Australia’s National
Science Agency

# Modelling Sectoral Technology and Emissions Pathways to 2035 and Net Zero Emissions – Final Report

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# Executive summary

**The Climate Change Authority (the authority) is developing its advice on the 2035 emissions reduction targets for Australia's next Nationally Determined Contribution (NDC), as requested by the Minister for Climate Change and Energy. Separately, to assist the Australian Government in developing a national net zero emissions by 2050 plan, the parliament requested that the authority undertake analysis 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 analysis, and this report, the potential 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 (°C), and the second sees global warming limited to 1.5°C with no or limited overshoot.**

As part of this process, the authority commissioned CSIRO, Australia's national science agency, 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 Contributions (NDC) and the associated sectoral plans.

The modelling undertaken by CSIRO examined six scenarios reflecting four levels of domestic decarbonisation ambition (A50, A45, A40, A35) with net-zero years ranging from 2050 to 2035, each with a corresponding level of emissions in 2035 as indicated in Table 1. The domestic scenarios were modelled under different global climate ambition settings of 2°C and 1.5°C (G2 and G1.5) to explore the macroeconomic, sectoral and environmental impact for Australia with different combinations of domestic and global ambition. Two additional sensitivity scenarios were modelled to investigate the impact of lower renewable uptake and are implemented as an upper limit (the "+RL" or "+Renewable Limit" scenarios).

Table 1 The modelled scenarios

| AUSTRALIAN AMBITION | | |
|---|---|---|
| Net Zero Year | 2035 emissions reduction over 2005 level* | |
| | Scenario Definition | Modelled Result |
| 2050 | -57% | -65%, -62% |
| 2045 | -62% | -65%, -62% |
| 2040 | -75% | -75%, -75%, -75% |
| 2035 | -100% | -94% |

| GLOBAL AMBITION | |
|---|---|
| Temperature Goal | |
| Below 2.0 °C | 1.5 °C |
| IEA/IPCC Ambition | |
| Moderate | High |
| A50/G2 | A50/G1.5 |
| A45/G2, A45/G2+RL | |
| A40/G2, A40/G2+RL | A40/G1.5 |
| | A35/G1.5 |

*The 2035 level of emissions represents the emission reduction relative to 2005 emissions. Modelled result values are from AusTIMES.

The modelling of Australia's global context assumes an orderly global transition with cost effective action across all countries and sectors, to achieve smooth greenhouse gas emissions reduction pathways aligned to IPPC and IEA scenarios for below 2°C and 1.5°C. Within these two global contexts, the modelling imposes four pathways for Australia's maximum net emissions and solves to find the least cost pattern of emissions and abatement across sectors in each period to 2050. The analysis assumes Australia achieves these net emissions pathways without international import or export of emissions units and includes land sector sequestration and the deployment of negative emissions technologies in Australia and internationally. The analysis covers all greenhouse gases from all sources, including non-$CO_2$ and non-energy emissions. The modelling uses an established CSIRO multi-model framework, including a global multi-sector multi-region economic model (GTEM), a detailed techno-economic multi-sector Australian model (AusTIMES), and a model of Australian agricultural production and land use (LUTO).

All scenarios overachieve on the 2030 target. This is because the least cost pathway smooths the rate of emissions reductions to avoid sharper more costly abatement action from 2030 to 2035 or 2040, bringing forward abatement investments. In brief, scenario A50/G2 (A50/G1.5) achieves net-zero emissions in 2050 with 153 (123) Mt of residual $CO_2$-equivalent (Mt $CO_2$-e) emissions. Scenario A45/G2 achieves net-zero in 2045 with a 141 Mt $CO_2$-e residual. Scenario A40/G2 (A40/G1.5) achieves net-zero emissions in 2040 with a 175 (177) Mt $CO_2$-e residual. The fastest rate of abatement is represented by scenario A35/G1.5, which achieves net zero emissions between 2035 and 2040 with a 170 Mt $CO_2$-e residual (Figure 1). The reduction in aggregate net emissions is achieved with a wide range of reductions in sectoral emissions. The largest reductions over the period 2020-2050 occur in the power sector and then, in decreasing order, industry (excluding agriculture), new land-based sequestration, transport, direct air capture (DAC[1]), agriculture, and buildings. The speed of emissions reduction also varies greatly across sectors where the power sector is the fastest to decarbonise and agriculture the slowest.

Detailed key findings are as follows.

1. **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 to the year 2030. By 2035, renewables account for at least 86% of the nation's electricity generation. Deployment of utility-scale storage capacity is significant reaching between 48 GW and 56 GW by 2050. 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% by 2050, with coal exiting the mix around 2035 and the remaining fossil fuel generation from natural gas. Electricity decarbonisation drives down emissions from energy use in housing and commercial buildings, mining (including mineral processing), and later in transport. If the uptake of renewables is constrained to less than 90% of generation, gas-fired generation with CCS sees significant uptake post 2035.

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[1] 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.

Figure 1 AusTIMES: Emissions by sector[2]

**Power is emissions from electricity generation. While negative emissions from direct air capture (DAC) and land-based sequestration are separated from gross agricultural emissions, the emissions from industry is a net figure and has embedded within it emissions capture from technologies such as carbon capture and storage (CCS). Land-use and land-use change (LULUCF) represents the 2023 Australian Government projections (DCCEEW, 2023b), while additional land-based sequestration from new-plantings is shown as "Land seq. (Future)". Agriculture is shown separate from industry, with the industry label being "Industry ex Agri" only to indicate the difference from previous work where they were not.**

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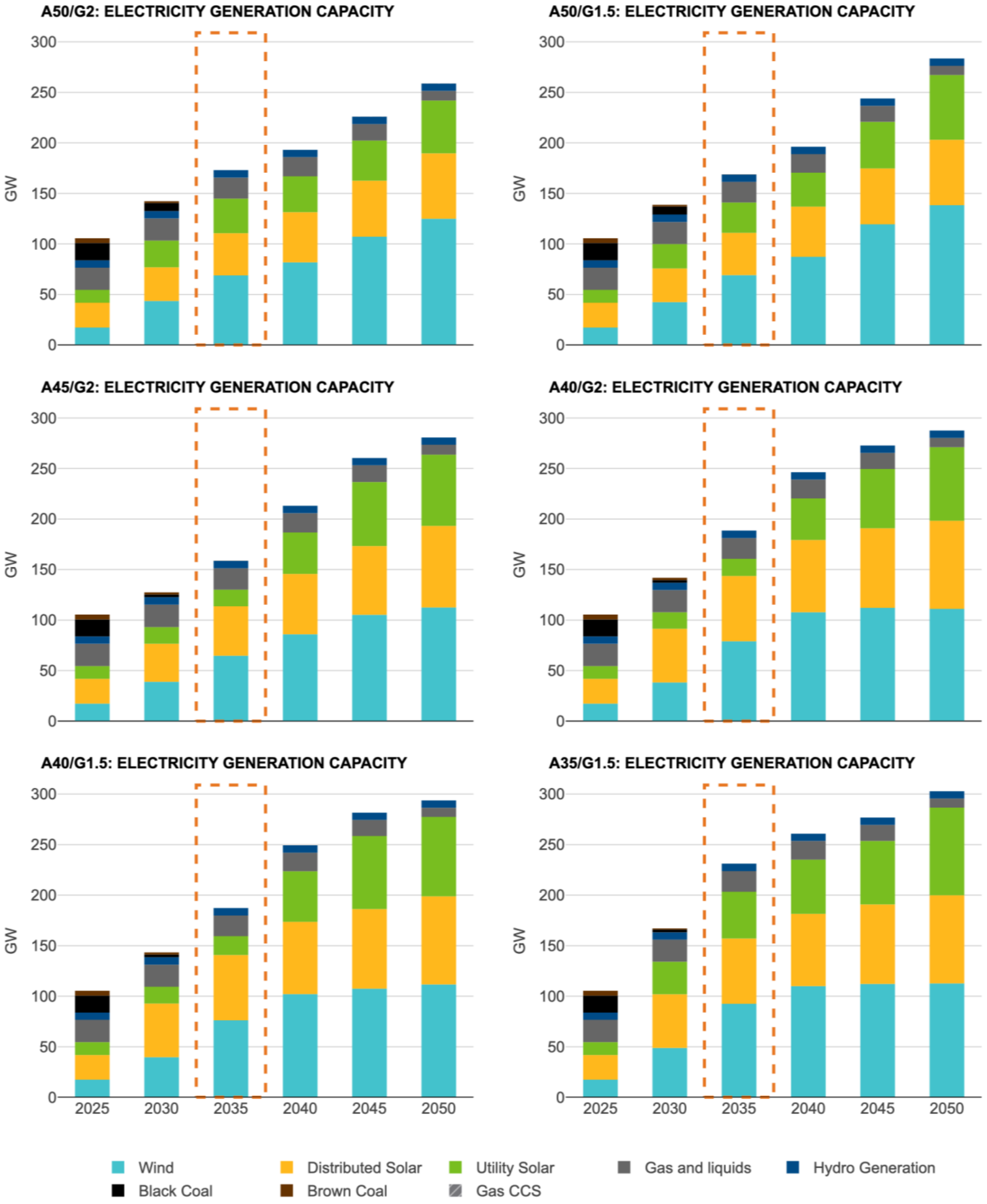
[2] While the model results presented here and in the corresponding Sector Pathways Review (Climate Change Authority, 2024) are the same, the sectoral categorisation of those results in this report differs from that used by the authority. See the Appendix A Technical supplement for the sectoral structure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


A50/G2: ELECTRICITY GENERATION CAPACITY

A50/G1.5: ELECTRICITY GENERATION CAPACITY

A45/G2: ELECTRICITY GENERATION CAPACITY

A40/G2: ELECTRICITY GENERATION CAPACITY

A40/G1.5: ELECTRICITY GENERATION CAPACITY

A35/G1.5: ELECTRICITY GENERATION CAPACITY

Figure 2 AusTIMES: Electricity generation capacity mix

2. **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 100 Mt $CO_2$-e per year by 2040 in the A50 and A45 scenarios, and to near 180 Mt $CO_2$-e in the A40 and A35 scenarios.** 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's net emissions vary strongly by scenario. The sector becomes a net sink around 2045 in the A50 scenarios, and between 2030 and 2035 in the A40 and A35 scenarios. However, the agricultural sector remains a substantial emitter given the contribution of difficult-to-abate livestock emissions. Land-based sequestration from additional plantings is projected to deliver between 40 and 130 Mt $CO_2$-e per year of negative emissions by 2050, depending on the scenario. 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.
3. **Residential and commercial building emissions fall to around 8 Mt per annum by 2035 and less than 2 Mt per annum by 2050**. Half of all reductions in building emissions result from decarbonisation of the electricity sector. Improvements in heating and cooling efficiency achieved through new and rebuilt stock 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 grew by more than 50%.
4. **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 nearly 6% of Australian car sales to around 32% (65%) by 2035, in A50/G2 (A40/G1.5). Light vehicles with an electric drivetrain reach 100% of sales by 2050 in A50/G2, and by 2040 in A40/G1.5 and A35/G1.5. Decarbonisation of long distance and heavy transport accelerates through 2030 to 2040. As much as two-thirds of freight transport is electrified by 2050, and the remainder uses low- or zero-emissions hydrogen and biofuels. 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.
5. **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 between 3 and 4 Mt by 2050.

