the estimates of Beckman et al. (2011) and the United States' Energy Information Administration (EIA, 2013).

The regional household

Each region in GTEM contains a representative household. The representative household undertakes three activities: (1) it owns and supplies all factors of production in the region; (2) it receives regional income comprising all factor payments, tax revenues and international transfers; and (3) it divides regional income across saving, household consumption and government consumption.

Figure 63 presents the nested utility structure of the regional household. At the top level of the nest the household determines the allocation of regional income across saving, household consumption and government consumption applying Cobb-Douglas preferences, i.e., each of these components is a fixed nominal share of regional income.

At the second level of the nest household consumption is distributed across the energy composite and individual non-energy commodities using a constant-differences-in-elasticities (CDE) function due to Hanoch (1975). The CDE functional form makes consumption a function of price and income parameters that are a non-linear function of income. More specifically, this formulation of household preferences gives certain properties that fit observed consumption patterns (McDougall, 2003). First, as regional income rises, budget shares of luxury goods rise while those of subsistence goods decline. Second, for a given level of regional income, a more populous region will demand more subsistence goods and less luxury goods. The second level of the nest also determines government consumption by commodity using Cobb-Douglas preferences.

At the third level the energy composite is determined using a CRESH function to represent the household's preference across coal, gas, petroleum, electricity and gas distribution. The CRESH parameter controlling substitution across energy commodities is 0.4. This value falls within the range of the literature (Stern, 2012). Also determined at the third level is the combination of domestic and imported commodities using CES preferences. The elasticities of substitution applied here are taken from the GTAP model (Aguiar et al., 2019).

Global and regional investment

The aggregation of household saving in all regions represents global investment, which is allocated across regions based upon the slow elimination of differences in regional rates of return on capital. Thus, regional saving can be allocated either domestically or internationally. In contrast, other factors of production (land, labour, natural resources) are internationally immobile. In each time period regional investment (net of depreciation) adds to the stock of capital as specified in the dynamic GTAP model (Ianchovichina and McDougall, 2000). Thus, we also adopt a similar treatment of time as a variable rather than an index and a zero-gestation lag for capital and debt accumulation.

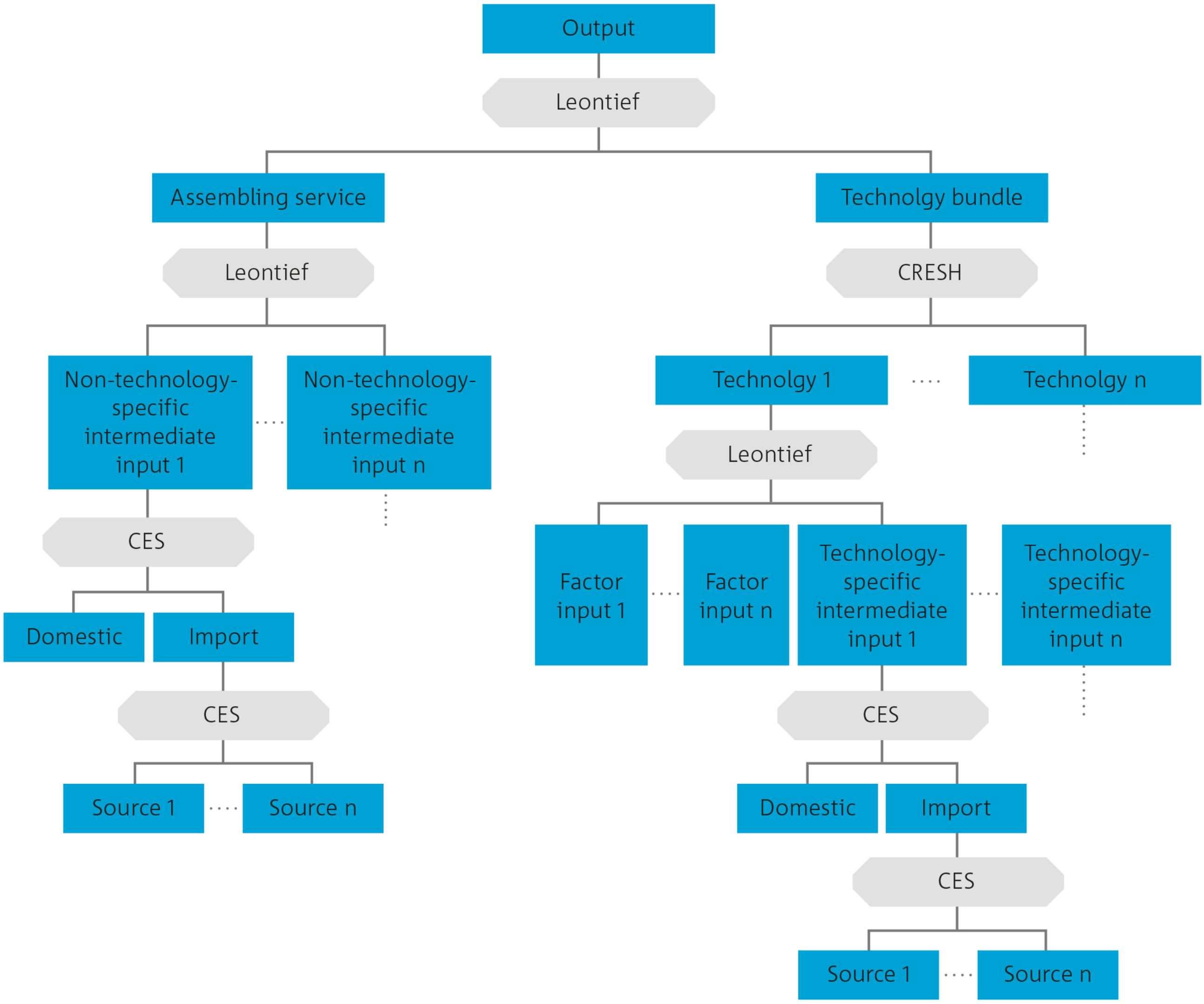


Figure 61 Production structure of a technology bundle industry

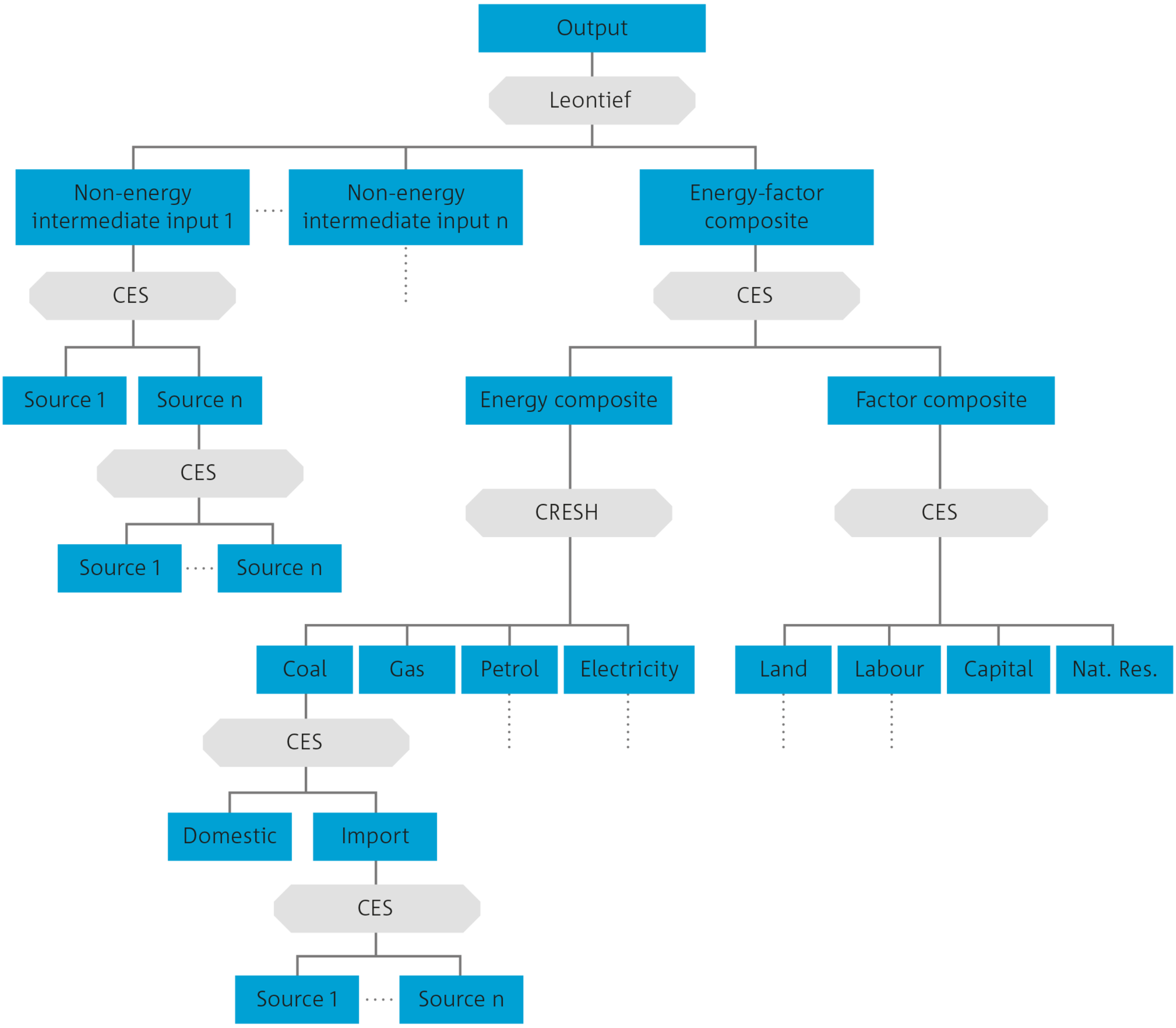


Figure 62 Production structure of a non-technology-bundle industry

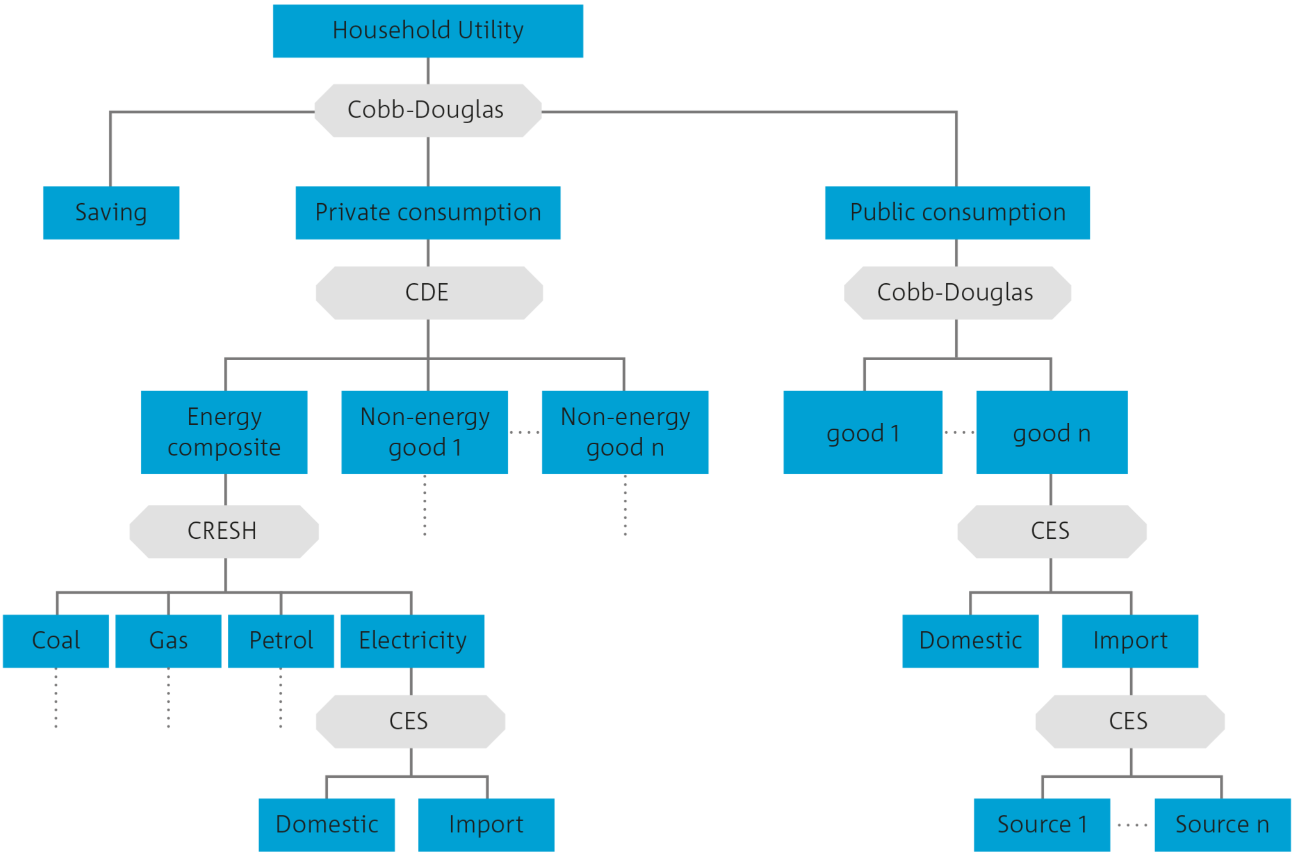


Figure 63 Utility structure of the regional household

International trade

As already noted, both imported and domestic commodities are used by firms and households. Once the total imports for a given commodity are determined in a region, these imports must be allocated across all regional sources. This is done using CES preferences where the elasticities of substitution are set at twice the value of the equivalent import-domestic elasticities.

