Australia's National
Science Agency

Modelling Sectoral Pathways to Net Zero Emissions

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Executive summary

To assist the Australian Government in developing a national net zero emissions by 2050 plan, the parliament requested that the Climate Change Authority (the authority) undertake a review of the potential technology transition and emissions pathways in six sectors – electricity and energy, transport, industry and waste, agriculture and land, resources and the built environment – that best support Australia's transition to net zero emissions by 2050. For both the authority's review, and this report, those pathways are examined under two levels of global climate ambition. The first is a world tracking to a global warming outcome of less than 2 degrees, and the second sees global warming limited to 1.5 °C degrees with no or limited overshoot.

As part of this process, the authority commissioned the CSIRO to model a suite of net zero emissions scenarios that will help to inform their advice to the Australian Government regarding the next Nationally Determined Contribution (NDC) and the associated sectoral plans.

The modelling undertaken by the CSIRO, Australia's national science agency, examined several scenarios. These scenarios were largely designed by the authority in consultation with CSIRO, two of which are featured in this report (with all scenarios shown in Figure 3 to be covered in a following report).

The global context for the first scenario is a world tracking to a global warming outcome of less than 2°C – named 'G2'. Within that context, the scenario sees Australia achieving net-zero by 2050 and is named 'A50/G2'. Under A50/G2, Australia meets its current emissions reduction targets – a 43% reduction on 2005 emissions by 2030 and net zero by 2050.

The global context for the second scenario is a world on a trajectory to limit global warming to 1.5°C with no or limited overshoot – named 'G1.5'. The G1.5 assumptions reflect greater global ambition and more rapid emissions reductions. Under that more ambitious global context, the scenario has Australia achieving net-zero in 2040 and is named 'A40/G1.5'. Under A40/G1.5, Australia meets its current targets, and also assumes a 75% reduction on 2005 emissions in 2035.

Key findings from the modelling are as follows.

1. **Both scenarios overachieve on the 2030 target. A50/G2 achieves net-zero in 2050 with 153 Mt of residual CO_2-equivalent (Mt CO_2-e) emissions. A40/G1.5 achieves net-zero in 2040 with a 177 Mt CO_2-e residual (Figure 1).**

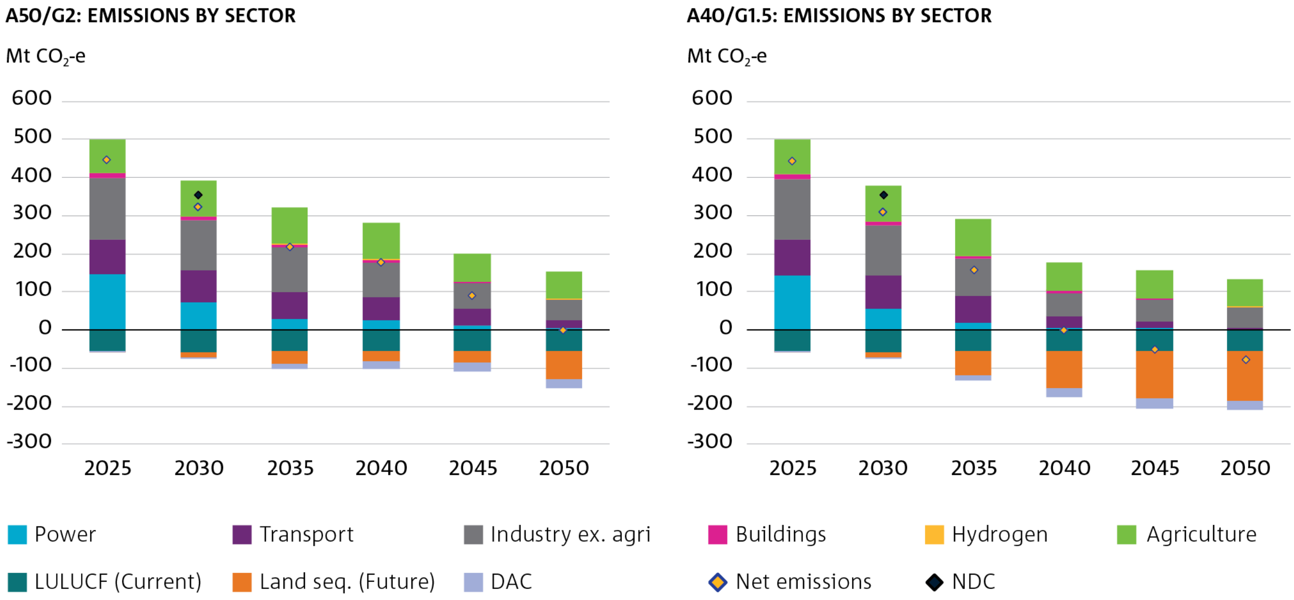

Figure 1 Emissions by sector[1]

While negative emissions from direct air capture (DAC) and sequestration from existing (LULUCF (Current) and future (Land seq. (Future)) land use change are separated from gross agricultural emissions (Agriculture), the emissions from industry (excluding agriculture / Industry ex. Agri) is a net figure and has embedded within emissions capture from technologies such as Carbon Capture and Storage (CCS).

The scale of emissions reduction varies greatly across sectors. In terms of emissions reduced across the 2025 to 2050 period, the greatest reductions are seen in the power sector, and then in decreasing order, industry (excl. agriculture), new land-based sequestration, transport, direct air capture (DAC[2]), agriculture, and then buildings. The rate of emissions reductions also varies greatly across sectors, where the power sector is by far the fastest to decarbonise, with agriculture being the slowest showing growth for the first decade, before declining due to the uptake of methane mitigation measures in livestock.

2. **Electricity decarbonisation is the largest source of near-term (by 2030) abatement.** Total generation capacity increases substantially (Figure 2) alongside the share of national electricity consumption that is met by renewable sources consistent with state/territory and national renewable energy targets in the near-term. By 2030, solar photovoltaic (solar PV) and onshore wind is projected to account for around 70 per cent of the nation's electricity generation. In A50/G2 that 70% is 103 GW and 251 TWh, and for A40/G1.5 is 109 GW and 238 TWh. Deployment of utility-scale and behind-the-meter battery storage is significant reaching around 54 GW (70 GW) by 2050, in A50/G2 (A40/G1.5) respectively. Pumped hydro storage more than doubles over this period. Fossil fuel use in the electricity sector falls from over 67% of total generation today to less than 8% (2%) by 2040, in A50/G2 (A40/G1.5) respectively.

[1] While the model results presented here and in the corresponding Sector Pathways Review (Climate Change Authority, 2024) are the same, the sectoral categorisation of those results in this report differs from that used by the authority. See the Appendix A Technical supplement for the sectoral structure of the AusTIMES model used here.

[2] While direct carbon dioxide removal technologies are modelled in AusTIMES as a direct air capture technology, many engineered sequestration technologies are still in a pre-commercial phase and the future technology composition remains uncertain.

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

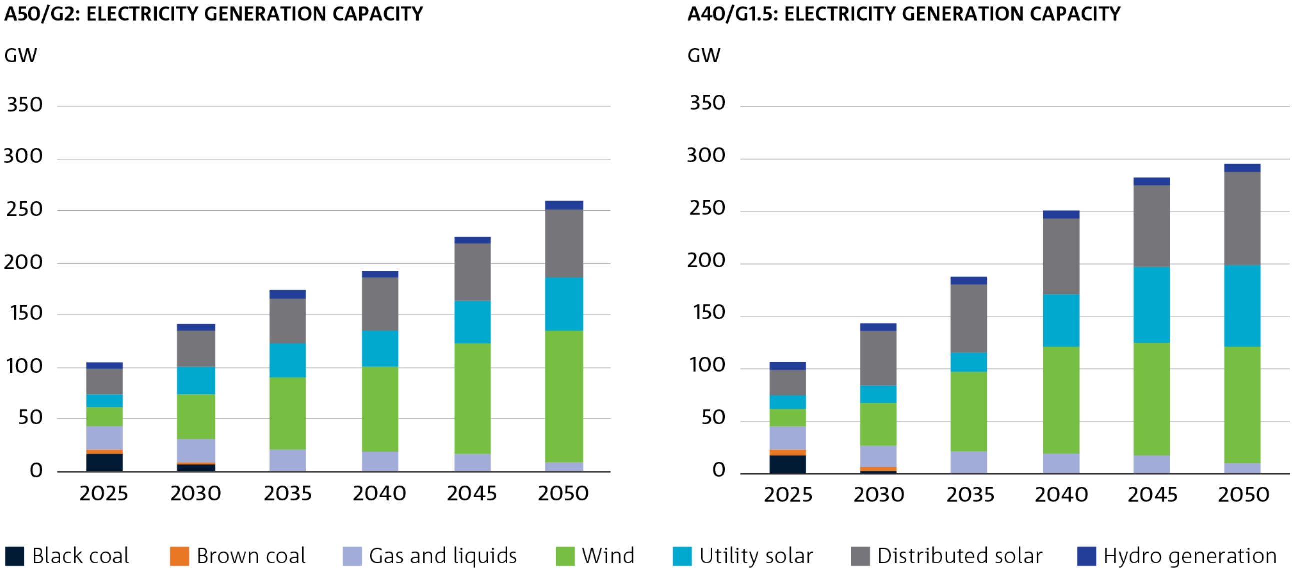

Figure 2 Electricity generation capacity (GW) mix

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 around 102 (176) Mt CO_2 per year by 2040 in A50/G2 (A40/G1.5) respectively.** Land use change and emerging solutions for reducing emissions from livestock are the key elements of the agricultural sector's decarbonisation pathway. The Agriculture, Forestry and Other Land Use (AFOLU) sector is a net emissions' sink by 2035 and 2045, in A40/G1.5 and A50/G2, respectively. However, the agricultural sector remains a substantial emitter given the contribution of difficult-to-abate livestock emissions in particular. Land-based sequestration is projected to deliver 129 (185) Mt CO_2-e a year of negative emissions by 2050, in A50/G2 (A40/G1.5) respectively. Negative emissions technologies are assumed to deliver a further 25 Mt CO_2-e from non-specific direct air carbon capture and storage technologies (DACCS) and other negative emission technologies.
4. **Residential and commercial building direct and energy use emissions fall to less than 2 Mt CO_2-e 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 account for significant improvements in residential and commercial building energy use. 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 the early stages of adoption in Australia need to become mainstream by the 2030s. Over the period to 2050, emissions from Australia's transport sectors fall toward zero. This occurs primarily due to electrification of the light vehicle fleet as adoption of battery electric vehicles (BEVs) increases from around 6% of Australian car sales to around 32% (65%) by 2035, in A50/G2 (A40/G1.5) respectively. Light vehicles with an electric drivetrain reach

100% of sales by 2050 (2040) in A50/G2 (A40/G1.5). Decarbonisation of long distance and heavy transport accelerates through 2030 - 2040. As much as two-thirds of freight transport is electrified by 2050, and the remainder uses low- or zero-emissions hydrogen. Decarbonisation in air transport and shipping is more modest prior to 2030 but accelerates in the 2030s as hydrogen carriers and sustainable aviation fuels become commercialised.

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 around 3 Mt (4 Mt) by 2050, in A50/G2 (A40/G1.5) respectively.
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. For both scenarios, this necessitates an increase in cement production of 80% by 2050 while emissions from the sector fall by 60% by 2050, with decarbonisation accelerating in the late 2030s. Iron ore mining follows a similar path, albeit driven by exports, and emissions falling to almost zero by 2050 through electrification exploiting renewables. The iron and steel industry sees a switch to hydrogen-based reduction and the uptake of melt basic oxygen furnace technologies in 2045 for A50/G2 (and the late 2030s for A40/G1.5) with carbon capture and storage (CCS) being taken up on existing technologies in the interim. CCS also assists with the decarbonisation of aluminium and cement. 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.** The implications are significant for Australia's export markets. Australian coal production is projected to fall by 13% (38%) by 2030 and then more dramatically to near 30% (75%) through 2050 in A50/G2 (A40/G1.5) respectively, with almost all remaining production being for metallurgical coal. Oil production is relatively flat in A50/G2 but falls by around 2/3 by 2050 in A40/G1.5. Gas production falls by 15% (39%) by 2050 in A50/G2 (A40/G1.5).
9. **However, non-fossil fuel mining continues to grow significantly**. Mining of iron ore and other commodities almost doubles by 2050 in both scenarios. 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.

Part I Overview

1 Overview

This report presents integrated modelling results showing abatement potential at the sector and subsector level for Australia's economy and energy systems under global and national assumptions for two scenarios. The results additionally indicate fuel use breakdown of those sectors over time, and technology uptake where appropriate.

1.1 Modelling scenarios

AUSTRALIAN AMBITION		GLOBAL AMBITION	
		Temperature Target	
		2.0°C	1.5°C
		IEA/IPCC Ambition Level	
Net Zero Year	**2035 Target (from 2005)**	**Moderate**	**High**
2050	-57%	**A50/G2**	A50/G1.5
2045	-62%	A45/G2	
2040	-75%	A40/G2	**A40/G1.5**
2035	-100%		A35/G1.5

Figure 3 The six modelled scenarios

The two scenarios highlighted in bold (A50/G2 and A40/G1.5) are the focus of this report.

We modelled four levels of domestic decarbonisation ambition with net-zero years ranging from 2050 to 2035, each with a corresponding 2035 emissions reduction target as indicated in Figure 3. These domestic scenarios were modelled under different global climate ambition settings (2.0°C and 1.5°C) to explore the macroeconomic, sectoral and environmental impact for Australia with different combinations of domestic and global ambition. The two global scenarios are modelled as follows (more detailed scenario assumptions are provided in Appendix A.2):

- **Global 1.5°C (G1.5) scenario:** a scenario where the world coordinates action to limit warming to 1.5°C. This is consistent with energy targets in the International Energy Agency's (IEA) 2021 WEO Net Zero Emissions by 2050 (NZE) scenario and the total greenhouse gas (GHG) emissions budget is consistent with the Intergovernmental Panel on Climate Change's (IPCC) IMP-Ren scenario in the sixth Assessment report (IPCC, 2022). Global fossil fuel use decreases and global engineered carbon dioxide removals is about 2.1 Gt by 2050. Australia's emissions pathway is endogenously determined by the GTEM model, and the global carbon price is also applied to Australia.
- **Global 2°C (G2) scenario:** a scenario where the world strengthens action to limit warming to below 2°C. This is consistent with energy targets in the IEA's 2021 WEO Announced Pledges (APS) scenario and the total GHG emissions budget is consistent with the IPCC's IMP-GS scenario (IPCC, 2022). Global fossil fuel use decreases and global engineered carbon dioxide removals is about 2 Gt by 2050. Australia's emissions pathway is

endogenously determined by the GTEM model, and the global carbon price is also applied to Australia.

In this report, we focus on two of the six scenarios identified in Figure 3.

- **A50/G2: 2°C world, Australia net zero in 2050** has global settings where the world strengthens action to limit warming to below 2°C. Under such global settings, Australia achieves its current 2030 target and reaches net zero in 2050. By 2035, Australia's GHG emissions are reduced by 57% relative to 2005. In this scenario, Australia's emissions pathway is exogenously constrained and the Australia carbon price deviates from the global carbon price.
- **A40/G1.5: 1.5°C world, Australia net zero in 2040** has global settings where the world coordinates action to limit warming to 1.5°C. Under such global settings, Australia overachieves on its 2030 target and reaches net zero in 2040. By 2035, Australia's GHG emissions are reduced by 75% relative to 2005. In this scenario, Australia's emissions pathway is exogenously constrained and the Australia carbon price deviates from the global carbon price.

In the remainder of this report, we use the short scenario names (i.e., A50/G2 and A40/G1.5). The detailed scenario assumptions and model implementation of A40/G2 and A40/G1.5 are provided in Appendix A.2.

1.2 Methodology

In this analysis, a multi-model approach has been tailored to downscale a combination of several IEA and IPCC scenarios to the Australian context. The approach coupled three models to derive contextualised Australian outputs:

1. **GTEM:** CSIRO's "Global Trade and Environment Model",[3] a computable general equilibrium (CGE) model, is used to represent the global macroeconomic impacts in each scenario and explores how they influence Australia through international investment and trade linkages.
2. **LUTO:** The "Land Use Trade-Offs" model is a spatially detailed land use change model for rural Australia which estimates the profitability of a range of existing and potential land uses, identifies potential land use transitions over space and time, and reports on a range of outcomes including land-sector carbon sequestration.
3. **AusTIMES:** The "Australian TIMES" model, which is an Australian implementation of The Integrated MARKAL-EFOM System (TIMES) that has been developed under the IEA Energy Technology Systems Analysis Project (ETSAP)[4]. CSIRO is a Contracting Party to ETSAP and has developed an Australian version of the TIMES model (AusTIMES) in collaboration with Climateworks Centre. AusTIMES provides a view based on least cost energy, emissions and

[3] https://research.csiro.au/ieem/gtem-c/ and as described in Cai et. al. (2015)

[4] https://iea-etsap.org/ [accessed 19 July 2022]

technology pathways, which details sectoral pathways of technology mix, energy mix and emissions for some sectors.

The GTEM model explores transitional risk impacts globally and how these influence Australia through international trade and investment linkages. Global settings are imposed in GTEM for a range of variables including emissions, energy usage and the technology mix in several important sectors (i.e., electricity, iron and steel, and land transport). The global emissions pathways are imposed via an endogenous global carbon price[5] that prices greenhouse gases for all emitters in all regions. This describes how scenarios G2 and G1.5 are implemented in GTEM. When implementing scenarios A50/G2 and A40/G1.5, the net emissions pathways for Australia are imposed via an endogenous domestic carbon price that is paid by all Australian emitters. The resulting GTEM results for Australia are used as inputs to LUTO and AusTIMES.

The impacts of pricing emissions on agriculture and land use are explored in the LUTO model. In LUTO the carbon price provides an incentive for greater carbon plantings and thus carbon sequestration. Carbon plantings compete with agriculture for the use of land. That exploration focuses on the economic transition whilst not taking into account 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 agricultural sectors, as well as some carbon removal activities such as afforestation and reforestation, will be an important area to focus on in future.

Specific technology paths are explored for the power, industry, transport, agriculture, and buildings sectors using the AusTIMES model. AusTIMES is calibrated to an Australian sectoral starting technology mix and is used to explore least-cost sectoral paths consistent with the national emissions trajectory. The AusTIMES emissions trajectory, industry output, population growth, exports, and technological removals are drawn directly from the GTEM, taking into account the land use change sequestration drawn from LUTO.

1.3 Emissions by sector

Australia's total net greenhouse gas emissions were around 433 Mt CO_2-e in 2021-22[6]. The modelled gross and net emissions by sector are shown for the two scenarios in Figure 4[7]. Both scenarios overachieve on the 2030 target. A50/G2 achieves net-zero in 2050 with 153 Mt of

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[5] The carbon price in GTEM represents the marginal cost of abatement. There is a positive non-linear relationship between the marginal cost of abatement and the degree of emissions abatement. Thus, higher emissions abatement exponentially raises the marginal cost of abatement and thus the carbon price. Note that the endogenous carbon price in these scenarios represents the potential implementation path via either a specific carbon price or a bundle of policies with the same price effect.

[6] See Australia's National Greenhouse Accounts: https://greenhouseaccounts.climatechange.gov.au/ [accessed 19 July 2024].

[7] Note that the results of Figure 4 are from the AusTIMES model, which takes the negative emissions trajectories from a converged iteration of the GTEM and LUTO models. For A50/G2, those negative trajectories were directly applied. However, for the A40/G1.5 scenario, the additional detail in the AusTIMES energy sector model revealed that additional abatement was required to meet the prescribed emissions trajectory. As such, the trajectory for abatement from new land-based sequestration for A40/G1.5 was replaced with that from the A40/G2 scenario, which exhibited greater uptake due to a higher average domestic carbon price over 2040 to 2050.

residual CO_2-equivalent (Mt CO_2) emissions. A40/G1.5 achieves net-zero in 2040 with a 177 Mt CO_2-e residual (Figure 4).

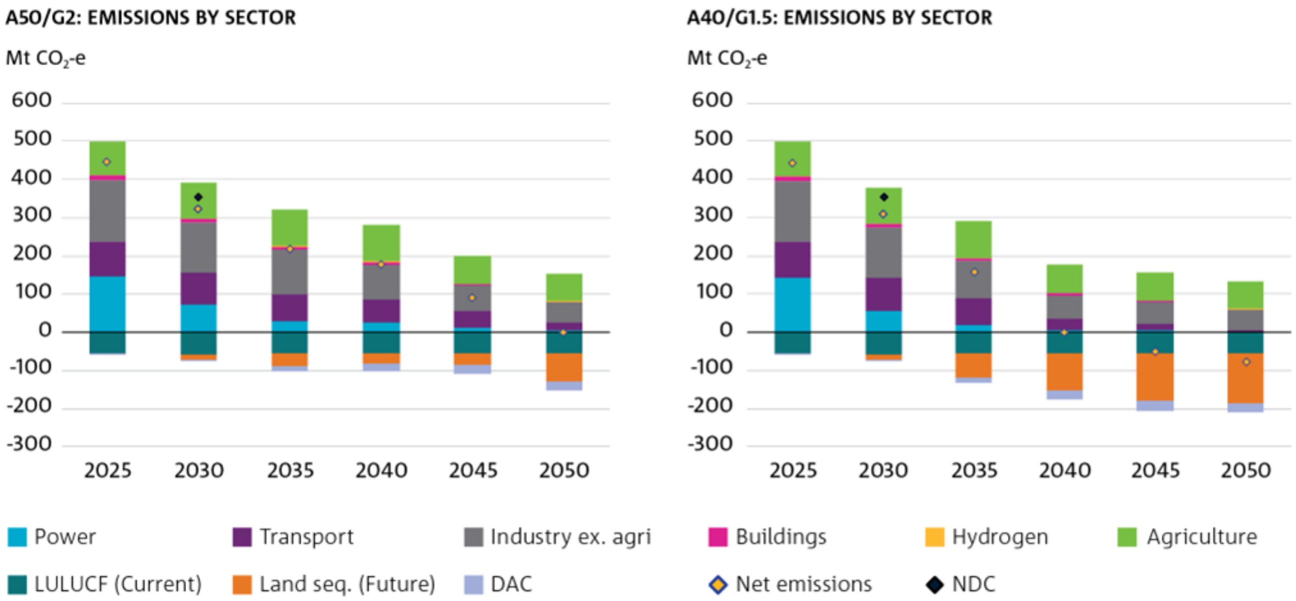

Figure 4 Emissions by sector

While negative emissions from direct air capture (DAC) and sequestration from existing (LULUCF (Current) and future (Land seq. (Future)) land use change are separated from gross agricultural emissions (Agriculture), the emissions from industry (excluding agriculture / Industry ex. Agri) is a net figure and has embedded within emissions capture from technologies such as Carbon Capture and Storage (CCS).

The scale of emissions reduction varies greatly across sectors. In terms of emissions reduced across the 2025 to 2050 period, the greatest reductions are seen in the power sector, and then in decreasing order, industry (excl. agriculture), new land-based sequestration, transport, DAC, agriculture, and then buildings. The difference in the hydrogen sector between scenarios is reflective of the uptake of steam methane reforming (SMR) versus SMR with CCS for a small fraction of production as indicated in Figure 15.

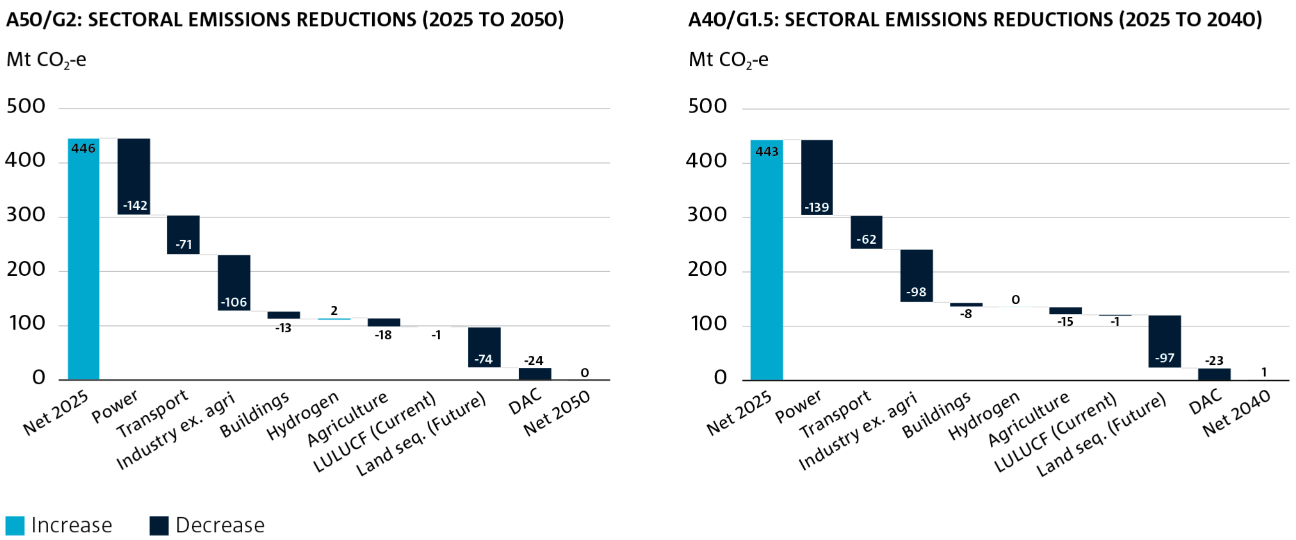

Figure 5 Emissions reduction by sector

The rate of emissions reduction across sectors varies greatly. This is illustrated in Figure 6 where the power sector is by far the fastest to decarbonise, with agriculture being the slowest showing growth for the first decade, before declining due to the uptake of methane mitigation measures in livestock. Comparing scenarios, the greater global ambition under the A40/G1.5 scenario translates to greater sequestration from land use due to the higher carbon price – and this greater uptake of land-based sequestration enables both achieving net zero by 2040, and slightly less abatement in the other sectors when compared to A50/G2.

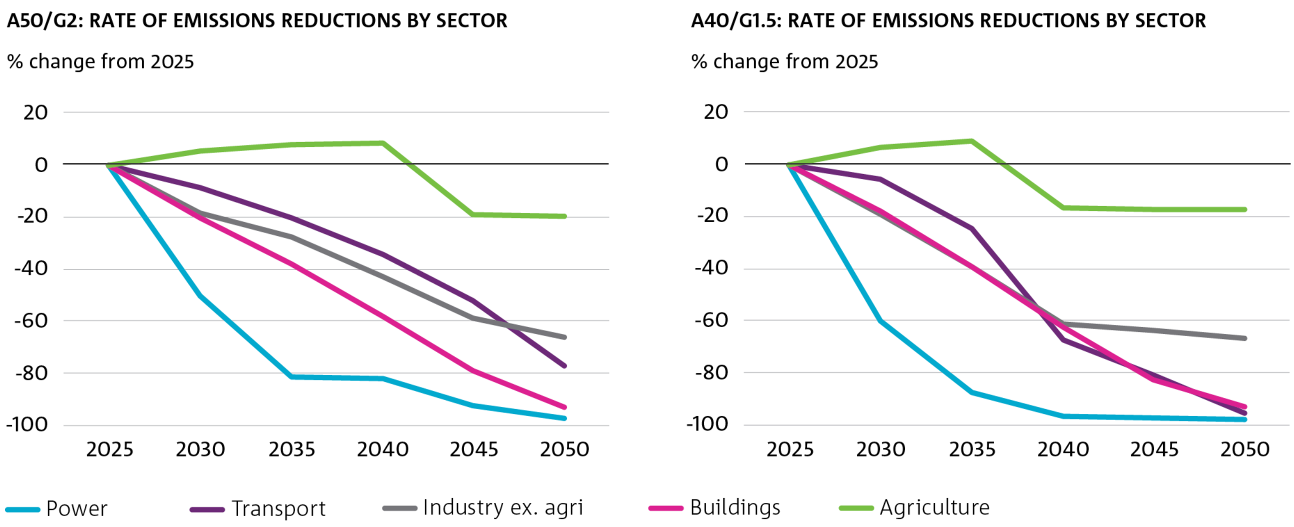

Figure 6 Emissions reduction rates by sector in percentage terms

There is also uptake of CCS technologies in some industrial sub-sectors such as gas extraction, power generation (A50/G2 only), cement, chemicals and hydrogen production (Figure 7).