6. **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 all 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 making use of renewables. The iron and steel industry sees a switch to hydrogen-based reduction and the uptake of melt basic oxygen furnace technologies in the 2040s for the A50 scenario and the late 2030s for the A40 scenario with CCS being taken up by 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.
7. **Fossil fuel export volumes decline significantly.** The implications are significant for Australia's export markets. Australian coal production volume is projected to fall by between 10% and 40% from 2020 to 2030 and then more dramatically to between 30% and 75% through 2050, with almost all remaining production being for metallurgical coal in the latter cases. Oil production volume is relatively flat in A50/G2 but falls by between one-third and two-thirds from 2020 to 2050 in the remaining scenarios. Gas export volume falls by 50% from 2020 to 2050 in A50/G2 but shows transient growth in other scenarios with all declining by at least 25% over the period through 2050.
8. **However, non-fossil fuel mining production continues to grow significantly.** Mining volumes of iron ore and other commodities almost double by 2050 in all 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 decarbonisation of 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.

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# Part I Overview

# 1 Overview

This report presents results for a suite of net zero emissions scenarios commissioned by the authority to inform their advice to the Australian Government regarding the next Nationally Determined Contributions (NDC) and the associated sectoral plans. The modelling examines six scenarios reflecting four levels of domestic decarbonisation ambition with net-zero years ranging from 2050 to 2035. The domestic scenarios were modelled under two global decarbonisation settings of 2°C and 1.5°C of warming and explore the macroeconomic, sectoral and environmental impact for Australia. Two sensitivity scenarios were also modelled to investigate the impact of lower renewable uptake and are implemented as an upper limit.

The modelling assumes an orderly global transition with cost-effective action across all countries and sectors, to achieve smooth greenhouse gas emissions pathways aligned to IPPC and IEA scenarios for 2°C and 1.5°C. Given these global settings, each domestic pathway solves for the least cost pattern of emissions and abatement across sectors in each period to 2050. The scenarios assume no international trade of emissions permits by Australia and include land-based and technology-based sequestration (negative emissions technologies) in Australia and internationally. The analysis covers all greenhouse gases from all sources. The modelling applies an established CSIRO multi-model framework by combining a global multi-sector multi-region computable general equilibrium economic model (GTEM), a detailed Australian techno-economic multi-sector energy model (AusTIMES), and an Australian agricultural production and land use model (LUTO).

The following sections provide detailed macroeconomic and sectoral results with a greater emphasis on the latter. The sectoral results particularly focus on the changes in sectoral emissions, energy use and technology uptake. The appendix provides extensive detail on each model's structure, data, model settings and calibration.

## 1.1 Modelling scenarios

Four levels of domestic decarbonisation ambition were modelled with net-zero years ranging from 2050 to 2035, each with a corresponding level of 2035 emissions reduction as indicated in Table 2. 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).

Table 2 The modelled scenarios

<table>
<tr><th colspan="3" rowspan="3">AUSTRALIAN AMBITION</th><th colspan="2">GLOBAL AMBITION</th></tr>
<tr><th colspan="2">Temperature Goal</th></tr>
<tr><th>Below 2.0 °C</th><th>1.5 °C</th></tr>
<tr><th rowspan="2">Net Zero Year</th><th colspan="2">2035 emissions reduction over 2005 level*</th><th colspan="2">IEA/IPCC Ambition</th></tr>
<tr><th>Scenario Definition</th><th>Modelled Result</th><th>Moderate</th><th>High</th></tr>
<tr><td>2050</td><td>-57%</td><td>-65%, -62%</td><td>A50/G2</td><td>A50/G1.5</td></tr>
<tr><td>2045</td><td>-62%</td><td>-65%, -62%</td><td>A45/G2, A45/G2+RL</td><td></td></tr>
<tr><td>2040</td><td>-75%</td><td>-75%, -75%, -75%</td><td>A40/G2, A40/G2+RL</td><td>A40/G1.5</td></tr>
<tr><td>2035</td><td>-100%</td><td>-94%</td><td></td><td>A35/G1.5</td></tr>
</table>

***Scenario definitions and modelled results represent emission reductions in 2035 relative to 2005 emissions. This report is a follow-on from Verikios et al. (2024) where only two scenarios (A50/G2 and A40/G1.5) were presented. Here all six scenarios, plus selected results for two additional scenarios that investigate the sensitivity to an imposed limit on the uptake of renewables (the "+RL" or "+Renewable Limit" scenarios), are presented. Note also that while the A35/G1.5 scenario targets net-zero in 2035, the modelling results indicate that this would require additional, unmodelled offsets (e.g., purchased via international trade), and as such, that scenario's emissions trajectory falls slightly short of net-zero by 2035. The modelled result values are from AusTIMES.**

- **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 Global Trade and Environment Model (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 removal 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.

Figure 3 shows the net carbon budgets of the 1.5°C scenario (G1.5) and 2°C scenario (G2), which 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.

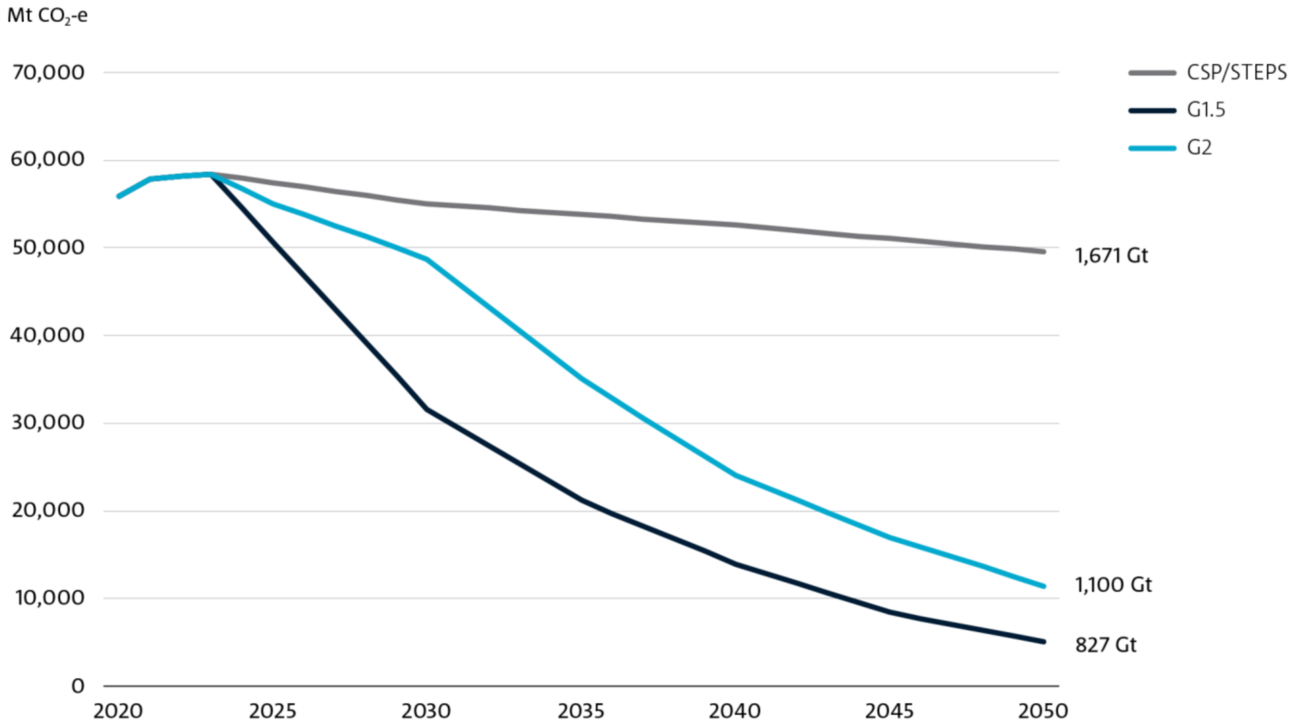

**Figure 3 GTEM Global carbon emissions pathways under CSP, G1.5 and G2**

**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).**

The six domestic scenarios are identified in Table 2. In all these scenarios Australia's emissions pathway is exogenously constrained, which results in an Australian carbon price which deviates from the global carbon price.

- **A50/G2: 2°C world, Australia achieves 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.
- **A45/G2: 2°C world, Australia achieves net zero in 2045** 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 2045. By 2035, Australia's GHG emissions are reduced by 62% relative to 2005.
- **A40/G2: 2°C world, Australia achieves net zero in 2040** 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 2040. By 2035, Australia's GHG emissions are reduced by 75% relative to 2005.
- **A50/G1.5: 1.5°C world, Australia achieves net zero in 2050** 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 2050. By 2035, Australia's GHG emissions are reduced by 57% relative to 2005.
- **A40/G1.5: 1.5°C world, Australia achieves 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.

- **A35/G1.5: 1.5°C world, Australia achieves net zero in 2035** 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 approaches net zero in 2035. By 2035, Australia's GHG emissions are reduced by 100% relative to 2005.

Henceforth we use the short scenario names (e.g., A50/G2, A40/G1.5, etc) to refer to particular scenarios. Detailed scenario assumptions and model implementation descriptions are provided in Appendix A.2.

Two additional scenarios were modelled in the Australian TIMES (AusTIMES) model to investigate the sensitivity to an imposed limit on the uptake of renewable energy:

- **A45/G2 + RL**: A45/G2 settings with an additional constraint that limits the share of renewable electricity generation to 67% in 2030 and 83% in 2035, consistent with the 2023 Department of Climate Change, Energy, the Environment and Water (DCCEEW) Emissions Projections baseline scenario, and to 90% after 2035 (DCCEEW, 2023b).
- **A40/G2 + RL:** A40/G2 settings with an additional constraint that limits the share of renewable electricity generation to 67% in 2030 and 83% in 2035, consistent with the 2023 DCCEEW Emissions Projections baseline scenario, and to 90% after 2035.