Energy use and greenhouse gas emissions

Energy accounting

Energy is embedded in energy goods. Therefore, the input-output flows of energy mirror those of coal, oil, gas, petroleum and electricity as represented in the GTEM database. The quantities of fossil fuel use are tracked by the input-output (IO) tables and are determined by market clearing conditions.

The energy data structure in GTEM captures the circulation of energy flows in the global economy. However, this approach poses a potential problem of double accounting, as commodity-embedded energy is sequentially transferred to other sectors through use of intermediate inputs. To avoid this problem, we exclude (crude) oil and calculate regional total primary energy output as the sum of domestically produced coal, petroleum, and gas that are either locally consumed or exported, plus nuclear- and renewable-generated electricity. This removes the potential for double accounting in the transformation of crude oil to petroleum, and fossil fuel to electricity. Similarly, regional total final energy use is calculated as the sum of imported and domestic coal, petroleum and gas that are directly consumed by the household and all non-electricity sectors, plus the electricity that is locally used.

Emissions accounting

Combustion-based GHG emissions (i.e., CO_2, CH_4, N_2O and F-gases) are directly linked to fossil fuel use of the representative household and each industrial sector and their emission intensities. For household consumption, the emission intensities are exogenous. For industrial use, the emission intensities respond to carbon-price-induced technological change drawing on Popp (2002). Process-based emissions are also determined by sectoral output and emission intensities. Non-combustion GHG emissions from agricultural sectors are based on the use of factor inputs. For instance, emissions from livestock are proportional to the sectoral use of capital (as a proxy for the scale of farming), and emissions from paddy rice are proportional to the sectoral use of land (as a proxy for planting area). No endogenous technological change is assumed.

Model Calibration

The key data inputs to GTEM are the IO tables and related data drawn from the GTAP 10 data base (Aguiar et al., 2019). This is a global data base produced by the Global Trade Analysis Project (GTAP); it describes bilateral trade patterns, production, consumption, investment and the intermediate use of commodities and services. It also contains supplementary data on energy and greenhouse gas emissions.

The GTEM data base is supplemented with output data on TB industries (i.e., iron and steel, electricity and land transport) mainly from the IEA and other sources. In simulating the IEA scenarios described in this work, many of the initial GTEM values for energy, emissions and TB outputs are made consistent with historical values reported by the IEA in their 2021 Net Zero Emissions report (see Table 19). This calibration is also made in a more detailed manner for Australian energy, emissions and TB output data available from official sources, e.g., Department of Industry, Science, Energy and Resources (Australian Energy Statistics (see https://www.energy.gov.au/government-priorities/energy-data/australian-energy-statistics), Australia's Emissions Projections 2021) (DISER, 2021a) and the Australian Energy Market Operator (see Integrated Assessment Plan) (AEMO, 2022). The calibration also applies projections on emissions and TB outputs that are available from official Australian sources.

Table 10 GTEM sectoral and regional aggregation

Sectors	Regions
Crops	Australia
Livestock	New Zealand
Forestry	China, Hong Kong
Fishing	Japan
Coal	South Korea
Oil	Rest of Asia
Gas	Indonesia
Other extraction	India
Food	Canada
Manufacturing	USA
Petroleum, coal products	Mexico
Chemicals	South America
Pharmaceuticals, rubber, plastics	Brazil
Other mineral products	EU15
Iron and steel	EU12
Other metals	Rest of Europe
Electricity	Russia
Gas manufacture, distribution	Middle East
Water	Africa
Construction	Rest of the world
Financial, insurance services	
Land transport	
Water transport	
Air transport	
Other services	

KPMG-EE energy and environment model of the Australian economy

The KPMG-EE model, like GTEM, is a hybrid model combining the top-down macroeconomic representation of a CGE model with the bottom-up engineering details of energy production. The KPMG-EE model is used in this work to downscale the global changes captured by the GTEM model in order to generate sectoral growth trajectories across the Australian economy. Unlike GTEM, KPMG-EE does not have a representation of greenhouse gas emissions by economic sector for the Australian economy. Therefore, we use AusTIMES (described below) to assist in calibrating the GTEM sectoral emissions and emission intensity pathways for key sectors of the Australian economy. The core data, theory and parameters of KPMG-EE is based on the model formally presented in Verikios et al. (2021). Below we provide an overview of KPMG-EE particularly aspects not captured in Verikios et al. (2021).

KPMG-EE models the economy as a system of simultaneous equations that represent interdependent economic agents operating in competitive markets. Economic theory specifies the behaviour and market interactions of economic agents, including consumers, investors, producers, and governments. These agents operate in domestic and foreign goods markets, and capital and labour markets. These relationships are equivalent to those represented in (Figure 59).

Defining features of the theoretical structure of KPMG-EE include:

- Optimising behaviour by households and businesses in the context of competitive markets with explicit resource and budget constraints.
- The price mechanism operates to clear markets for goods and primary factors.
- At the margin, costs are equal to revenues in all economic activities.

<u>Agent behaviour in KPMG-EE</u>

Producers are characterised by a representative firm in each sector producing a single commodity. Commodities are distinguished between those destined for export markets and those destined for domestic markets. Energy goods are treated separately to other intermediate goods and services in production and are complementary to primary factors.

The supply of labour is determined by a labour-leisure trade-off that allows workers in each occupation to respond to changes in after-tax wage rates thus determining the hours of work they offer to the labour market. The overall supply of labour is normalised on working-age population. In standard form, labour supply is represented by 8 broad occupations that map to ANZSCO (Australian and New Zealand Standard Classification of Occupations) 1-digit occupations. The supply of and demand for labour by occupation determines the occupational wage rate. Each labour type can move across industries in a region given occupational wage rates.

Household consumption decisions are determined by a linear expenditure system (Stone, 1954) that distinguishes between subsistence (necessity) and discretionary (luxury) consumption. Households can also change their mix of imported and domestically-produced commodities given CES preferences. In the short run, total household spending moves with household disposable income. In the long run, total household spending adjusts to ensure there is a constraint on the economy’s accumulation of net foreign liabilities.

Investment behaviour is industry specific and is positively related to the expected rate of return on capital. This rate takes into account company taxation, a variety of capital allowances and the structure of the dividend imputation system.

Model Calibration

The key data inputs to KPMG-EE are IO tables from the Australian Bureau of Statistics (ABS, 2020). The tables quantify the flows of goods and services from producers to various uses: intermediate inputs to production, inputs to capital creation (i.e., investment), household consumption, government consumption and exports. The IO tables also quantify the flows associated with primary factor inputs: labour, capital, land, and natural resources. In KPMG-EE, the data inputs are combined with the model's theoretical structure to quantify behavioural responses, including:

- Price and wage adjustments are driven by resource constraints.
- Tax and government spending adjustments are driven by budget constraints.
- Input substitution possibilities in production.
- Responses by consumers, investors, foreigners, and other agents to changes in prices, taxes, technical changes, and taste changes.

Behavioural responses relating to household demand and import-domestic substitution are driven by parameters estimated using Australian data; see Verikios et al. (2021), sections 16 and 17. In this work we apply KPMG-EE with 51 commodities, see Table 11.

Table 11 KPMG-EE commodity aggregation

Commodities			
Sheep, grains, beef and dairy cattle	Textiles, clothing, footwear	Electricity transmission and distribution	Information, media, telecommunications
Poultry and other livestock	Wood products	Gas supply	Finance
Other agriculture	Pulp, paper, printing	Water, sewerage, drainage	Insurance and superannuation funds
Aquaculture	Petroleum, coal products	Residential construction	Rental, hiring services, real estate
Forestry and logging	Pharmaceuticals, medicines	Non-residential construction	Ownership of dwellings
Fishing, hunting and trapping	Chemicals, rubber, plastics	Other construction	Professional, scientific, technical services
Coal mining	Non-metallic mineral products	Wholesale, retail trade	Administrative, support services
Oil extraction	Iron, steel	Accommodation, food & beverage services	Public administration, order, safety
Gas extraction	Other metal products	Road transport	Education, training
Iron ore mining	Transport equipment	Rail transport	Health, residential, social services
Other extraction	Electrical and other equipment	Water, other transport	Arts, recreation
Food	Other manufacturing	Air transport	Other services
Beverages	Electricity generation	Postal, warehousing services	

Source: KPMG-EE

KPMG-EE, like GTEM, distinguishes "technology bundle" (TB) electricity industries from other industries. In this work we explicitly represent 11 electricity technologies, see Table 12. Each of these technologies represent individual industries. However, each electricity industry produces the same commodity (electricity generation).[69] Note that this differs from the technology bundle approach in GTEM where each technology bundle essentially represents a satellite model and database. Note that KPMG-EE does not distinguish heterogeneous technologies for iron, steel, and land transport in the way that GTEM does.

[69] This means the IO table in KPMG-EE is non-square with 51 commodities and 61 industries.

Table 12 KPMG-EE electricity technologies

Electricity technologies
Coal
Oil
Gas
Hydro
Wind
Solar
Other renewables
Coal CCS
Oil CCS
Gas CCS
Bioenergy CCS

Source: KMPG-EE

In creating multiple electricity technologies in KPMG-EE we rely on data published by:

- The Australian Government: Australian Energy Statistics (see https://www.energy.gov.au/government-priorities/energy-data/australian-energy-statistics),
- The Australian Energy Market Operator (see https://www.aemo.com.au/), and
- Commonwealth Scientific and Industrial Organisation (CSIRO) (e.g., Graham and Havas, 2021).

Specifically, for the CSP scenario the electricity technologies in KPMG-EE are calibrated to follow AEMO projections from their Integrated Assessment Plan. In the CSP and CRD scenarios energy intensity by sector in KPMG-EE is also calibrated to move in a fashion that is consistent with sectoral energy intensity changes generated by GTEM. For the CRD scenario selected sectoral energy intensities are made consistent with sectoral energy intensity changes generated by AusTIMES via an iterative process; the relevant sectors are iron ore, other mining, non-metallic mineral products, iron and steel, and other metal products.

A.2.3 High emission sectors emission paths using AusTIMES

AusTIMES

The Integrated MARKAL-EFOM System (TIMES) has been jointly developed under the IEA's Energy Technology Systems Analysis Project (ETSAP). 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's website.[70]

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).