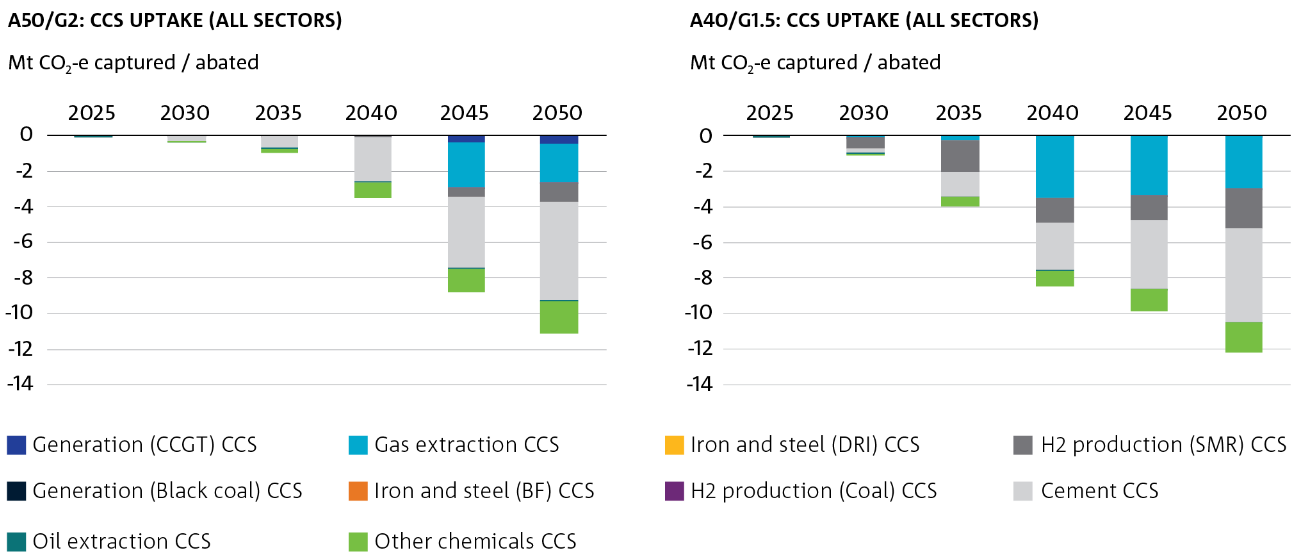

Figure 7 CCS uptake across all sectors

Part II Sectors

2 Sectors

2.1 Overview

Table 1 shows average GTEM growth rates in three global macroeconomic indicators over each decade from 2020 to 2050, and over the entire period. These indicators are gross domestic product (GDP), GDP per capita, and the consumer price index (CPI). Between the two global contexts (G2 and G1.5), and when averaged over the entire period, the average growth rates in these indicators show only minor differences whereby output growth is slightly higher and price growth is slightly lower in G2 versus G1.5[8]. This reflects the difference in climate change mitigation by 2050 between the two scenarios, i.e., global net emissions respond by -79% in G2 compared with -91% in G1.5. A larger reduction in global net emissions (as in G1.5) means a higher global carbon price and thus a higher global marginal cost of abatement. Over the whole period, a higher global marginal cost of abatement means slightly lower output growth and slightly higher price growth as pricing emissions raises the price of output and this in turn reduces output; this is what we observe in Table 1. This relationship can also be seen over the decadal timeframes with G1.5 showing lower GDP growth earlier (when compared with G2), which is indicative of the slightly more rapid climate change mitigation in G1.5. While the differences in output and price effects between the two scenarios are minor at the global level there are significant differences for some regions, e.g., Russia and Africa. However, we do not report the non-Australian regional results as they are not the focus of this report.

Table 1 Global macroeconomic indicators

	2020-2030	2030-2040	2040-2050	2020-2050
Net emissions (percentage change)				
G2	-13	-51	-53	**-79**
G1.5	-43	-56	-64	**-90**
Real GDP (average annual percentage change)				
G2	3.09	1.93	2.10	**2.37**
G1.5	3.01	1.97	2.11	**2.36**
Real GDP per capita (average annual percentage change)				
G2	2.11	1.15	1.48	**1.58**
G1.5	2.03	1.18	1.49	**1.57**
Consumer price index (average annual percentage change)				
G2	2.58	2.06	2.92	**2.52**
G1.5	2.63	1.99	2.99	**2.54**

[8] Note that the results in Table 1 show minor differences between the two global scenarios. These results are generated using a model (GTEM) that assumes certainty equivalence, which means that the differences in scenario results only reflect differences in scenario inputs. However, each scenario is subject to parameter and input uncertainty that we do not explore in this report. This means the results presented in Table 1 for each scenario can be thought of as point estimates within (unreported) confidence intervals due to variation in parameter values and inputs. The minor differences in results between the two scenarios mean that the confidence intervals for each scenario largely overlap. Put differently, given parameter and input uncertainty the two global emission pathways are statistically indistinguishable from each other in terms of the global results presented in Table 1. This is not true for other unreported results for these scenarios that show significant differences.

Table 2 presents Australian macroeconomic indicators under two “global scenarios” (G2 and G1.5) where the Australian emissions trajectory responds endogenously to global activity and the global carbon price, and two “domestic scenarios” (A50/G2 and A40/G1.5) where the Australian emissions trajectory is exogenously imposed via a domestic carbon price to achieve the prescribed targets.

Table 2 Australian macroeconomic indicators

	2020-2030	2030-2040	2040-2050	2020-2050
Net emissions (percentage change)				
G2	-32			**-114**
G1.5	-57			**-123**
A50/G2	-28			**-100**
A40/G1.5	-37			**-115**
Real GDP (average annual percentage change)				
G2	3.08	1.88	1.96	**2.31**
G1.5	2.97	1.88	1.94	**2.26**
A50/G2	3.09	1.95	2.03	**2.35**
A40/G1.5	3.03	1.81	2.12	**2.32**
Real GDP per capita (average annual percentage change)				
G2	1.72	0.71	0.97	**1.13**
G1.5	1.61	0.71	0.95	**1.09**
A50/G2	1.73	0.78	1.04	**1.18**
A40/G1.5	1.67	0.64	1.13	**1.15**
Consumer price index (average annual percentage change)				
G2	2.00	2.17	3.29	**2.48**
G1.5	1.89	1.95	3.52	**2.45**
A50/G2	2.00	2.09	3.21	**2.43**
A40/G1.5	1.80	1.74	3.66	**2.40**
Employment (average annual percentage change)				
G2	1.01	0.45	0.49	**0.65**
G1.5	0.97	0.46	0.48	**0.64**
A50/G2	1.02	0.47	0.50	**0.66**
A40/G1.5	1.00	0.40	0.57	**0.66**

Note that A50/G2 uses G2 as its parent scenario while A50/G1.5 uses G1.5. The results in the G2 and G1.5 rows are from GTEM solutions where Australia’s emissions trajectory responded endogenously to global activity (referred to as the “global scenarios”). The results in the A50/G2 and A40/G1.5 rows are from GTEM solutions where Australia’s emissions trajectory was exogenously imposed to meet the specific targets (referred to as the “domestic scenarios”).

As mentioned above, in the global scenarios the global carbon price is higher in G1.5; thus, Australian net emissions fall by more in G1.5 (123%) than in G2 (114%). As a higher marginal cost of abatement is imposed on Australia in G1.5, growth in GDP (and related indicators such as GDP per capita and employment) is slightly lower in G1.5 (2.26%) compared to G2 (2.31%). However, Australian price growth is slightly lower in G1.5 compared to G2. This is related to the size of the terms of trade (i.e., the ratio of export prices to import prices) loss that Australia experiences in both global scenarios. Global mitigation causes global demand for fossil fuels and their price to grow more slowly than other commodities. With significant fossil fuel exports, this means the growth in overall Australian export prices is lower than overall import prices thus lowering Australia's terms of trade and the growth in domestic prices (i.e., the CPI).

Turning to the two domestic scenarios, these impose particular paths in Australian net emissions that differ from the endogenous response observed in the global scenarios. Scenario A40/G1.5 is designed to achieve net zero emissions in 2040 and continue falling until 2050, whereas A50/G2 is designed to achieve net zero emissions in 2050 by following a linear path. When compared to the global scenarios, the imposed emissions trajectories for the domestic scenarios show smaller reductions over 2020-2050. As such, Australia's mitigation effort and carbon price is lower in the domestic scenarios. This means we observe greater Australian output growth in A50/G2 (A40/G1.5) compared to G2 (G1.5) and smaller price growth. However, these differences are minor.

2.2 Electricity and Energy sector

Historically, power generation in Australia has relied on coal- and gas-fired generation for grid power, and predominantly diesel generation in off-grid systems. Despite the historical dominance of non-renewable centralised electricity generation, there has recently been significant growth in the deployment of distributed rooftop solar photovoltaic (PV) systems, especially on residential buildings, followed by large-scale renewable generation (primarily onshore wind and solar PV). Australian Energy Statistics report that in FY2023, electricity generation was around 274 terawatt-hours (TWh), of which 47 per cent was coal-fired, followed by non-hydro renewables at 28 per cent, natural gas at 18 per cent, hydro at 6 per cent, and oil (mainly diesel) at around 2 per cent (DCCEEW, 2023).

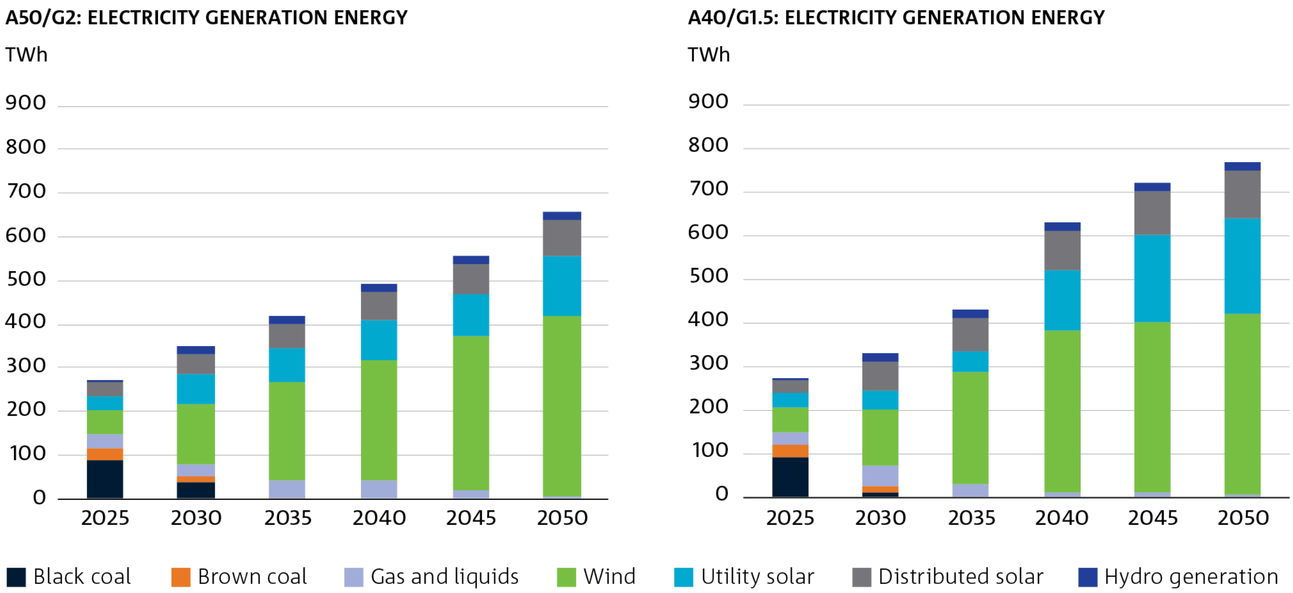

Figure 8 Electricity generation (TWh) by generation type

Under both A50/G2 and A40/G1.5 scenarios, the projected generation mix in Figure 8 shows significant change from its current mix, with the share of non-renewable electricity generation declining rapidly by 2030 consistent with near-term state/territory and national renewable energy targets and announced closures of coal-fired generators. In the medium-term, the increasing share of variable renewable energy (VRE) is mainly in the form of onshore wind farms, followed by an accelerated deployment of utility-scale solar PV farms and battery energy storage. In terms of the fraction of energy generated from renewable sources, Figure 9 shows that both scenarios reach more than 75% by 2030. A40/G1.5 reaches more than 98% by 2040 and A50/G2 by 2045. The remainder is mainly gas-fired generation. Although A50/G2 experiences higher growth in electricity consumption compared to A40/G1.5 out to 2030, increased electrification in industry and transport in A40/G1.5, along with greater hydrogen production through electrolysis, results in higher levels of electricity consumption in A40/G1.5 in the long-term.

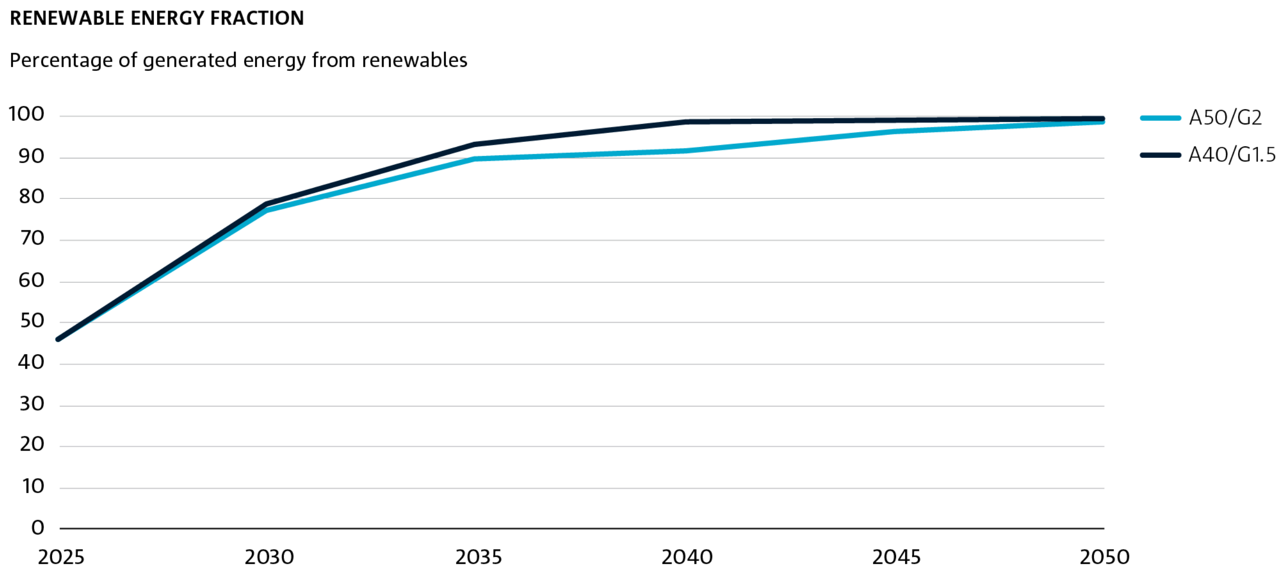

Figure 9 Renewable energy fraction of generation

The transformation of the electricity system is also significant from a capacity standpoint as shown in Figure 10.

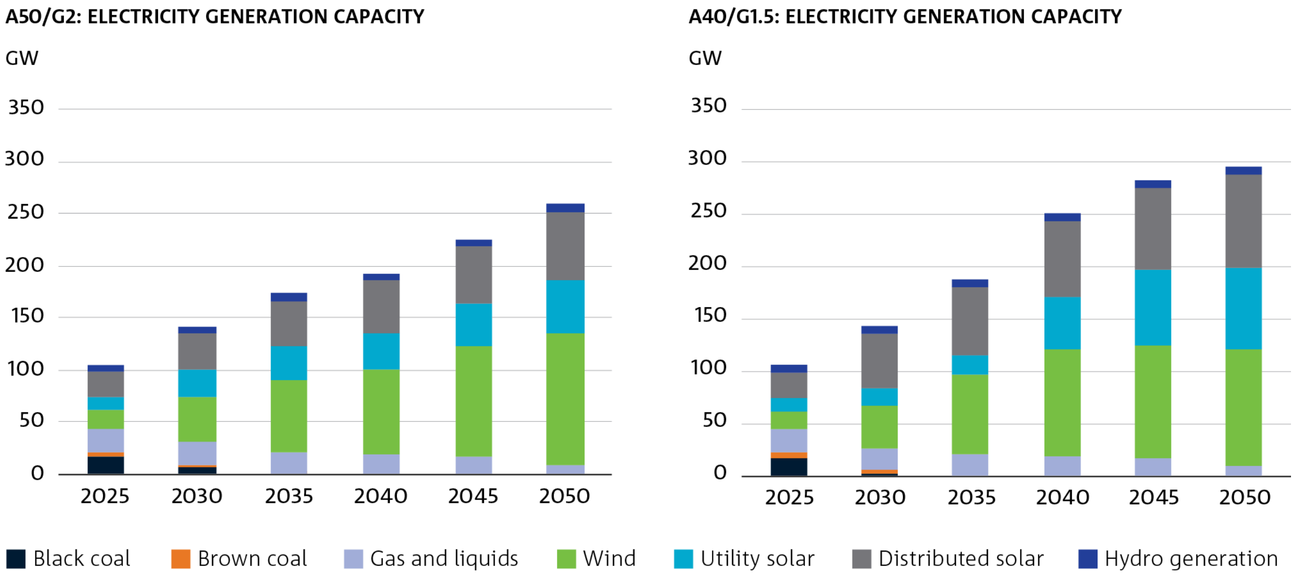

Figure 10 Electricity generation capacity (GW) mix

The near-term state/territory and national renewable energy targets to 2030 mean that under A50/G2 an average yearly deployment of around 8 GW of utility-scale renewables and 1.5 GW of storage would be required. For A40/G1.5 this is less generation capacity at 5.2 GW per year, but more storage discharge capacity at 2 GW per year. This rate is similar post 2030 to 2035 and then a more accelerated deployment is needed based on the additional electrification, especially in road transport.

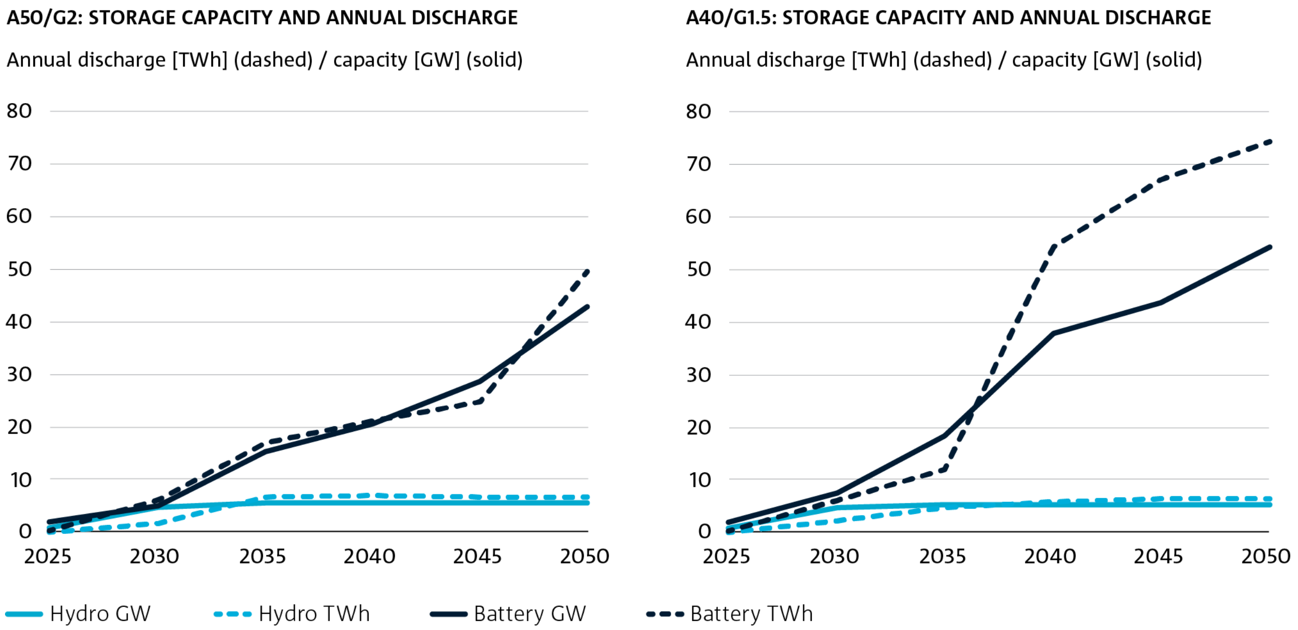

Figure 11 Utility-scale storage capacity over time in TWh and GW

The deployment of utility-scale storage in both scenarios is significant (Figure 11). In A50/G2 there is a greater share of short-duration storage over the projection period than in A40/G1.5 due to persistence of gas-fired generation. In A40/G1.5 the share of four- and eight-hour batteries is greater from 2040 onwards as there is less gas-fired generation and increased need for energy shifting of renewable energy.

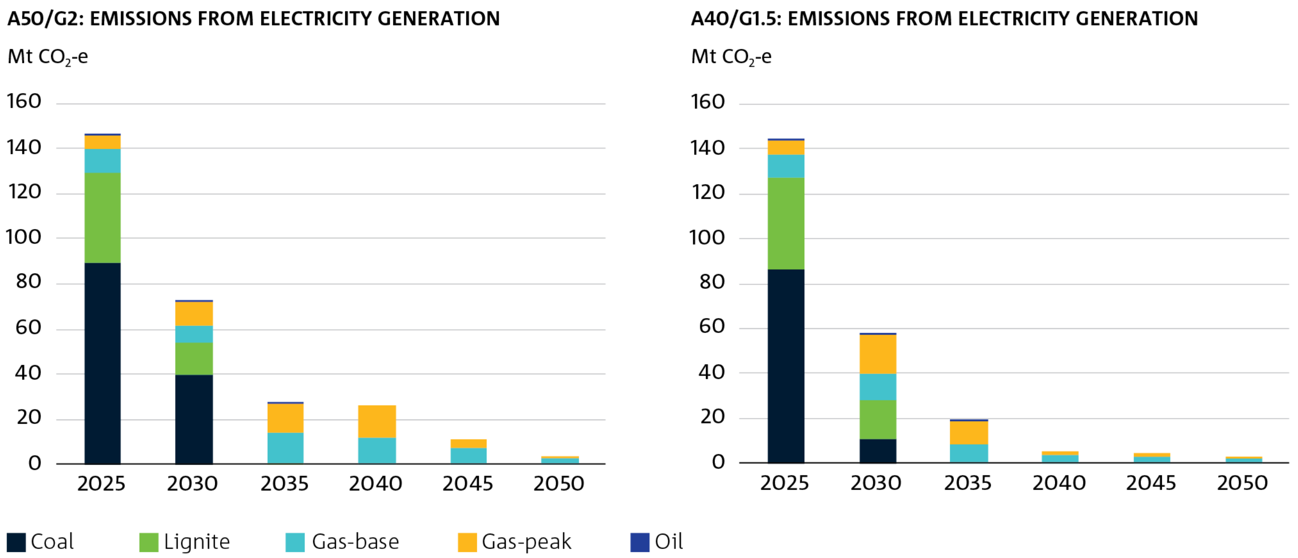

Figure 12 Emissions from the electricity and energy generation sector

The transition of the power sector to an electricity system dominated by variable renewables is also reflected in the profile of emissions from electricity generation (Figure 12). From around 145 Mt CO_2-e in 2025, emissions decline rapidly to around 72 Mt CO_2-e in A50/G2 and 57 Mt CO_2-e in A40/G1.5 by 2030. This is accelerated following the phase-out of coal-fired generation by 2035 in both scenarios with some emissions remaining due to gas-fired power generation. However, by 2035 the emissions intensity has declined to around 0.06 t/MWh and 0.04 t/MWh in A50/G2 and A40/G1.5, respectively (Figure 13). In A50/G2 there is also about 0.3 Mt CO_2-e in 2045 and 0.5 Mt CO_2-e (2050) of abatement from CCS on Combined Cycle Gas Turbine (CCGT) generation. There is no uptake of CCGT with CCS in A40/G1.5.

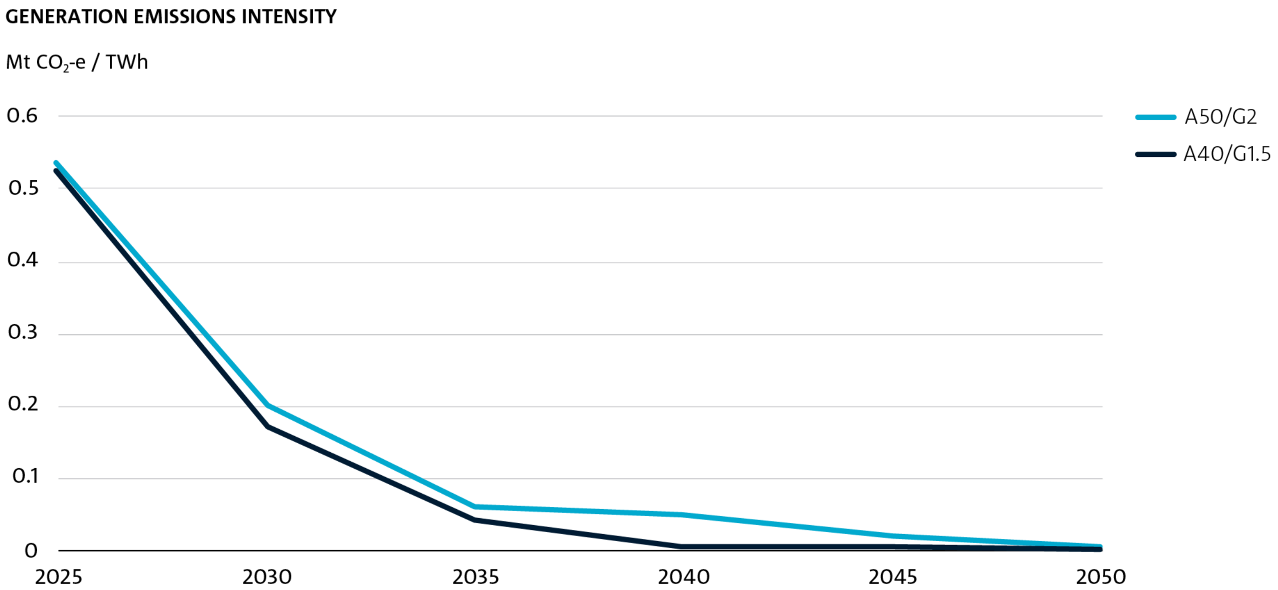

Figure 13 Emissions intensity of generation over time

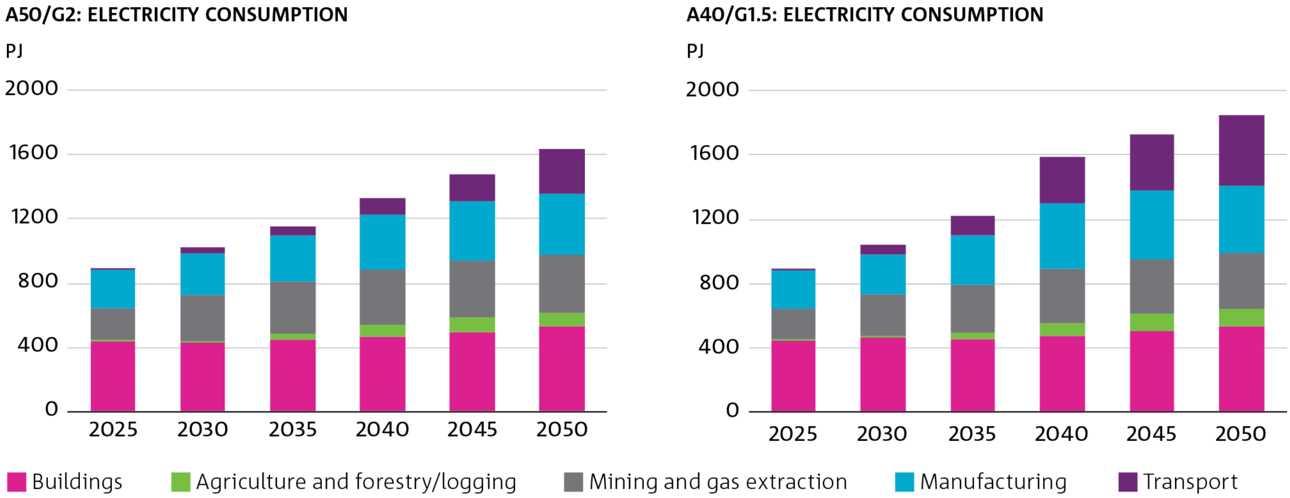

Figure 14 Electricity consumption by sector

Another factor impacting the scale of the electricity system is the increased power generation required for hydrogen production. In the AusTIMES model, hydrogen can be produced by five different production pathways: alkaline electrolysis; proton exchange membrane (PEM) electrolysis; steam methane reforming (SMR) with carbon capture and storage (CCS); brown coal gasification with CCS; and SMR without CCS.[2]