## 1.2 Methodology

In this analysis, a multi-model approach has been tailored to downscale a combination of several IEA and IPCC scenarios to an 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 establish the economic context (i.e., export and import demand and prices, primary factor demands and prices, etc) and explore the economic impacts in each scenario.
2. **LUTO:** The "Land Use Trade-Offs" model is a spatially detailed land use change model of rural Australia that 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 technology pathways, which details sectoral pathways of technology mix, energy mix and emissions for some sectors.

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[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]

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 GHG 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 prices GHG for 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. While the AusTIMES emissions trajectory, industry output, population growth, exports, and technological removals are drawn directly from GTEM (and taking into account the land use change sequestration drawn from LUTO), for the A35/G1.5 scenario, the AusTIMES emission trajectory deviated from that of GTEM and the scenario definitions as described in the following paragraph.

## 1.3 Projected emissions by sector

Australia's total net GHG emissions were around 433 Mt of $CO_2$-equivalent (Mt $CO_2$-e) emissions in 2021-22[6]. The modelled gross and net emissions by sector are shown in Figure 4[7]. All scenarios overachieve on the 2030 target. A50/G2 (A50/G1.5) achieve net-zero in 2050 with 153 (123) Mt of residual gross $CO_2$-e. A45/G2 achieves net-zero in 2045 with a 141 Mt $CO_2$-e residual. A40/G2 (A40/G1.5) achieves net-zero in 2040 with a 175 (177) Mt $CO_2$-e residual. A35/G1.5 achieves net zero between 2035 and 2040 with a 170 Mt $CO_2$-e residual (Figure 4) and represents the most ambitious trajectory the AusTIMES model was able to achieve within the model assumptions and without using international offsets.

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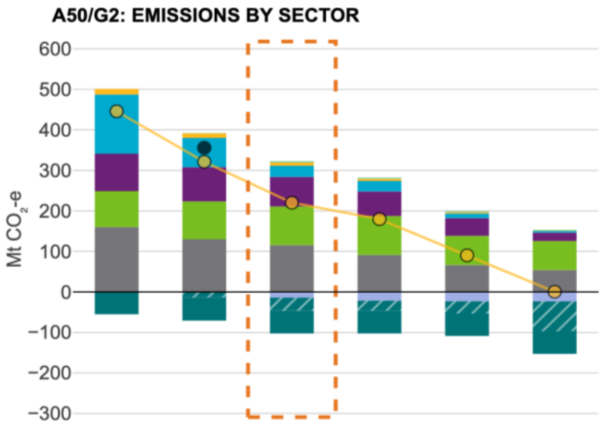
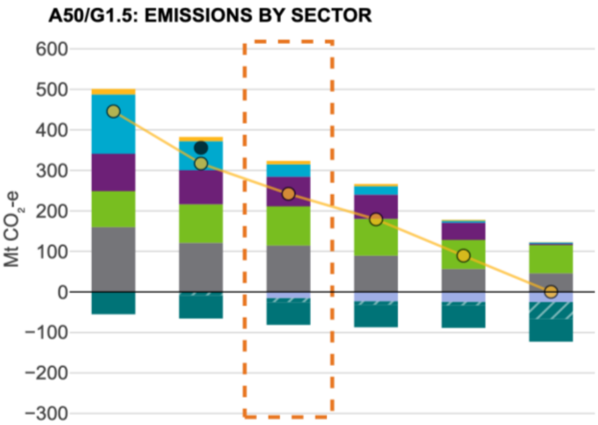
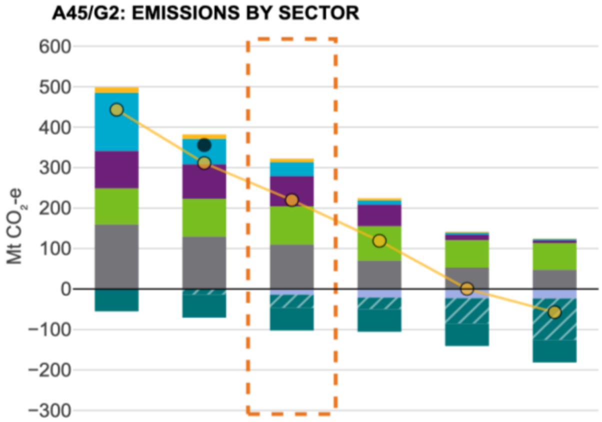
[5] The carbon price in GTEM represents the marginal cost of abatement. There is a positive non-linear relationship between the marginal cost of abatement and the degree of emissions abatement. Thus, higher emissions abatement exponentially raises the marginal cost of abatement and thus the carbon price. 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.

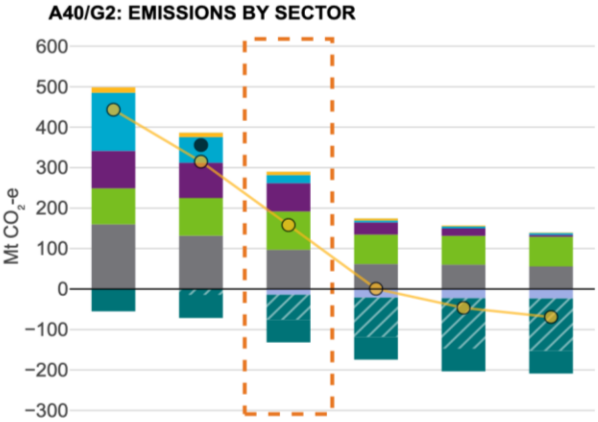
[6] 432.6 Mt $CO_2$-e in 2021-22 according to Australia's National Greenhouse Accounts: https://greenhouseaccounts.climatechange.gov.au/ [accessed 19 July 2024].

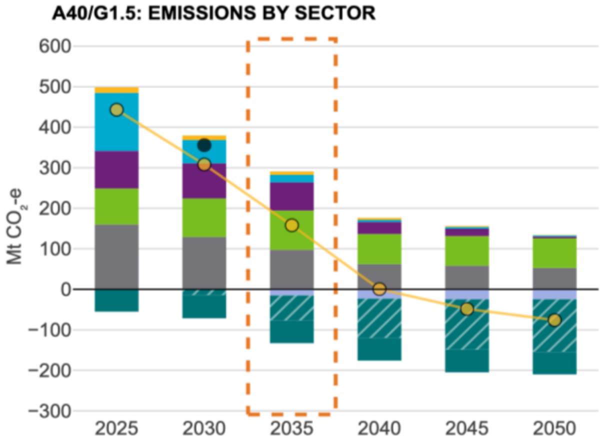
[7] Note that the results of Figure 4 are from the AusTIMES model, which takes the negative emissions trajectories from a converged iteration of the GTEM and LUTO models. For all scenarios except A40/G1.5 negative trajectories were directly applied. However, for the A40/G1.5 scenario, the additional 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.

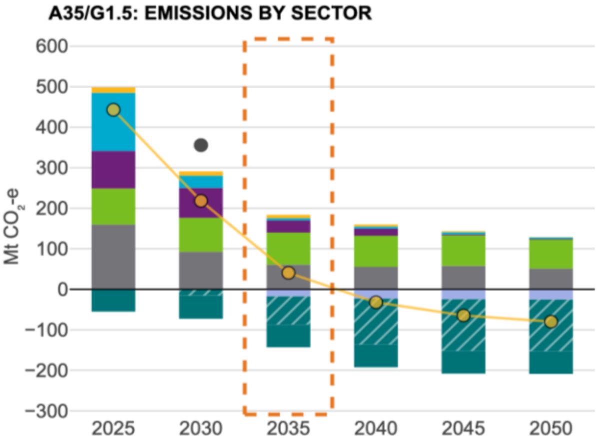

A50/G2: EMISSIONS BY SECTOR
Mt CO$_2$-e
600
500
400
300
200
100
0
−100
−200
−300


A50/G1.5: EMISSIONS BY SECTOR
Mt CO$_2$-e
600
500
400
300
200
100
0
−100
−200
−300


A45/G2: EMISSIONS BY SECTOR
Mt CO$_2$-e
600
500
400
300
200
100
0
−100
−200
−300


A40/G2: EMISSIONS BY SECTOR
Mt CO$_2$-e
600
500
400
300
200
100
0
−100
−200
−300


A40/G1.5: EMISSIONS BY SECTOR
Mt CO$_2$-e
600
500
400
300
200
100
0
−100
−200
−300
2025
2030
2035
2040
2045
2050


A35/G1.5: EMISSIONS BY SECTOR
Mt CO$_2$-e
600
500
400
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200
100
0
−100
−200
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2025
2030
2035
2040
2045
2050

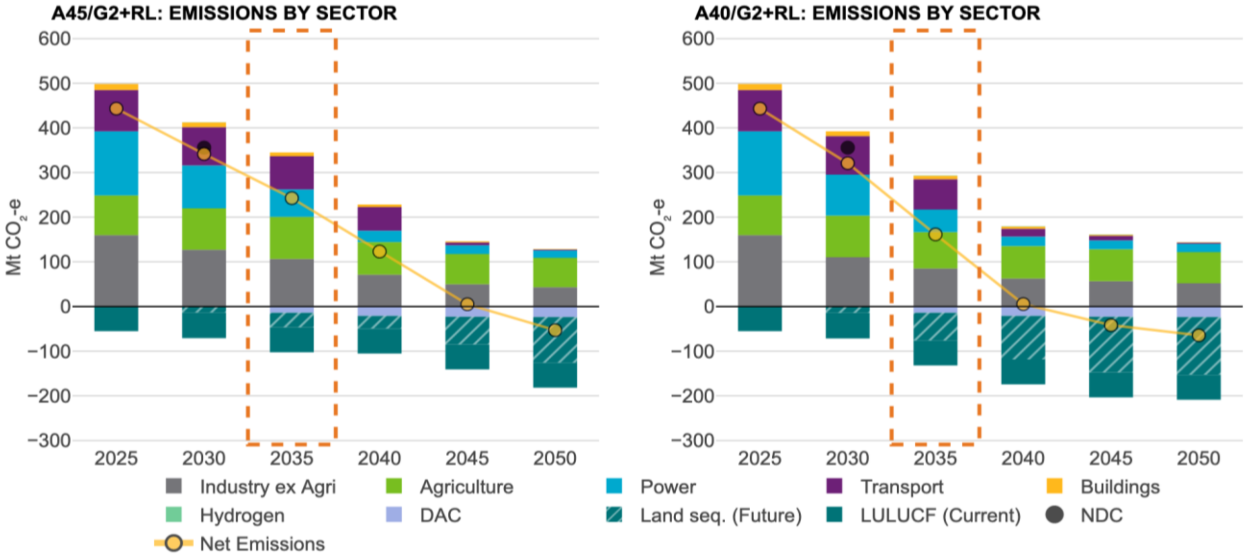


Figure 4 AusTIMES: Emissions by sector

**Power is emissions from electricity generation. While negative emissions from direct air capture (DAC) and land-based sequestration are separated from gross agricultural emissions, the emissions from industry is a net figure and has embedded within it emissions capture from technologies such as carbon capture and storage (CCS). Land-use and land-use change (LULUCF) represents the 2023 Australian Government projections (DCCEEW, 2023b), while additional land-based sequestration is modelled using LUTO.**

The scale of emissions reduction varies greatly across sectors (Figure 5). 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.