Partial equilibrium modelling incorporates various technologies associated with each supply option and allows a market equilibrium to be calculated. It allows for competing technologies to be evaluated simultaneously, without any 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 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 that are subject to non-financial 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.

Compared to economywide CGE models, partial equilibrium models represent a narrower system scope of a limited number of economic sectors, assuming that service demands, prices, and/or price elasticities of the remainder of the economy are exogenous phenomena. However, a partial equilibrium model is better able to explicitly represent investment in distinct categories of real capital, such as industrial production capacity, buildings or transport vehicles, as stocks, which in CGE models are typically less detailed.

Structural features

AusTIMES model has the following structural features:

- Coverage of all states and territories (ACT, NSW, NT, QLD, SA, TAS, VIC, WA).
- Time is represented in annual frequency (2015-2050).
- Demand sectors include agriculture (8 sub-sectors), mining (6 sub-sectors), manufacturing (19 sub-sectors), other industry (5 sub-sectors), commercial and services (11 building types), residential (3 building types), road transport (10 vehicle segments) and non-road transport (aviation, rail, shipping).
- Detailed representation of the electricity sector (detailed in Section A.2.4).

[70] https://iea-etsap.org/index.php/documentation

- 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.

Model inputs

AusTIMES has been calibrated to a base year of 2015 based on the state/territory level energy balance (Office of the Chief Economist, 2016), Emissions inventories | ANGA, National Inventory by Economic Sector (DEE, 2017a), stock estimates of vehicles in the transport sector (ABS, 2016a), data on the existing power generation fleet (ACIL Allen, 2014a; 2014b; AEMO, 2015; ESAA, 2016) and installed capacity of distributed generation (CER, 2018; AEMO, 2018).

When updates to these data sources (*Australian Energy Statistics, National Greenhouse Gas Inventory, Motor Vehicle Census, ISP Input and Assumptions Workbook*) are released for what are now historical years (2016, …, 2020), historical years are re-calibrated in the model.

For given time paths of the exogenous (or input) variables that define the economic environment (these can differ by scenario), AusTIMES determines the time paths of the endogenous (output) variables (i.e., technology uptake, fuel use, emissions).

Objective function

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

$$NPV = \sum_{r=1,y=REFYR}^{R,2050} \frac{ANNCOST_{r,y}}{(1+d)^{(y-REFYR)}}$$

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,

YEARS: set of years for which there are costs,

R: region.

While minimizing total discounted cost, the model must satisfy a large number of constraints (the so-called 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 these constraints are available in Part I of the TIMES model documentation.[71]

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

Although restricting the formulation to a linear model provides significant advantages for computational optimisation, it does not permit the representation of minimum investment (or plant shut-down) scale. This can represent a poor approximation to reality where minimum typical investment scale is large relative to total stocks.

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 outlined below. 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 NTNDP (National Transmission Network Development Plan) zones in the National Electricity Market (NEM); 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.
- 29 new electricity generation and storage technologies: black coal pulverised fuel; black coal with 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); 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; Northern Territory, Queensland, Tasmania and Victoria Renewable Energy Targets; small-scale renewable energy scheme; NSW Energy Security Target.

End-use sectors

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 13).

Table 13 Mapping of AusTIMES to ANZSIC industry subsectors

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

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

Growth in industry subsectors in AusTIMES is projected using several data sources, including:

- Forecasts of sectoral activity developed through the *Pathway to Deep Decarbonisation Project* (ClimateWorks Australia, et al., 2014), drawing on results of CGE analysis by the Centre of Policy Studies at Victoria University.
- Asset-level assumptions for alumina, aluminium, steel and petroleum refining facilities.
- Recent trends of changes in energy use by sector, drawing on historical data from the Department of the Environment and Energy (DEE) (2017b).

Additionally, through the *Australian Industry Energy Transitions Initiative*, CSIRO/CWA have and continue to develop a granular understanding of heavy industry, including considerations around asset renewal, new technologies being trialled or considered, etc.

Demand for Australian energy exports are based on *International Energy Agency* scenarios. AusTIMES can implement energy efficiency and electrification of technologies based on capital costs, equipment lifetime and fuel costs, if it is economically attractive. 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 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 setting of abatement solutions in a given scenario is informed by the scenario narratives. Exogenous abatement potentials are derived from the *Decarbonisation Futures* report (ClimateWorks Australia, 2020)

Although the partial equilibrium framework permits the representation of industrial production capacity as a stock, this is not currently implemented for most of the industries explicitly represented in AusTIMES. In the absence of a stock model of production capacity, additional production capacity is implicitly assumed to have the same technical and economic characteristics as the existing plant, that is, there is no assumption that new investment represents a step change in technology.

Residential buildings

The stock of buildings is sourced from the *Residential Buildings Baseline Study* (EnergyConsult, 2016), 2016 ABS *Census* data on housing,[72] Australian Bureau of Statistics' 2016 *Household and Family Projections* (ABS, 2016b), *Australian Energy Statistics*, and the Australian Sustainable Built Environment Council's *Low Carbon High Performance* report (ASBEC, 2016).

AusTIMES projects baseline energy consumption and can also implement energy efficiency and electrification of technologies based on capital costs, equipment lifetime and fuel costs, if it is

[72] https://www.abs.gov.au/census/find-census-data/historical Historical Census data, Australian Bureau of Statistics

economically attractive. Hurdle rates (i.e., technology specific discount rates) can be adjusted for different building types to reflect the levels of ambition of the building owners.

The residential building types, end-use service demands, and fuel types are listed below (Table 14).

Table 14 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	Gas
Apartments	Cooking	Hydrogen
	Water heating	LPG
	Appliances	Wood
	Lighting	

All residential buildings experience a business-as-usual efficiency improvement at no cost. Additional 'best practice' energy efficiency and electrification options are available, at an additional incremental cost. Should these be economically attractive, they will be taken up in the model.

All assumptions on costs and savings are derived from the Low Carbon High Performance report (ASBEC, 2016).

Commercial buildings

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

AusTIMES projects baseline energy consumption and can also implement energy efficiency and electrification of technologies based on capital costs, equipment lifetime and fuel costs, if it is economically attractive. Hurdle rates can be adjusted for different building types to reflect the levels of ambition of the building owners.

The commercial building types, end-use service demands, and fuel types are listed below (Table 15).

Table 15 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	Hydrogen
Office	Appliances	
Public building	Lighting	
Retail	Equipment	
Supermarket		
School		
Tertiary		
Data centre		
Aged care		

All commercial buildings experience a business-as-usual efficiency improvement at no cost. Additional ‘best practice’ energy efficiency and electrification options are available, at an additional incremental cost. Should they be economically attractive, they will be taken up in the model.

All assumptions on costs and savings are derived from the *Low Carbon High Performance* report (ASBEC, 2016).

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 16).

Table 16 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 the Australian Bureau of Statistics data on vehicle stock (ABS, 2016), average kilometres travelled (ABS, 2017), the Bureau of Infrastructure, Transport and Regional Economics (BITRE, 2019) and the Australian Government’s *Australian Energy Statistics* data (Office of the Chief Economist, 2017) on fuel use, NGA emission factors for fuel (DEE, 2017a), population/GSP projections, assumptions around future vehicle costs and efficiency improvements (Graham et al., 2020), oil price projections (IEA, 2020a) and production costs on biofuels (Campey et al., 2017). The delivery price of electricity and hydrogen for road transport is endogenously determined within AusTIMES.

Key outputs at a state/territory level include uptake of different vehicle types (numbers), fuel consumption (PJ), greenhouse gas emissions (kt), and costs (capital, maintenance, fuel in million dollars).

There is less detailed representation of non-road transport, implemented on a fuel basis. The market segments and fuel categories are listed below (Table 17).

Table 17 Non-road transport market segments and fuels

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

Agriculture

Energy use in agriculture is minimal although emissions are significant. The mapping of AusTIMES to ANZSIC industry subsectors is displayed below (Table 18).

Table 18 Mapping of AusTIMES to ANZSIC agriculture subsectors

AusTIMES subsector (agriculture)	ANZSIC (2006) codes
Agriculture - sheep and cattle	0141, 0142, 0143, 0144
Agriculture - dairy	16
Agriculture - other animals	017, 018, 019
Agriculture - grains	0145, 0146, 0149, 015
Agriculture - other agriculture	011, 012, 013
Agriculture - agricultural services and fishing	02, 04, 052
Forestry - forestry and logging	03, 051

Carbon forestry

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 focusses specifically on the agriculture sector. While not integrated into AusTIMES, emerging findings from this work can be drawn upon to sense-check assumptions or results as required.

Carbon forestry sequesters the volume of carbon that would be profitable to supply, where delivery of carbon credits would provide higher economic return than competing agricultural land uses. The available supply and cost curves are informed by previous CSIRO analysis, separate to AusTIMES, but aligned post model runs.

A.2.4 DER Adoption Model

Adoption projections method overview

The projections undertaken are for periods of months, years and decades. Consequently, the projection approach needs to be robust over both shorter- and longer-term projection periods. Longer term projection approaches tend to be based on a theoretical model of all the relevant drivers including human behaviour and physical drivers and constraints. These models can overlook short term variations from the theoretical model of behaviour because of imperfect information, unexpected shifts in key drivers and delays in observing the current state of the market.

Shorter term projection approaches tend to be based on extrapolation of recent activity without an underlying theory of the drivers. These include regression analysis and other types of trend extrapolation. While trend analysis will generally perform the best in the short term, extrapolating a trend indefinitely will lead to poor results since eventually a fundamental driver or constraint on the activity will assert itself, changing the activity away from past trends.

Based on these observations about the performance of short- and long-term projection approaches, and our need to deliver both long and short projections, this report applies a combination of short-term trend models and a long-term theory-based adoption model.

Trend model

For periods of monthly to several years (up to June 2021-22), trend analysis is applied to produce the projections based on historical solar data. The trend is estimated as a linear regression against 2 years of monthly data with dummy variables against each month to account for trends in monthly sales. A non-linear relationship was explored but was not preferred. Compared to previous projections we have shortened the historical data used in the linear projection to ensure it is tracking the most recent trends. As such, the regression takes the following form:

$$X_m = f(month\ in\ sequence, month\ of\ year\ dummy\ variable)$$

Where X is the (m) monthly activity of the following possible activities solar PV installations and capacity by residential and commercial segments. The installation trend is more important because we also carry out a regression on system size trends and use the multiple of system size and installation projections to project PV capacity (before degradation or other capacity losses).

For solar PV system less than 100kW, regressions are calculated at the postcode level, while the remainder of activities are calculated the state level. For some larger non-scheduled solar PV, we have only used the last 24 months of data due to significant inactivity. For batteries and electric vehicles annual state data is often only available and so the regression is simply a function of the year.

Adoption in consumer technology markets

The consumer technology adoption curve is a whole-of-market-scale property that we can exploit for the purposes of projecting adoption, particularly in markets for new products. The theory posits that technology adoption will be led by an early adopter group who, despite high payback periods, are driven to invest by other motivations such as values, autonomy and enthusiasm for new technologies. As time passes, fast followers or the early majority take over and this is the most rapid period of adoption. In the latter stages the late majority or late followers may still be holding back due to constraints they may not be able to overcome, nor wish to overcome even if the product is attractively priced. These early concepts were developed by authors such as Rogers (1962) and Bass (1969).

In the last 50 years, a wide range of market analysts seeking to use the concept as a projection tool have experimented with a combination of price and non-price drivers to calibrate the shape of the adoption curve for any given context. Price can be included directly or as a payback period or return on investment. Payback periods are relatively straightforward to calculate and compared to price also capture the opportunity cost of staying with the existing technology substitute. A more difficult task is to identity the set of non-price demographic or other factors that are necessary to capture other reasons which might motivate a population to slow or speed up their rate of adoption. CSIRO has previously studied the important non-price factors and validated how the approach of combining payback periods and non-price factors can provide good locational predictive power for rooftop solar and electric vehicles (Higgins et al., 2014; Higgins et al., 2012).