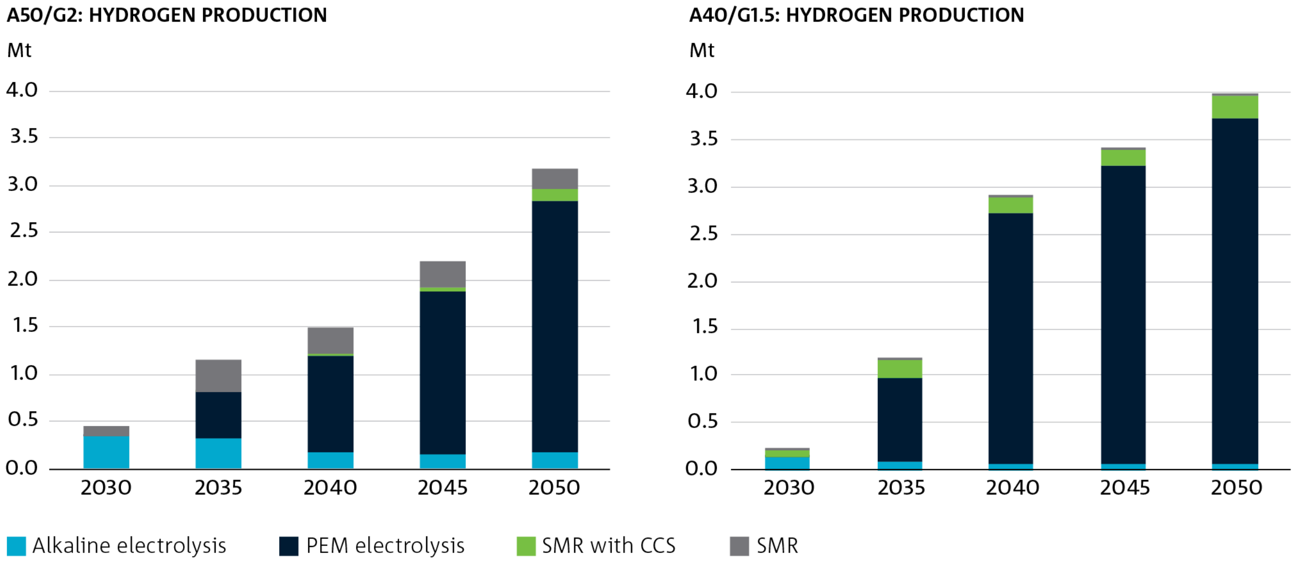

Figure 15 Hydrogen production by technology

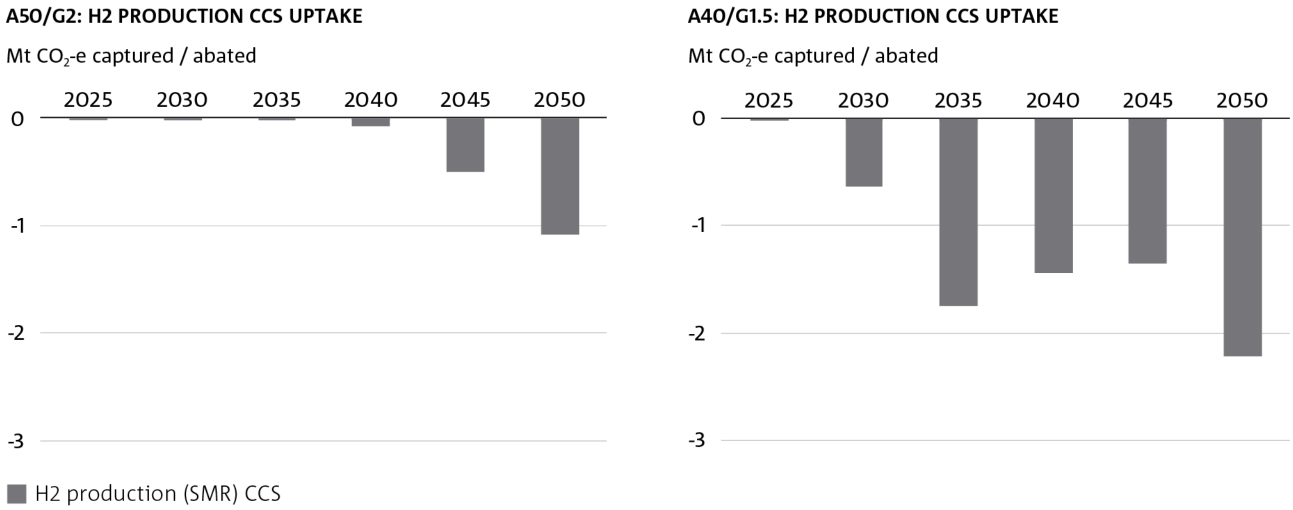

Figure 16 CCS uptake in H2 production

In the less emissions constrained scenario (A50/G2) there is greater hydrogen production from steam methane reforming throughout the projection period whereas in A40/G1.5 the emissions from hydrogen production are captured and stored (Figure 15). In both scenarios, most of the hydrogen production is from electrolysis. Hydrogen demand increases more rapidly in A40/G1.5 due to the more stringent emissions reduction trajectory and need for hard to abate sectors to decarbonise (see Figure 17 for the sectoral breakdown of domestic hydrogen consumption). Hydrogen production increases to around 2.9 Mt per year in 2040 and 4 Mt in 2050 in A40/G1.5. This has implications on the additional power generation capacity required for hydrogen production via electrolysis. In A40/G1.5 for example, this implies an additional 113 TWh of electricity production by 2040 and 155 TWh by 2050.

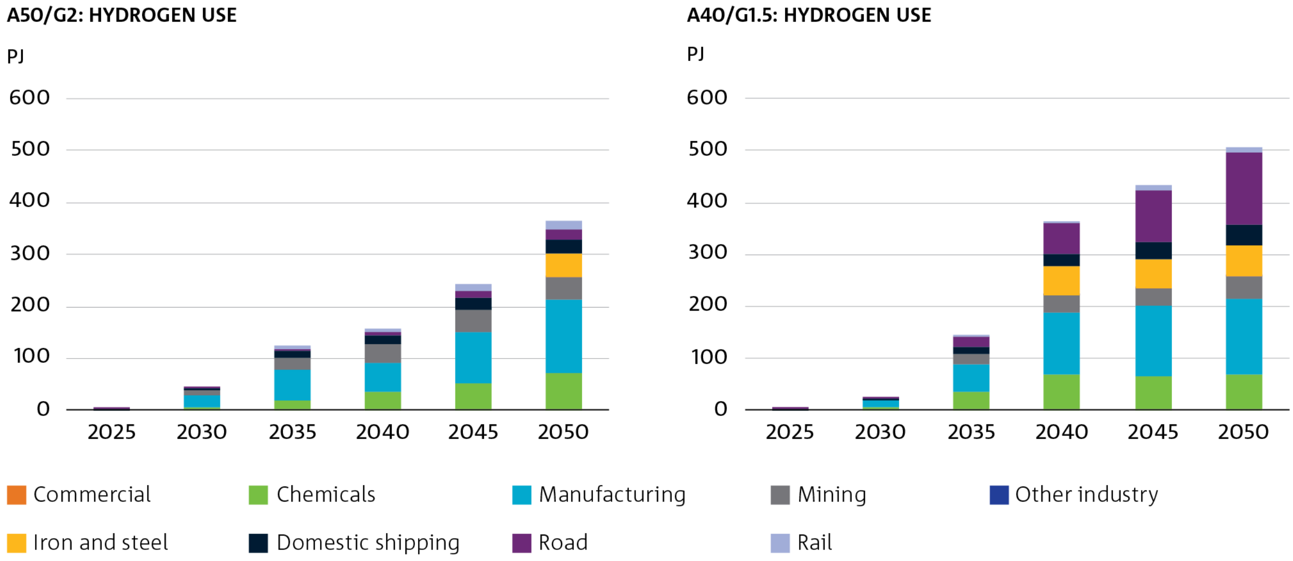

Figure 17 Hydrogen consumption by sector

2.3 Industry and Resources

2.3.1 Industry Sector Output

The growth in output of the industries in this sector are inherited from GTEM[9]. For most industries represented in the modelling, output increases over the projection period and is similar between scenarios (see Figure 18 for aggregated output in energy terms).

[9] The GTEM industry output is smoothed to be linear before being used as an input to the AusTIMES model.

INDUSTRY OUTPUT FOR INCREASING SUBSECTORS

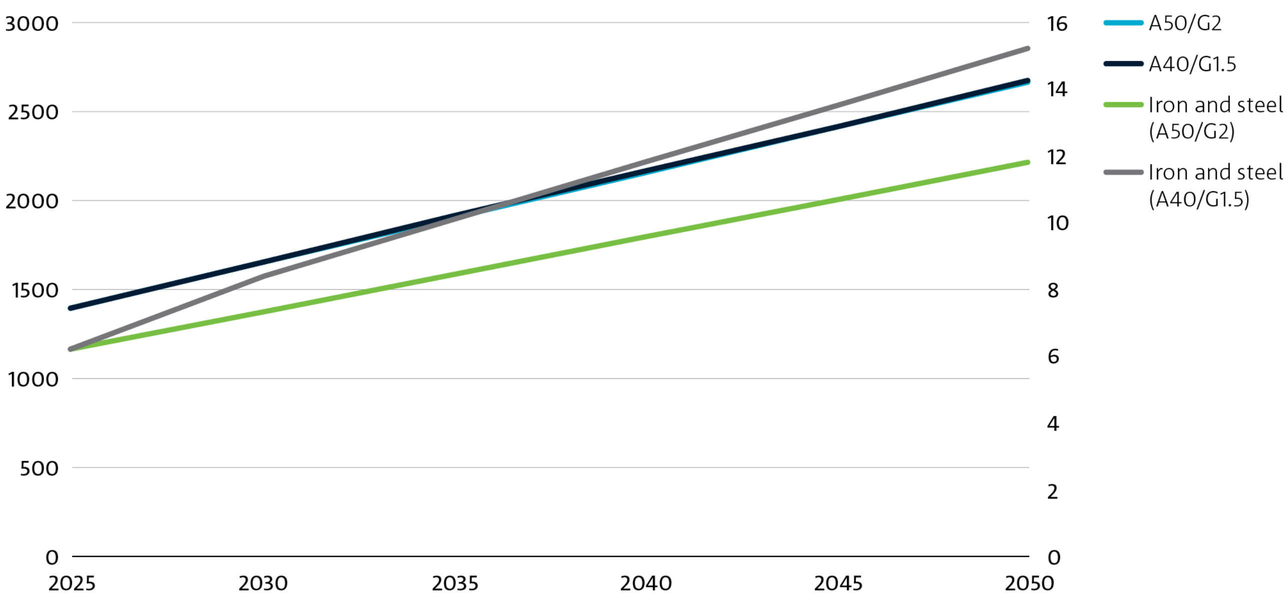

Figure 18 Industry output aggregated over for the majority of (all increasing) industry subsectors in energy terms[10]

Iron and Steel is represented separately as it is represented in real (Mt) units in the model, in contrast to the other industries which are all represented in equivalent energy units. It is also noted that GTEM shows 93% of iron and steel is for domestic use in 2020.

Industries which exhibit negative growth are coal mining, gas extraction, gas export, oil mining, and petroleum refining. The assumed output of these declining industries is shown in Section 2.3.4 below (Figure 23).

2.3.2 Industry Sector Energy Consumption and Intensity

Despite the overall industry growth through to 2050, the energy consumption remains largely flat. This increase in energy efficiency is the result of a combination of autonomous energy efficiency improvements, and specific technology adoptions and process improvements. Figure 19 shows the scale of these improvements reaching more than one-third of the 2050 counterfactual energy demand (see Figure 19) and represents the largest of the technology adoptions across the industry sector. The specific industries which exhibit the largest energy improvements include alumina (via mechanical vapour recompression and hydrogen calcination), iron ore mining (via electrification in material handling and some fuel cell uptake in heavy trucking), gas export (LNG, via compressor electrification and waste heat recovery), ammonia (via feedstock substitution of natural gas for hydrogen[11]), and cement (via material substitution of Portland cement).

[10] In AusTIMES, the output over time of most industries is represented as the energy consumed by that industry to produce a given output. The factor which maps output to energy consumed is determined at the base year (here 2021) and is constant for future years such that explicit energy efficiency uptake in future years produce energy to meet this projected base year energy demand. The one exception is the Iron and Steel sector which is represented in Mt units (hence it being represented separately in the above chart).

[11] Although this substitution shifts the energy consumption to electricity used to produce the hydrogen.

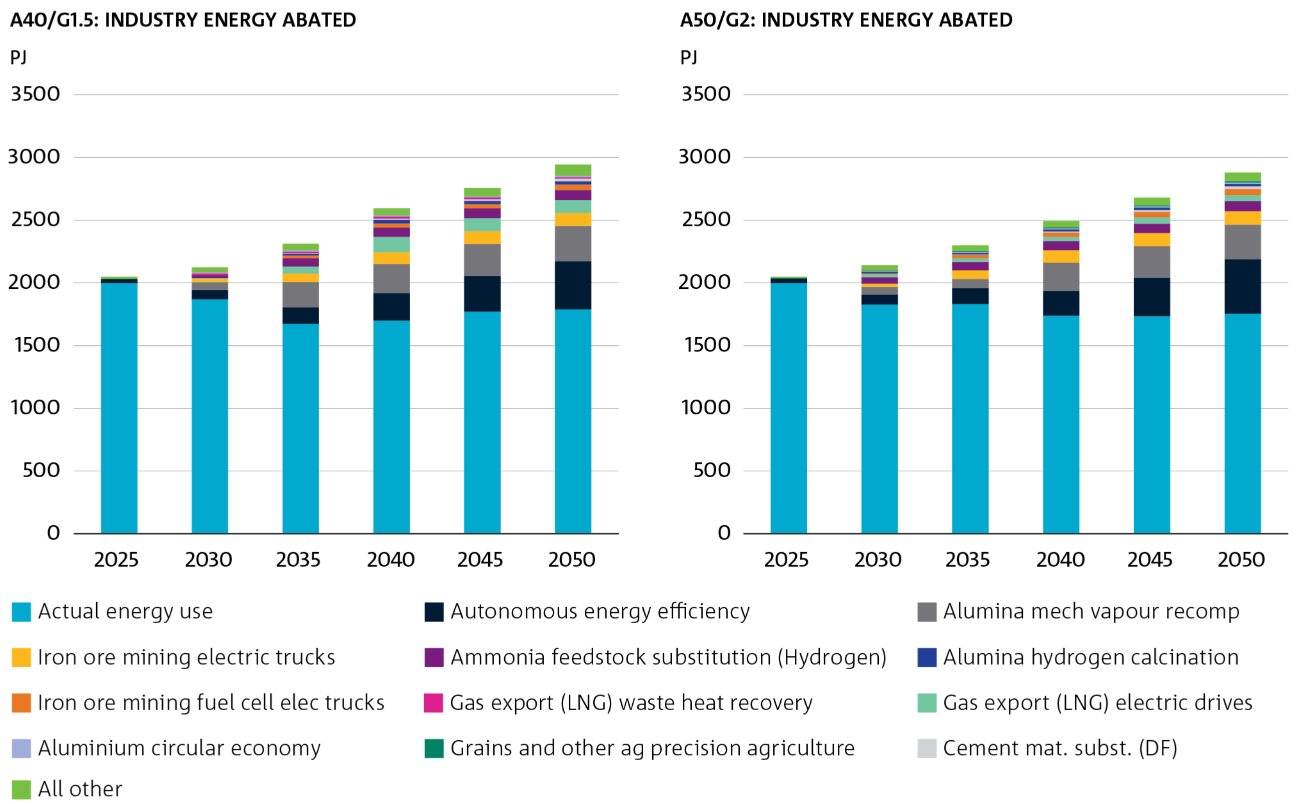

Figure 19 Industrial energy abated compared to counterfactual energy efficiency

This figure shows how the energy efficiency, process improvements, material substitutions, and new technology adoptions contribute to a reduced energy demand over the counterfactual.

The fuel source breakdown of the energy consumption that remains after the new efficiencies, technologies, and processes have been adopted is shown in Figure 20. This shows the use of coal is phased out around 2045 in A50/G2 and 2040 in A40/G1.5, oil (mainly diesel) declining significantly on the same timeline, and natural gas reducing to less than half of present consumption. Electricity use approximately doubles by 2050, and hydrogen uptake complements the decline in natural gas.

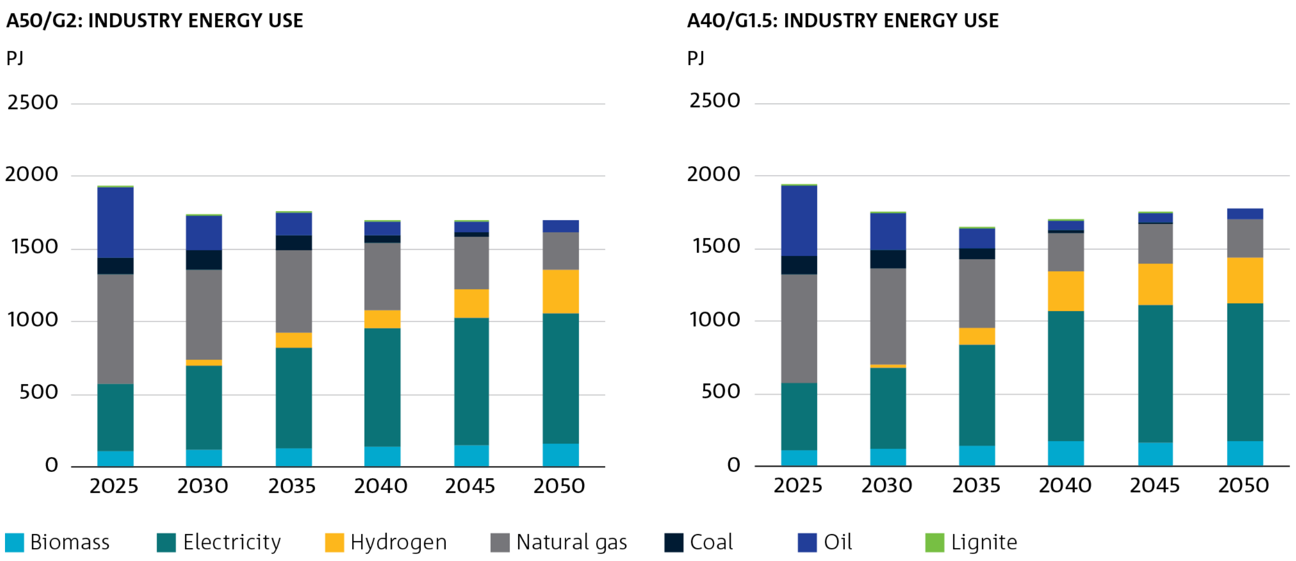

Figure 20 Industry energy use by fuel type

2.3.3 Industry Sector Emissions Reduction and Intensity

Emissions are reduced to approximately one-third of their 2025 levels by the net zero year in both scenarios (see Figure 21). The reduction in emissions is driven by the combination of increased electrification (Figure 20), hydrogen fuel use (see Figure 17), reductions to energy intensity (see Figure 19), and uptake of carbon capture and other abatement technologies (see Figure 22).

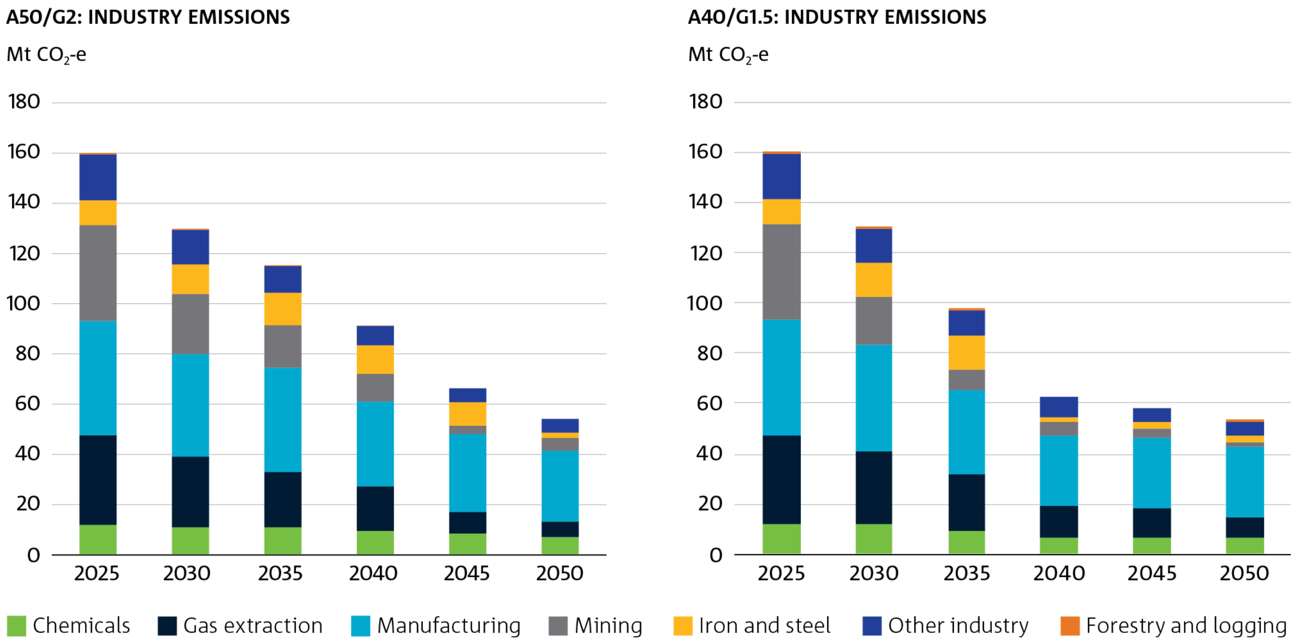

Figure 21 Industry emissions by subsector

Most industry subsectors (mining, gas extraction, iron and steel, and other industry) exhibit abatement of a majority fraction of their present emissions. See Section 2.3.4 for a further breakdown of resource extraction (mining plus gas extraction). However, the manufacturing (which includes aluminium and cement) and chemicals industry subsectors are more resistant to emissions reduction (see Section 2.3.5 for further breakdown).

Carbon capture and uptake of emissions reducing technologies (e.g., material substitutions and process improvements) play significant roles in achieving emissions reductions across the industry sector and in both scenarios as is indicated by the difference between counterfactual (no uptake of emissions capture or abatement related process improvements) and captured/abated emissions trajectories shown in Figure 22.

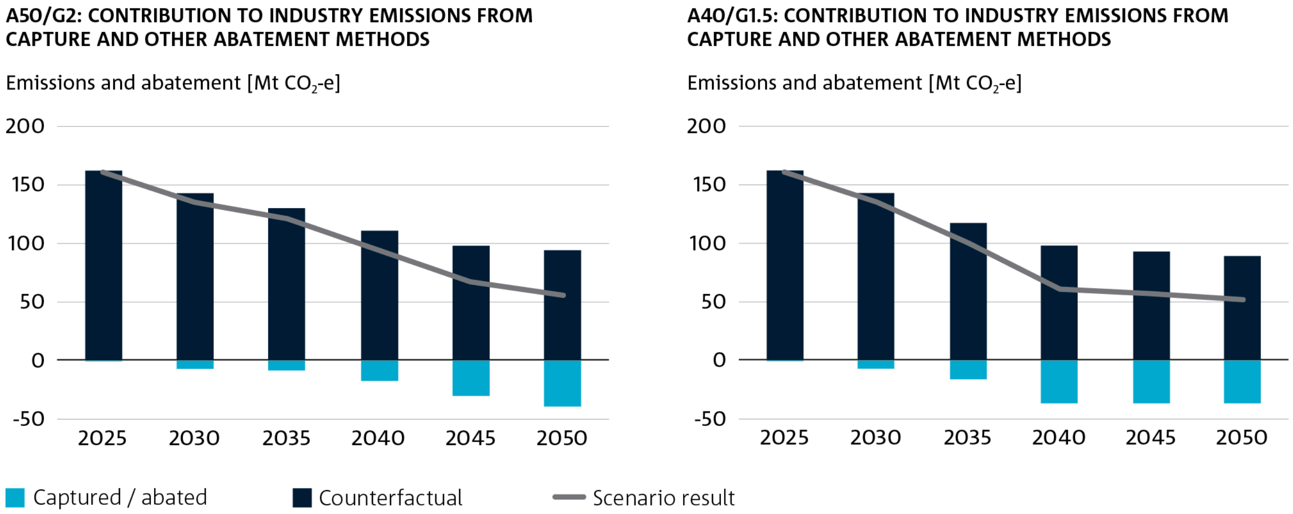

Figure 22 Industry sector abatement technology and process uptake

The counterfactual emissions are those which would occur if the carbon capture and other abatement technologies and process improvements were not taken up. This view demonstrates the scale of the reductions associated with those.

2.3.4 Industry Subsector(s): Mining and gas extraction/export

The energy use in fossil fuel extraction is shown in Figure 23, with coal, gas, and oil all declining.

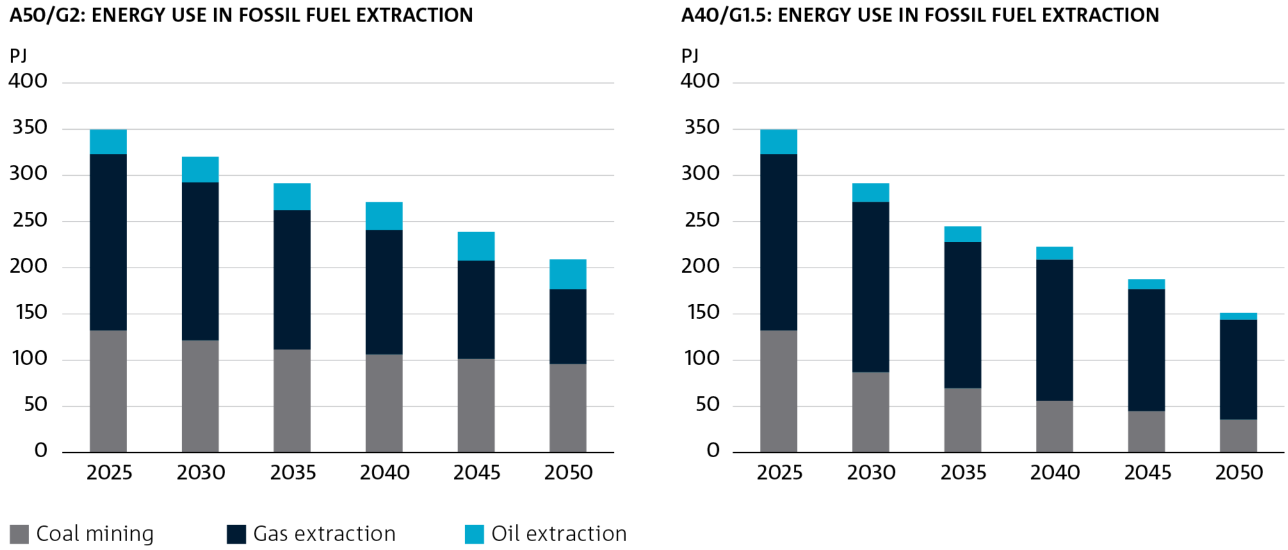

Figure 23 Energy use in fossil fuel extraction

Figure 24 shows the energy use for the resource extraction sector in general (including processing of LNG for export). The bauxite, copper, lithium, nickel, zinc, non-metal ores, (here all grouped under “Other Mining”), and iron ore exhibit growth similar to the overall industry growth shown in Figure 18. The reductions in coal, gas, and oil extraction energy use are balanced by increases in iron ore and other mining, and together with the switching to either electric or fuel cell heavy trucking for the growing iron ore mining industry, lead to a relatively flat energy consumption across the resource extraction industries (Figure 24). The increase in gas export in A40/G1.5 is driven by the faster global decarbonisation under that scenario and the subsequent higher demand for gas as a nearer term interim fuel in 2040 and 2045.