In the two sensitivity scenarios where the uptake of renewables is constrained, the power sector shows a smaller emissions reduction (by 29 Mt in A40/G2+RL and 34 Mt in A45/G2+RL in 2030) when compared to the unconstrained equivalents. In 2050, power sector emissions are 14 Mt higher in the RL scenarios but with increased uptake of CCS in electricity generation from gas. The smaller emission reductions in the power sector are offset by increased reductions in the industry, transport, and agriculture sectors. The extra reductions in the industry sector are primarily in the alumina and gas extraction industries, with electrification technologies deployed earlier than in the base scenarios. Additionally, energy efficiency improvements in other industry sub-sectors play a significant role in offsetting the smaller reductions in the power sector. The additional reductions in transport are via increased uptake of biofuels and electrification, and for agriculture they occur primarily in sheep and cattle, and grains and other agriculture.

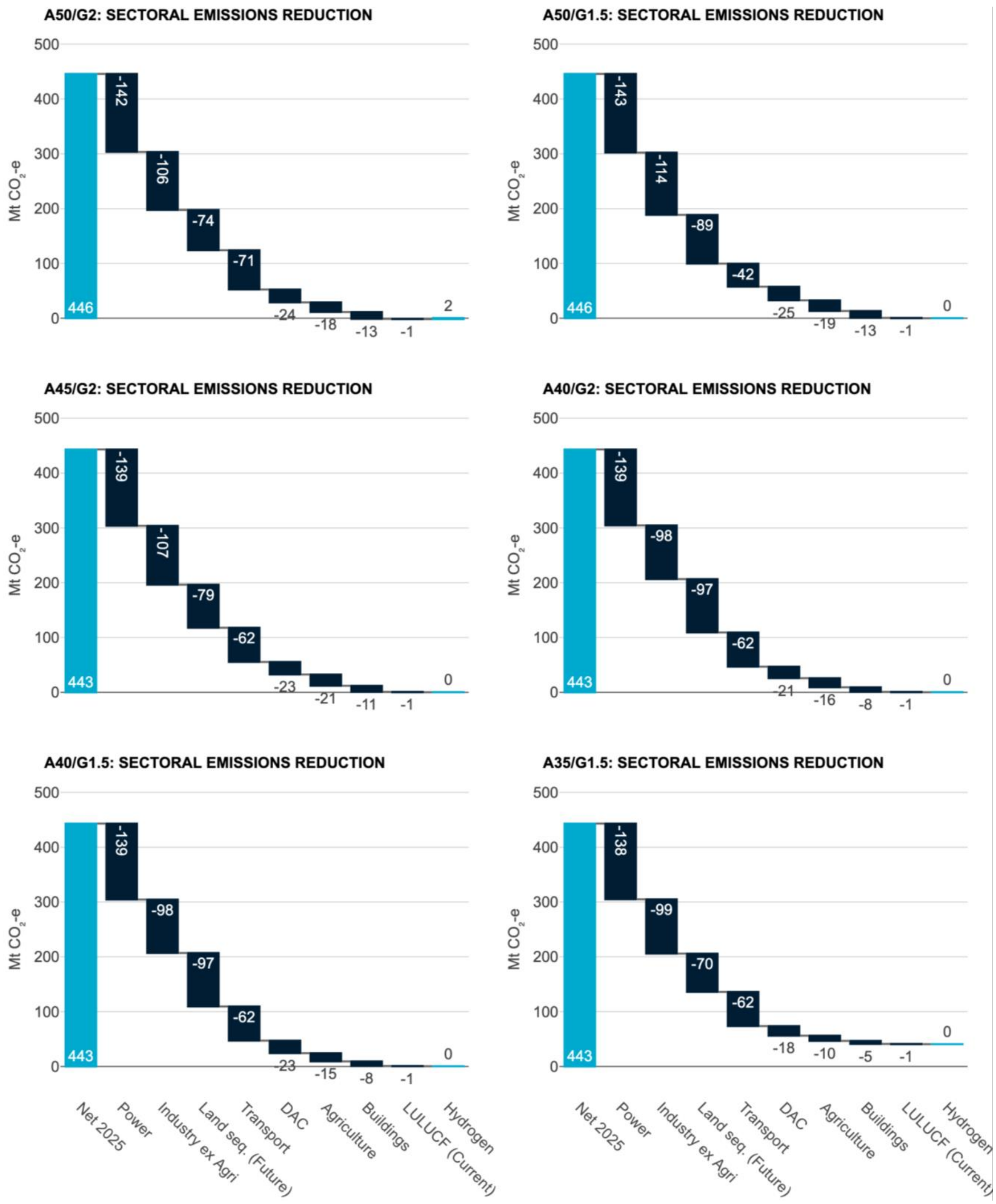


**Figure 5 AusTIMES: Emissions reduction by sector**

**Emissions reductions are from 2025 through the goal net-zero year for each scenario. For A35/G1.5 the differences are from 2025 to 2035, such that net-zero is not reached (until approximately 2038). Also, the difference between the net 2025 emissions between the two A50 scenarios and the other scenarios is due to earlier retirement of two coal powered generators in the later four scenarios.**

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 across scenarios, the greater global ambition under the A40/G1.5 scenario translates into greater sequestration from land use due to the higher carbon price – and this greater uptake of land-based sequestration enables the achievement of net zero by 2040, and slightly less abatement in the other sectors when compared to A50/G2. In A35/G1.5, the most significant difference is that uptake of abatement technologies and methods in agriculture start earlier (2030, see Figure 43) such that the sector shows declining emissions from 2025, in contrast to the other scenarios.

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). The A35/G1.5 scenario shows the most contrast to the other scenarios with the uptake of CCS in gas extraction reaching almost 4 Mt in 2030.