As noted previously, the general projection approach including some examples of the types of demographic or other factors that could be considered for inclusion. We also indicate an important interim step, which is to calibrate the adoption curve at appropriate spatial scales (due to differing demographic characteristics and electricity prices) and across different customer segments (due to differences between customers' electricity load profiles).

Once the adoption curve is calibrated for all the relevant factors, we can evolve the rate of adoption over time by altering the inputs according to the scenario assumptions.[73] For example, differences in technology costs and prices between scenarios will alter the payback period and lead to a different position on the adoption curve. Non-price scenario assumptions such as available roof space in a region will result in different adoption curve shapes (particularly the height at saturation). Data on existing market shares determines the starting point on the adoption curve.

[73] Note that to "join" the short- and long-term projection models we assume that the trends projected to 2021-22 are seen as historical fact from the perspective of the long-term projection model and as such calibrate the adoption curve from that point.

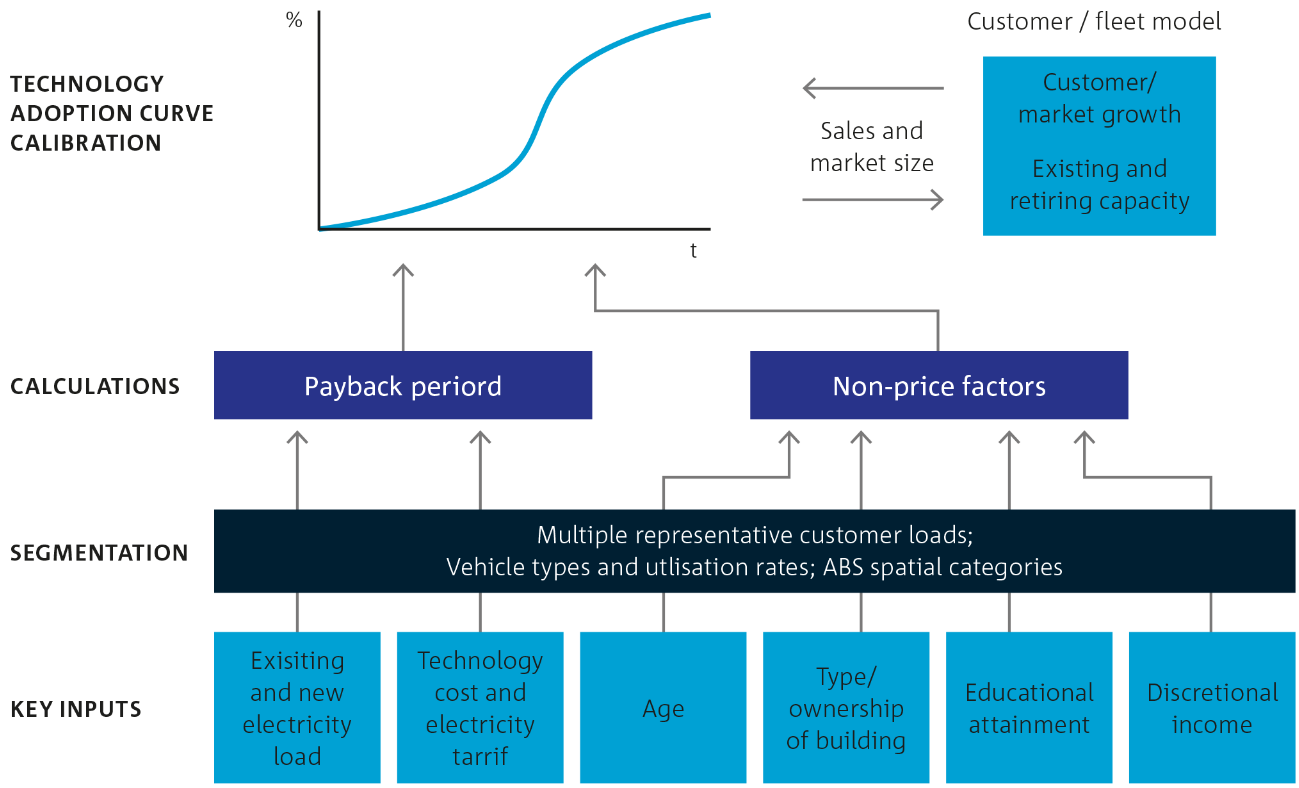


Figure 64 Adoption model methodology overview

The methodology also takes account of the total size of market available, and this can differ between scenarios. While we may set a maximum market share for the adoption curve based on various non-financial constraints, maximum market share is only reached if the payback period falls. Maximum market share assumptions are outlined in the Data Assumptions section.

All calculations are carried out at the Australian Bureau of Statistics Statistical Area Level 2 (SA2) as this aligns to the available demographic data. However, we convert the technology data back to postcodes or aggregate up to the state level as required. The Australian Bureau of Statistics publishes correspondence files which provide conversion factors for moving between alternative commonly used spatial disaggregation. Each spatial disaggregation can also be associated with a state for aggregation purposes.

A.3 Model settings and calibration

A.3.1 Model settings

The tables below list important assumptions made in applying GTEM, KPMG-EE and AusTIMES for each scenario. The theme of these choices is to maintain, as far as possible, consistency in settings across the three models and with previous relevant CSIRO studies.

Note that the ultimate GTEM settings described in the tables below represent the outcome of extensive sensitivity analysis with respect to substitution parameters and model closure (i.e., the choice of exogenous and endogenous variables). We do not present the results of this analysis due to space constraints.

Table 19 Treatment of key variables in GTEM

Variable	CRD scenario	CSP scenario
Macroeconomic variables	Movements in regional population and regional debt-to-GDP ratios match the CSP scenario Movements in regional labour supply, regional GDP, regional employment and the global CPI are endogenously determined within GTEM	Movements in regional population, regional labour supply, regional GDP, regional employment and the global CPI are applied. These values are based on combining the latest NIGEM baseline with population and GDP forecasts from Oxford Economics as reported in the IEA's *Net Zero by 2050* report Regional debt-to-GDP ratios are stabilised by 2050
GHG shadow price	Endogenously responds to emissions targets	US$10 in low-income regions and US$20 in high-income regions in 2021
Emissions	Global net CO_2 emissions budget of 500 Gt Global non-CO_2 emissions carbon budget of 326 Gt Global AFOLU CO_2 emissions budget of 40 Gt (included in net CO_2 emissions budget of 500 Gt)	Global and selected regional CO_2 emissions pathways via shifts in emission intensity Global and selected regional electricity CO_2 emissions pathways Global CO_2 emissions pathways for selected industries – basic chemicals, iron and steel, land transport, water transport, and air transport Global and regional AFOLU CO_2-eq emissions pathways from GLOBIOM Source: IEA Stated Policies scenario
Electricity output and technology mix	Global electricity output pathway Global electricity technology mix pathway Source: IEA NZE scenario	Global and regional electricity output pathways Global electricity technology mix pathway Source: IEA Stated Policies scenario
Fossil fuel output	Global coal and gas output pathways from IEA NZE scenario	Global coal, oil and gas output pathways from IEA Stated Policies scenario
Energy efficiency	1.5% annual energy efficiency improvement for households and firms Extra 0.5% annual energy efficiency improvement for iron and steel, non-ferrous metals, and all transport sectors Extra 0.5%-1% annual efficiency improvement in use of fossil fuels	1.5% annual energy efficiency improvement for households and firms Extra 0.5% annual energy efficiency improvement for iron and steel, non-ferrous metals, and all transport sectors

Note: The CSP scenario also includes historical and projected Australian aggregate and sectoral emissions sourced from DISER (2021).

Table 19 mentions the treatment of regional debt-to-GDP ratios such that they stabilise by 2050. This is accomplished by applying shifts in the Cobb-Douglas demand for saving by the regional household described in section A.2.2.

Table 20 IEA targets applied in the CSP scenario

	CSP scenario				
	2019	2020	2030	2040	2050
Non-AFOLU CO_2 emissions (Mt CO_2)					
Global	35,966	34,156	36,267	na	33,903
China	11,198	11,356	11,385	na	8,341
Japan	1,071	996	797	na	513
India	2,475	2,304	3,305	na	3,687
USA	4,826	4,303	3,969	na	2,936
Brazil	443	421	461	na	532
EU	2,744	2,485	1,957	na	1,208
Russia	1,691	1,612	1,727	na	1,619
Middle East	1,886	1,849	2,150	na	2,644
Africa	1,370	1,297	1,617	na	2,287
Electricity and heat sectors CO_2 emissions (Mt CO_2)					
Global	13,933	13,530	12,425	na	9,915
China	5,242	5,362	5,019	na	3,684
Japan	483	456	270	na	106
India	1,172	1,124	1,344	na	915
USA	1,682	1,501	1,053	na	607
Brazil	64	51	30	na	36
EU	811	715	388	na	196
Russia	791	762	785	na	706
Middle East	681	682	692	na	789
Africa	501	478	488	na	475
Other sectoral CO_2 emissions (Mt CO_2)					
Chemicals	1,182	1,160	1,382	1,456	1,428
Iron and steel	2,500	2,591	2,945	2,861	2,743
Road transport	6,043	5,419	6,391	6,311	6,194
Water transport	866	811	999	1,063	1,171
Air transport	1,027	606	1,242	1,463	1,631
Energy supply (EJ)					
Unabated coal	162.2	155.8	150.2	132.9	116.8
Oil	187.9	171.4	198.5	199.6	198.3
Unabated natural gas	141.4	138.7	155.9	168.0	174.0

	CSP scenario				
	2019	2020	2030	2040	2050
Electricity generation (TWh)					
Global	26,959	26,762	33,575	40,553	46,703
China	7,509	7,787	10,232	na	13,187
Japan	1,037	1,003	984	na	1,055
India	1,637	1,609	2,545	na	5,000
USA	4,371	4,243	4,490	na	5,175
Brazil	626	605	752	na	1,148
EU	4,080	3,952	4,601	na	5,594
Russia	1,120	1,057	1,253	na	1,488
Middle East	1,202	1,189	1,616	na	2,764
Africa	839	827	1,215	na	2,384
Electricity technology mix (TWh)					
Coal	9,911	9,467	8,733	7,418	6,189
Oil	966	752	716	500	393
Natural gas	4,843	6,356	6,257	7,112	7,858
Nuclear	2,790	2,692	3,115	3,517	3,711
Hydro	4,236	4,347	5,087	5,872	6,739
Wind	1,421	1,596	4,102	6,628	8,805
Solar	694	846	3,538	6,857	9,968
Bioenergy	672	709	1,145	1,500	1,852
Coal with CCS	1	1	11	78	104
Gas with CCS	0	0	9	9	13
Bioenergy with CCS	0	0	0	0	0

Table 20 and Table 21 indicate that electricity technology targets are applied in the CSP and CRD scenarios. The targets are applied via equi-proportional shifts in the regional supply curves for each technology. Thus, the CRESH parameter controlling substitution across electricity technologies discussed in section A.2.2 operates conditional on these supply curve shifts and not independently of them.