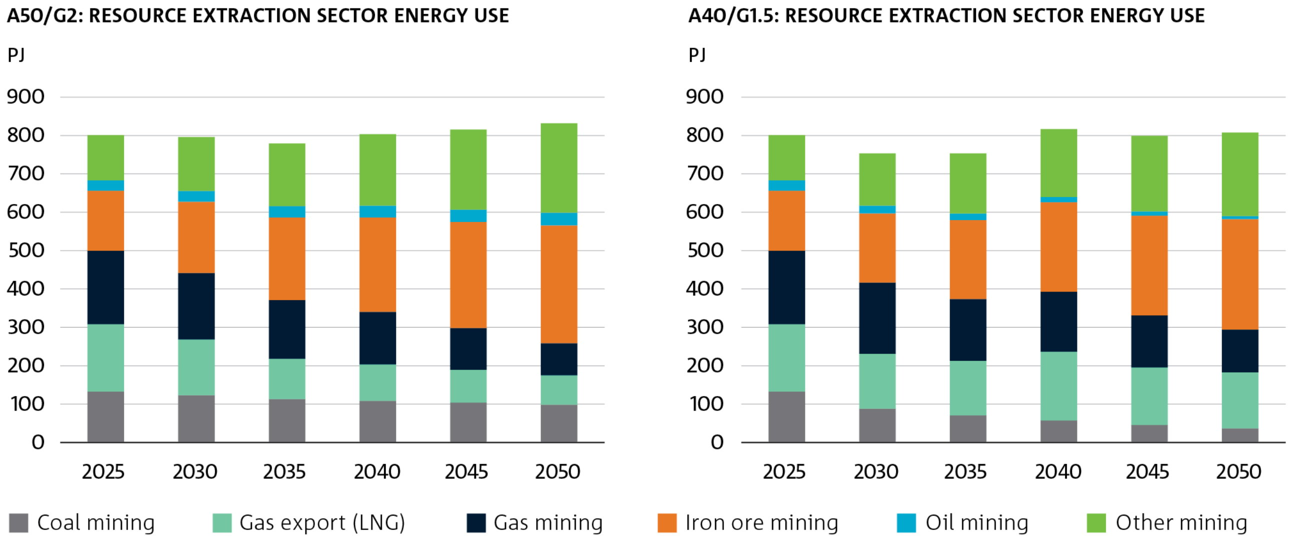

Figure 24 Energy use by resource extraction (mining, gas extraction and export industries)

Emissions associated with the resource extraction sector steadily decrease through to 2050. Figure 25 shows that coal mining and gas extraction make up the bulk of emissions for this subsector and are driven by coal and gas exports.

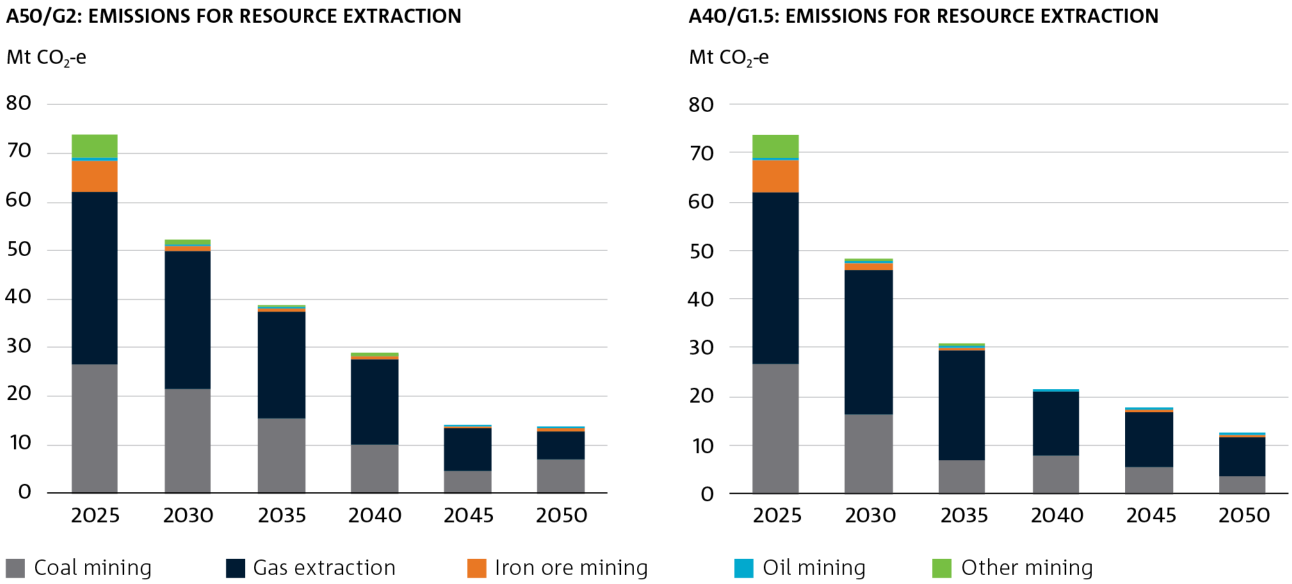

Figure 25 Resource extraction (mining plus gas extraction) emissions

Figure 26 further details the technology and process uptake driving the reduction in emissions. In addition to replacing diesel engines in heavy machinery and transportation with electric or fuel cell drivetrains, methane fugitives reducing methods in coal mining, and CCS in gas and oil extraction. In the gas export industry, further leak detection and repair (LDAR) and the centralisation of gas supply networks are shown to contribute.

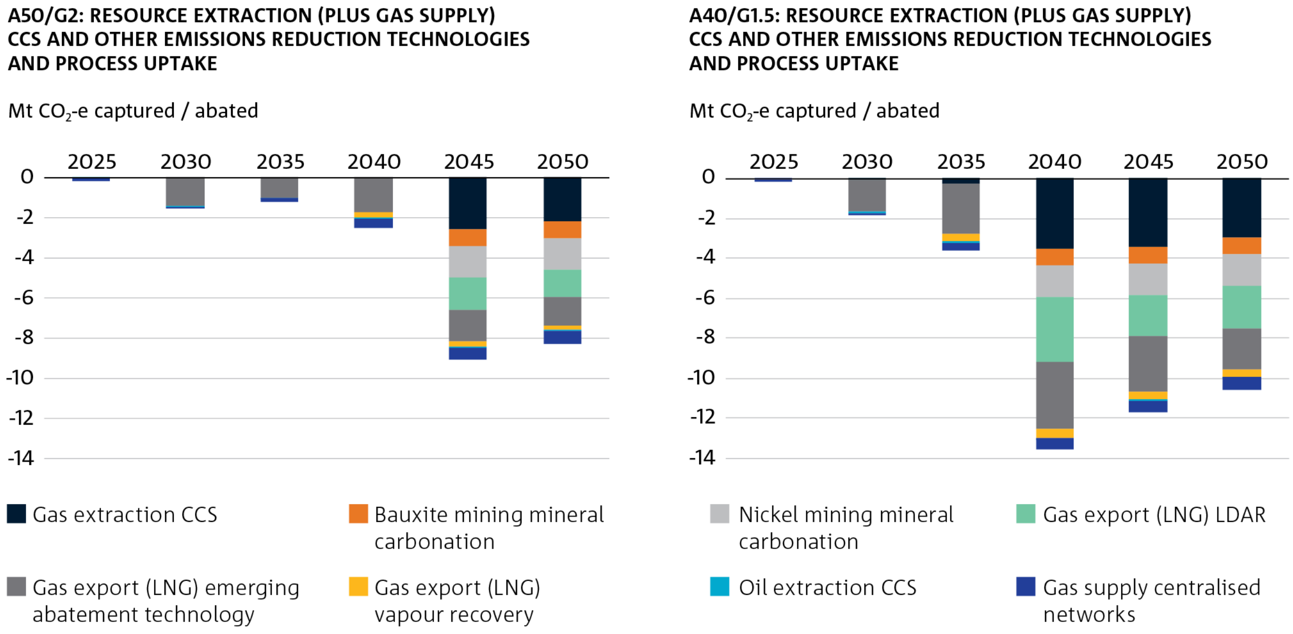

Figure 26 Resource extraction (plus Gas Supply) sector uptake of CCS and other emissions reducing processes and technologies.

2.3.5 Industry Subsector(s): Iron and Steel

For the iron and steel industry, the AusTIMES model includes several production technology pathways. These include the present-day blast furnace (BF), electric arc furnace (EAF), and direct reduced iron (DRI), but also hydrogen based DRI (H2 DRI) and melt basic oxygen furnaces (MBOF) as costed options which can be taken up. As indicated below (Figure 27), the selected technology path depends on the scenario. For A50/G2 the switch to MBOF and H2 DRI does not occur until after 2045, whereas it occurs after 2035 for A40/G1.5.

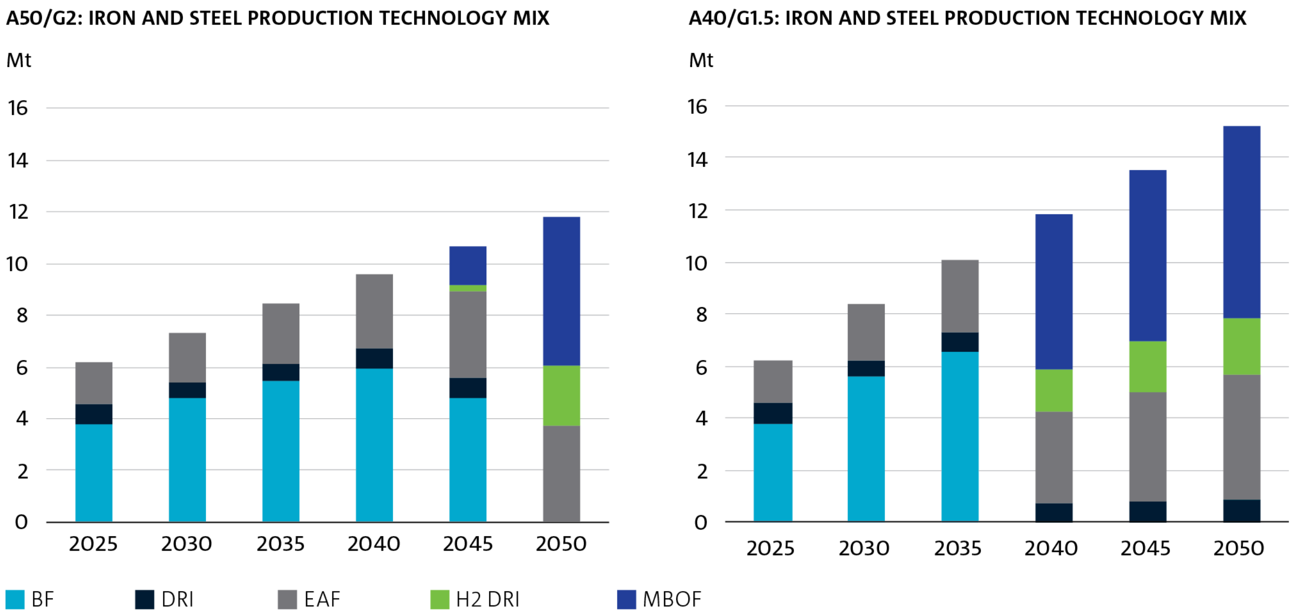

Figure 27 Iron and steel production technology mix

The switch to H2 DRI and MBOF results in increase in energy consumption as indicated in Figure 28, but a significant reduction in emissions as shown in Figure 29.

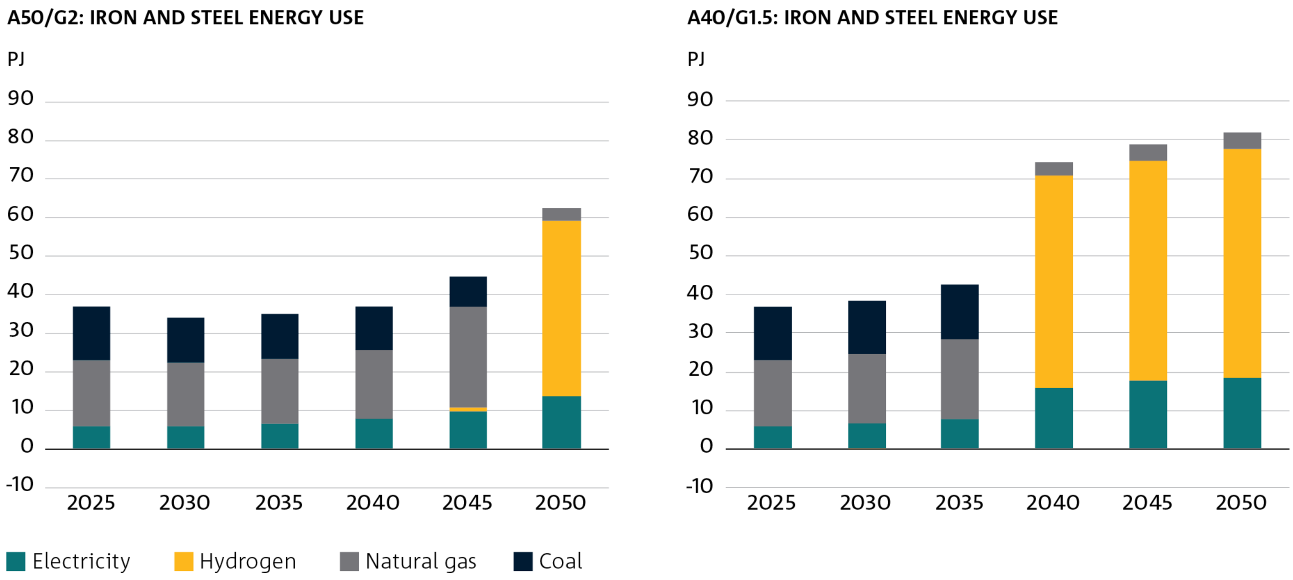

Figure 28 Iron and steel energy use by fuel type

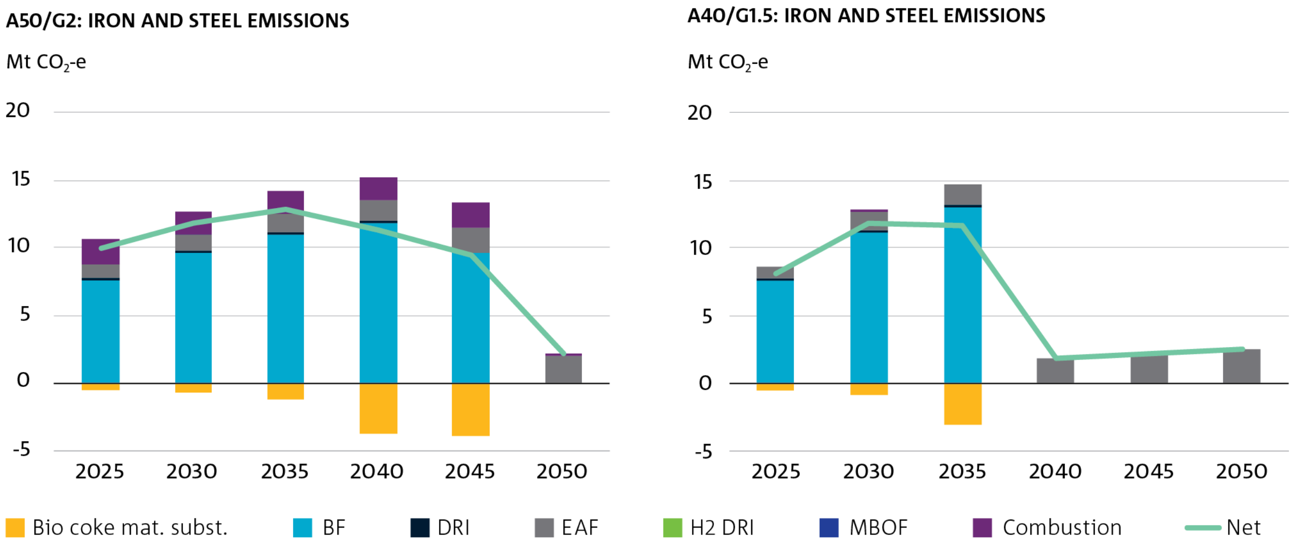

Figure 29 Iron and steel emissions by technology

2.3.6 Industry Subsector(s): Manufacturing and Chemicals

The manufacturing industry subsector includes alumina, aluminium, cement, food and beverages, non-metallic construction materials (not cement and lime), paper products, petroleum refining, other non-ferrous metals refining and smelting, other metal product manufacturing, and other manufacturing. Decarbonisation of the manufacturing subsector is delayed by the increasing emissions from "Other non-ferrous metals refining and smelting" (e.g., copper, zinc, nickel, lead, etc), increasing emissions from Food and beverages, and (somewhat less) from the hard to abate cement industry (Figure 30).

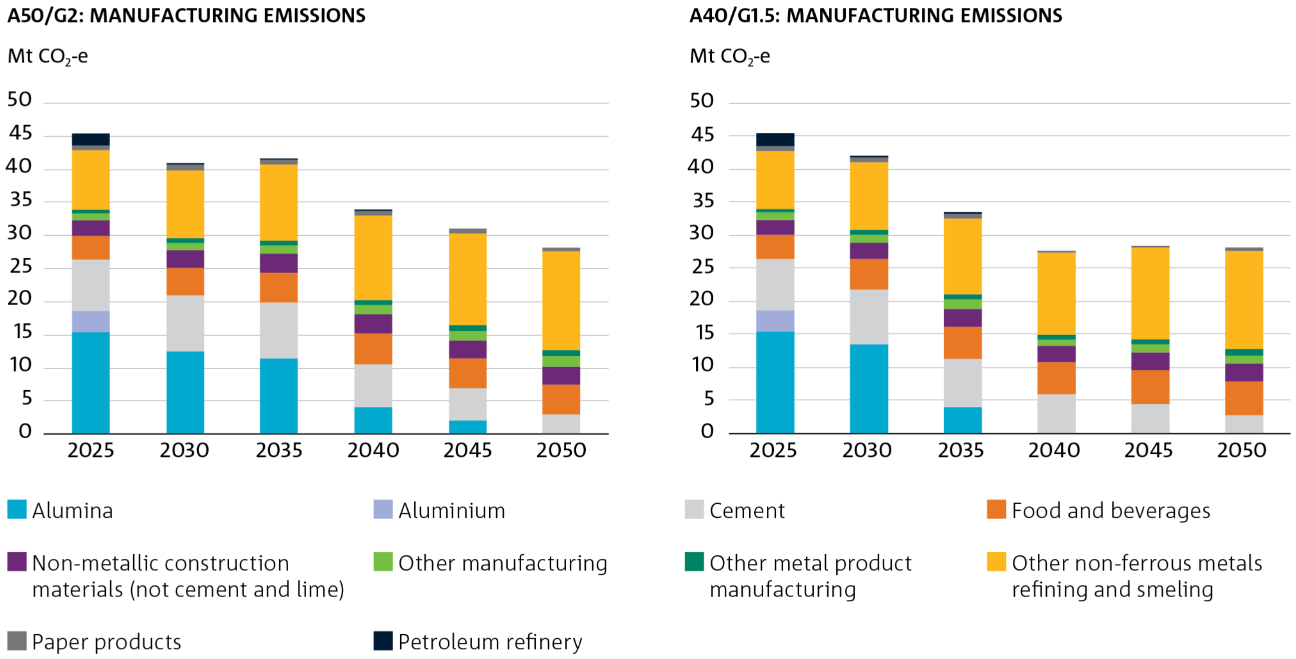

Figure 30 Manufacturing emissions by industry

The emissions reductions observed in the manufacturing sector are primarily illustrated in Figure 31, where contributions from the aluminium industry (through inert anode adoption), the cement industry (through CCS and material substitution), and the iron and steel industry (through bio-coke material substitution) are highlighted.

Since the reductions seen in Figure 30 for Alumina are driven by reduced energy consumption, they do not appear in Figure 31. Rather, those reductions appear in Figure 19 as reduced energy consumption, and therefore reduced emissions, due to the uptake of mechanical vapor recompression.

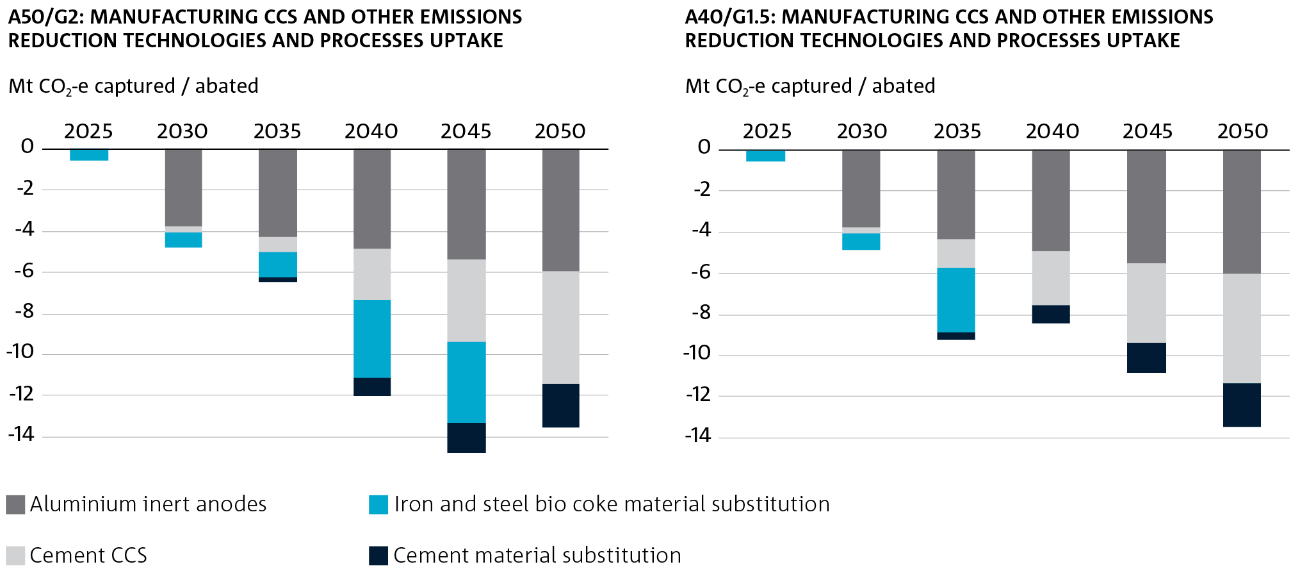

Figure 31 Manufacturing uptake of CCS and other emission reducing technologies and processes

The reductions seen (in Figure 21) in the chemicals industry emissions are shown Figure 32 to be the result of a combination of CCS uptake in Other chemicals, and process emissions abatement in the same industry (via catalyst process improvements).

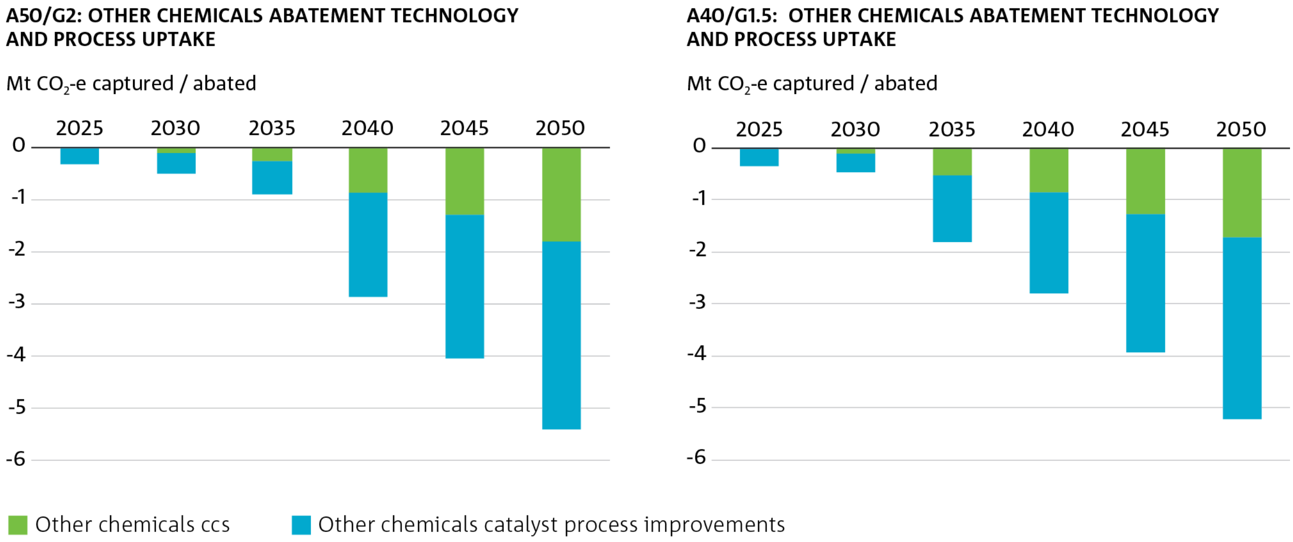

Figure 32 Other Chemicals abatement technology and process uptake

2.4 Transport sector

Over the period 2025 to 2050, emissions from the transport sector drop by more than 75% in A50/G2 and more than 95% in A40/G1.5. These reductions are driven by road transport electrification. In the near-term to 2030, there is increased deployment of more efficient internal combustion engine vehicles (especially hybrids), and to some extent battery electric vehicles (BEV). This impacts light vehicles the most as this accounts for the vast majority of vehicle fleet. Over time, there is greater deployment of electric vehicles especially in the A40/G1.5 scenario to meet the more stringent emissions reduction target. There is also modest uptake of fuel cell electric vehicles in freight applications in the A40/G1.5 scenario. The portion of the fleet made up of internal combustion engine vehicles drops to less than 10% in A50/G2, and to zero in A40/G1.5 by 2050.

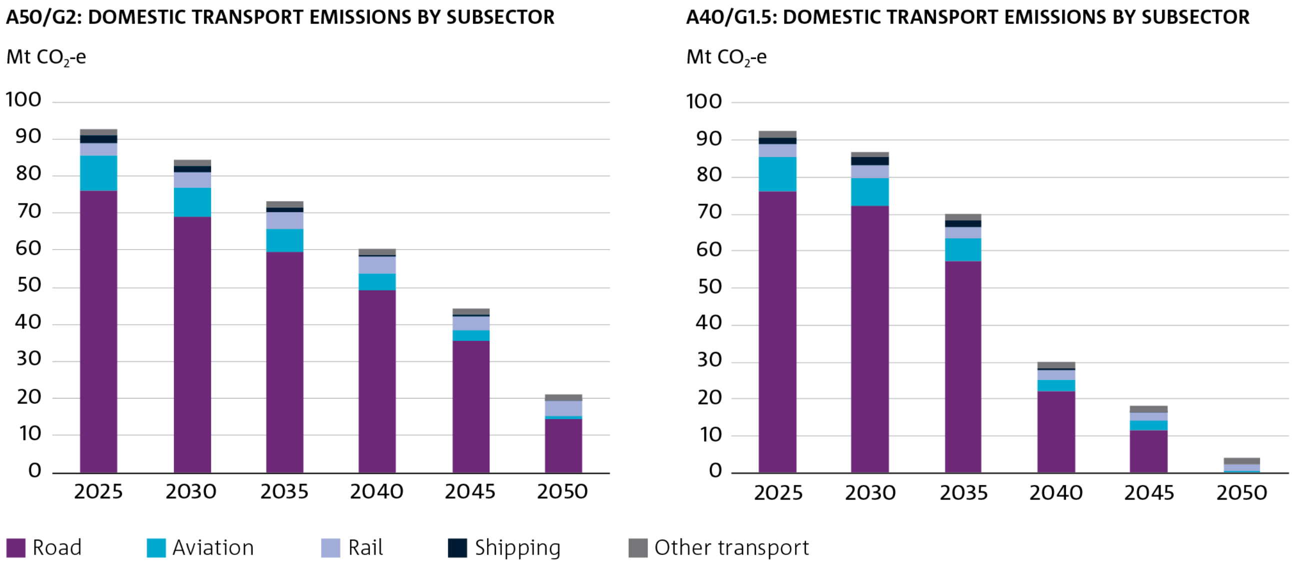

Figure 33 Transport sector emissions by transport mode

At the beginning of the projection period, most of the 1400 PJ energy consumption in 2025 is oil derived fuels of petrol and diesel in road transport (light and heavy vehicles) and kerosene in domestic aviation. The biofuel consumption is mainly low-blend ethanol (E10) in some Eastern states with a small amount of biodiesel consumption due to mandates in NSW and QLD. Similarly, there is modest liquefied petroleum gas (LPG) consumption in petrol internal combustion engine (ICE) vehicles converted after market, although this consumption declines over time as its attractiveness diminishes due to announced increases in excise rates on LPG.