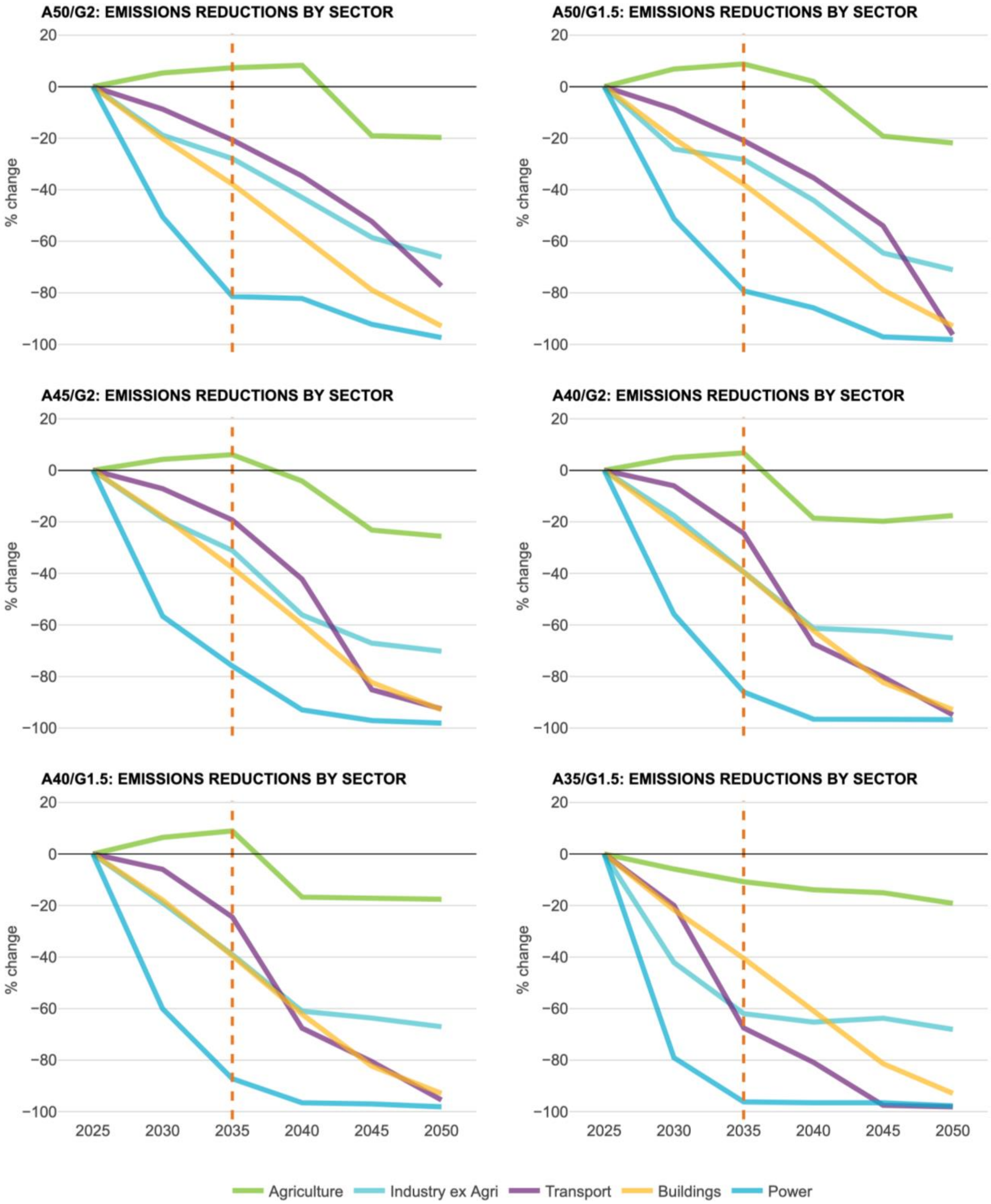


Figure 6 AusTIMES: Emissions reduction change by sector

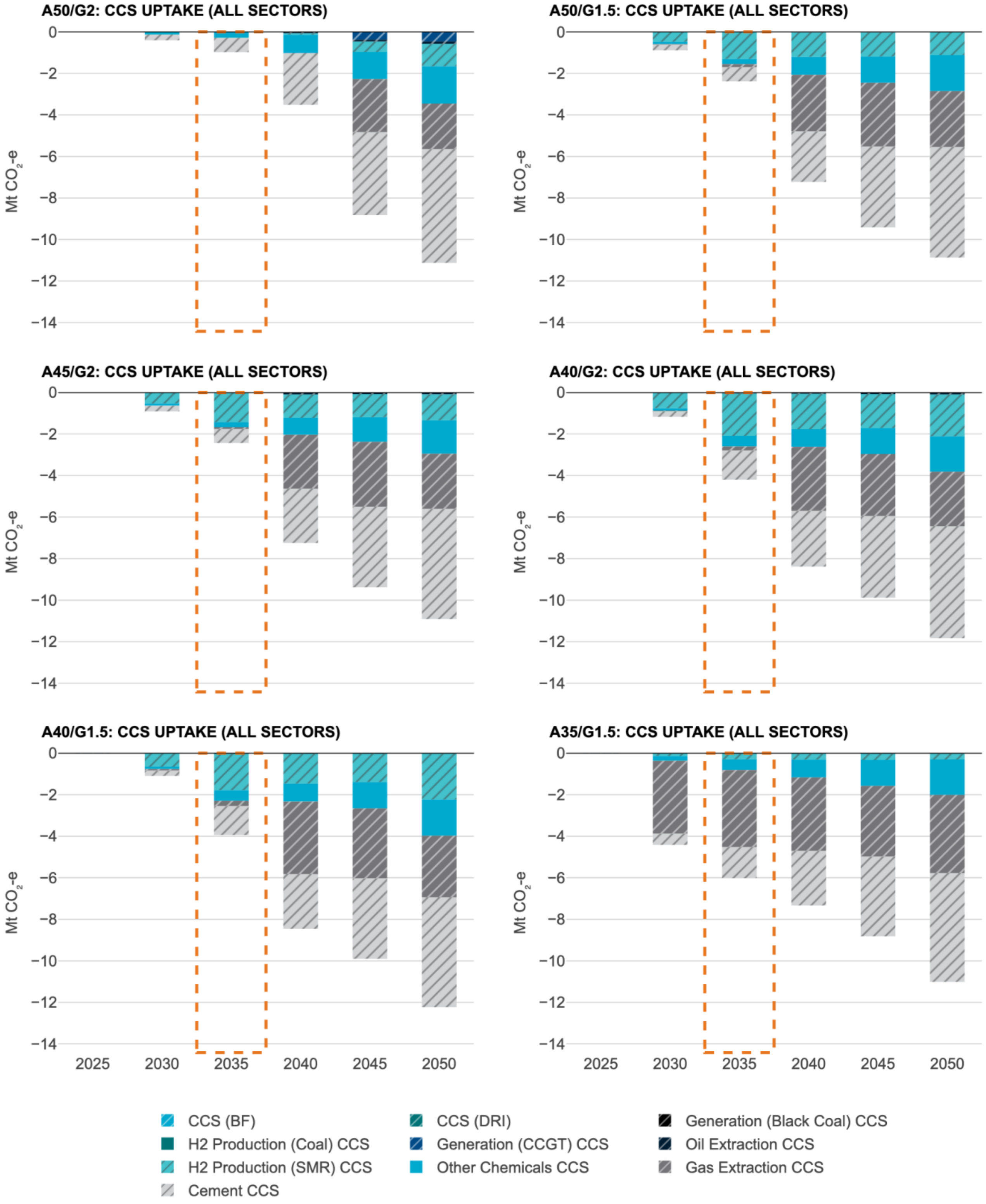


Figure 7 AusTIMES: Additional CCS uptake across all sectors

# Part II Sectors

# 2 Sectors

## 2.1 Overview

Table 3 shows the cumulative percentage change of five global macroeconomic indicators in 2035 and 2050 relative to 2020, and the compound average annual growth rates over the period 2020-2050. These indicators are real gross domestic product (GDP), real GDP per capita, real household consumption, employment and real wage rate. Comparing the two global contexts (G2 and G1.5), and when averaged over the entire period, the average growth rates in real GDP and real GDP per capita are slightly higher in G2 than G1.5. This reflects the difference in climate change mitigation by 2050 between the two scenarios, i.e., global net emissions respond by -79% by 2050 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 lower output growth as pricing emissions raises the price of output and this in turn reduces output, as observed in Table 3. However, it should be noted that this analysis does not account for the benefits of avoided climate change impacts in either scenario. While employment and the real wage rate are also slightly higher in G2 compared to G1.5, real household consumption is slightly lower. This reflects a slightly lower saving rate in Australia in G1.5 than in G2. Note that in GTEM the regional saving rate adjusts to ensure that the net-debt-to-GDP ratio stabilises over the simulation period.

**Table 3 GTEM: Global macroeconomic indicators**

| | 2035 (% increase vs 2020) | 2050 (% increase vs 2020) | 2020-2050 (Annual Avg growth rate) |
|---|---|---|---|
| **Real GDP** | | | |
| **G2** | 48.57 | 103.58 | 2.40 |
| **G1.5** | 47.37 | 102.04 | 2.37 |
| **Real GDP per capita** | | | |
| **G2** | 29.64 | 61.15 | 1.60 |
| **G1.5** | 28.60 | 59.94 | 1.58 |
| **Real household consumption** | | | |
| **G2** | 35.87 | 88.29 | 2.13 |
| **G1.5** | 34.21 | 94.77 | 2.25 |
| **Employment** | | | |
| **G2** | 11.59 | 19.09 | 0.58 |
| **G1.5** | 10.89 | 18.49 | 0.57 |
| **Real wage rate** | | | |
| **G2** | 43.03 | 78.39 | 1.95 |
| **G1.5** | 39.86 | 74.65 | 1.88 |

**Note: The first column is the cumulative percentage change in 2035 relative to 2020; the second one is the cumulative percentage change in 2050 relative to 2020; the third column is the compound average annual growth rate during the period of 2020-2050.**

Table 4 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 six “domestic scenarios” as described in Figure 4 where the Australian emissions trajectory is exogenously imposed via a domestic carbon price to achieve the emissions constraints.

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 (2.12%) compared to G2 (2.16%). 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).

Table 4 GTEM: Domestic macroeconomic indicators

| | 2035 (% increase vs 2020) | 2050 (% increase vs 2020) | 2020-2050 (Annual Avg rate growth) |
|---|---:|---:|---:|
| **Real GNP** | | | |
| **G2** | 46.88 | 103.35 | 2.39 |
| **G1.5** | 46.59 | 106.61 | 2.45 |
| **A50/G2** | 46.98 | 98.93 | 2.32 |
| **A45/G2** | 46.88 | 96.75 | 2.28 |
| **A40/G2** | 46.52 | 96.96 | 2.29 |
| **A50/G1.5** | 45.68 | 97.97 | 2.30 |
| **A40/G1.5** | 45.34 | 96.17 | 2.27 |
| **A35/G1.5** | 41.91 | 93.74 | 2.23 |
| **Real GDP** | | | |
| **G2** | 49.12 | 100.14 | 2.34 |
| **G1.5** | 47.85 | 97.72 | 2.30 |
| **A50/G2** | 49.66 | 101.01 | 2.35 |
| **A45/G2** | 49.52 | 98.18 | 2.31 |
| **A40/G2** | 49.04 | 98.55 | 2.31 |
| **A50/G1.5** | 49.23 | 101.05 | 2.36 |
| **A40/G1.5** | 48.81 | 98.87 | 2.32 |
| **A35/G1.5** | 44.25 | 95.97 | 2.27 |
| **Real GDP per capita** | | | |
| **G2** | 22.89 | 41.65 | 1.17 |
| **G1.5** | 21.84 | 39.94 | 1.13 |
| **A50/G2** | 23.33 | 42.27 | 1.18 |
| **A45/G2** | 23.22 | 40.27 | 1.13 |

| | | | |
|---|---|---|---|
| **A40/G2** | 22.82 | 40.53 | 1.14 |
| **A50/G1.5** | 22.99 | 42.30 | 1.18 |
| **A40/G1.5** | 22.63 | 40.75 | 1.15 |
| **A35/G1.5** | 18.87 | 38.70 | 1.10 |
| **Real household consumption** | | | |
| **G2** | 51.70 | 114.20 | 2.57 |
| **G1.5** | 51.26 | 130.14 | 2.82 |
| **A50/G2** | 50.85 | 102.68 | 2.38 |
| **A45/G2** | 50.94 | 101.62 | 2.36 |
| **A40/G2** | 50.83 | 100.60 | 2.35 |
| **A50/G1.5** | 47.69 | 104.59 | 2.41 |
| **A40/G1.5** | 47.75 | 102.13 | 2.37 |
| **A35/G1.5** | 46.39 | 98.23 | 2.31 |
| **Employment** | | | |
| **G2** | 12.89 | 21.80 | 0.66 |
| **G1.5** | 12.62 | 21.70 | 0.66 |
| **A50/G2** | 13.11 | 21.96 | 0.66 |
| **A45/G2** | 13.05 | 21.41 | 0.65 |
| **A40/G2** | 12.90 | 21.66 | 0.66 |
| **A50/G1.5** | 13.01 | 21.87 | 0.66 |
| **A40/G1.5** | 12.86 | 21.79 | 0.66 |
| **A35/G1.5** | 11.42 | 21.57 | 0.65 |
| **Real wage** | | | |
| **G2** | 31.92 | 61.60 | 1.61 |
| **G1.5** | 29.83 | 60.72 | 1.59 |
| **A50/G2** | 33.56 | 62.87 | 1.64 |
| **A45/G2** | 33.06 | 58.05 | 1.54 |
| **A40/G2** | 31.92 | 60.19 | 1.58 |
| **A50/G1.5** | 32.78 | 62.10 | 1.62 |
| **A40/G1.5** | 31.58 | 61.38 | 1.61 |
| **A35/G1.5** | 20.77 | 59.46 | 1.57 |