Table 21 IEA targets applied in the CRD scenario

	CRD scenario			
	2020	2030	2040	2050
Non-AFOLU net CO_2 emissions (Mt CO_2)				
Global	34,156	21,147	6,316	0
Energy supply (EJ)				
Coal (unabated + CCUS)	155.8	71.9	31.6	17.2
Oil	171.4	137.4	79.2	42.2
Natural gas (unabated + CCUS)	139.1	129.4	74.6	60.7
Electricity generation (TWh)				
Global	26,762	37,316	56,553	71,164
Electricity technology mix (TWh)				
Coal	9,467	2,947	0	0
Oil	716	189	6	6
Natural gas	6,257	6,222	626	253
Wind	1,596	8,008	18,787	24,785
Solar	846	7174	17,911	24,855
Coal with CCS	1	289	966	663
Gas with CCS	0	170	694	669
Bioenergy with CCS	709	1,407	2,676	3,279
Carbon capture use and storage (Mt CO_2)				
Fossil fuels and processes	39	1325	na	5245
Direct air capture	0	70	na	630
Bioenergy	1	255	na	1380

Table 22 Inputs applied for demographic and economic variables in the CSP scenario

	2020-2030	2031-2040	2041-2050
Population (average annual %-change)			
Global	0.97	0.78	0.61
Australia	1.02	0.82	0.71
New Zealand	0.72	0.49	0.31
China	0.19	-0.10	-0.33
Japan	-0.45	-0.63	-0.69
South Korea	-0.01	-0.27	-0.61
Rest of Asia	0.89	0.56	0.28
Indonesia	0.92	0.63	0.38
India	0.88	0.58	0.28
Canada	0.80	0.63	0.49
USA	0.55	0.47	0.34
Mexico	0.91	0.61	0.35
South America	1.03	0.70	0.46
Brazil	0.54	0.23	-0.01
EU15	-0.02	-0.12	-0.24
EU12	-0.02	-0.12	-0.24
Rest of Europe	-0.34	-0.51	-0.63
Russia	-0.16	-0.30	-0.23
Middle East	1.69	1.31	1.07
Africa	2.61	2.32	2.01
Rest of World	0.96	0.75	0.58
Real GDP (average annual %-change)			
Global	2.43	2.07	2.52
Australia	2.61	1.96	2.13
New Zealand	2.30	1.95	2.38
China	4.84	2.88	2.95
Japan	0.67	-0.15	0.42
South Korea	2.28	2.27	2.68
Rest of Asia	3.75	3.31	3.35
Indonesia	3.80	3.07	3.10
India	4.99	5.06	4.54
Canada	1.69	1.60	2.05
USA	1.73	1.64	2.32
Mexico	1.54	1.60	2.30
South America	0.74	0.79	1.19

	2020-2030	2031-2040	2041-2050
Brazil	2.06	1.92	2.48
EU15	1.27	0.93	1.62
EU12	1.26	0.87	1.60
Rest of Europe	2.18	1.89	2.38
Russia	1.67	1.05	1.45
Middle East	2.74	2.58	2.68
Africa	3.28	4.24	4.56
Rest of World	2.81	2.42	2.79
Consumer price index (average annual %-change)			
Global	2.57	1.91	2.59

Table 23 Treatment of key variables in KPMG-EE

Variable	CRD scenario	CSP scenario
Macroeconomic variables - real	GTEM CRD scenario results for Australia are applied to KPMG-EE. These are shifts in export demand, land supply and natural resource supply. Population moves with the CSP scenario. Net foreign liabilities-to-GDP ratio moves with the CSP scenario	GTEM CSP scenario results for Australia are applied to KPMG-EE. These are government consumption, shifts in export demand, shifts in investment, labour productivity, land supply, natural resource supply, population, employment, and labour supply. Net foreign liabilities-to-GDP ratio stabilises by 2050
Macroeconomic variables - prices	GTEM CRD scenario results for Australia are applied to KPMG-EE. These are CIF import prices.	GTEM CSP scenario results for Australia are applied to KPMG-EE. These are shifts in FOB export prices, CIF import prices and the consumer price index.
GHG shadow price	GTEM CRD scenario results for Australia representing the GHG shadow price are applied to KPMG-EE. These are represented as ad valorem tax rates on output, intermediate inputs and household consumption	GTEM CSP scenario results for Australia representing the GHG shadow price applied to KPMG-EE. These are represented as ad valorem tax rates on output, intermediate inputs and household consumption
Electricity output and technology mix	Endogenous	Consistent with GTEM CSP scenario results for Australia
Fossil fuel output	Endogenous	Endogenous
Energy efficiency	Consistent with GTEM CRD scenario results for Australia Selected sectoral energy intensities are made consistent with sectoral energy intensity changes in AusTIMES via an iterative process; the relevant sectors are iron ore, other mining, non-metallic mineral products, iron and steel, and other metal products.	Consistent with GTEM CSP scenario results for Australia

Table 24 Treatment of key variables in AusTIMES

Variable	CRD scenario	CSP scenario
Emissions	Shadow CO_2 price from GTEM reaches $38 by 2030 and $345 by 2050	Shadow CO_2 price from GTEM reaches $31 by 2030-2050
Industrial sectoral economic growth	Consistent with KPMG-EE. Lower growth in demand for steel, aluminium, alumina, bauxite	Higher growth in demand for steel, aluminium, alumina, bauxite
Coal retirements	Coal capacity in each NEM state consistent with 2022 ISP "Progressive Change" scenario	Coal capacity in each NEM state consistent with 2022 ISP "Strong Electrification" sensitivity scenario.
Global capital costs for power generation and battery storage	Derived from Graham et al. (2021): *GenCost 2020-21,* "Net Zero by 2050" scenario.	Derived from Graham et al. (2021): *GenCost 2020-21,* "Current Policies" scenario.
Uptake of distributed energy (rooftop PV and customer batteries)	Consistent with "Export Superpower" scenario in 2021 CSIRO projections	Consistent with "Current Trajectory" scenario in 2021 CSIRO projections
Transport Sector	1.5 degrees scenario (lower growth in transport demand)	Steady Progress scenario (higher growth in transport demand)
Building technology changes	High propensity for uptake of electrification and energy efficiency measures	Moderate propensity for uptake electrification measures, high propensity for uptake of energy efficiency
Aluminium sector	Energy efficiency measures in Aluminium smelting reaches 11kWh/kg by 2050. Inert Anode technology implemented from 2040-50	Energy efficiency measures in Aluminium smelting reaches 12.5kWh/kg by 2050.

A.3.2 Carbon budget assumptions

Table 25 Global and Australian carbon budgets in GTEM

	CRD scenario	CSP scenario
Global temperature outcome	Global temperature rise limited to 1.5°C by 2100 (with a 50% probability and no overshoot)	Global temperature rise limited to 2.7°C by 2100 (with a 50% probability).
Global CO_2 budget	500 Gt of CO_2 over 2020-2050 comprising 460 Gt of energy and industrial process emissions and 40 Gt of emissions from AFOLU *Emissions constrained based on IEA NZE global CO_2 budget*	1,410 Gt of CO_2 over 2020-2050 comprising 1,253 Gt of energy and industrial process emissions and 157 Gt of emissions from AFOLU *Emissions constrained based on IEA NZE global CO_2 budget*
Global non-CO_2 budget	326 Gt CO_2-eq over 2020-2050 *Emissions constrained based on IPCC Sixth Assessment Report non-CO_2 budget*	472 Gt CO_2-eq over 2020-2050
Global emissions budget (CO_2 and non-CO_2)	826 Gt CO_2-eq over 2020-2050	1,883 Gt CO_2-eq over 2020-2050
Global LULUCF emissions budget	31 Gt CO_2 over 2020-2050 *Emissions constrained based on GLOBIOM NZE scenario*	115 Gt CO_2 over 2020-2050 *Emissions constrained based on GLOBIOM STEPS scenario*
Global negative emissions technology budget	132 Gt CO_2 over 2020-2050 *CO_2 sequestration based on IEA NZE negative emissions technologies*	6 Gt CO_2 over 2020-2050 *Budget constrained to minimal growth of negative emissions technologies*
Australian CO_2 budget	921 Mt CO_2 over 2020-2050	8,768 Mt CO_2 over 2020-2050 *Emissions constrained to 2030 based on DISER (2021)*
Australian non-CO_2 budget	3,761 Mt CO_2-eq over 2020-2050	4,589 Mt CO_2-eq over 2020-2050 *Emissions constrained to 2030 based on DISER (2021)*
Australian emissions budget (CO_2 and non-CO_2)	4,682 Mt CO_2-eq over 2020-2050	13,358 Mt CO_2-eq over 2020-2050
Australian LULUCF emissions budget	-2,859 Mt CO_2 over 2020-2050 *Emissions constrained based on GLOBIOM NZE scenario*	-501 Mt CO_2 over 2020-2050 *Emissions constrained to 2030 based on DISER (2021)*
Australian negative emissions technology budget	1,587 Mt CO_2 over 2020-2050	0.18 Mt CO_2 over 2020-2050 *Budget constrained to minimal growth of negative emissions technologies*

Note: Blue text indicates constraint imposed for relevant variable.

A.3.3 Building sector assumptions data and results tables

Table 26 Building sector key assumptions data

Parameter	Modelled value	Source
Average floorspace **Existing dwellings 2020**	192 m^2 (detached housing) 121 m^2 (townhouses and apartments)	Derived from Australian Bureau of Statistics data
Average floorspace **New dwellings 2020**	234 m^2 (detached housing) 134 m^2 (townhouses and apartments)	
Floorspace growth **New dwellings**	18% growth from 2020-2030 (detached housing) 7.5% growth (townhouses and apartments)	NatHERS database (CSIRO, 2022)
Energy efficiency improvement between residential 6-star and 7-star rating	21-27% for new dwellings from 2022	NatHERS (2019) and NatHERS (2022)
Energy consumption average change due to household renovation	Not modelled	

Table 27 Buildings emissions: CRD and CSP scenarios, residential and commercial, direct and indirect (Mt CO_2)

			2020	2030	2040	2050
CRD	**Residential**	**Direct emissions**	10.0	3.4	1.3	0.02
		Electricity emissions	40.6	5.8	1.8	0.70
	Commercial	**Direct emissions**	5.4	3.4	1.8	0.82
		Electricity emissions	39.5	5.4	1.7	0.72
CSP	**Residential**	**Direct emissions**	10.0	7.3	7.3	8.0
		Electricity emissions	40.6	17.6	10.4	1.6
	Commercial	**Direct emissions**	5.4	4.6	4.2	4.0
		Electricity emissions	39.5	17.5	10.5	1.8

Table 28 Buildings emissions intensities: CRD and CSP scenarios, residential and commercial, (kg CO_2/m^2)

		2020	2030	2040	2050
CRD	**Residential**	39.5	6.1	1.8	0.3
	Commercial	154.6	24.7	8.0	2.8
CSP	**Residential**	39.5	16.6	9.9	4.6
	Commercial	154.6	62.1	33.5	10.7

A.3.4 Transport sector results table

Table 29 Road vehicle fuel use, CRD scenario (PJ pa)

	2020	2030	2040	2050
Compressed natural gas	3.7	2.3	0.5	0.0
Diesel	572	589	254	0
Ethanol 10%	65	44	16	0
Electricity	0	62	236	361
Ethanol	0	0	0	0
Hydrogen	0	20	89	144
Liquified petroleum gas	11.1	2.8	0.1	0.0
Petrol	488	417	150	0

Source: AusTIMES

A.3.5 Some industry technology assumptions data

Table 30 Capital costs premium for vehicle fuel switching in mining, and boiler fuel switching in alumina refining and cement production

Sector	Parameter	Modelled value	Other relevant references
Bauxite mining, iron ore mining	Electric vehicle premium	13.0 $/MJ pa in 2020 9.3 $/ MJ pa in 2050	• Lutsey and Nicholas (2019)
	Fuel cell vehicle premium	27.5 $/MJ pa in 2020 4.7 $/ MJ pa in 2050	• Bethoux (2020)
Alumina refining, cement production	Hydrogen boiler costs	Additional 10.0-11.7 $/MJ pa in 2020 15.60 $/MJ pa in 2050	• Element Energy and Jacobs (2018) Section 7.3
	Boiler conversion for biomass suitability	Additional 100-130 $/MJ pa in 2020 100-128 $/MJ pa in 2050	

Source: ClimateWorks Australia (2021)