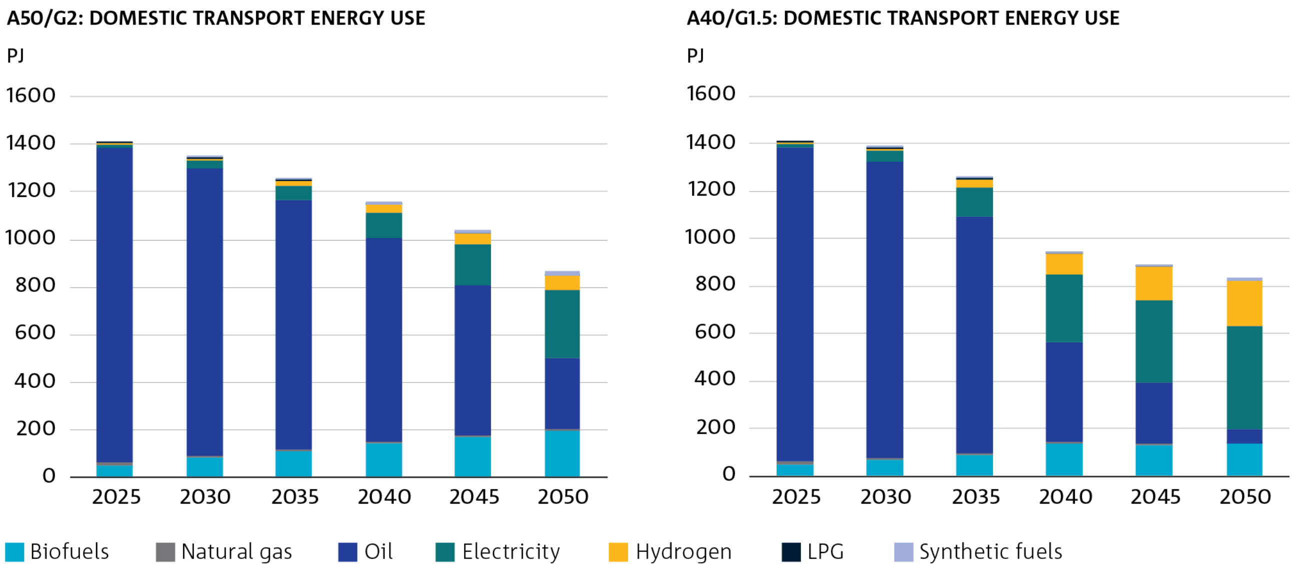

Figure 34 Domestic transport energy consumption by fuel type

Over the projection period, the share of oil-derived fuels declines as the road fleet electrifies and there is greater uptake of biofuels in aviation and to a lesser extent domestic shipping. There is also uptake of hydrogen, mainly in road freight and shipping and to some extent in rail transport. There is only modest uptake of synthetic fuels in aviation.

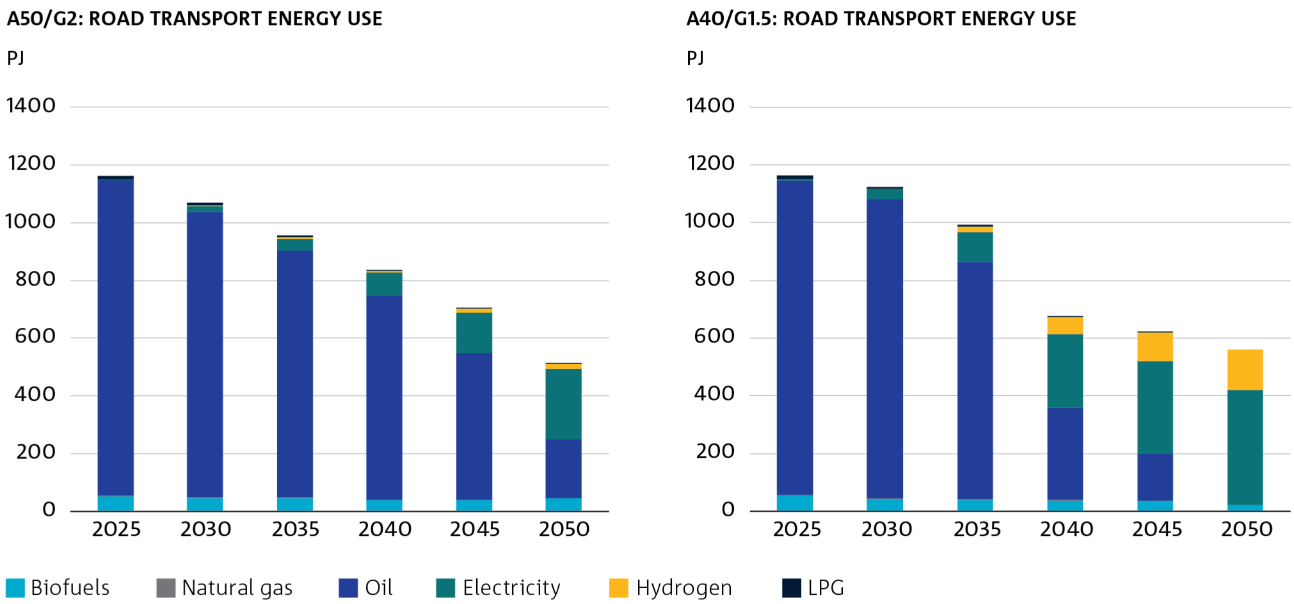

Figure 35 Energy consumption in road transport by fuel type

Fuel consumption is currently dominated by road transport, but with the accelerated uptake of electric vehicles (EVs) followed by fuel cell electric vehicles (FCEVs), its relative share of domestic transport fuel consumption declines over the projection period. The introduction of fuel efficiency standards for light vehicles combined with the electrification of road transport (and to a lesser extent rail and aviation) accelerates the decline in the overall level of fuel use in road transport (Figure 35), reflecting the greater efficiency of the electric drivetrain to deliver more kilometres per unit of energy. Informed by earlier work (Graham, 2022), this acceleration occurs in the mid-2030s as electric vehicles dominate new vehicle sales, especially in the A40/G1.5 scenario. In the A40/G1.5 scenario, emissions decline from road transport to zero by 2050.

Currently, final energy consumption in domestic aviation[12] is dominated by oil-derived kerosene. In both scenarios, there is significant uptake of bio-kerosene (biofuels in charts) reflecting the need for a "drop-in" near-zero emissions fuel for kerosene in existing turbine aircraft to meet increasing stringent emissions reduction targets. There is also uptake of electric aircraft particularly for short-haul routes and some hydrogen-based synthetic kerosene (synthetic fuels in chart), from 2035 onwards (Figure 36). It is also notable that the overall level of fuel consumption in the A40/G1.5 scenario in the long-term is much less than A50/G2 due to much greater efficiency in energy use per passenger and tonne kilometre.

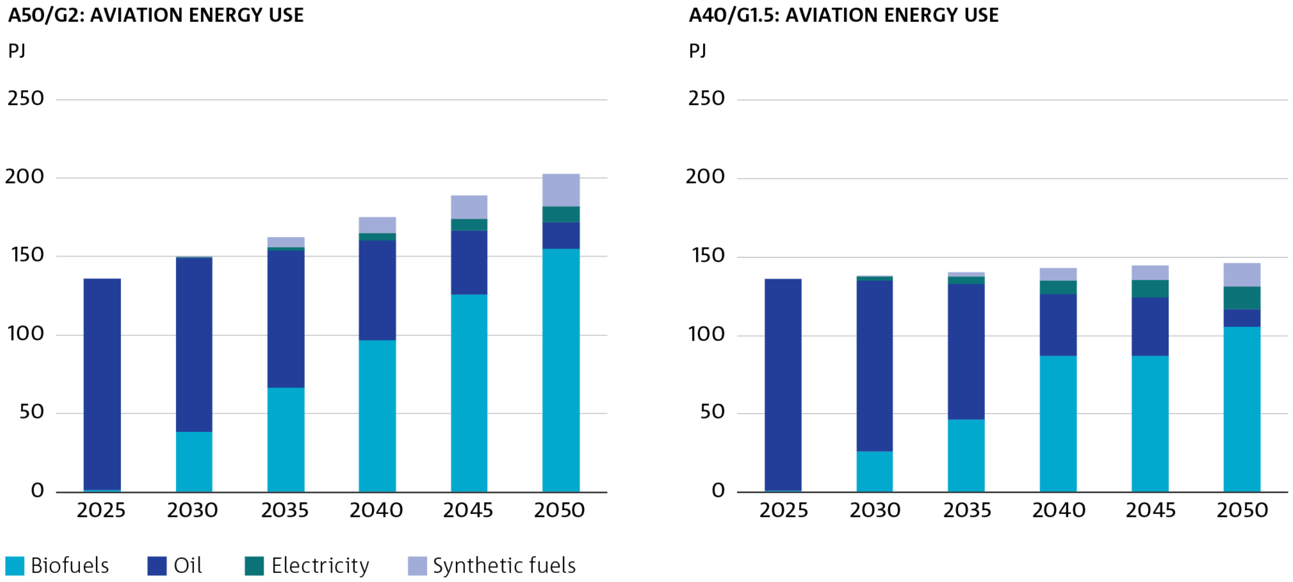

Figure 36 Fuel consumption in domestic aviation by fuel type

[12] Table F of the Australian Energy Statistics splits fuel consumption out for domestic and international aviation. For international aviation, although the fuel is refined and/or supplied in Australia, it is consumed by outbound aircraft and is not included in the National Greenhouse Gas Inventory (NGGI) and emissions reduction target that is modelled.

Final energy consumption in rail transport is dominated by electrified rail (principally for passenger services) and diesel (for freight and regional passenger services), although there are some variations by jurisdiction. Increased use of electricity is somewhat constrained due to expansion of passenger services (additional services or new lines – e.g., light rail) but more likely possible due to hybrid diesel/electric transitioning to battery electric trains. Hydrogen could also be a future option for decarbonising non-electrified rail that currently uses diesel (and sees some take-up in both scenarios - Figure 37). Some key advantages of using hydrogen over battery electric trains are the longer range, faster refuelling time and there are no issues with payload. It is also notable that the overall level of fuel consumption in the A40/G1.5 scenario in the long-term is much less than A50/G2 due to much greater efficiency in energy use per tonne kilometre.

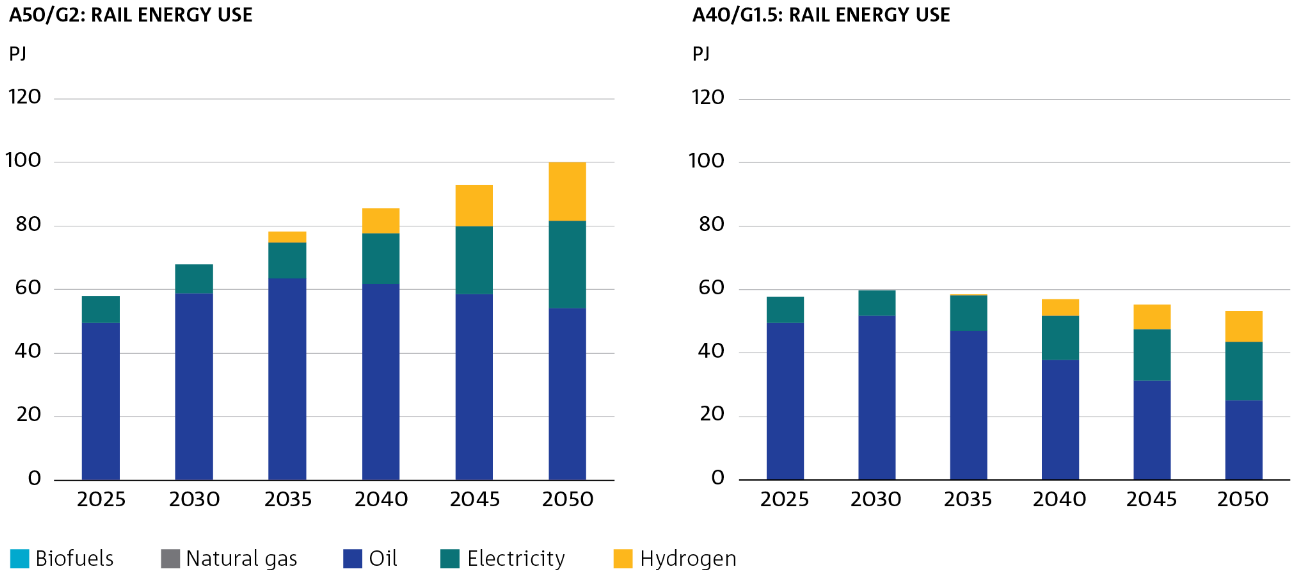

Figure 37 Energy consumption in domestic rail by fuel type

2.5 Built Environment sector

The built environment sector encompasses emissions from residential housing and commercial buildings. The residential housing sector is made up of homes consisting of three different dwelling types; separate houses (70%), apartments (16%), and townhouses 13% (Census, 2021; ABS, 2022). The average growth rate across this sector to 2050 is 1.81% per annum. The commercial building sector consists of a range of commercial floorspace uses such as hospitals, accommodation, offices, public buildings, retail, and education facilities. The average growth rate in floorspace to 2050 is 1.56% per annum. These growth rates are a function of the ABS projections for residential, and the Commercial Building Energy Consumption Baseline Study for commercial.

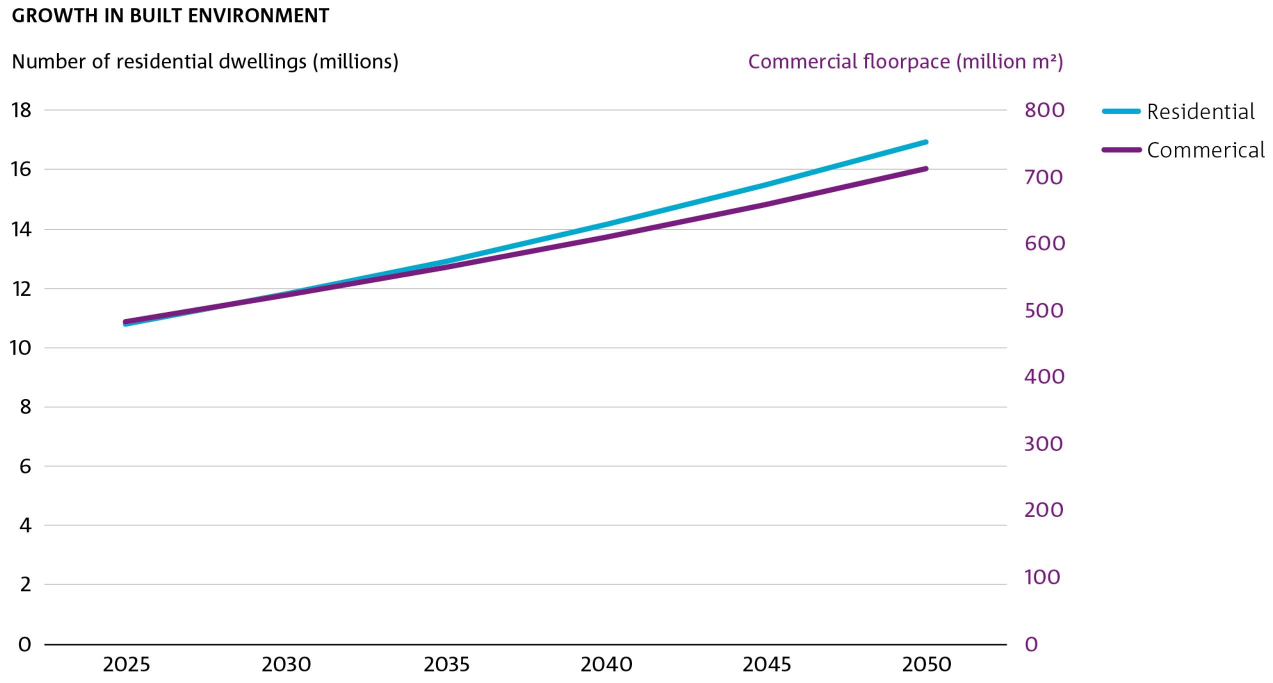

Figure 38 Built environment (residential and commercial) growth

The modelling results shows that the emissions from the built environment sector (both commercial and residential buildings) in 2025 amount to 78 Mt CO_2-e. These emissions are made up of Scope 1 emissions which are direct emissions that can be controlled and managed by buildings operations, such as from onsite combustion of fossil fuels such as natural gas for heating and cooking. Scope 2 emissions are indirect emissions, which are emissions produced from purchased energy, which is itself produced offsite, predominantly electricity. Scope 2 emissions account for about 83% of total emissions in 2025. The sharp reduction in emissions from this sector can be observed, residential emissions have fallen to virtually zero, and commercial emissions to a very low level by 2050 (Figure 39). Initial large reductions can be seen in the Scope 2 emissions which is largely due to the decarbonisation of the electricity sector and towards the latter part of the projection Scope 1 emissions begin to fall. Energy efficiency and new technologies have an impact on emissions but the sharp fall in emissions is not accompanied by a sharp corresponding decline in energy consumption and is examined in more detail in Figure 40.

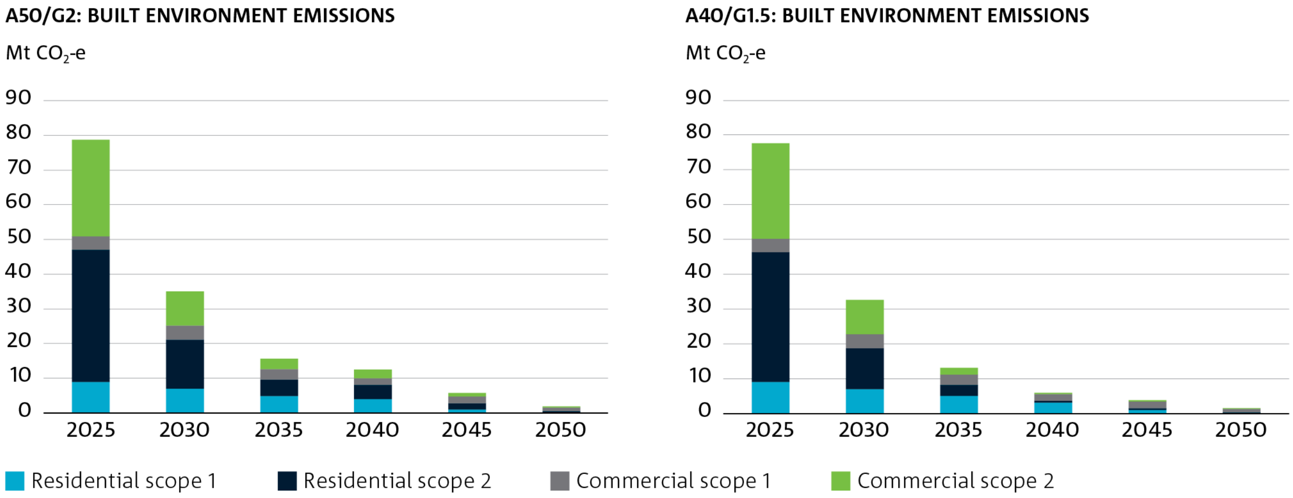

Figure 39 Built environment sector emissions

Scope 1 emissions results are generated by the AusTIMES based on the use of fossil fuels such as natural gas and oil. Conversely, scope 2 emissions are calculated manually using the electricity sector's emissions intensity and buildings electricity consumption results produced by the model.

Energy consumption in the buildings sector (Figure 40) is driven by economic and population growth and offset by energy efficiency and electrification advancements (which have their own efficiency dividend). In 2025, the energy consumption totals 478 PJ in residential buildings and 246 PJ in commercial buildings. Over the modelling period, residential final energy consumption has fallen by 11% and 12% in A50/G2 and A40/G1.5 respectively, while commercial consumption has fallen by 20% and 15%, respectively.

In residential buildings, electricity consumption is projected to increase by around 35% by 2050 whereas natural gas and LPG consumption is expected to be phased out by 2050 in both scenarios. Conversely, in commercial buildings, electricity consumption is forecasted to remain relatively constant with a slight fall of 3% to 2050 in A50/G2 scenario and slight rise of 4% to 2050 in A40/G1.5. The largest fall in consumption is oil of around 91% followed by natural gas of around 32%, although consumption persists in both fuels until 2050, and natural gas is not completely phased out as it is in the residential sector.

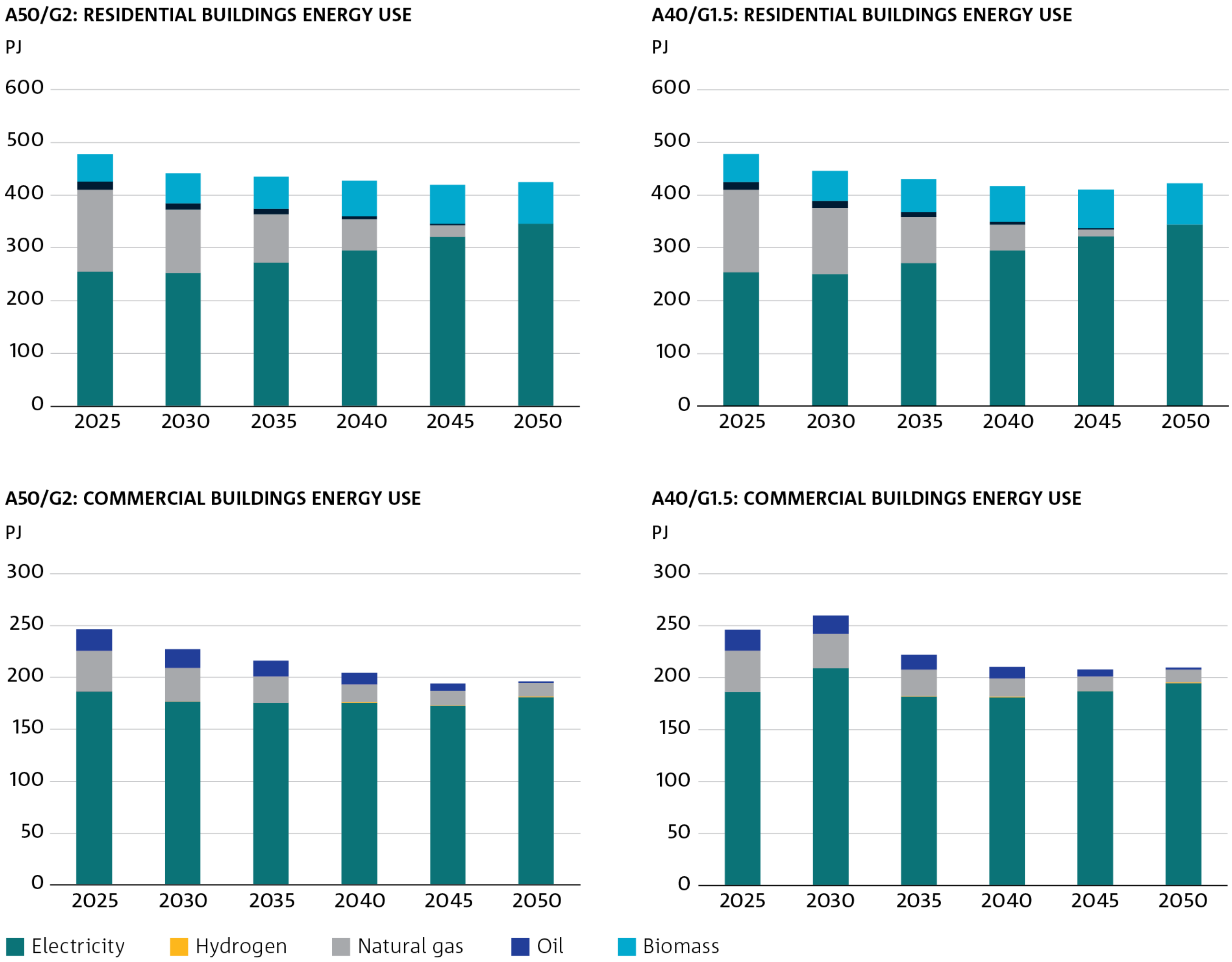

Figure 40 Buildings energy consumption by fuel type

While the model has the option to blend hydrogen into the natural gas supply, this is only taken up in the supply to commercial buildings to around 10% by volume by 2050. There is no hydrogen uptake in residential buildings where gas is phased out. Biomethane is also an option to blend into the gas supply. However, due to its cost, no biomethane uptake is observed in either scenario.

As noted in previous work (Reedman et al., 2022), residential energy consumption from wood (Biomass in Figure 40) does not have fuel switching pathways implemented in AusTIMES, and simply grows with residential activity projections. While wood is a significant energy source, it is also highly inefficient when compared with electricity; fuel switching to electricity is likely to only represent a small increase in electricity consumption.

2.6 Land and Agriculture sector

Agriculture sectors include various crops and livestock as well as fishing and forestry sectors. Agricultural output is similar between the two scenarios and approximately doubles between 2025 and 2050 for aspects other than livestock (sheep and cattle) and forestry and logging. Livestock is assumed to be kept at the current level in both scenarios which is consistent with the long run trend and ABARES projections. Forestry and logging are also flat in energy terms.

As shown in Figure 41, the emissions from agriculture are dominated by livestock (sheep and cattle), followed by grains and other agriculture, and then dairy. That figure also shows that the agricultural sector also supports the largest source of negative emissions in the form of the existing inventory of land-based sequestration (labelled LULUCF), and new plantings (Land Seq. (Future)). Comparing those new plantings for land-based sequestration between scenarios, A40/G1.5 (see right panel of Figure 41) shows more than double the new plantings compared to A50/G2. This is a result of the higher carbon price under the A40/G1.5[13], such that monoculture and environmental plantations which receive payments for storing carbon are better able to compete with existing agricultural land uses in economic terms; so, more landholders are incentivised to change from agricultural production to carbon sequestration by planting trees. However, while they offer the potential for mitigation in the short term, sequestration from trees will peak and then decline, and there is a limit to the land that can be used to store carbon. As such, there is a need to consider longer-term alternative means for carbon capture such as engineered approaches, as well as further emissions reductions.

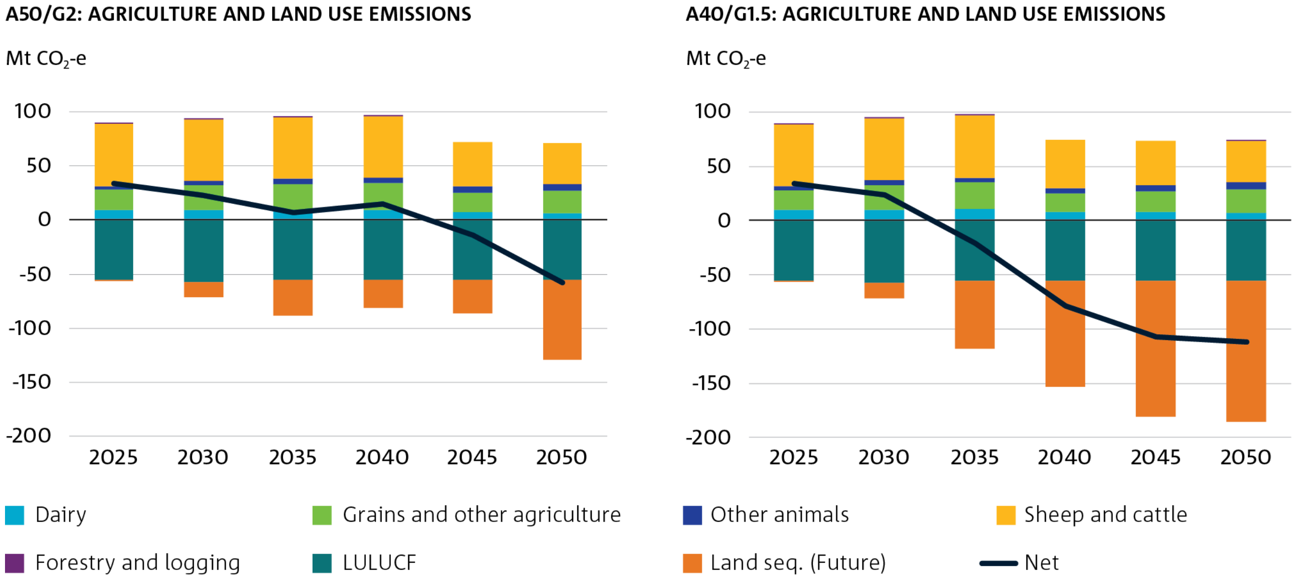

Figure 41 Land and agriculture emissions by subsector

[13] And also, under the A40/G2 scenario from which the new land-based sequestrations are sourced for use in A40/G1.5

Figure 42 shows the reductions in gross emissions in this sector are the result of methane mitigation measures in Sheep, Cattle, and Dairy (e.g., feed additives, rumen modifiers, and vaccination against methanogenic archaea), and precision agriculture in Grains and Other Agriculture. For example, the introduction of feed additives (e.g., Asparagopsis, 3-nitrooxypropanol, synthetic bromoform products, and potentially genetically modified yeast) could significantly reduce enteric methane emissions from cattle and sheep (Honan et al., 2022; Kinley et al., 2016). While the referenced studies have shown that feed additives can significantly reduce emissions in controlled conditions, the scaling up of production and distribution represents significant uncertainty in the magnitude of widespread adoption. As such, and to supplement the costing-based uptake of the technology, a maximum abatement potential is applied as an input assumption. This is set at 30% of gross Dairy and Sheep and Cattle methane emissions by 2050 for both scenarios (based on the low end of the ranges of published abatement potentials, e.g., Yu et al., 2021, Roque et al., 2021). Also, precision agriculture technologies, such as variable rate application of fertilizers, soil carbon management practices, and digital tools for real-time monitoring of crop health, are expected to reduce emissions in Grains and Other Agriculture (Robertson et al., 2012). The start date of all these measures is another input assumption to the modelling, here set to 2030. As these measures are costed in the AusTIMES modelling, they are only taken up in the model when they become cost effective, which happens earlier in A40/G1.5 than in A50/G2.