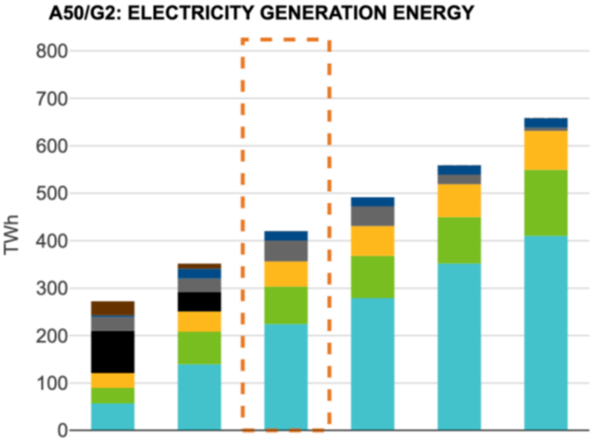
**Note that the first column is the cumulative percentage change in 2035 relative to 2020; the second one is the cumulative percentage change in 2050 relative to 2020; the third column is the compound average annual growth rate during the period of 2020-2050. The results in the G2 and G1.5 rows are from GTEM solutions where Australia's emissions trajectory responded endogenously to global activity (referred to as the "global scenarios"). The results with "A" rows are from GTEM solutions where Australia's emissions trajectory was exogenously imposed to meet the specific emissions constraints (referred to as the "domestic scenarios").**

Turning to the six domestic scenarios, a comparison of the scenarios with the same global settings shows that as the emissions reduction is deepened and net zero emissions is reached earlier, there will be generally slower GDP growth (higher GDP losses) and higher CPI growth over the entire period (2020 to 2050). The differences in employment are not significant. Note also that average Australian GDP growth rates in all domestic scenarios are equal to or higher than in the global scenarios (G2 and G1.5) while emissions reductions are all equal to or lower. This implies that an endogenously determined Australian emissions reduction response to the global scenarios would be slightly more ambitious than the domestic trajectories imposed via the above prescribed domestic emissions constraints.

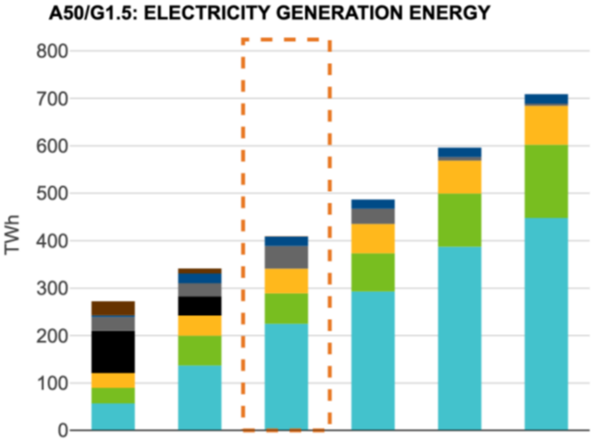
A pairwise comparison of a given domestic emissions trajectory under different global settings shows slightly higher average GDP growth and lower average CPI growth over 2025-2050 under the G1.5 global settings versus the G2 global settings. This indicates that for a given domestic emissions trajectory Australia's marginal abatement and economic cost is slightly lower the higher degree of abatement in the rest of the world. This is because the more the world decarbonises the more Australia will decarbonise as an endogenous response without any policy intervention. The main mechanism causing this is reduced global demand for fossil fuels (due to global decarbonisation) means reduced fossil fuel exports and production by Australia. As fossil fuel extraction is a major Australian emitter, a smaller Australian fossil fuel industry due to global decarbonisation reduces the amount of policy-induced decarbonisation (i.e., pricing of GHG) required under a given domestic emissions trajectory. Decarbonisation due to structural change is less costly than due to policy intervention.

## 2.2 Electricity and Energy sector

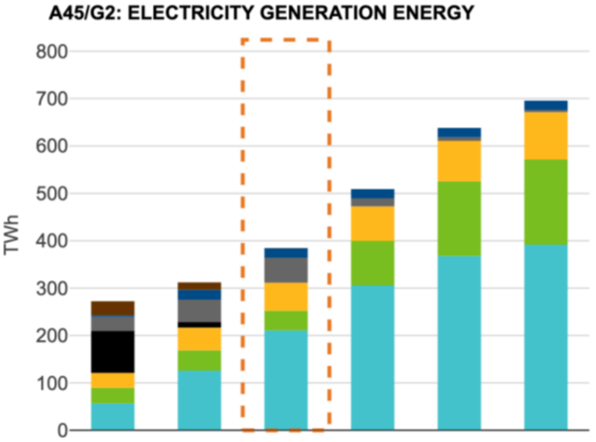
Historically, power generation in Australia has relied on coal- and gas-fired generation for grid power, and predominantly diesel generation in off-grid systems. Despite the historical dominance of non-renewable centralised electricity generation, there has recently been significant growth in the deployment 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% was coal-fired, followed by non-hydro renewables at 28%, natural gas at 18%, hydro at 6%, and oil (mainly diesel) at around 2% (DCCEEW, 2023a).