A.3.6 Aluminium sector assumptions data

Table 31 Aluminium sector techno-economic data

Sector	Parameter	Modelled Value	Source	Other relevant references
Bauxite mining	Mining equipment electrification (substitution for diesel, maximum)	0% in 2020, 7.5% by 2025, 30% by 2030, 55% by 2040, 60% by 2050	Based on CWA (2021)	• VCI (2020)
	Mining equipment hydrogen fuel cell (maximum)	0% in 2020, 60% by 2050		
Alumina refining	Mechanical vapour recompression electrification (maximum fuel substitution, and earliest start year)	0% in 2025, 15% by 2030, 60% by 2050 2025 start in WA, 2035 in Qld 37.5% efficiency improvement		
	Hydrogen fuel in calcination (maximum fuel substitution, and earliest start year)	0% in 2030, 25% by 2050 2035 start in Qld, 2040 in WA		
	Boiler electrification Boiler hydrogen substitution Boiler biomass substitution (% maximum permitted)	0% in 2020 15% by 2030, 60% by 2050		
	Boiler electrification costs	Additional 9.7 $/MJ pa in 2020 12.9 $/MJ pa in 2050		• Element Energy and Jacobs (2018) • ITP Thermal (2019), Appendix E
Aluminium smelting	Direct process emissions		DCCEEW (2020)	Frederick and Haque (2015)
	Reduced electricity usage (kWh/kg aluminium)	11.0 by 2050 (CRD scenario) 12.5 (CSP)	Based on Matthews et al. (2020) p10	
	Inert anode costs	Assumed no additional cost		
	Inert anode minimum uptake	30% by 2040, 90% by 2050		
	Inert anode additional electricity requirements	3.04 kWh/ kg Aluminium	U.S. Department of Energy (2007) Section 6.2.2	
	Additional aluminium recycling	Not modelled		• Benjas Pty Ltd (2021)

A.3.7 Cement sector assumptions data

Table 32 Cement sector techno-economic data

Parameter	Modelled value	Source	Other relevant references
Reduced demand for concrete due to construction efficiency, alternative materials, waste reduction in concrete production.	10% reduction by 2050	VDZ (2022) p6	• GCCA (2022) p24, 22% for construction efficiency and 10% for waste reduction. • BZE (2017) p18, 15% reduction
Recarbonation post-construction	20% of process emissions 10 years (i.e., 2030) to recognise	Based on VDZ (2022) Section 6.5	
Carbon Capture and Storage maximum emissions capture, earliest start year	0% in 2020, 30% by 2050 Start in 2020		
Carbon Capture and Storage cost ($/ t CO_2)	117.50 in 2040 112.50 in 2050	VDZ (2022) Table 3, p32	
Carbon Capture and Storage Additional energy consumption	3.22 MJ/ t kg CO_2	Voldsund et al (2019) Table 16 2216 MJ/ t clinker	
Alternative fuels substitution for coal	18% in 2020, 30% by 2030 60% by 2050	VDZ (2022) Table 1, §7.3	
Alternative fuels biomass content	40% in 2020, 50% by 2030		
Maximum hydrogen substitution	0% in 2020, 10% by 2030		
Autonomous energy efficiency improvement	None assumed		• IEA (2018) 3% by 2050 • VDZ (2022)
Geopolymer (clinker-free) cement	Not modelled		• BZE (2017) p24: Up to 50% of the market and p25: 80% reduction in emissions intensity

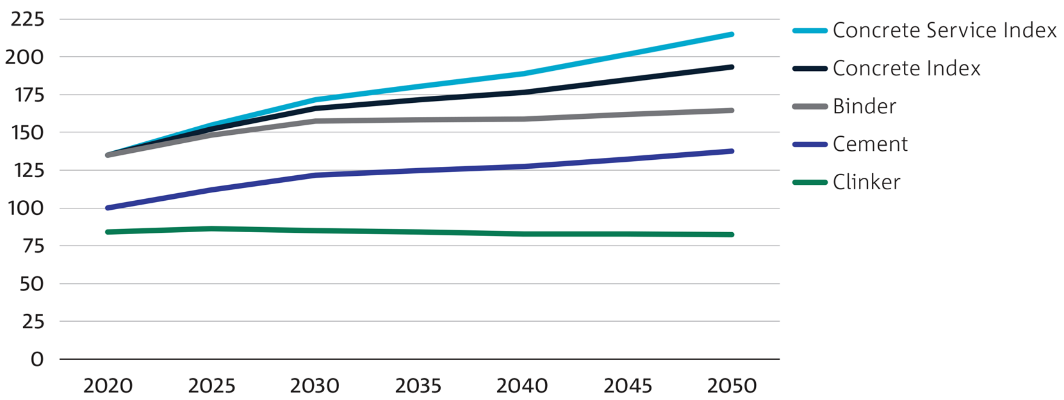
Table 33 Clinker, binder, concrete ratio projection assumptions data

Row	Parameter	2020	2030	2050	Derivation
1	Clinker to concrete ratio index	84	72	58	
2	Cement to concrete ratio index	100	99	96	
3	Binder to concrete ratio index	135	128	115	
4	Binder to concrete savings from 2020		5.2%	14.8%	Row 3
5	Low clinker/ high blend cement Clinker to cement ratio	84%	72.7%	60.4%	Rows 1 and 2
6	Clinker to binder ratio	62.2%	56.3%	50.4%	Rows 1 and 3

Source: Based on VDZ (2022), Table 1, Section 7.3, Compare row 5 with IEA (2018), p23, 72% in 2050

CEMENT INDUSTRY GROWTH INDICES

INDEX: CEMENT IN 2020 (Mt)=100



EMISSIONS INTENSITY IN CEMENT SECTOR: CRD

Index: cement emissions intensity in 2020 (kgCO_2-eq/t)=100

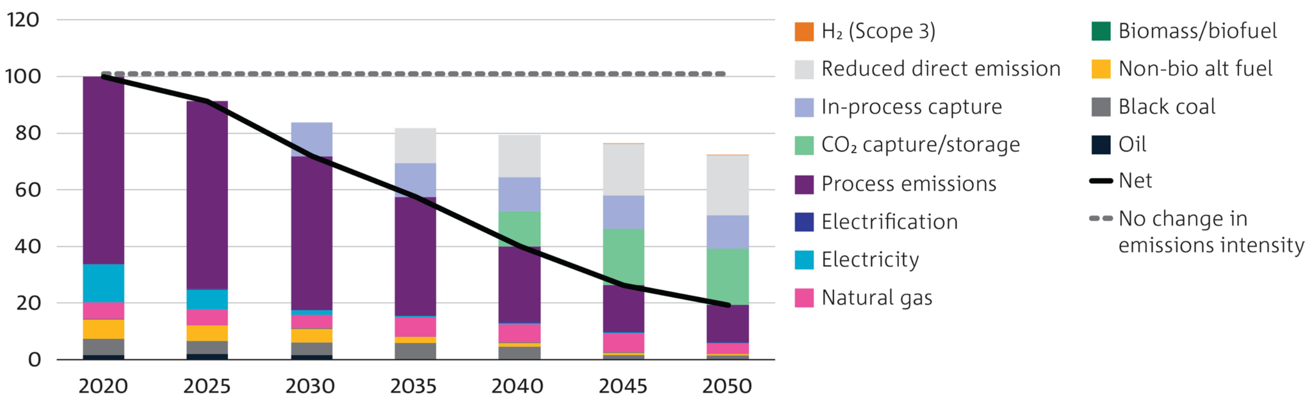


Figure 65 Cement industry adjustment factors and emissions intensity index in terms of tonnes of cement[74]

[74] The upper figure displays the projected growth in cement sector demand, adjusted by the data in Table 32 and Table 33. The lower figure excludes emissions from imported clinker and is based on an assumption of cement production in 2019-2020 of 11.7 Mt. Noting that 2019-2020 domestic clinker production was 5.2 Mt (VDZ, 2022), it follows that the estimated emissions intensity in 2020 in the chart is based on 44.4% t domestic clinker/ t cement demand. The clinker to cement ratio in 2020 is taken as 84%, so there is 52.9% domestic clinker to total clinker requirements for both domestic and imported cement. Projections assume domestic clinker production remains the same proportion of total clinker requirements as initial year, imported cement remains at the same proportion of domestic cement demand, and emissions from the production of supplementary cementitious materials and other non-clinker components of cement and binder are negligible.

A.3.8 Iron and steel sector assumptions data

Table 34 Iron and steel sector techno-economic data

Sector	Parameter	Modelled value	Source	Other relevant references
Iron ore mining	Maximum electrification (mining equipment)	0% in 2025, 60% by 2050	Based on CWA (2021)	• VCI (2020)
	Maximum fuel switching to hydrogen fuel cells (mining equipment)	0% in 2025, 60% by 2050		
Steel refining	Hydrogen contribution to natural gas DRI-EAF maximum	0% in 2020, 20% by 2050		
	Biomass contribution to natural gas DRI-EAF maximum	0% in 2020, 5% by 2050		
	Hydrogen contribution to blast furnace maximum	0% in 2020, 30% by 2050c		
	Biomass contribution (substitution for pulverised coal injection) to blast furnace maximum	0% in 2020 30% of energy by 2045 in CRD scenario 65% by 2050 in CRD 30% by 2050 in CSP	Based on Wang et al. (2014)	
	Carbon Capture and Storage maximum	0% in 2040 30% of emissions from blast furnace or DRI (natural gas) EAF by 2050		
	Carbon Capture and Storage Cost ($/ t CO_2)	117.50 in 2040 112.50 in 2050	VDZ (2022) Table 3, p32	
	Direct emissions from blast furnace production			• Frederick and Haque (2015)

Table 35 Steel production techno-economic data

Parameter	Units	Blast furnace	Recycled scrap electric arc furnace (EAF)	Direct reduced iron (natural gas) EAF	Direct reduced iron (hydrogen) EAF
Maximum market share	%	No limit	28% in all states except Vic & NSW	10% in 2030 100% by 2050	5% by 2030 33% by 2040 100% by 2050 all states except WA
Energy intensity	GJ/ t steel	19.9	4.1	16.4	15.2
Coal energy use	%	65.0	-	-	-
Gas energy use	%	32.5	36	85	58
Electricity energy use	%	2.5	64	15	42
Capital expenditure (2020)	$M/ Mtpa	1100	680	1400	1750
Capital expenditure (2050)	$M/ Mtpa	780	500	770	950
Operating expenditure (2020)	$/ t	120	70	170	170
Operating expenditure (2050)	$/ t	60	40	60	60
Raw material costs	$/ t	210	350	250	250

Source: IEA (2020b2020b) for costs, Fig 1.13 and Fig 2.11, based on 1USD=1.38AUD

A.4 Benchmarking and model testing

A.4.1 Model outputs and comparison to other integrated assessment models

The setup of integrated assessment models, and even more so the coupling of such models at the global, national, and specific sectoral levels is a complex undertaking with many free variables which must be decided upon as part of scenario downscaling. As such, it is important to benchmark the results of the CRD and CSP scenarios where possible to ensure the scenarios being examined are consistent with the work upon which it is a downscaling of, i.e., the IEA NZE and STEPS scenarios. Since the IEA results are global, the most accessible benchmark is the comparison of the equivalent global model used here (CSIRO GTEM) with both the IEA NZE results, and where possible, results from the IPCC and NGFS III integrated assessment models. In the following section, a selection of benchmarks is presented to demonstrate sufficient alignment with these other efforts.