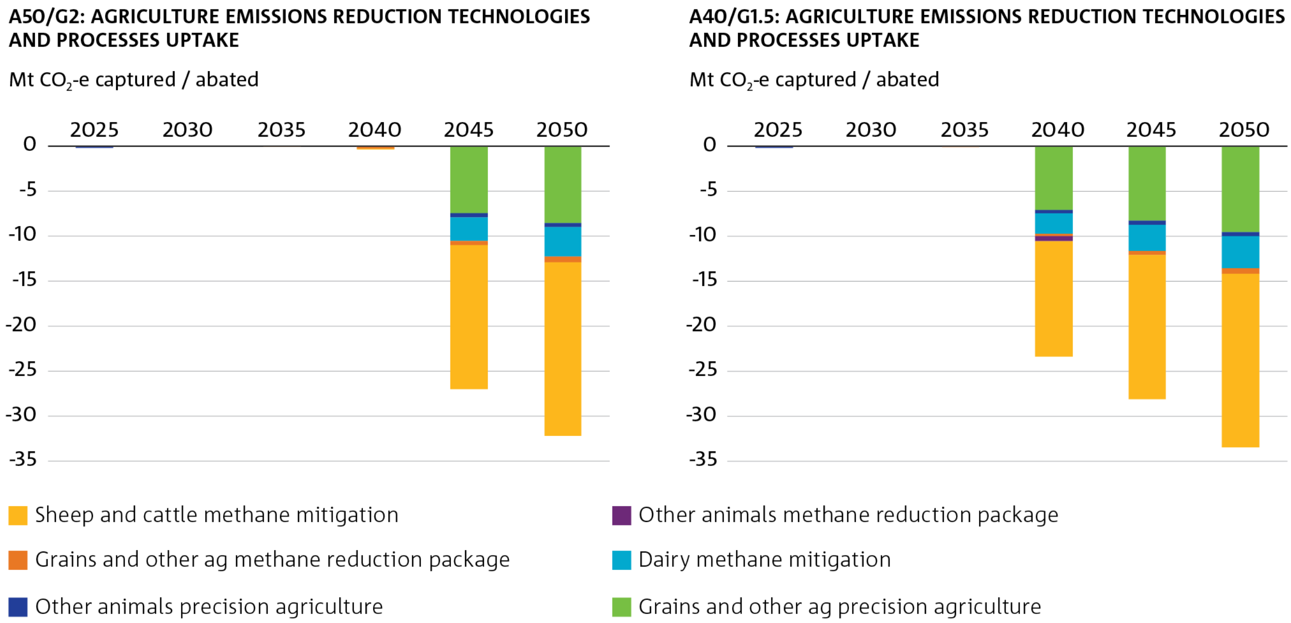

Figure 42 Agriculture emissions reductions technology and process uptake

Appendix A Technical supplement

A.1 Model framework and integration

A.1.1 The suite of models and how they are integrated

In this analysis, a multi-model approach has been tailored to downscale a combination of several IEA and IPCC scenarios to the Australian context. The approach coupled three models to derive contextualised Australian outputs:

1. **GTEM:** CSIRO's "Global Trade and Environment Model," a CGE model, is used to represent the global macroeconomic impacts in each scenario and explores how they influence Australia through international investment and trade linkages.
2. **LUTO:** The "Land Use Trade-Offs" model is a spatially detailed land use change model for rural Australia which estimates the profitability of a range of existing and potential land uses, identifies potential land use transitions over space and time, and reports on a range of outcomes including land-sector carbon sequestration.
3. **AusTIMES:** The "Australian TIMES" model, which is an Australian implementation of The Integrated MARKAL-EFOM System (TIMES) that has been developed under the IEA Energy Technology Systems Analysis Project (ETSAP)[14]. CSIRO is a Contracting Party to ETSAP and has developed an Australian version of the TIMES model (AusTIMES) in collaboration with Climateworks Centre. AusTIMES provides a view based on least cost energy, emissions and technology pathways, which details sectoral pathways of technology mix, energy mix and emissions.

CSIRO's GTEM model[15] explores transitional risk impacts globally and how these influence Australia through international linkages and trade impacts. We also consider how the carbon price and the impacts on agricultural sectors would impact on the land use change and the potential carbon planting and carbon sequestration, which is explored in LUTO 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 whole-

[14] https://iea-etsap.org/ [accessed 19 July 2022]

[15] https://research.csiro.au/ieem/gtem-c/ and as described in Cai et. al. (2015)

of-economy emissions trajectory and trading conditions drawn from GTEM, taking into account the land use change emissions drawn from LUTO.

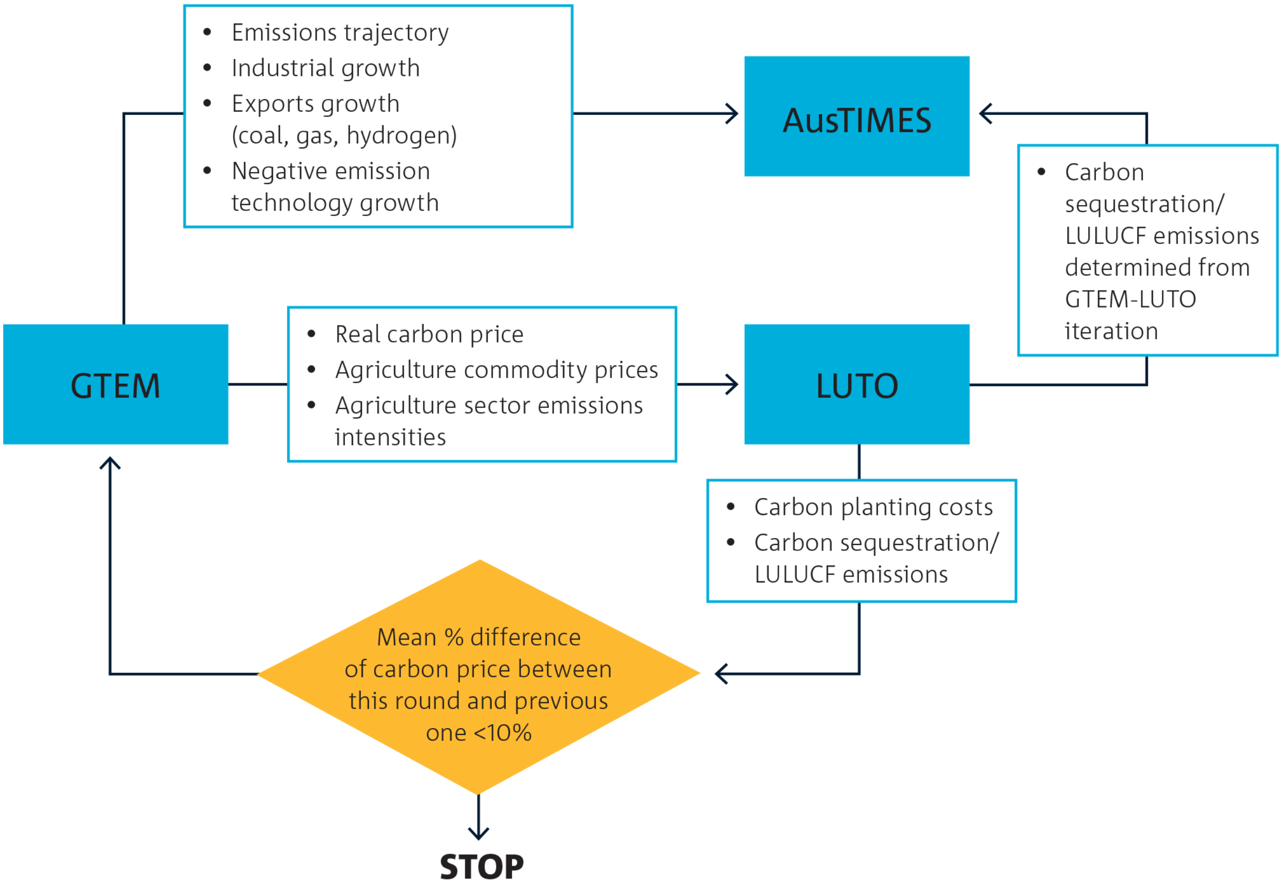

Figure 43 An overview of the interrelationship of input sources across the model suite

A.1.2 Integrated modelling

(i) 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.

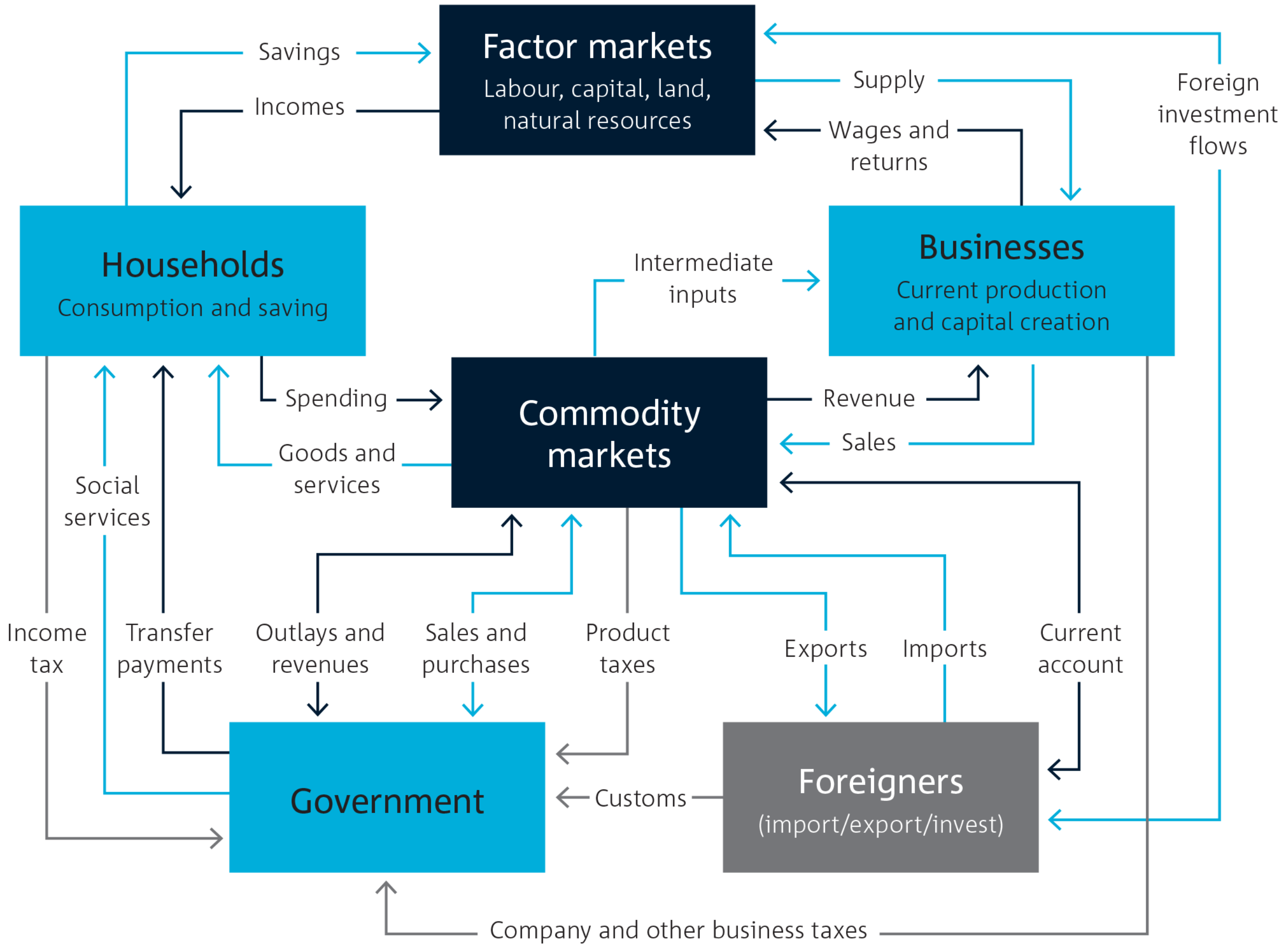

Figure 44 Interactions between agents within a given aggregate region in GTEM

Source: Whitten et al (2022).

Firms and production

<u>Technology bundle industries</u>

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 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), nine emission-free technologies (nuclear; hydro; wind; solar; biogas; other bioenergy; waste; hydrogen; and geothermal, wave and other renewables), and four low-emission technologies (carbon capture and storage for coal, oil, gas, and bioenergy).

Figure 44 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 the primary factor composite (which comprises land, labour, capital and natural resources) and technology-specific intermediate inputs. The primary composite is a CES combination of the individual primary factors). Finally, intermediate inputs used by the assembling service and each technology are CES aggregates of domestic and imported intermediate inputs. This means there is imperfect substitution between imported and domestic goods and services. 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 45). 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 (IEA, 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 46 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.

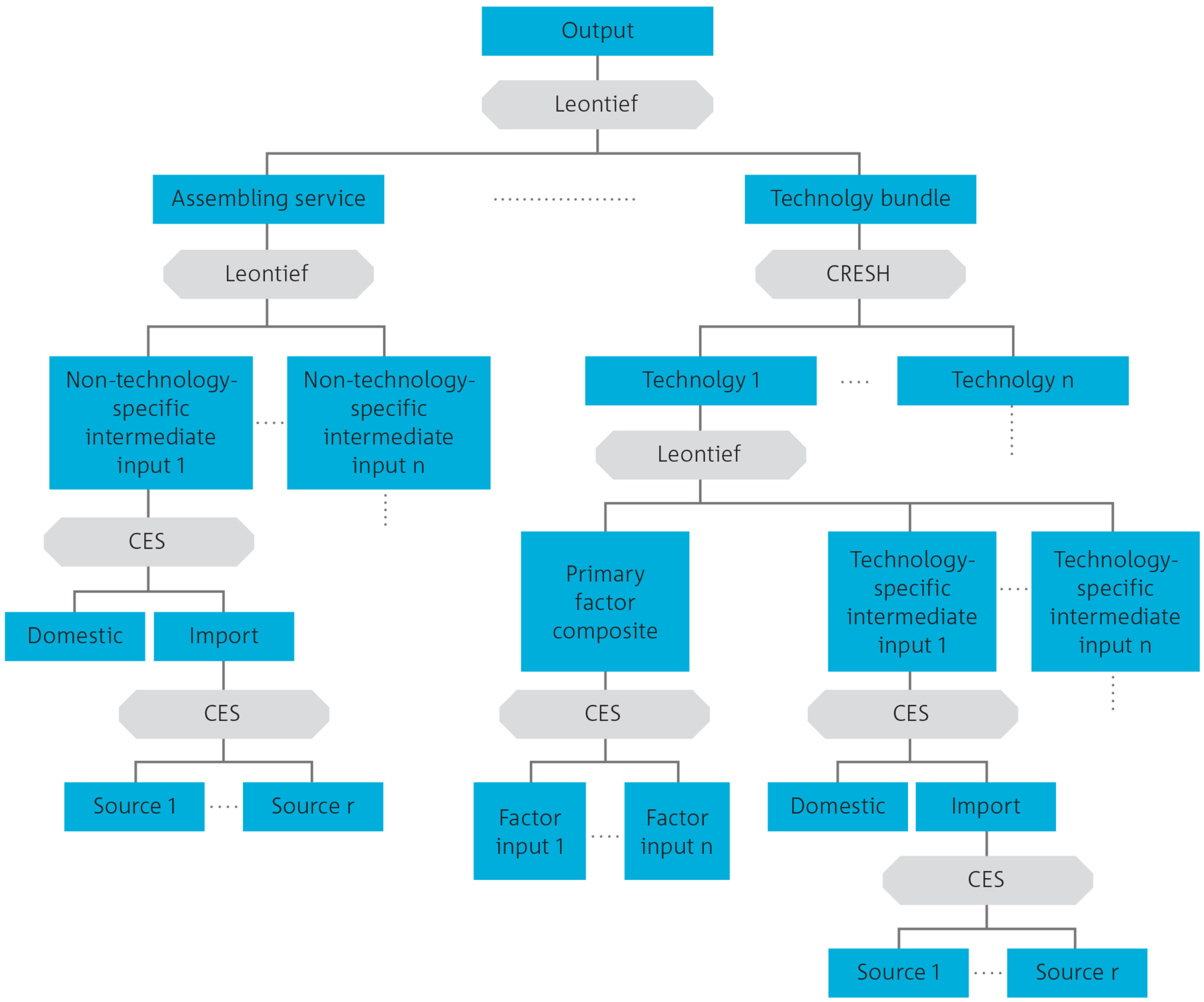

Figure 45 Production structure of a technology bundle industry

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).

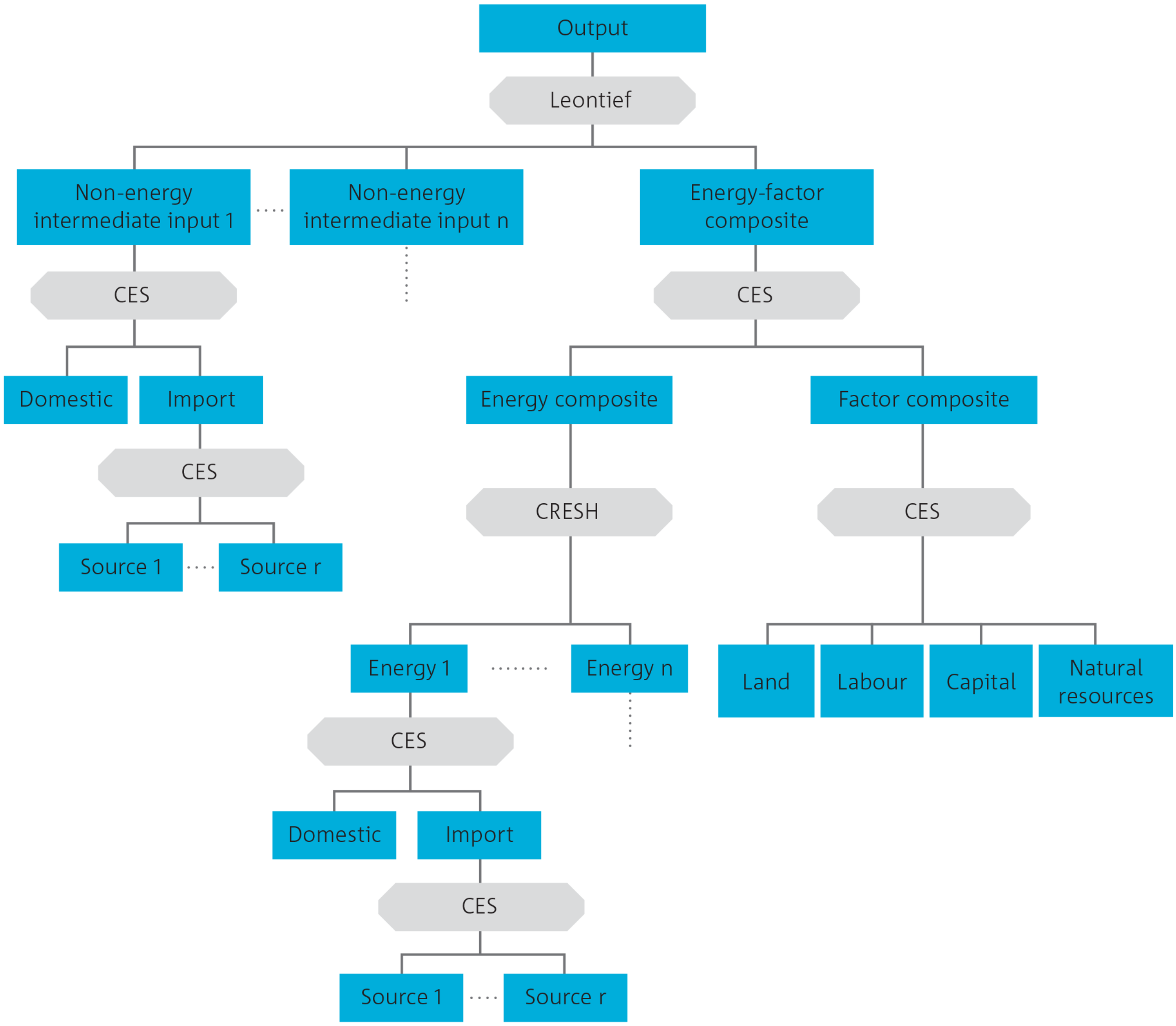

Figure 46 Production structure of a non-technology-bundle industry

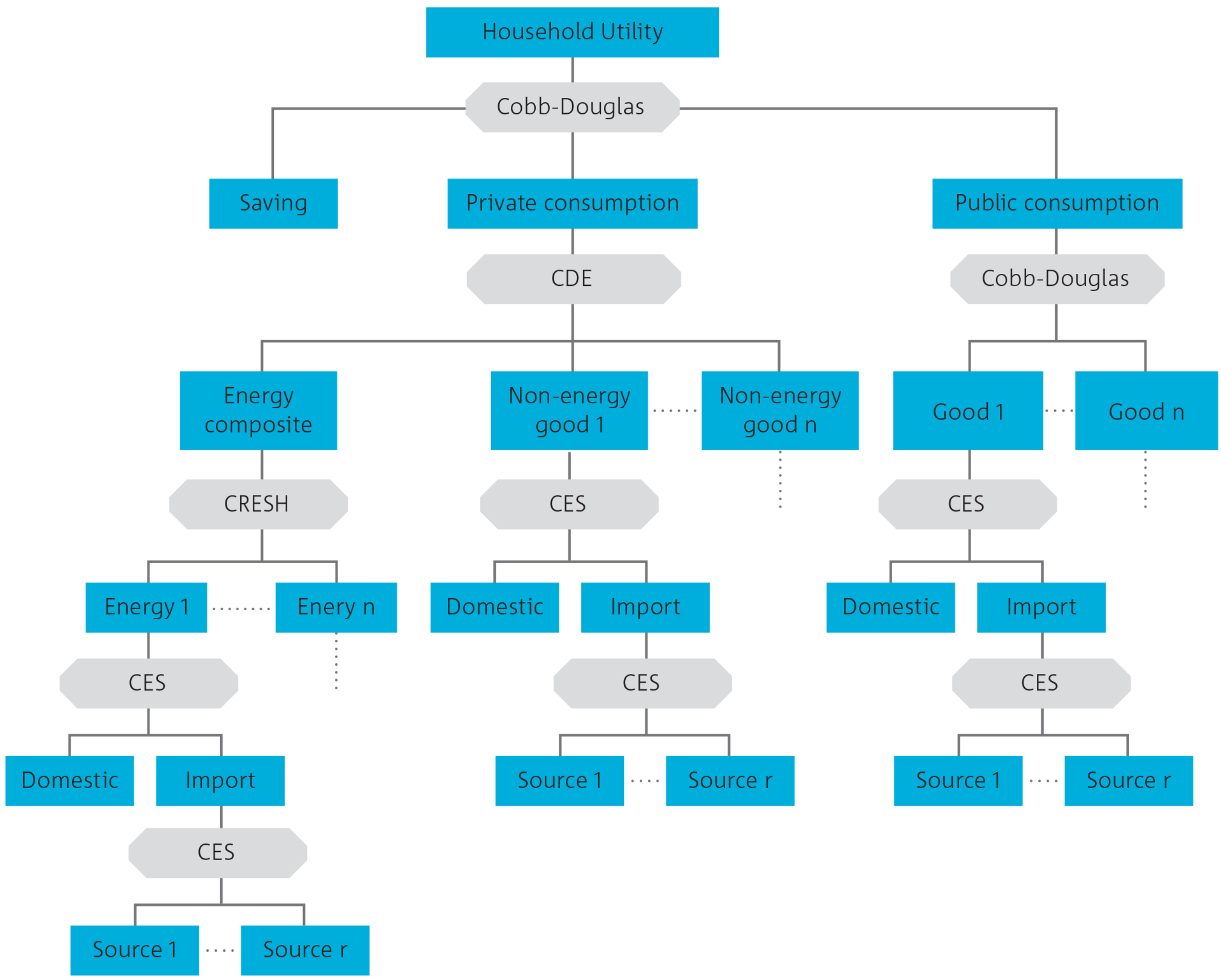

Figure 47 Utility structure of the regional household

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.

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

GTEM has a comprehensive representation of GHG emissions (i.e., CO_2, CH_4, N_2O and F-gases) and their sources. There are three broad categories of emission sources represented that relate to consumption and production: combustion-based emissions, output-based emissions and agriculture, forestry and other land use (AFOLU) emissions.

Combustion-based emissions are directly linked to fossil fuel use of the representative household and each industrial sector and their respective emission intensities, i.e., one intensity for consumption and one intensity per industrial sector per fossil fuel. 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).

There are two types of output-based emissions represented: process-based emissions (i.e., those relating to industrial processes that chemically or physically transform materials such as cement production) and fugitive emissions (i.e., the release of GHG emissions during the extraction, processing, transformation and delivery of fossil fuels to the point of final use). Output-based emissions are linked to industry output and emission intensities. The emission intensities respond to carbon-price-induced technological change drawing on Popp (2002).

AFOLU emissions are treated differently depending on the relevant activity. Combustion-based emissions by agricultural industries are treated as described above for other industries. Non-combustion GHG emissions by agricultural industries are based on the use of primary factor inputs and emission intensities. For instance, N_2O emissions from livestock are proportional to the sectoral use of capital (as a proxy for the scale of farming) and the N_2O emission intensity, and CH_4 emissions from paddy rice are proportional to the sectoral use of land (as a proxy for planting area) and the CH_4 emission intensity. The emission intensities respond to carbon-price-induced technological change drawing on Popp (2002). Forestry and other land use emissions are represented but do not respond to any model mechanism. Instead, these emissions evolve over time to reflect external information, e.g., as official projections, expert judgement or output from another model (e.g., LUTO).

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. We also have an individual hydrogen sector so that we can model how the development of hydrogen technology would impact the TB industries. 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 11). 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, 2021) and the Australian Energy Market Operator (see Integrated Assessment Plan) (AEMO, 2022b). The calibration also applies projections on emissions and TB outputs that are available from official Australian sources.

Table 3 GTEM sectoral and regional aggregation

Sectors		Regions	
1. Paddy rice	19.Food	1. Australia	19. Africa
2. Wheat	20. Other manufacturing	2. New Zealand	20. Rest of the world
3. Other Grains	21. Petroleum, coal products	3. China, Hong Kong	
4. Veg & Fruit	22. Hydrogen production	4. Japan	
5. Oil Seeds	23. Chemicals	5. South Korea	
6. Cane & Beet	24. Pharmaceuticals, rubber, plastics	6. Rest of Asia	
7. Fibre crops	25. Other mineral products	7. Indonesia	
8. Other crops	26. Iron and steel	8. India	
9. Cattle	27. Other metals	9. Canada	
10. Other animal production	28. Electricity	10. USA	
11. Raw milk	29. Gas manufacture, distribution	11. Mexico	
12. Wool	30. Water, waste	12. Rest of South America	
13. Forestry	31. Construction	13. Brazil	
14. Fishing	32. Financial, insurance services	14. EU15	
15. Coal	33. Land transport	15. EU12	
16. Oil	34. Water transport	16. Rest of Europe	
17. Gas	35. Air transport	17. Russia	
18. Other extraction	36. Other services	18. Middle East	

(ii) LUTO

The Land Use Trade-Offs model, LUTO, (Connor et al., 2015) is a spatially detailed land use change model for rural Australia which takes the Australian Bureau of Agricultural and Resource Economics and Sciences' National Land Use map (ABARES, 2010) and CSIRO's agricultural profitability mapping (Marinoni et al., 2012) as a starting point and estimates the profitability of a range of existing and potential land uses over time at an approximately 1.1 km spatial resolution. For this modelling, LUTO was run in profit maximisation mode using exogenous agricultural price paths, carbon price paths and changes in emissions intensity supplied by GTEM, the Global Trade and Environment Model. Decisions to change to the most profitable land use are made subject to capacity constraints, permanence requirements and profit thresholds.