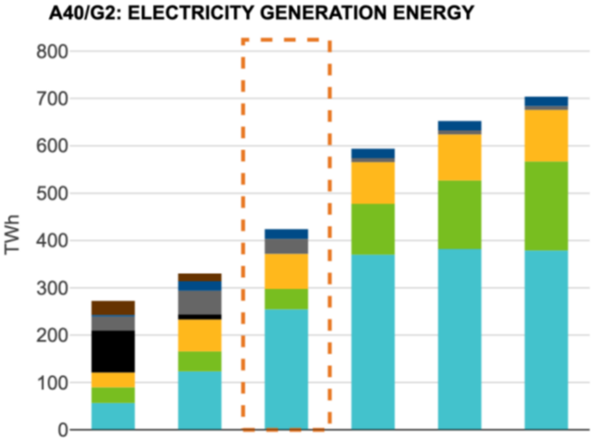
A50/G2: ELECTRICITY GENERATION ENERGY



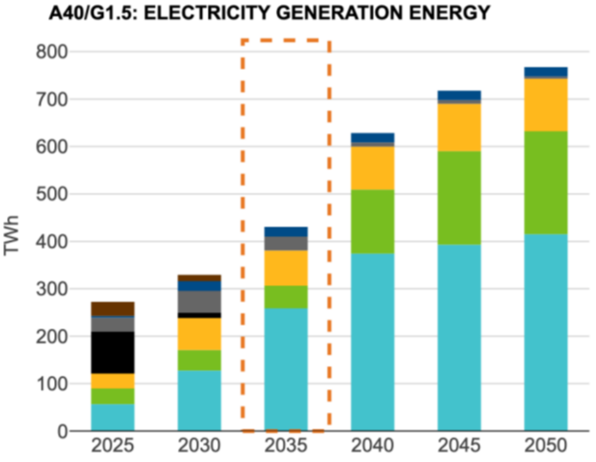
A50/G1.5: ELECTRICITY GENERATION ENERGY



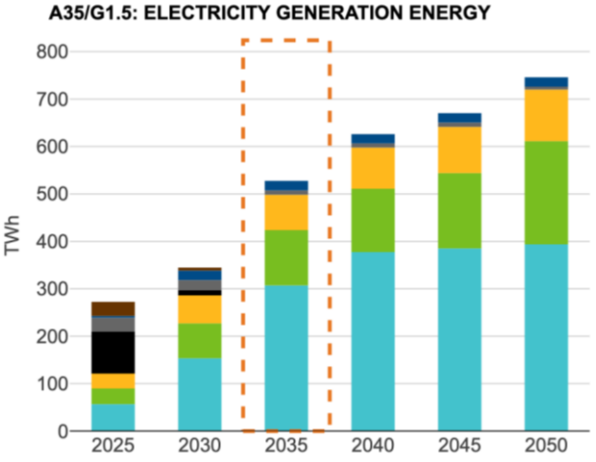
A45/G2: ELECTRICITY GENERATION ENERGY



A40/G2: ELECTRICITY GENERATION ENERGY



A40/G1.5: ELECTRICITY GENERATION ENERGY



A35/G1.5: ELECTRICITY GENERATION ENERGY

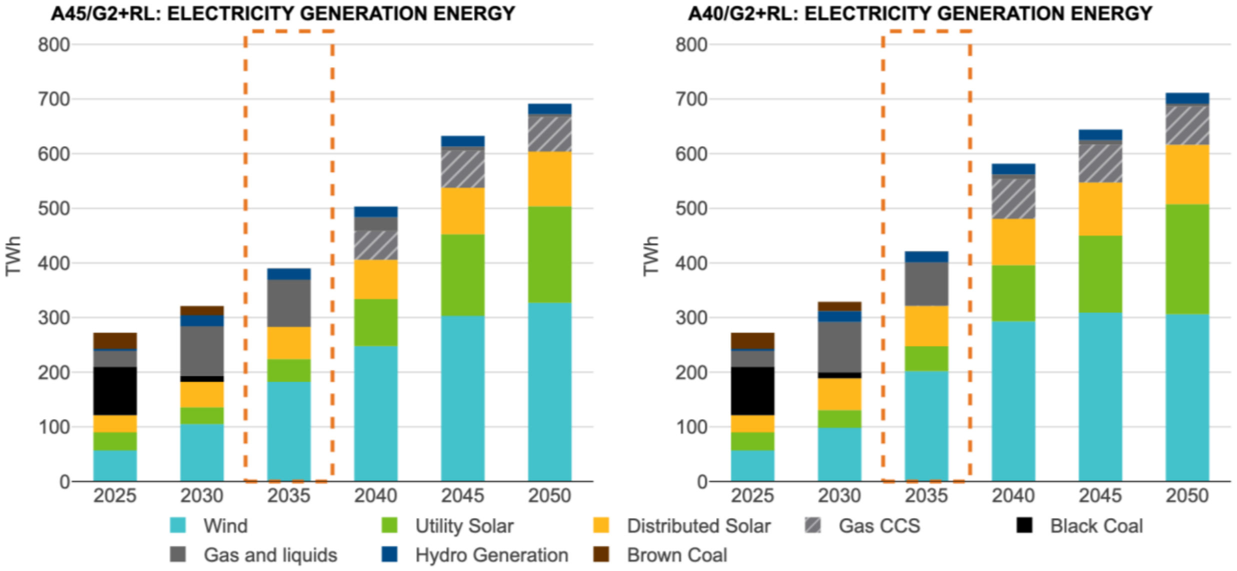


Figure 8 AusTIMES: Electricity generation by generation type

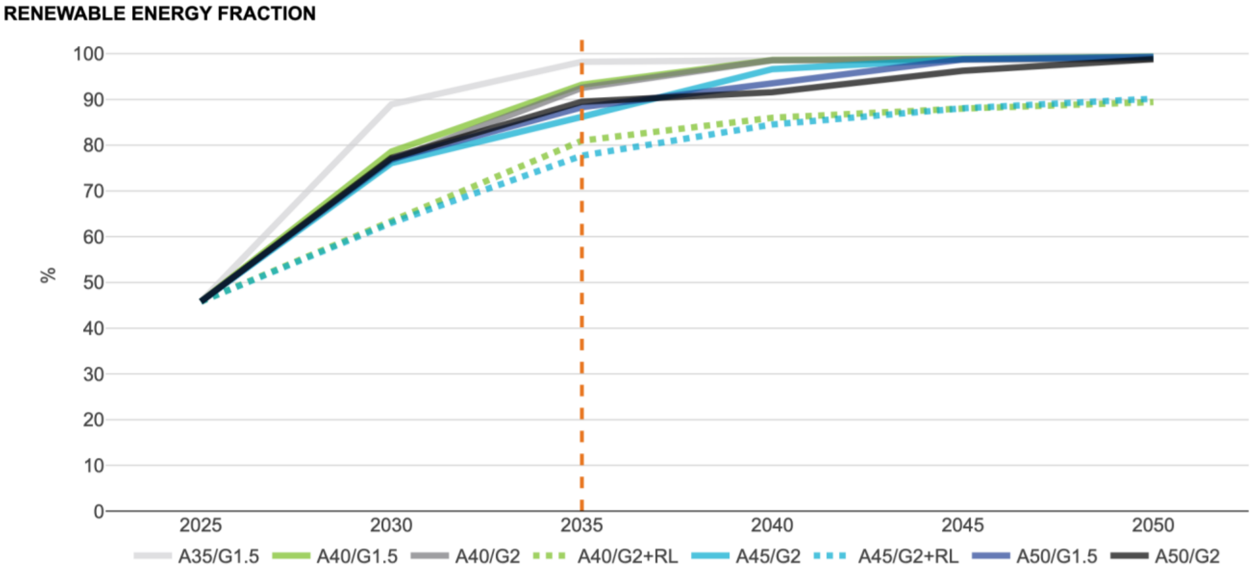
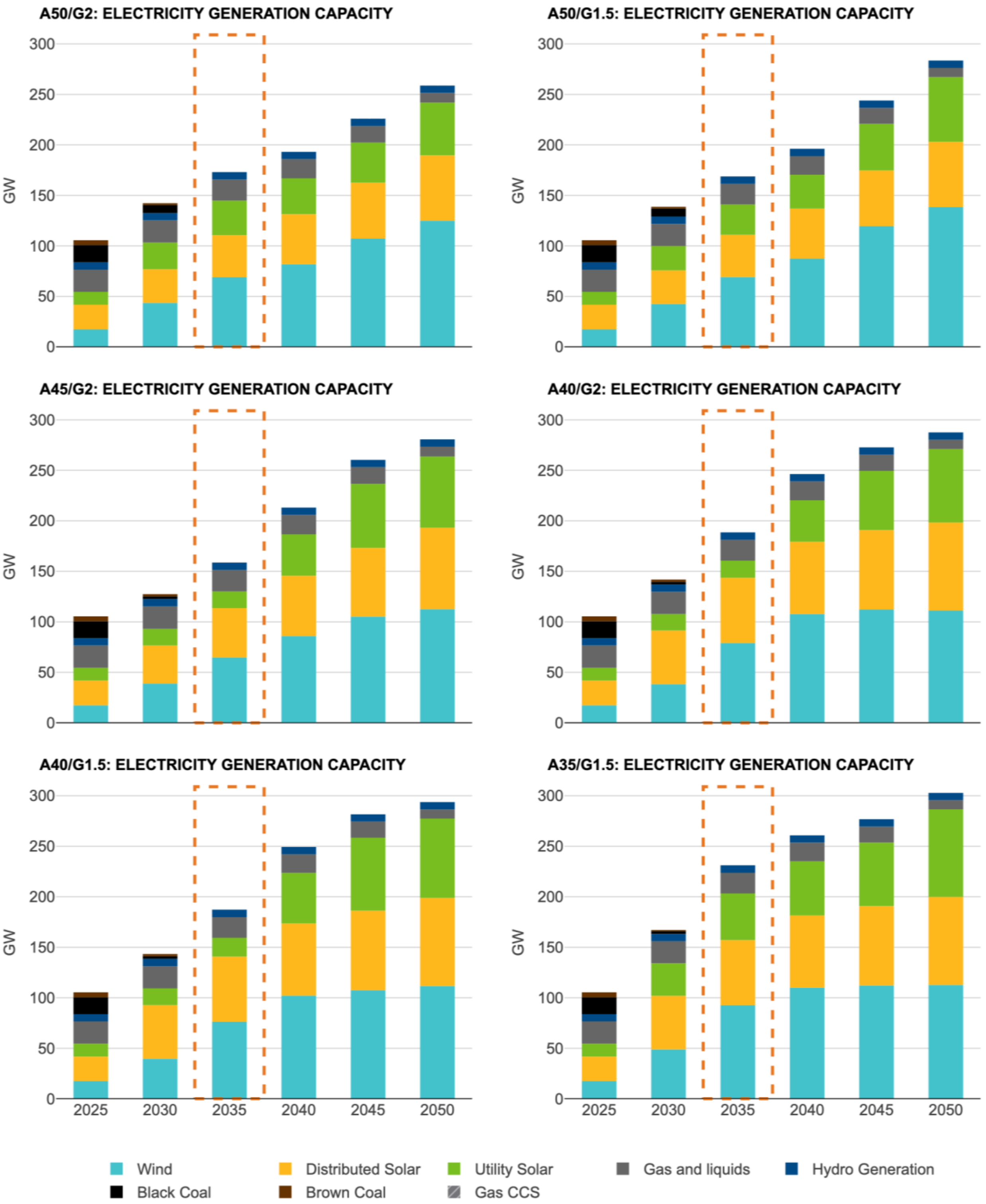


Figure 9 AusTIMES: Renewable energy fraction of generation

Under all 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 all scenarios reach at least 86% by 2035. 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 A35/G1.5 by 2035, and in A40/G1.5 and A35/G1.5 in the long-term.

The renewable constrained sensitivity cases ("+RL") have an additional constraint that limits the share of renewable electricity generation to 67% in 2030 and 83% in 2035. This is consistent with the 2023 DCCEEW Emissions Projections baseline scenario. The uptake of renewables is additionally constrained to 90% after 2035, with the results showing significant differences from their base scenarios (A40/G2 and A45/G2). The differences are increased gas-fired generation (without CCS) in the near term (out to 2035) with some uplift in brown coal-fired generation in 2030. Post 2035, gas with CCS is deployed as the next lowest cost option with near-zero emissions displacing the lower-cost zero-emissions wind generation from the base scenarios.

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


A50/G2: ELECTRICITY GENERATION CAPACITY
A50/G1.5: ELECTRICITY GENERATION CAPACITY
A45/G2: ELECTRICITY GENERATION CAPACITY
A40/G2: ELECTRICITY GENERATION CAPACITY
A40/G1.5: ELECTRICITY GENERATION CAPACITY
A35/G1.5: ELECTRICITY GENERATION CAPACITY
GW
0
50
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150
200
250
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Hydro Generation
Black Coal
Brown Coal
Gas CCS

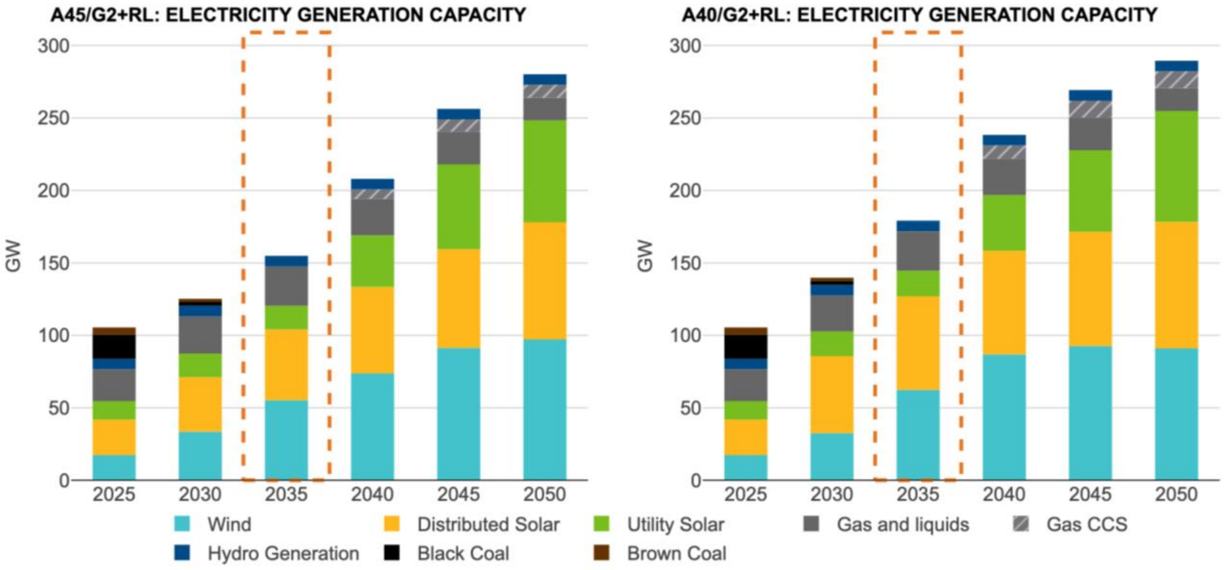


Figure 10 AusTIMES: Electricity generation capacity mix

The near-term state/territory and national renewable energy targets to 2030 mean that under all scenarios there is an average yearly deployment of between 6.5-11 GW of renewables and 1.5-3.8 GW of utility storage would be required. 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.