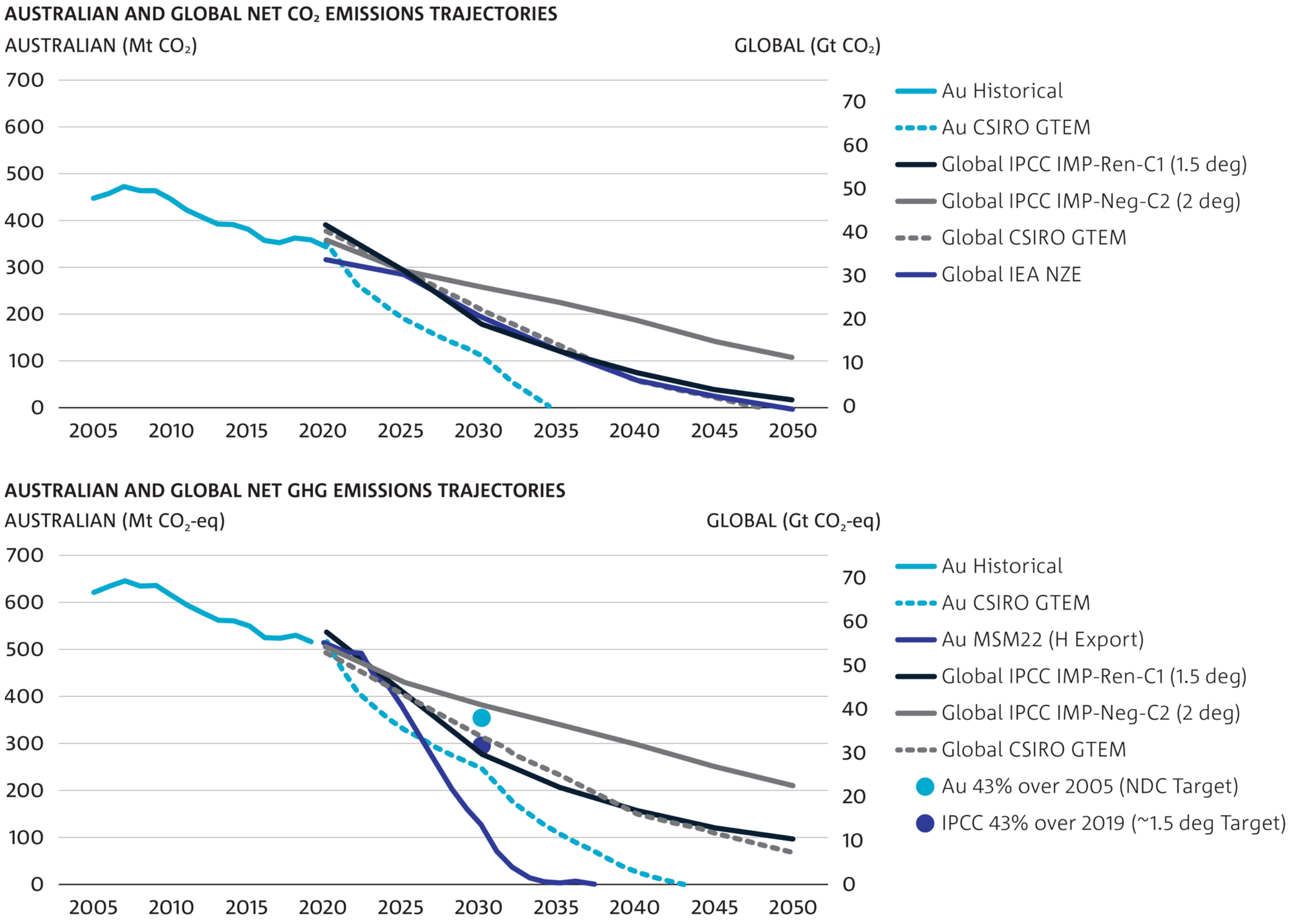


Figure 66 (top) CO_2 only, and (bottom) total GHG emissions trajectories showing our global modelling relative to IEA and IPCC 1.5°C[75]

[75] Data sources: IEA NZE (International Energy Agency (2021a), Net Zero by 2050, IEA, Paris: Net Zero by 2050 Scenario - Data product - IEA. License: Creative Commons Attribution CC BY-NC-SA 3.0 IGO); IPCC (van der Wijst, K.; Byers, E.; Riahi, K.; Schaeffer, R.; van Vuuren, D. (2022)): Data for Figure SPM.5 - Summary for Policymakers of the Working Group III Contribution to the IPCC Sixth Assessment Report. MetadataWorks, 04 April 2022. 10.48490/rbkj-8684); Australian historical (https://www.greenhouseaccounts.climatechange.gov.au/); Australian National Determined Contribution Communication 2022 (DISER, 2022b).

GLOBAL BENCHMARKING: CARBON BUDGET (CO_2 ONLY)

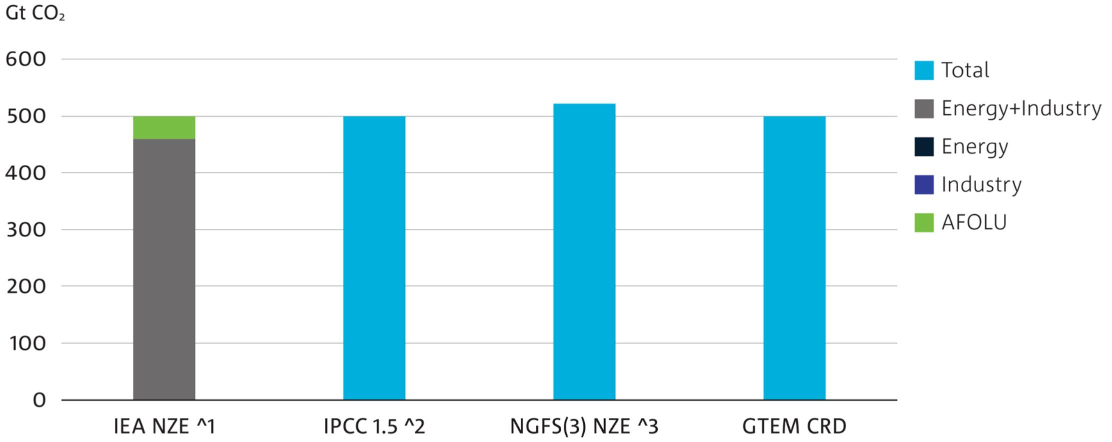


Figure 67 Global model benchmark for CO_2 only carbon budget

GLOBAL BENCHMARK: NEGATIVE EMISSION TECHNOLOGY USAGE IN 2050

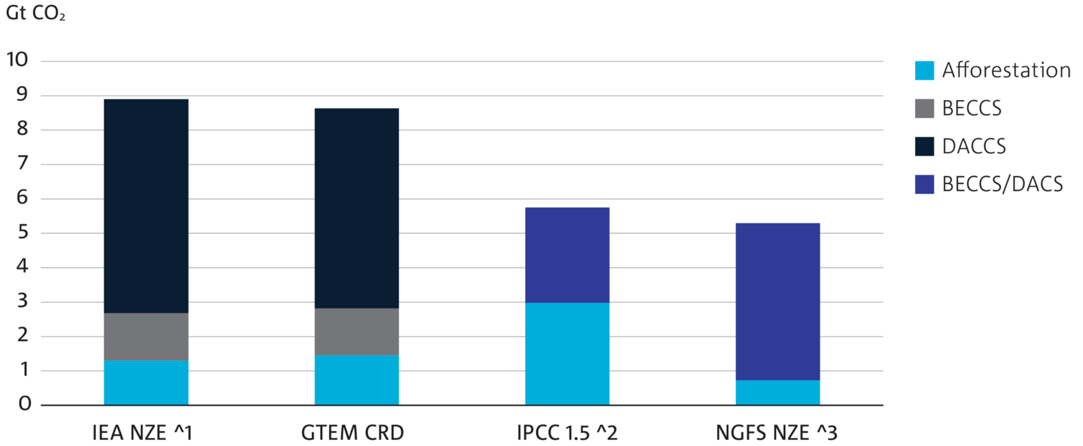


Figure 68 Global model benchmark for the use of negative emissions technologies in 2050

Source: Figures 67 and 68: References: ^1 Net Zero by 2050: A Roadmap for the Global Energy Sector, International Energy Agency;[76] ^2 Pathak et al. (2022) Technical Summary. In: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change;[77] ^3 NGFS Climate scenarios Data Set (3.4) [Data set];[78]

[76] https://doi.org/10.1787/c8328405-en

[77] https://www.ipcc.ch/report/ar6/wg3/about/how-to-cite-this-report/; DOI:10.1017/9781009157926.002

[78] https://zenodo.org/record/5782904#.Y2SLm3ZBwuU; DOI:10.5281/zenodo.5782903.

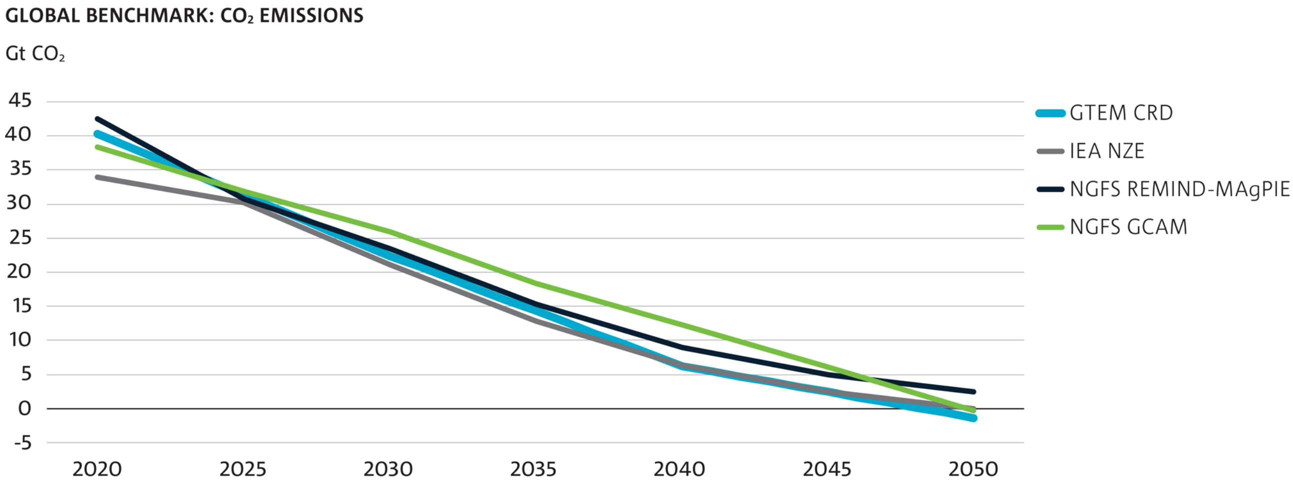


Figure 69 Benchmarking comparison of the global CO_2 profiles for CRD scenarios modelled by GTEM under this work with that modelled within the IEA and NGFS (via REMIND-MAgPIE and GCAM approaches)

Source: International Energy Agency (2021a), Net Zero by 2050, IEA, Paris[79]

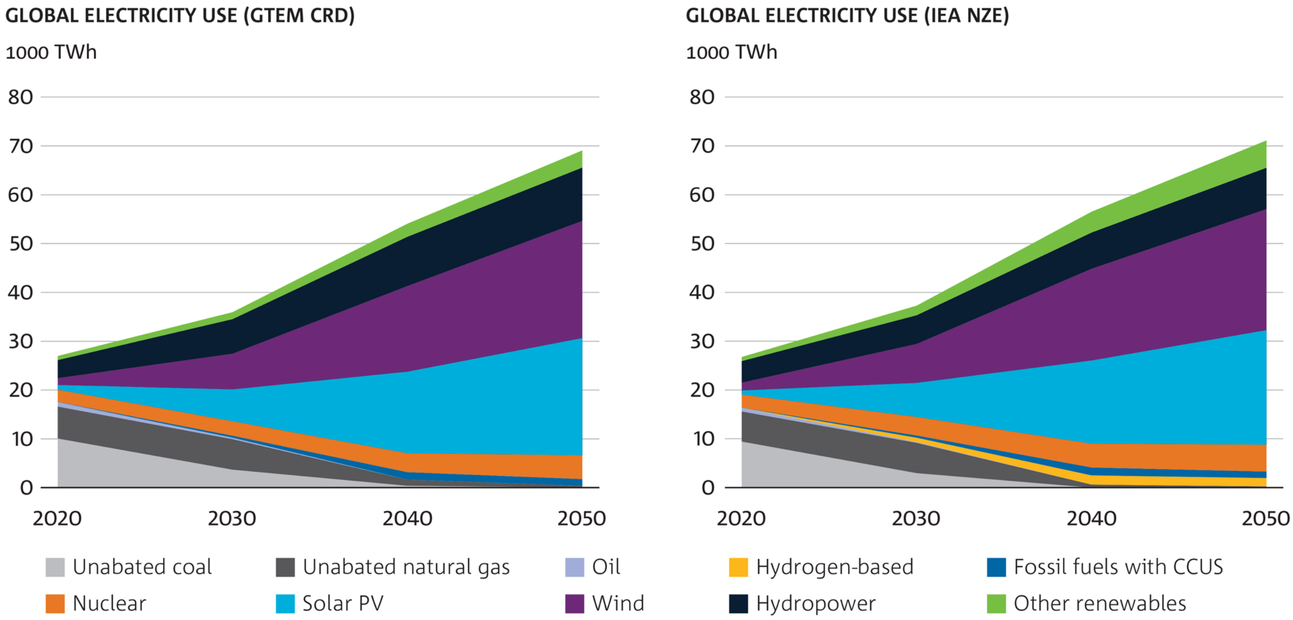


Figure 70 Benchmark comparison of GTEM CRD and IEA NZE (data for Figure 3.10 of that report) for global electricity use makeup