The extent of the LUTO study area in which land use can change from current agriculture to reforestation is currently the cleared agricultural land of eastern, south-western, and southern Australia, here defined as the intensive agriculture zone. Additionally, changes in agricultural production for the extensive agricultural areas of Australia are modelled separately, applying the same assumptions regarding productivity changes and climate impacts for national reporting of change over time (Figure 48).

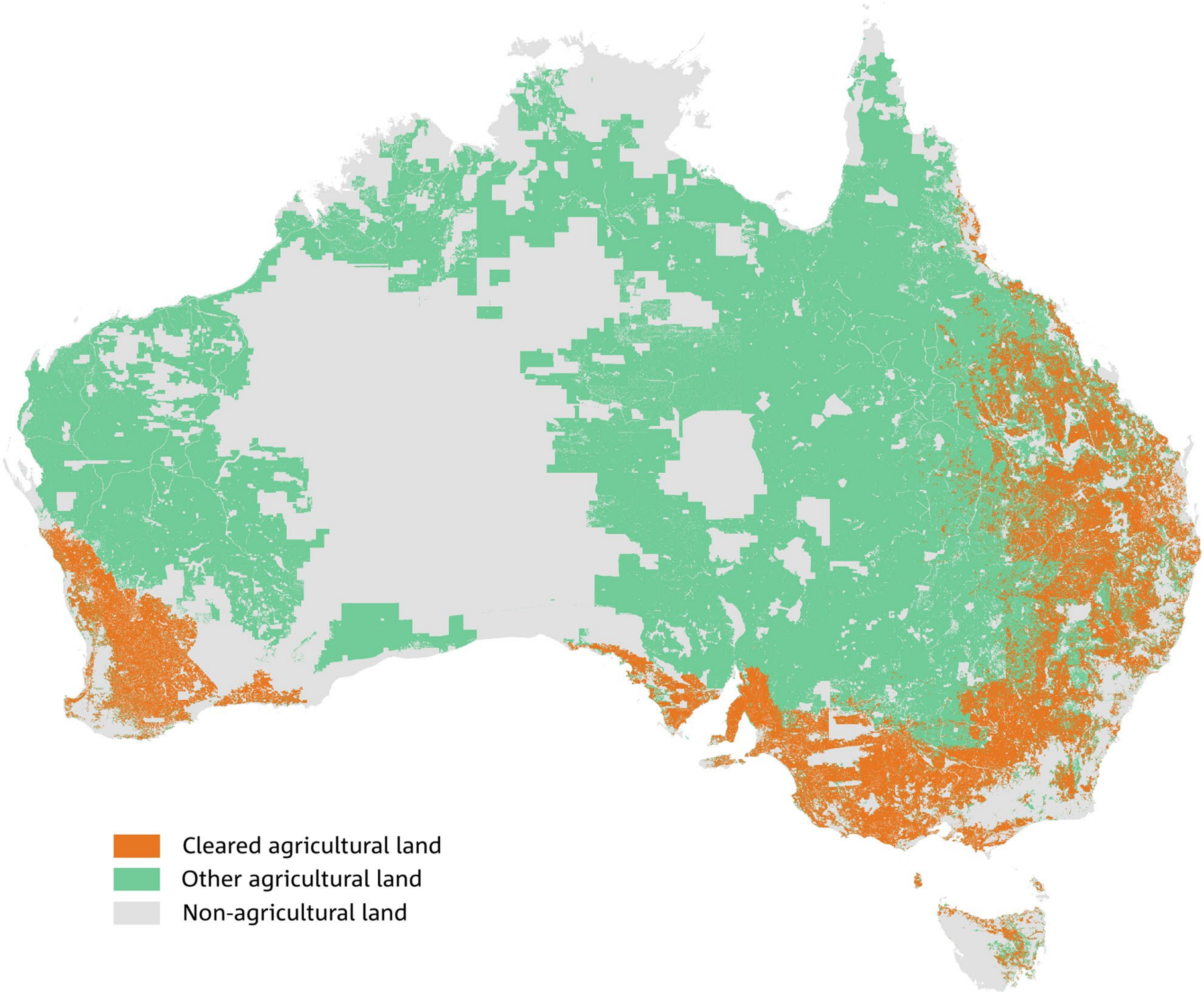

Figure 48 Agricultural zones defined for modelling

The main update from previous modelling is that LUTO now uses FullCAM (https://www.dcceew.gov.au/climate-change/publications/full-carbon-accounting-model-fullcam) to model tree growth, consistent with the Australian Carbon Credit Units (ACCU) Scheme (https://cer.gov.au/schemes/australian-carbon-credit-unit-scheme/accu-scheme-methods). This replaces the estimates of tree growth previously used in LUTO which were based on based on the 3-PG modelling used in the Joint Venture Agroforestry project (Polglase et al, 2008). The two land uses modelled with FullCAM in LUTO are environmental plantings and mallee plantings.

The mallee plantings land use is a monoculture plantation funded by a carbon price. Environmental plantings can be funded by a carbon price or a combination of carbon price and biodiversity incentive. Spatial biodiversity priorities are identified using a Generalized Dissimilarity Model (Ferrier, 2007) with higher biodiversity priority areas increasing the representation of plant communities. Higher biodiversity priority areas are targeted for funding through the annual distribution of a biodiversity fund, with the fund used to pay for the gap between the most profitable land use and carbon returns from environmental plantings at a location thus increasing the biodiversity benefit of land use change. The fund increases from $200m in 2025 to just under $1bn in 2050. The biodiversity fund was used as a modelling mechanism to help achieve around 30% biodiversity plantings. To further improve biodiversity outcomes only environmental plantings were allowed in bioregions (Department of Agriculture, Water and the Environment,

2020) with less than 30% of pre-settlement native vegetation cover (Figure 49) which was calculated using the pre-European vegetation layer from the NVIS (NVIS, 2020).

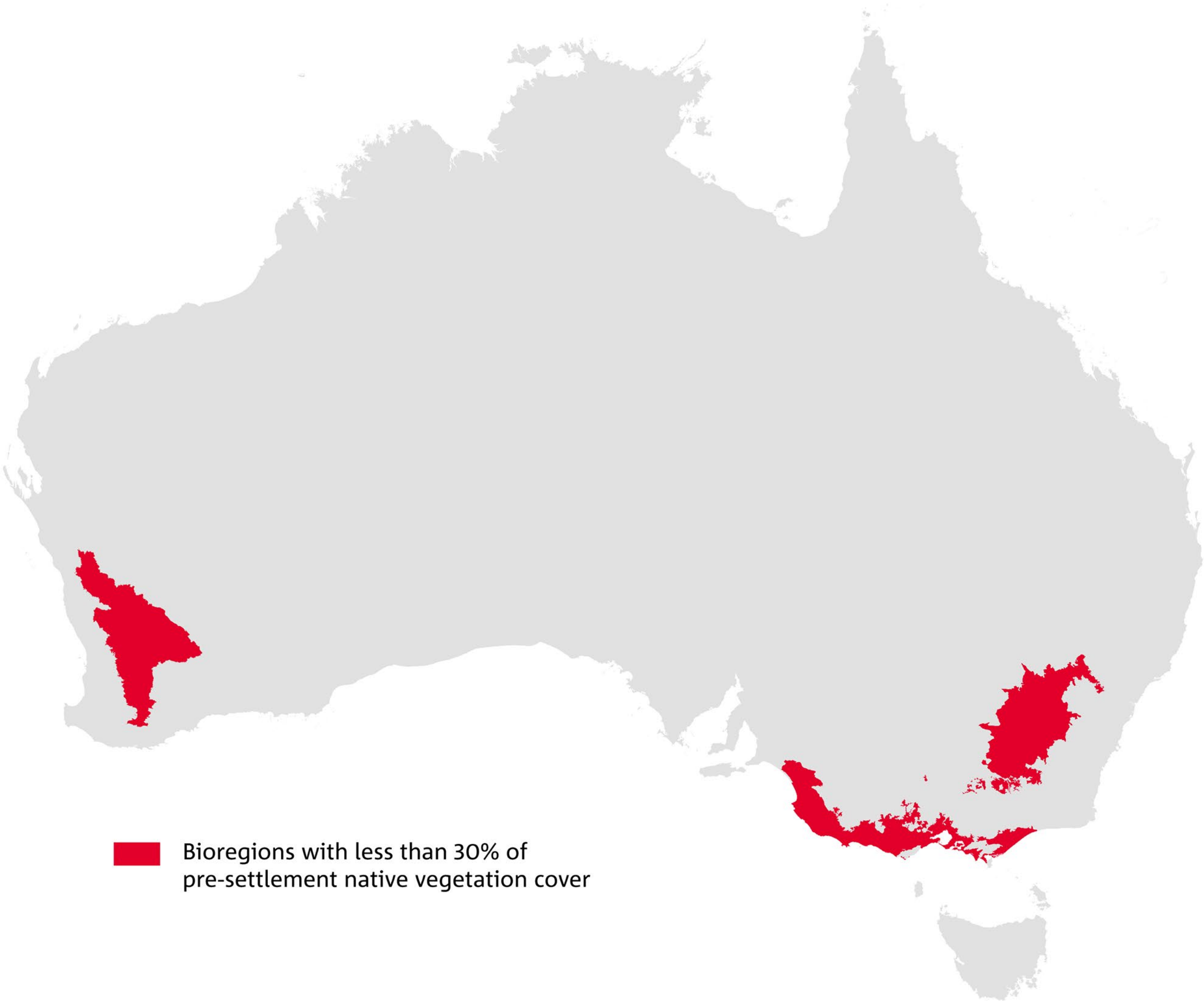

Figure 49 Bioregions where only environmental plantings allowed

Decisions to move to new land use are based on their profitability relative to the profitability of the agricultural land use at each location. Profitability of plantations is calculated as the annualised net present value of revenue from annual payments for carbon sequestered using the carbon price at the year of establishment and taking into account establishment and annual management costs. A discount rate of 7% was used. As with previous modelling, hurdles to adoption of new land uses were implemented using a profit threshold. A conservative 5x hurdle rate was used, the new land use must be five times or more profitability than agriculture at a location before land use will change and is a means for accommodating delays in the uptake of the new land use due to landholder hesitancy. Once planted, a 100-year permanence period is assumed and a 5% risk of reversal buffer consistent with the Emissions Reduction Fund scheme reduces creditable sequestration to counter risks of carbon reversal that may occur from fire or other natural disturbances.

A major impact on uptake of plantations is the annual capacity for the supply of seedlings and labour required for carbon and biodiversity plantations. An initial area constraint which restricted the total annual area of plantations to no more than 22,500 ha was used to address this plantings capacity constraint. Once this area was planted in one year the capacity then increases gradually to a final cap of 260,000 ha per year. A further area constraint was used to achieve approximately 30% of area planted to environmental plantings.

A 1.5% p.a. increase in cropping productivity and horticulture productivity was assumed based on the 30-year average of climate-adjusted cropping productivity improvements, as reported by ABARES (https://www.agriculture.gov.au/abares/research-topics/productivity/agricultural-productivity-estimates). No productivity increases for cattle and sheep were assumed in order to achieve a livestock density no greater than it was at the time of the 2005-06 land use survey. A 0.2% increase in tree productivity was also assumed.

Consistent with the Long-Term Emissions Reduction Plan analysis (https://www.dcceew.gov.au/sites/default/files/documents/australias-long-term-emissions-reduction-plan-modelling.pdf) a water policy targeting stressed catchments was implemented. A cap-and-trade mechanism similar to Connor et al. (2016) has been implemented to cap total water use in water-stressed catchments. The cap on water use was applied to Class C and D catchments as identified by the National Water Commission (2012), defined in Table 4, and mapped in Figure 50. The cap operates as follows:

1. Current total agricultural water use for a stressed catchment is calculated and used as the basis for the cap for that catchment.
2. Plantations and agriculture within a catchment then compete for this water. A location will only switch to carbon plantings if carbon plantings is more profitable at that location and an equivalent amount of water is displaced from irrigated agriculture at the same or other locations within the catchment.
3. If those conditions hold then land use will switch from agriculture to carbon plantings at the location and the irrigated agriculture will change to non-irrigated agriculture, being dryland sheep.

Monoculture and environmental plantings in rainfall areas greater than 600mm in these catchments were required to purchase a water license, with prices adapted from Burns et al (2011). Assumed cost of license was updated with recommendations from ABARES (pers. comm).

Table 4 Characteristics of categories of water stress from the National Water Commission

Category	Classification	Characteristics
C	Highly water stressed relative to other systems	• Likely high level of development and/or water regime change • Likely moderate risk of overuse/overallocation • Likely moderate to high risk of compromising environmental assets, ecosystem functions or the long-term sustainability of the resource
D	Most water stressed	• Likely very high level of development and/or water regime change • Likely high risk of overuse/overallocation • Likely high risk of compromising environmental assets, ecosystem functions or the long-term sustainability of the resource

Source: National Water Commission (2012, p. xiii)

Catchment	Label	Catchment	Label
BARRON RIVER	A	AVOCA RIVER	O
BURNETT RIVER	B	LODDON RIVER	P
BRISBANE RIVER	C	CAMPASPE RIVER	Q
PINE RIVER	D	GOULBURN RIVER	R
CONDAMINE-CULGOA RIVERS	E	THOMSON RIVER	S
GWYDIR RIVER	F	GLENELG RIVER	T
DARLING RIVER	G	MOORABOOL RIVER	U
MACQUARIE-BOGAN RIVERS	H	WERRIBEE RIVER	V
HAWKESBURY RIVER	I	YARRA RIVER	W
LACHLAN RIVER	J	LATROBE RIVER	X
MURRUMBIDGEE RIVER	K	BUNYIP RIVER	Y
MURRAY-RIVERINA	L	LOWER MURRAY RIVER	Z
UPPER MURRAY RIVER	M	WARREN RIVER	AA
SNOWY RIVER	N		

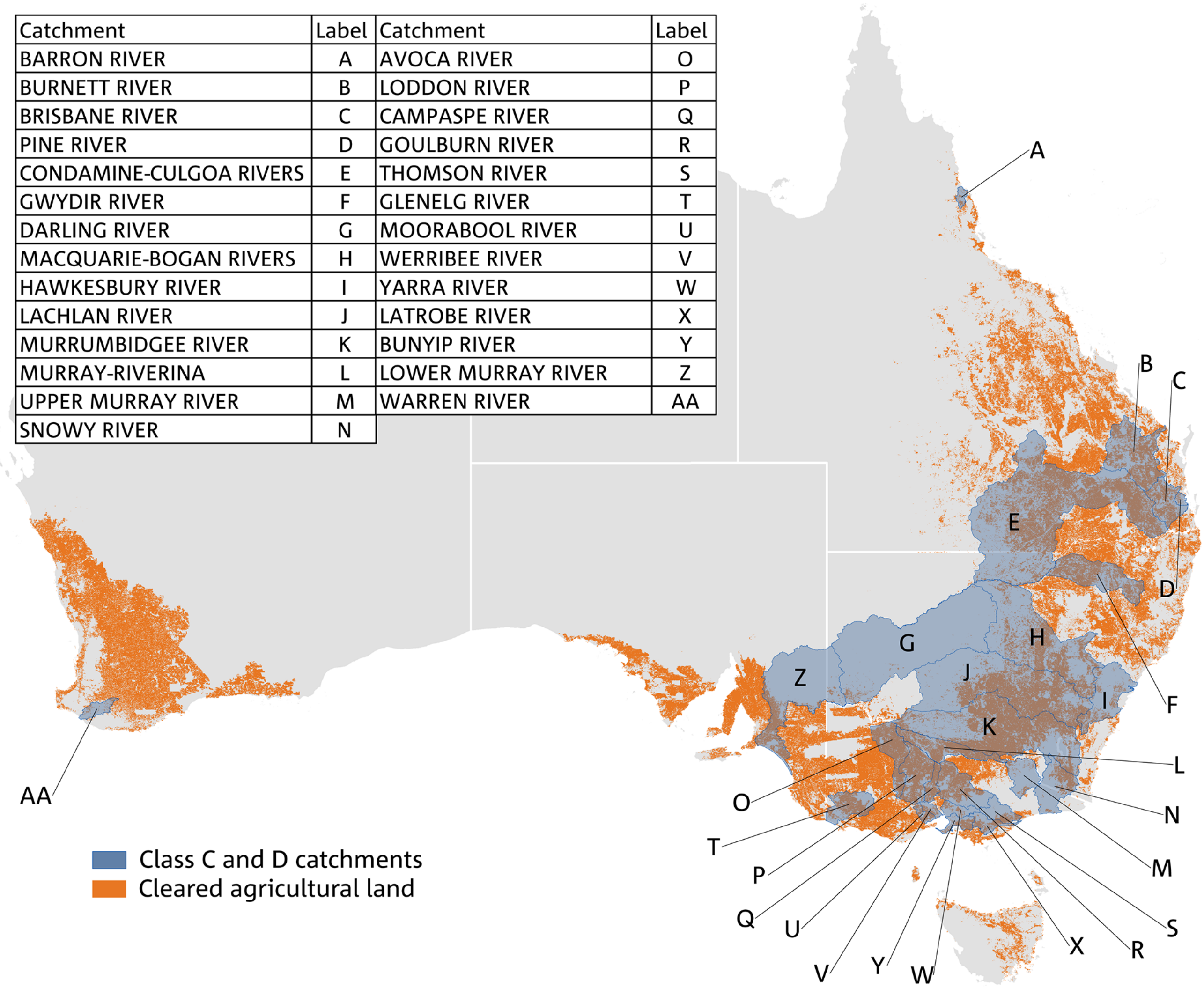

Figure 50 Water-stressed catchments

GTEM-LUTO integration

Figure 43 briefly illustrated the iteration process between GTEM and LUTO. GTEM was initially run for each scenario, producing agricultural price paths, carbon price paths and changes in emissions intensity which were used as exogenous inputs to LUTO for estimating future annual profitability of agriculture and reforestation land uses. Outputs of annual land-sector sequestration and costs of sequestration achieved from the initial LUTO model run were fed back into GTEM to inform the global model of the impacts of a carbon price on land use change, and the resulting sequestration achieved, in Australia, resulting in changes in annual carbon and agricultural price outputs from GTEM. These updated GTEM price paths were then used in LUTO. This iterative process of outputs exchange from GTEM-to-LUTO and LUTO-to-GTEM was continued until a convergence in carbon price was achieved. For this modelling exercise convergence was defined as a less than 10% mean absolute difference in annual carbon price for the 2041-2050 period between iterations for each scenario. Once convergence was achieved, LUTO was run with the final GTEM outputs.

(iii) AusTIMES

CSIRO implemented the six specified scenarios in the AusTIMES model for the authority's sectoral pathways to net-zero emissions. AusTIMES, an Australian implementation of 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 Centre.

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 (https://iea-etsap.org/index.php/documentation).

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

Partial equilibrium modelling 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).
- End-use sectors include agriculture (8 sub-sectors), mining (11 sub-sectors), manufacturing (21 sub-sectors), other industry (5 sub-sectors), commercial and services (7 building types), residential (3 building types), road transport (10 vehicle segments) and non-road transport (aviation, rail, shipping).
    - Each sector has information regarding energy consumption and assumed efficiency gains, as well as options regarding which primary energy sources can be consumed, additional costed fuel switching or efficiency improvements, options for avoiding non-energy emissions and potential for carbon capture and storage (CCS).
- Representation of fuel types across the end-use sectors:
    - Industry and agriculture: Oil (mainly diesel), black coal, brown coal, natural gas, hydrogen, biomethane, electricity and other bioenergy (e.g., bagasse in existing applications, biodiesel)
    - Residential buildings: Natural gas, liquid petroleum gas, hydrogen, biomethane, wood, and electricity
    - Commercial buildings: Oil (as reported in Australian Energy Statistics), natural gas, hydrogen, biomethane, and electricity
    - Transport: oil (mainly petrol, diesel, kerosene, fuel oil), biofuels (ethanol, biodiesel), liquid petroleum gas, natural gas, electricity, and hydrogen.
- Detailed representation of the electricity sector (see below).

- 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.
- Detailed representation of the end-use sectors (see below).

Model calibration and inputs

The AusTIMES model for this study has been calibrated to a base year of 2021 based on the latest state/territory level energy balance (DCCEEW, 2022b), national inventory of greenhouse gas emissions (DCCEEW, 2022a), stock estimates of vehicles in the transport sector (ABS, 2021b), data on the existing power generation fleet (AEMO, 2022a) data source for Western Australia (WA Government, 2020) and installed capacity of distributed generation (Graham and Mediwaththe, 2022). The economic activity, population growth, distributed energy resources, capital costs of generation technologies, projected uptake of DER (i.e., rooftop solar PV, behind-the-meter batteries), and projected road and non-road transport demand, electric and fuel cell vehicle uptake for road transport, and minimum electrification of non-road transport (i.e., rail and aviation) are sourced from various sources.

Objective function

TIMES is formulated as a linear optimisation 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.

While minimizing total discounted cost, the model must satisfy many constraints which express the physical and logical relationships that must be satisfied to properly describe the energy system. Details on these constraints are available in Part I of the TIMES model documentation (ETSAP, 2016).

Decarbonisation objectives in AusTIMES

The implementation of decarbonisation objectives in AusTIMES has several options:

- Implementing an annual carbon price trajectory per scenario that results in sufficient emissions reduction to meet the scenario objective.
- Implementing annual net emission target/s which represent the desired pathway.
- Implement a point target (usually at the net zero year) and a carbon budget to be consumed across all years prior to the net zero year.

The modelling for the scenarios in this report utilised the second option by specifying net emissions targets for each year, together with maximum constraints which impose Australian Government commitments under the Paris Agreement.

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.
- 33 new electricity generation and storage technologies: black coal pulverised fuel; black coal with CO_2 capture and sequestration (CCS); brown coal pulverised fuel; brown coal with CCS; combined cycle gas turbine (CCGT); open-cycle gas turbine (OCGT); gas CCGT with CCS; gas reciprocating engine; biomass; biomass with CCS; pumped storage hydro (PSH) with 8 hours 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); large-scale concentrated solar thermal (CST) with 8 hours of storage; residential rooftop solar PV; commercial rooftop solar PV; hot fractured rocks (enhanced geothermal); conventional geothermal; wave; tidal; hydrogen reciprocating engine; diesel reciprocating engine; small modular nuclear reactor; grid battery with 1 hour of storage; grid battery with 2 hours of storage; grid battery with 4 hours of storage; grid battery with 8 hours of storage; residential battery; commercial battery.

End-use sectors

Industry

The industry sector disaggregated into a number of sub-sectors which are classified based on the Australian and New Zealand Standard Industrial Classification (ANZSIC) 2006 divisions. The mapping of AusTIMES to ANZSIC industry subsector is listed the following table.

Table 5 Mapping of AusTIMES to ANZSIC (2006) industry subsectors

Aus-TIMES subsector (industry)	ANZSIC (2006) codes	ANZSIC Division
Industry - Coal mining	06	Division B
Industry - Oil mining	07 (part)	Division B
Industry - Gas mining	07 (part)	Division B
Industry - Iron ore mining	0801	Division B
Industry - Bauxite mining	0802	Division B
Industry - Lithium mining	0809 (part)	Division B
Industry - Copper mining	0803	Division B
Industry - Nickel mining	0806	Division B
Industry - Zinc mining	0807	Division B
Industry - Other non-ferrous metal ores mining	0804, 0805, 0809 (part)	Division B
Industry - Other mining	09	Division B
Industry - Meat products	111	Division C
Industry - Other food and drink products	112, 113, 114, 115, 116, 117, 118, 119	Division C
Industry - Textiles, clothing and footwear	13	Division C
Industry - Wood products	14	Division C
Industry - Paper products	15	Division C
Industry - Printing and publishing	16	Division C
Industry - Petroleum refinery	17	Division C
Industry - Ammonia	181 (part)	Division C
Industry - Fertilisers	1831	Division C
Industry - Explosives	1892	Division C
Industry - Other chemicals	181 (part), 182, 183 (part), 185, 189 (part)	Division C
Industry - Rubber and plastic products	19	Division C
Industry - Non-metallic construction materials (not cement)	201, 202, 209	Division C
Industry - Cement	203	Division C
Industry - Iron and steel	211	Division C
Industry - Alumina	2131	Division C
Industry - Aluminium	2132	Division C
Industry - Other non-ferrous metals	2133, 2139	Division C
Industry - Other metal products	212, 214, 22	Division C
Industry - Motor vehicles and parts	231	Division C
Industry - Other manufacturing products	239, 24, 25	Division C
Industry - Gas supply	27	Division D
Industry - Gas export (LNG)	07 (part)	Division B
Industry - Water supply	28	Division D
Industry - Construction services	30, 31, 32	Division E
Industry - Waste	29	Division D
Industry – Refrigeration and Air Conditioning	32	Division E

Baseline energy use in industry is disaggregated by subsector and fuel type which include black coal, brown coal, bioenergy, oil, natural gas, electricity, hydrogen and biomethane.

Growth in industry subsectors in AusTIMES is derived from various sources, including

- Projections of sectoral activity derived from CSIRO’s GTEM model.
- Assumptions at the asset level for alumina, aluminium, steel, and petroleum refining facilities.

- Recent trends reflecting changes in energy consumption by sector, drawing upon historical data from the Australian Energy Statistics published by the Department of Climate Change, Energy, the Environment and Water (DCCEEW, 2022b).

AusTIMES can implement energy efficiency, electrification, and fuel switching 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.

Coal fugitive abatement technologies were sourced from unpublished analysis by Ernst & Young using the EY Net Zero Centre model of the Australian joint SGM-ACCU carbon market (EY Net Zero Centre, 2023).

Hydrogen and biomethane uptake in industry is implemented endogenously to service end-uses through pipeline blending with natural gas. In this case, and similar to natural gas, hydrogen, and biomethane are categories of fuel available to these end uses. AusTIMES can make the decision to switch natural gas demand to hydrogen and/or biomethane if it is economically attractive based on costs of fuels involved and the carbon price. The fuel cost of hydrogen and biomethane is determined through optimisation of investment in fuel production capacity and operation to deliver fuels to end-uses at the lowest cost.

Assuming hydrogen and biomethane replaces natural gas with existing pipeline infrastructure, the capital cost of switching from natural gas to hydrogen technologies are not considered. Costs associated with upgrading gas network infrastructure to accept high blends of hydrogen and/or biomethane are also not considered. It is therefore necessary to explicitly set a limit on blended hydrogen or biomethane in the gas network in modelled scenarios. Where that limit is assumed to be higher than currently understood upper limits, any costs associated with reaching that limit are not considered by the objective function.

In addition to hydrogen and or biomethane blended via the gas supply network, it is assumed that some subsectors may have access to a direct supply of hydrogen that could replace larger portions of natural gas use. This is particularly true for subsectors that may be very large natural gas users or may currently be using natural gas as a feedstock to produce hydrogen. The subsectors affected are Alumina, Ammonia, Fertilisers, Explosives, Other chemicals, Iron and steel, and Petroleum refining. More restricted use cases for a direct supply of hydrogen are available in metal ore mining subsectors and Gas Export.

Agriculture

In AusTIMES, the agriculture sector is represented as a subset of industry. Energy use in agriculture is minimal although non-energy emissions are significant. The mapping of AusTIMES to ANZSIC industry subsectors is displayed below (Table 6).

Table 6 Mapping of the AusTIMES to ANZSIC agriculture subsectors

Aus-TIMES subsector (agriculture)	ANZSIC (2006) codes	ANZSIC Division
Agriculture - Sheep and cattle	0141, 0142, 0143, 0144, 0145 (part)	Division A
Agriculture - Dairy	016	Division A
Agriculture - Other animals	017, 018, 019	Division A
Agriculture - Grains	0145 (part), 0146, 0149, 015	Division A
Agriculture - Other agriculture	011, 012, 013	Division A
Agriculture - Agricultural services and fishing	02, 04, 052	Division A
Forestry - Forestry and logging	03, 051	Division A

Growth in agriculture subsectors in AusTIMES is derived from various sources, including:

- Projections of sectoral activity derived from CSIRO's GTEM model.
- Recent trends reflecting changes in energy consumption by sector, drawing upon historical data from the Australian Energy Statistics published by the Department of Climate Change, Energy, the Environment and Water (DCCEEW, 2022b).

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

Transport

The transportation sector is divided into two main components: road and non-road transport. AusTIMES provides an extensive overview of road transport, categorised into six sub-categories: motorcycles, passenger vehicles, light commercial vehicles, rigid trucks, articulated vehicles, and buses. The range of assumptions made for the road transport sector relate to vehicle stock (ABS, 2021b), average vehicle kilometres travelled (ABS, 2020), vehicle energy efficiency improvement (Graham, 2022), uptake of alternate vehicle technologies, internal combustion vehicle availability and retirement, biofuel availability and production costs (Butler et al., 2021), oil price projections (Lewis Grey Advisory, 2022), National Greenhouse Account (NGA) emission factors for fuel (DCCEEW, 2023), economic and population growth (ABS), registration and insurance costs (state/territory government websites), and vehicle maintenance costs. The delivery price of electricity and hydrogen for road transport is endogenously determined within AusTIMES. The road transport segments, vehicle types and fuel categories are listed below (Table 7).

Table 7 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

In AusTIMES, the representation of non-road transport is less detailed and is based on fuel types, encompassing rail, aviation, and shipping modes. The key inputs for this mode of transport include fuel consumption (BITRE, 2019; DCCEEW, 2022b), NGA emissions factor for fuel (DCCEEW, 2023), economic and population growth (ABS), oil price projections (Lewis Grey Advisory, 2022), assumptions regarding activity and fuel efficiency improvements) (Graham, 2022), and production costs on biofuels (Butler et al., 2021). The delivery price of hydrogen for aviation and shipping is endogenously determined within the AusTIMES. The non-road transport market segments and fuel categories are listed below (Table 8).

Table 8 Non-road transport market segments and fuels

Market segments	Fuels
Rail	Diesel Electricity Biofuel Hydrogen
Aviation – domestic	Avgas Kerosene Biofuel Electricity Synthetic kerosene Hydrogen
Shipping – domestic	Fuel oil Diesel Biofuel Hydrogen

Buildings

The building sector includes both residential housing and commercial buildings. The stock of residential buildings is sourced from the Residential Buildings Baseline Study (DISER, 2022), 2021 ABS Census on number of dwellings, by state (ABS, 2021a), 2016 ABS household and family projections (ABS, 2019), Australian Energy Statistics (DCCEEW, 2022b) and the Low Carbon High Performance Report (ClimateWorks Australia, 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. Energy efficiency and electrification rates are consistent across all six scenarios to align with the level of ambition outlined in each scenario narrative.

The residential building types, end-use service demands, and fuel types are listed below (Table 9).

Table 9 Residential building types, end-use service demands and fuel types

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

All residential buildings experience an autonomous efficiency improvement at no cost. Additional endogenous 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* (ClimateWorks Australia, 2016).

Hydrogen and biomethane uptake in residential buildings is modelled as a category of fuel available for pipeline blending with natural gas. AusTIMES can make the decision to switch natural gas demand to hydrogen or biomethane if it is economically feasible based on the costs of fuels involved and the carbon price.

The fuel cost of hydrogen and biomethane is determined through optimisation of investment in their production capacity and operation to deliver these fuels to end-uses at least cost. Assuming hydrogen and/or biomethane replaces natural gas with existing pipeline infrastructure, the capital cost of switching from natural gas to hydrogen technologies is not considered. Costs associated with upgrading the gas supply network to receive higher blends of hydrogen and/or biomethane are also not considered.

The stock of commercial buildings is sourced from the Commercial Buildings Baseline Study (DCCEEW, 2022c), Australian Energy Statistics (DCCEEW, 2022b), and the Low Carbon High Performance Report (ClimateWorks Australia, 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.

The commercial building types, end-use service demands, and fuel types are listed below (Table 10).

Table 10 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
Office	Water heating	Biomethane
Public building	Appliances	Oil
Retail	Lighting	Hydrogen
School	Equipment	
Aged care		

Similar to residential buildings, all commercial buildings undergo an autonomous efficiency improvement at no cost. Additional endogenous 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* (ClimateWorks Australia, 2016).

Hydrogen and biomethane uptake in commercial buildings is modelled as a category of fuel available for pipeline blending with natural gas. AusTIMES can make the decision to switch natural gas demand to hydrogen or biomethane if it is economically feasible based on the costs of fuels involved and the carbon price.

The fuel cost of hydrogen and biomethane is determined through optimisation of investment in their production capacity and operation to deliver these to end-uses at least cost. Assuming hydrogen and/or biomethane replaces natural gas with existing pipeline infrastructure, the capital cost of switching from natural gas to hydrogen technologies is not considered. Costs associated with upgrading the gas supply network to receive higher blends of hydrogen and/or biomethane are also not considered.

A.2 Model settings and calibration

A.2.1 Model settings

As mentioned in Section 1.1, the two scenarios analysed in this report are based on different global and domestic assumptions. The CSIRO Stated Policies (CSP) scenario is the ultimate baseline for all scenarios modelled here. The CSP scenario was developed in Brinsmead et al. (2023); it is based on stated policies internationally and within Australia and projects a 2.6°C temperature increase by 2100. It was developed to translate the IEA's Stated Policies Scenario (STEPS) (International Energy Agency, 2021) to an Australian context.

To the CSP scenario we add global assumptions to construct G1.5 and G2 based on CSP scenario to reflect different global environments. But under G1.5 and G2 we do not specify any particular constraints for Australia while in the domestic scenarios Australia's constraints and policies are specified and imposed based on G1.5 or G2.

The tables below list important assumptions made in applying GTEM, LUTO 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.

Table 11 Treatment of key variables in GTEM

Variable	CSP scenario	G1.5 scenario	G2 scenario
Macroeconomic variables	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 National Institute Global Econometric Model (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 (IEA, 2021a)	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 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
GHG shadow price	US$10 in low-income regions and US$20 in high-income regions in 2021	Endogenously responds to emissions targets	Endogenously responds to emissions targets
Emissions	Global and selected regional CO_2 emissions pathways via shifts in emission intensity Global CO_2 emissions pathways for selected industries – basic chemicals, iron and steel, land transport, water transport, and air transport are from IEA Stated Policies scenario in *IEA World Energy Outlook 2021* Global and regional AFOLU greenhouse gas emissions pathways are from GLOBIOM (Frank et al., 2021), For Australia, use Australia's *NGGI*'s 2023 June Quarterly Update for calibrating the historical emissions till 2023 and using DCCEEW's *2023 Australian Emissions Projections* for the period of 2024-2035. For Australia's LULUCF emissions, keep it flat after 2035 but for other emissions, no constraints are put.	Consistent with IMP-Ren scenario carbon budget in the *IPCC sixth Assessment Report*: Global net GHG emissions budget of 827 Gt CO_2-e	Consistent with IPCC IMP-GS scenario's carbon budget the *IPCC sixth Assessment Report*: Global net GHG emissions budget of 1,110 Gt CO_2-e
Electricity output and technology mix	Global and regional electricity output pathways Global electricity technology mix pathway Source: IEA Stated Policies scenario from *IEA World Energy Outlook 2021* Australia's electricity output and technology mix pathway is consistent with AusTIMES' latest projection Source: AusTIMES (CSIRO)	Global electricity output pathway Global electricity technology mix pathway Source: IEA NZE scenario from *IEA World Energy Outlook 2021*	Global electricity output pathway Global electricity technology mix pathway Source: IEA APS scenario from *IEA World Energy Outlook 2021*
Fossil fuel output	Global coal, oil and gas output pathways from IEA Stated Policies scenario *(IEA WEO, 2021)*	Global coal and gas output pathways from IEA NZE scenario *(IEA WEO, 2021)*	Global coal and gas output pathways from IEA APS scenario *(IEA WEO, 2021)*
Energy efficiency	1.5% annual energy efficiency improvement for households and firms	1.5% annual energy efficiency improvement for households and firms	1.5% annual energy efficiency improvement for households and firms

Variable	CSP scenario	G1.5 scenario	G2 scenario
	Extra 0.5% annual energy efficiency improvement for iron and steel, non-ferrous metals, and all transport sectors	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	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

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 11 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.1.2. In G1.5 and G2 scenarios, emissions quotas were also applied within the overall global emissions budget to reflect the principle of common but differentiated responsibility between countries.

Table 12, Table 13 and Table 14 indicate that electricity technology targets are applied in the CSP and G1.5 and G2 scenarios. The targets are applied via equiproportional shifts in the regional supply curves for each technology. Thus, the CRESH parameter controlling substitution across electricity technologies discussed in section A.1.2 operates conditional on these supply curve shifts and not independently of them.

Table 12 IEA targets (STEPS scenario from *IEA World Energy Outlook 2021*) applied in the 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

Table 13 IEA energy targets (NZE scenario from *IEA World Energy Outlook 2021*) applied in the G1.5 scenario

	2020	2030	2040	2050
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
Hydrogen	0	21.4	49.2	69.7
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
Hydrogen and ammonia	0	875	1,857	1,713
Carbon capture use and storage (Mt CO_2-e)				
Fossil fuels and processes	39	1,325	na	5,650
Direct air capture	0	70	na	630
Bioenergy	1	255	na	1,475

Table 14 IEA energy targets (APS scenario from *IEA World Energy Outlook 2021*) applied in the G2 scenario

	2020	2030	2040	2050
Energy supply (EJ)				
Coal (unabated + CCUS)	155.8	141.5	113.5	102.2
Oil	171.4	185.1	162.4	147.6
Natural gas (unabated + CCUS)	139.1	146.5	136.1	133.2
Hydrogen	0	2.5	13.7	22.7
Electricity generation (TWh)				
Global	27,262	34,532	45,744	54,772
Electricity technology mix (TWh)				
Coal	9,467	7,926	5,779	3,047
Oil	716	450	361	291
Natural gas	6,257	6,522	5,488	5,691
Wind	1,596	5,115	10,508	14,384
Solar	833	4,190	9,262	14,194
Coal with CCS	1	43	804	1,113
Gas with CCS	0	89	348	616
Bioenergy with CCS	0	47	284	443
Hydrogen and ammonia	0	100	376	517
Carbon capture use and storage (Mt CO_2-e)				
Fossil fuels and processes	39	1,325	na	5,245
Direct air capture	0	70	na	630
Bioenergy	1	255	na	1,380

Table 15 Inputs applied for demographic and economic variables in the CSP scenario

	2020-2030	2030-2040	2040-2050
Population* (average annual %-change)			
Global	0.97	0.78	0.61
Australia**	1.46	1.16	0.98
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
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

* All regional population growth assumptions (except for Australia) are based on the latest NIGEM baseline adjusted for consistency with the decadal population forecasts reported in the IEA's Net Zero by 2050 report.

**Australia's population growth assumption is from *2023 Intergenerational Report* (Commonwealth of Australia, 2023)

Table 16 Treatment of key variables in AusTIMES

Variable	A50/G2 Scenario	A40/G1.5 Scenario
Emissions	Exogenously imposed net trajectory reaching net zero in 2050. Land-use sequestration (-129 Mt CO_2-e in 2050) is from LUTO, and technological based removals (-24 Mt CO_2-e in 2050) match those imposed in GTEM.	Exogenously imposed net trajectory reaching net zero in 2040. Land-use sequestration (-185 Mt CO_2-e in 2050) is from LUTO, and technological based removals (-25 Mt CO_2-e in 2050) match those imposed in GTEM.
Industrial sectoral economic growth	Increasing industry output over the period for all industries except coal mining, oil mining, gas extraction and export, and petroleum refining. Iron and Steel output is near 12 Mt by 2050. These growths are outputs of the GTEM model.	Similar total output over increasing industries (in energy terms) as A50/G2. A notable difference is Iron and Steel which increases to near 15 Mt by 2050. These growths are outputs of the GTEM model.
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 "Hydrogen Export" scenario.
Global capital costs for power generation and battery storage	Derived from Graham et al. (2023): *GenCost Consultation Draft 2023-24,* "Current Policies" scenario.	Derived from Graham et al. (2023): *GenCost Consultation Draft 2023-24,* "Net Zero by 2050" scenario.
Uptake of distributed energy (rooftop PV and customer batteries)	Consistent with "Net Zero" scenario in 2022 CSIRO projections	Consistent with "Export Superpower" scenario in 2022 CSIRO projections
Transport Sector	Progressive Change scenario (higher growth in transport demand)	Hydrogen Export scenario (lower growth in transport demand)
Building technology changes	High propensity for uptake of electrification and energy efficiency measures	High propensity for uptake of electrification and energy efficiency measures

A.2.2 Carbon emissions pathway assumptions

The net carbon budgets of G1.5 and G2 (see Figure 51) are consistent with IMP-Ren and IMP-GS scenarios in IPCC 6th assessment report (IPCC, 2022), respectively. There are no specific budgets for CO_2 emissions and non-CO_2 emissions. The emissions trajectories are then based on IMP-Ren and IMP-GS scenarios, respectively, but adjusted for historical global emissions. GTEM takes the net emissions pathway as a constraint and derives a global carbon price given this constraint.

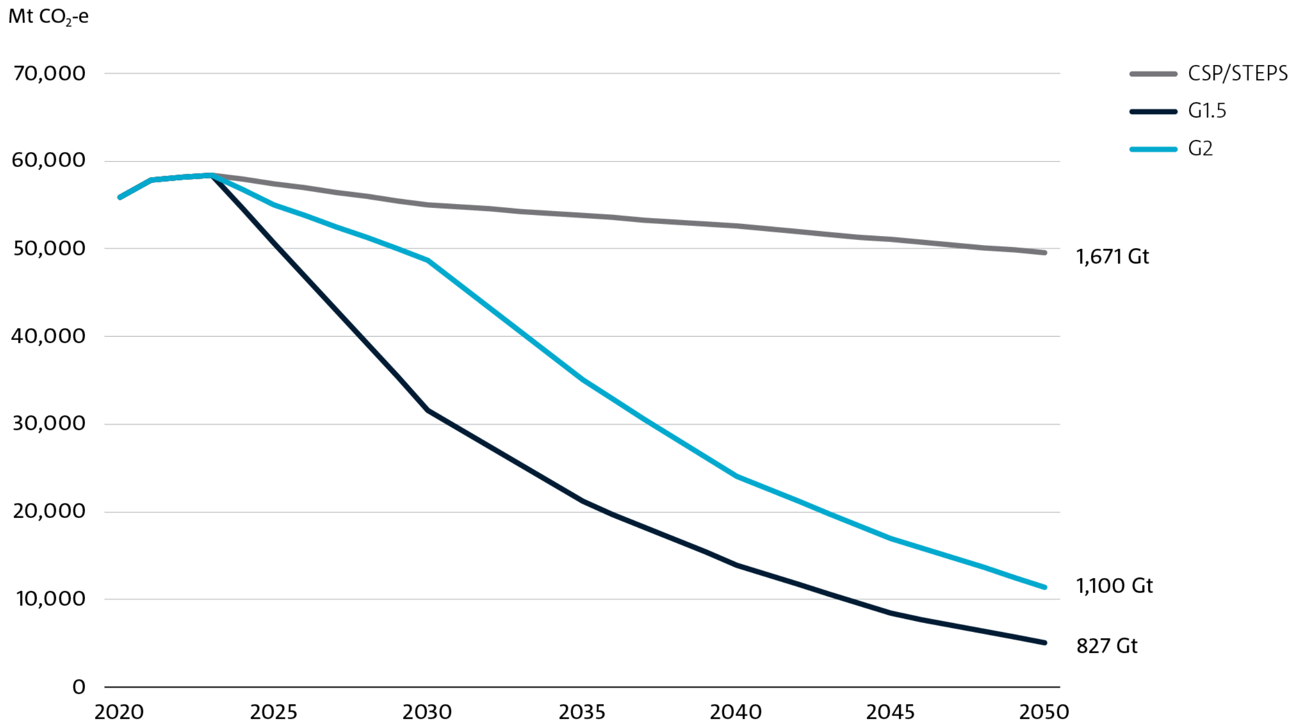

Figure 51 Global carbon emissions pathways under CSP, G1.5 and G2

The carbon budget for each scenario is indicated as a label on each scenario's curve (in Gt CO_2-e over the 2020 to 2050 period).

Table 17 illustrates Australia's net emissions pathways under different assumptions and global scenarios. It should be noted that once the net emissions hits zero, the gross emissions, excluding LULUCF emissions but including emissions captured or removed by negative emissions technologies, would be held constant afterwards till 2050.

Table 17 Australia's emissions pathways imposed under the GTEM domestic scenarios

Year	A50/G2 ($Mt\ CO_2$-e)	A40/G1.5 ($Mt\ CO_2$-e)
2020	473	473
2021	465	465
2022	465	465
2023	460	460
2024	445	445
2025	430	430
2026	415	415
2027	400	400
2028	385	373
2029	370	342
2030	355	311
2031	337	280
2032	319	249
2033	301	218
2034	284	187
2035	266	156
2036	248	124
2037	230	93
2038	213	62
2039	195	31
2040	177	0
2041	160	Hold gross emissions (excl. LULUCF emissions) constant till 2050
2042	142	
2043	124	
2044	106	
2045	89	
2046	71	
2047	53	
2048	35	
2049	18	
2050	0	

These emissions reduction targets are implemented as an upper bound in AusTIMES.

A.2.3 Additional specific assumptions

Additional assumptions or constraints on specific sectors and models are listed in Table 18.

Table 18 Additional assumptions

Model	Assumptions/constraints
GTEM	Australia does not participate in global emissions trading. Australia's coal and gas outputs in the A40/G1.5 and A50/G2 scenarios are no higher than that in the G1.5 and G2 scenarios, respectively. Australia's coal output in G2 is capped to a linear decrease to a maximum of 70% of initial levels in 2050. Australia's livestock sectors (Cattle and Raw Milk) outputs are kept at 2020 levels till 2050 as a proxy for constant herd cattle numbers. DACCS and BECCS technology starts to take up after 2030. All sequestration in GTEM and AusTIMES is assumed to occur domestically within Australia – the use of international offsets is not considered.
LUTO	Under the current Australian Carbon Credit Unit Scheme Reforestation by environmental or mallee plantings FullCAM method 2014, mallee eucalypt plantings are excluded from areas that receive more than 600 mm of long-term average rainfall unless planting meets exemption requirements. For this modelling, no rainfall restriction was imposed on mallee eucalypt plantings. GFDL-ESM2M global climate used to model agricultural and plantation climate impacts Agricultural greenhouse gas emissions costs applied with agricultural emissions intensity changes from GTEM impacting these costs over time
AusTIMES	Australia and state/territory renewable energy targets/policies are included in all scenarios. Hydrogen and biomethane fuels are incorporated into the model as a decarbonisation option for buildings and industry. Land and technical (LULUCF & DAC) sequestrations are imposed exogenously in this realisation of AusTIMES. CCS is solved for endogenously. Energy efficiency and electrification are assumed to reduce carbon footprint and offer cost savings for homeowners. The transport sector results do not include emissions and fuel use from international aviation, and international shipping. Australia's national vehicle emissions *'New Vehicle Efficiency Standard'* (NVES) is imposed as a model constraint.

References

ABARES (2010). Land Use of Australia, Version 4, 2005-06, Canberra, Australia

ABS (2019). Household and Family Projections, Australia.

ABS (2020). Survey of Motor Vehicle Use, Australia.

ABS (2021a). Housing: Census.

ABS (2021b). Motor Vehicle Census, Australia. ABS, Canberra.

ABS (2022). Housing: Census.

AEMO (2022a). Inputs, assumptions and scenarios workbook.

AEMO (2022b). Integrated System Plan. Australian Energy Market Operator (AEMO), Australia.

Aguiar, A., Chepeliev, M., Corong, E.L., McDougall, R., van der Mensbrugghe, D. (2019). The GTAP Data Base: Version 10. Journal of Global Economic Analysis 4, 1-27.

Beckman, J., Hertel, T., Tyner, W. (2011). Validating energy-oriented CGE models. Energy Economics 33, 799-806.

BITRE (2019). Australian Infrastructure Statistics - Yearbook 2019.

Brinsmead, T., Rendall, A., Baynes, T., Butler, C., Kelly, R., Adams, P., Hayward, J., Reedman, L., Nolan, M., Lennox, J., Kevin, H., Katherine, W., Maryam, A., Ray, M.M., Lyle, C., Lu, Y., Nuu, C., Jeremy, Q., Kanudia, A., (2019). Australian national outlook 2019: technical report, Canberra, Australia: CSIRO.

Butler, C., Denis-Ryan, A., Graham, P., Kelly, R., Reedman, L., Stewart, I., Yankos, T., (2020). Decarbonisation Futures: Solutions, actions and benchmarks for a net zero emissions Australia: Technical Report.

Butler, C., Maxwell, R., Graham, P., Hayward, J., (2021). Australian Industry Energy Transitions Initiative: Phase 1 Technical Report.

Burns, K., Hug, B., Lawson, K., Ahammad, H. and Zhang, K., (2011). Abatement potential from reforestation under selected carbon price scenarios, ABARES Special Report, Canberra, July.

Cai, Y.Y., Newth, D., Finnigan, J., Gunasekera, D. (2015) A hybrid energy-economy model for global integrated assessment of climate change, carbon mitigation and energy transformation. Applied Energy 148, 381-395.

Climate Change Authority (2024). *Sector Pathways Review*, Climate Change Authority, Australian Government.

ClimateWorks Australia (2016). Low Carbon. High Performance: Modelling Assumptions, ClimateWorks Australia prepared for the Australian Sustainable Built Environment Council.

Connor, J.D., Bryan, B.A., Nolan, M., Stock, F., Dunstall, S., Graham, P., Ernst, A., Newth, D., Grundy, M. and Hatfield-Dodds, S. (2015). Modelling continental land use change and ecosystem services with market feedbacks at high spatial resolution. Environmental Modelling & Software 69, 141–154.

Connor, J., Bryan, B., Nolan, M. (2016). Cap and trade policy for managing water competition from potential future carbon plantations. Environmental Science & Policy 66, 11–12.

Commonwealth of Australia (2023). Intergenerational Report 2023: Australia’s future to 2063. Commonwealth of Australia, Parks, Australia.

Department of Agriculture, Water and the Environment (2020). Interim Biogeographic Regionalisation for Australia (Regions - States and Territories) v. 7 (IBRA) [ESRI shapefile]

DCCEEW (2022a). Australia's National Greenhouse Accounts.

DCCEEW (2022b). Australian Energy Update 2022.

DCCEEW (2022c). Commercial Building Baseline Study 2022.

DCCEEW (2023). National Greenhouse Accounts Factors: 2023.

DISER (2021). Australia’s emissions projections 2021, October, Australia.

DISER, (2022). 2021 Residential Baseline Study for Australia and New Zealand for 2000 to 2040.

EIA (2013). Implied U.S. Natural Gas Supply Elasticities in the AEO2014 Reference Case. US Energy Information Administration, US.

ETSAP (2016). IEA-ETSAP Optimization Modeling Documentation.

EY Net Zero Centre (2023). Extract on Coal Mine Methane Emissions in Safeguard Mechanism Market Model. Available at https://www.ey.com/en_au/sustainability/australias-safeguard-mechanism-and-the-transition-to-net-zero [accessed 30 January 2024]

Ferrier S., Manion G., Elith J., and Richardson K., (2007). Using generalised dissimilarity modelling to analyse and predict patterns of beta diversity in regional biodiversity assessment. Diversity and Distributions 13, 252–264.

Frank, S., Gusti, M., Havlík, P., Lauri, P., DiFulvio, F., Forsell, N., Hasegawa, T., Krisztin, T., Palazzo, A., and Valin, H. (2021). Land based climate change mitigation potentials within the agenda for sustainable development. Environmental Research Letters. Volume 16(2)024006.

Graham, P., Havas, L. (2021). Electric vehicle projections 2021, CSIRO, Australia.

Graham, P., Mediwaththe, C. (2022). Small-scale solar PV and battery projections 2022, CSIRO, Australia.

Hanoch, G. (1975). Production and Demand Models with Direct or Indirect Implicit Additivity. Econometrica 43, 395-419.

Honan M., Feng X., Tricarico J.M., Kebreab E. (2022). Feed additives as a strategic approach to reduce enteric methane production in cattle: modes of action, effectiveness and safety. Animal Production Science 62, 1303-1317; https://doi.org/10.1071/AN20295

Ianchovichina, E., McDougall, R. (2000). Theoretical structure of dynamic GTAP. Purdue University, US.

IEA (2021). *World Energy Outlook 2021*. International Energy Agency (IEA), Paris. Source: https://www.iea.org/reports/world-energy-outlook-2021.

IEA (2021a). *Net Zero by 2050: A Roadmap for the Global Energy Sector*, 3rd and 4th Editions (May and October 2021). International Energy Agency (IEA), Paris.

IPCC (2022). Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, in: P.R. Shukla, J.S., R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley (Ed.). Cambridge University Press, Cambridge, UK and New York, NY, USA.

Kinley Robert D., de Nys Rocky, Vucko Matthew J., Machado Lorenna, Tomkins Nigel W. (2016). The red macroalgae Asparagopsis taxiformis is a potent natural antimethanogenic that reduces methane production during in vitro fermentation with rumen fluid. Animal Production Science 56, 282-289; https://doi.org/10.1071/AN15576

Lewis Grey Advisory (2022). Gas Price Projections for Eastern Australia, 2023 Update.

Marinoni O., Garcia J.N., Marvanek S., Prestwidge D., Clifford D., and Laredo L.A. (2012). Development of a system to produce maps of agricultural profit on a continental scale: An example of Australia. Agricultural Systems 105, 33–45.

McDougall, R. (2003). A new regional household demand system for GTAP. Purdue University, US.

Modelling least-cost technology pathways to decarbonise the New South Wales energy system by 2050. Renewable and Sustainable Energy Transition 3, 100041.

National Water Commission, (2012). Assessing water stress in Australian catchments and aquifers. Australian Government, Canberra.

NVIS (2020). National Vegetation Information System V6.0 © Australian Government Department of the Environment and Energy 2020.

Polglase, P., Paul, K., Hawkin, C., Siggins, A., Turner, J., Booth, T., Crawford, D., Jovanovic, T., Hobbs, T., Opie, K., Almeida, A. and Carter, J. (2008). Regional Opportunities for Agroforestry Systems in Australia. RIRDC Publication No. 08/176, October 2008, Canberra.

Popp, D. (2002). Induced innovation and energy prices. American Economic Review 92, 160-180.

Reedman, L., Chew, M.S., Gordon, J., Sue, W., Brinsmead, T., Hayward, J., Havas, L. (2021) Multi-sector energy modelling.

Robertson, M.J., Llewellyn, R.S., Mandel, R., Lawes, R., Bramley, R.G.V., Swift, L., & C. O'Callaghan (2021). Adoption of variable rate fertiliser application in the Australian grains industry: status, issues and prospects. Precision Agric 13, 181–199. https://doi.org/10.1007/s11119-011-9236-3

Roque, B.M., Venegas, M., Kinley, R.D., de Nys, R., Duarte, T.L., Yang, X., Kebreab, E. (2021). Red seaweed (Asparagopsis taxiformis) supplementation reduces enteric methane by over 80 percent in beef steers. PLoS One. 2021 Mar 17;16(3):e0247820. doi: 10.1371/journal.pone.0247820. PMID: 33730064; PMCID: PMC7968649.

Stern, D.I. (2012). Interfuel Substitution: A Meta-Analysis. Journal of Economic Surveys 26, 307-331.

WA Government (2020). Whole of System Plan Appendix B - Assumptions Workbook.

Whitten, S., Verikios, G., Kitsios, V., Mason-D’Croz, D., Cook, S., Holt, P. (2022). Exploring Climate Risk in Australia: The economic implications of a delayed transition to net zero emissions. CSIRO, Australia.

Yu, G., Beauchemin, K.A., Dong, R. (2021). A Review of 3-Nitrooxypropanol for Enteric Methane Mitigation from Ruminant Livestock. Animals (Basel). 2021 Dec 13;11(12):3540. doi: 10.3390/ani11123540. PMID: 34944313; PMCID: PMC8697901.

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