Source: 'International Energy Agency (2021a), Net Zero by 2050, IEA, Paris'[80]

[79] https://doi.org/10.5281/zenodo.7198430

[80] https://doi.org/10.5281/zenodo.7198430

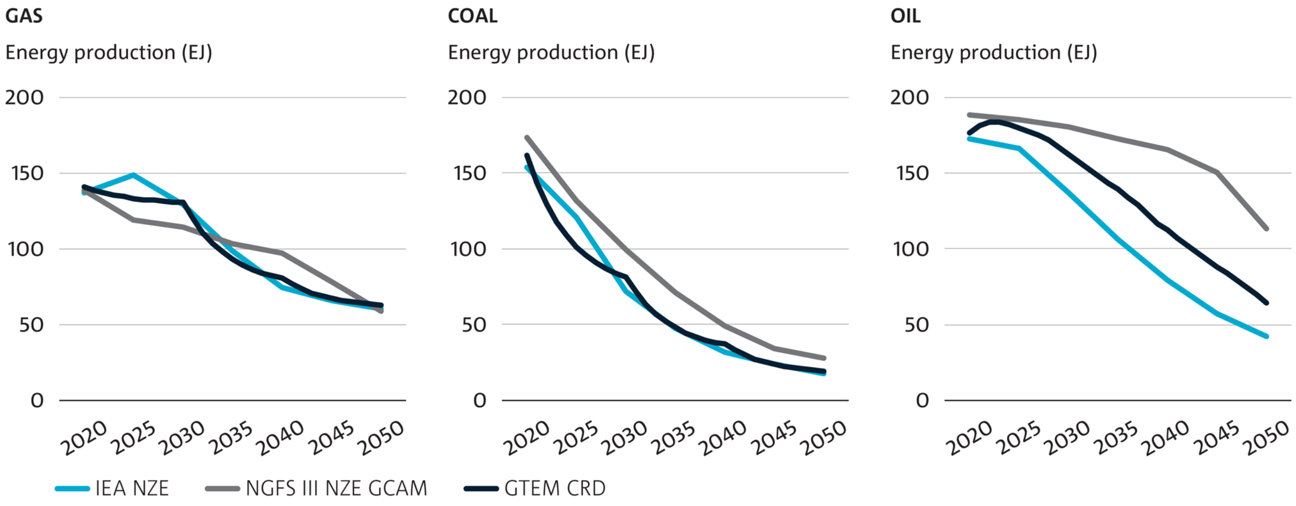


Figure 71 Benchmarking comparison of the global energy production profiles for CRD scenarios modelled by GTEM under this work with that modelled within the IEA and NGFS (via their GCAM approach)

Source: International Energy Agency (2021a), Net Zero by 2050, IEA, Paris[81]

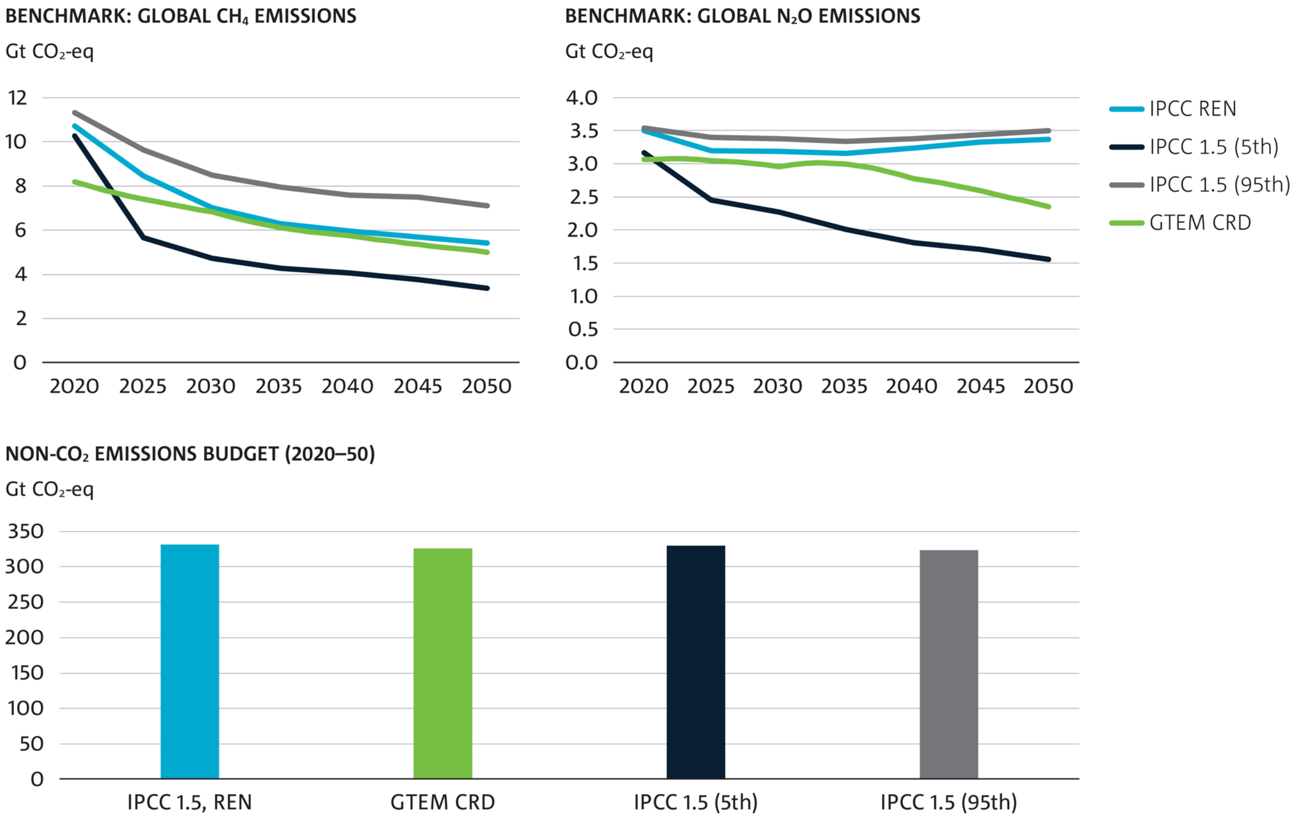


Figure 72 Benchmarking comparison of non- CO_2 emissions from GTEM and IPCC6 WGIII scenarios. Also, comparison of the non-CO_2 emissions budget based on the data from IPCC6 WGII Figure SPM.5

Source: International Energy Agency (2021a), Net Zero by 2050, IEA, Paris[82]. IPCC (2022).

[81] https://doi.org/10.5281/zenodo.7198430

[82] https://doi.org/10.5281/zenodo.7198430

Appendix B Glossary

Term	Details
ACCU	Australian Carbon Credit Units
AE	Alkaline electrolysis
AEMO	Australian Energy Market Operator
AFOLU	Agriculture, Forestry and Other Land Use
ANZSCO	Australian and New Zealand Standard Classification of Occupations
ANZSIC	Australian and New Zealand Standard Industrial Classification
APS	Announced Pledges Scenario
ARENA	Australian Renewable Energy Agency
AusTIMES	Australian TIMES Model
BECCS	Bioenergy with Carbon Capture and Storage
BHP	BHP Group Limited (Broken Hill Proprietary, formerly BHP Billiton)
CBA	Commonwealth Bank of Australia
CBAM	European Carbon Border Adjustment Mechanism
CCS	Carbon Capture and Storage
CCUS	Carbon Capture Utilisation and Storage
CEFC	Clean Energy Finance Corporation
CES	Constant Elasticity of Substitution
CGE	Computable General Equilibrium
CH_4	Methane
CMIP	Climate Model Intercomparison Project
CO_2	Carbon Dioxide
CO_2-eq	Carbon Dioxide equivalent
CRESH	Constant Ratios of Elasticities of Substitution, Homothetic
CWC (CWA)	ClimateWorks Centre (previously ClimateWorks Australia)
DACCS	Direct Air Capture with Carbon Capture and Storage
EVs	Electric vehicles

Term	Details
EU	European Union
ETSAP	Energy Technology Systems Analysis Project
F-gases	Fluorinated gases
GDP	Gross Domestic Product
GFANZ	Glasgow Financial Alliance for Net Zero
GHG	Greenhouse gases
GJ	Gigajoules
GCAM	Global Change Assessment Model
Gt	Gigatonne
GTEM	Global Trade and Environment Model
H_2	Hydrogen gas
Hydro	Hydroelectric energy generated by moving water
IAM	Integrated Assessment Model
ICE	Internal combustion engine
IEA	International Energy Agency
IMO	International Marine Organisation
IO	Input-output
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
ISP	AEMO's Integrated System Plan
KPMG-EE	KPMG Energy and Environment Model
kt	Kilotonne
LCV	Light commercial vehicle
LNG	Liquified natural gas
LULUCF	Land use, land-use change and forestry
MAgPIE	Model of Agricultural Production and its Impact on the Environment
MARKAL	Market Allocation
MPP	Mission Possible Partnership (a global decarbonisation alliance)
Mt	Megatonne

Term	Details
MWh	Megawatt hours
N_2O	Nitrous Oxide
NABERS	National Australian Built Environment Rating System
NDCs	Nationally Determined Contributions set by Parties of the Paris Agreement
NEM	National Electricity Market
Neg Tech	Negative Emissions Technologies
NGFS	Network of Central Banks and Supervisors for Greening the Financial System
NGFS GCAM	NGFS Global Change Assessment Model
NGFS REMIND	NGFS Regional Model of Investments and Development
NGFS MESSAGE	NGFS Model for Energy Supply Strategy Alternatives and their General Environmental Impact
Non-bio alt fuel	Alternative fuels (commonly from waste) of non-biological origin
NZBA	Net-Zero Banking Alliance
NZE	Net Zero Emissions by 2050 Scenario
NTNDP	National Transmission Network Development Plan
Origin	Origin Energy Australia
OECM	One Earth Climate Model (see Teske et al., 2020)
Parties	Parties of the Paris Agreement
PEM	Proton exchange membrane
p-km	passenger-kilometre (a unit of transport service)
PRI RPS	Inevitable Policy Response
RHS	Right hand side
RTVP	Roof top photovoltaic
SAF	Sustainable aviation fuel
SCM	Supplementary cementitious material
SDS	Sustainable Development Scenario
SMR	Steam Methane Reforming
Solar PV	Solar Photovoltaic

Term	Details
SSP2	Shared Socioeconomic Pathway 2
STEPS	Stated and Existing Policies Scenario
TB	Technology bundle
Tech	Technology
t-km	tonne-kilometre (a unit of transport service)
UNFCCC	United Nations Framework Convention on Climate Change
UNEP	United Nations Environment Programme
v-km	vehicle-kilometre (a unit of transport service)
WEO	World Energy Outlook (International Energy Agency)

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