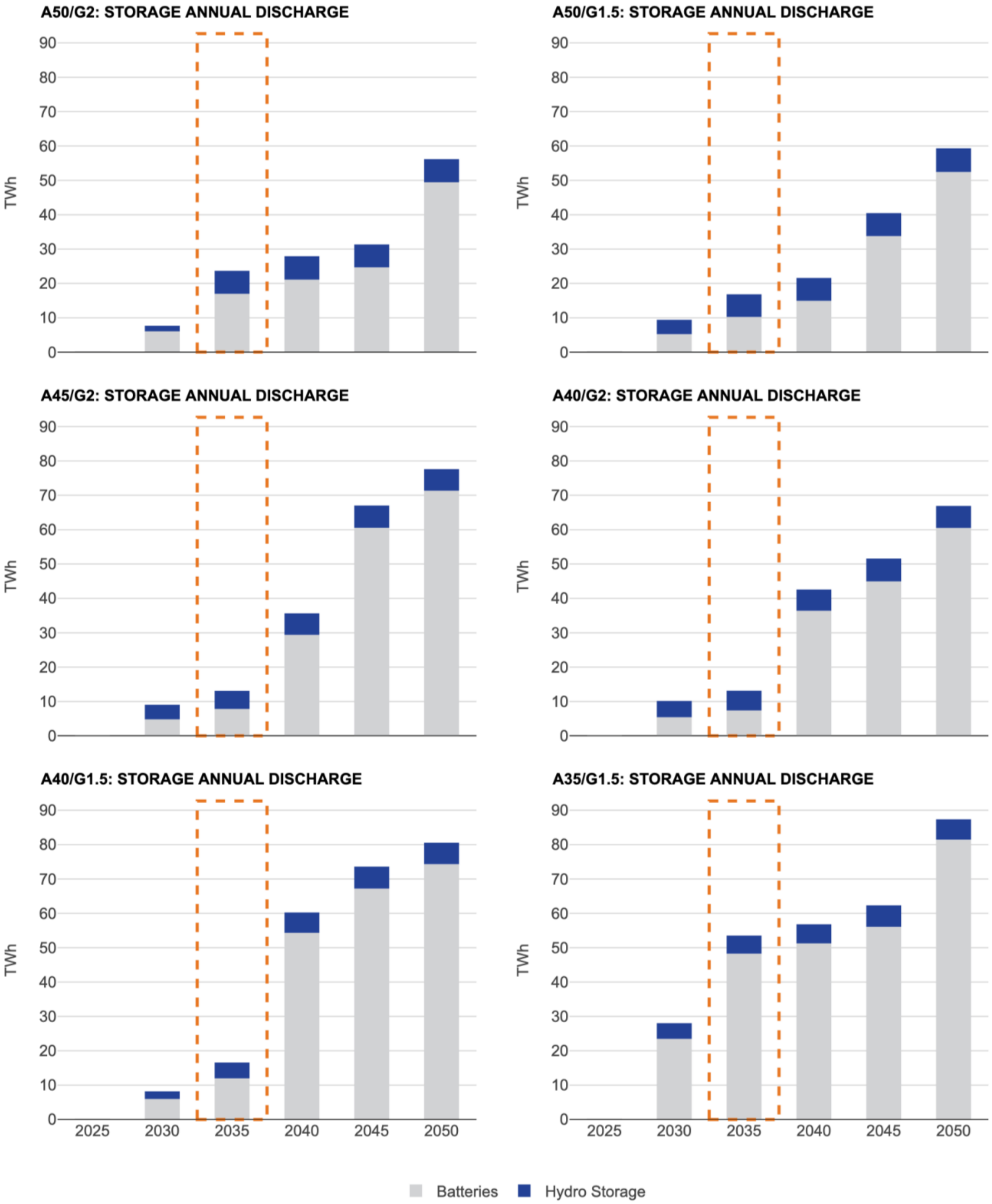


Figure 11 AusTIMES: Utility-scale storage annual discharge

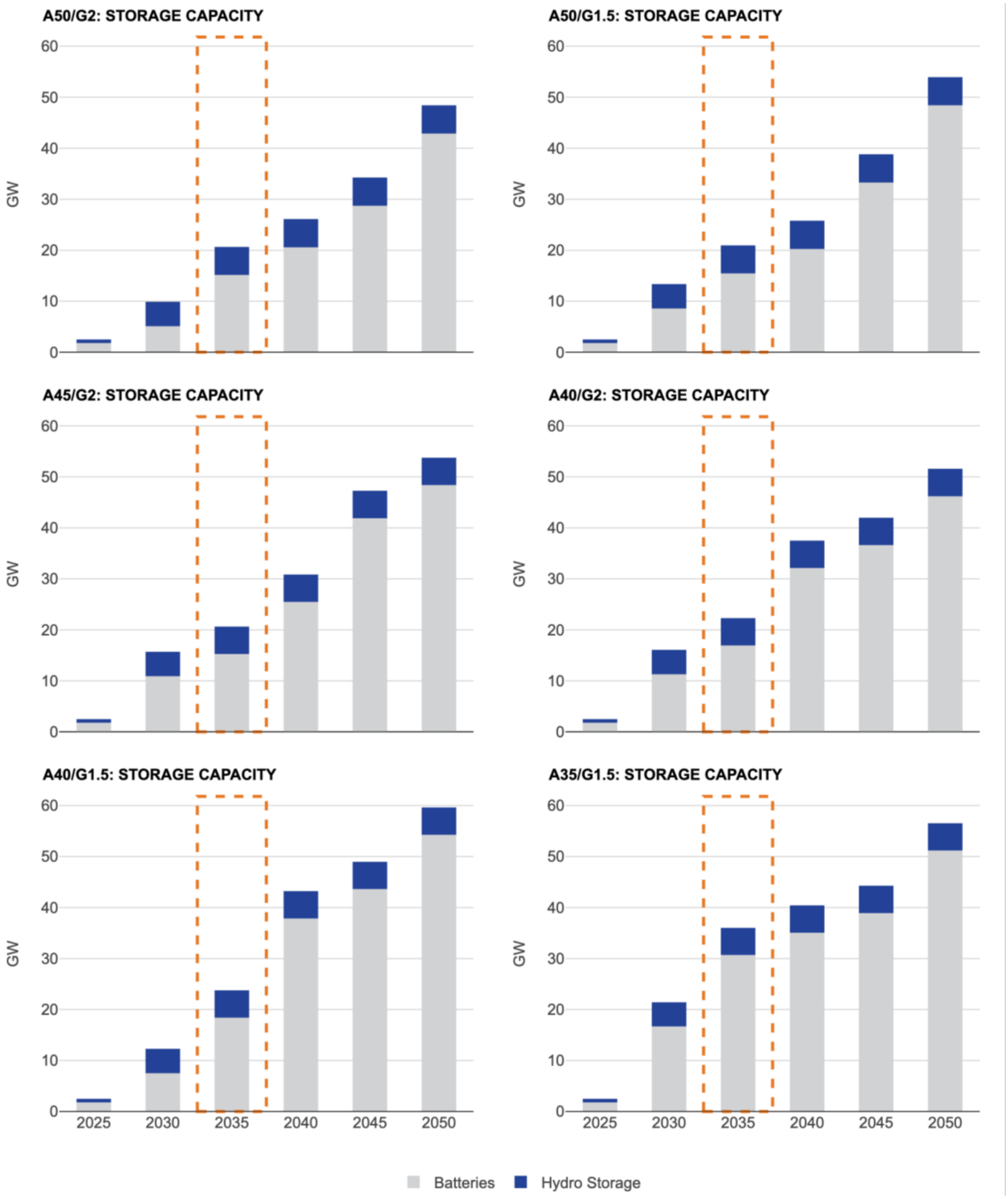
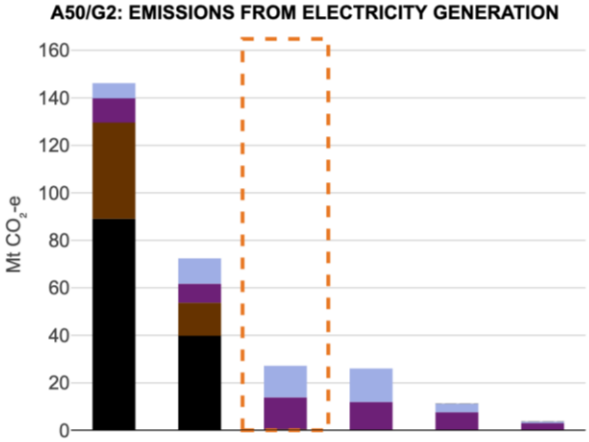
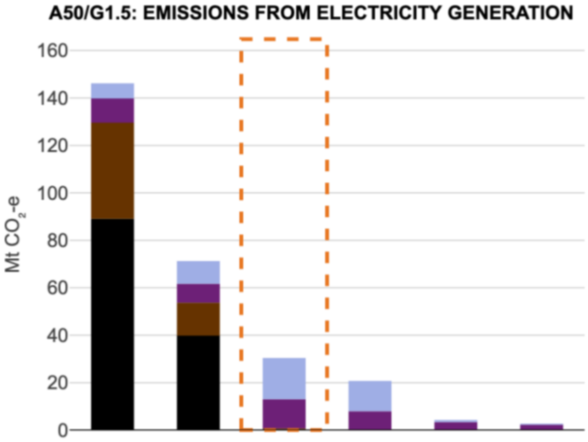
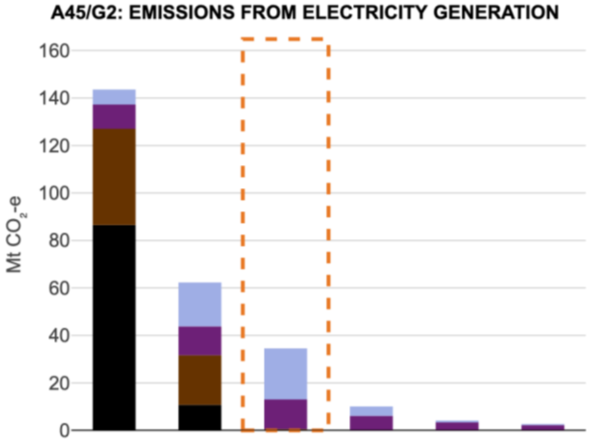


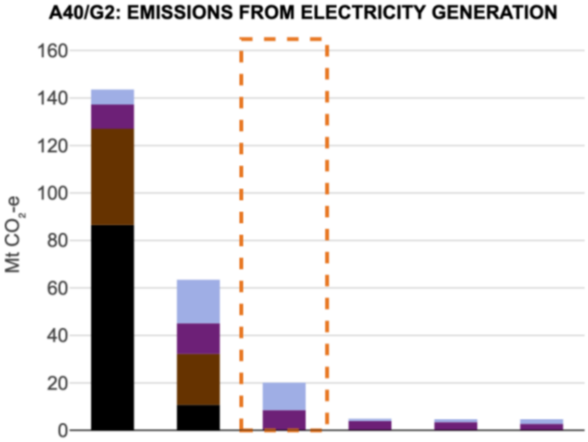
Figure 12 AusTIMES: Utility-scale storage capacity

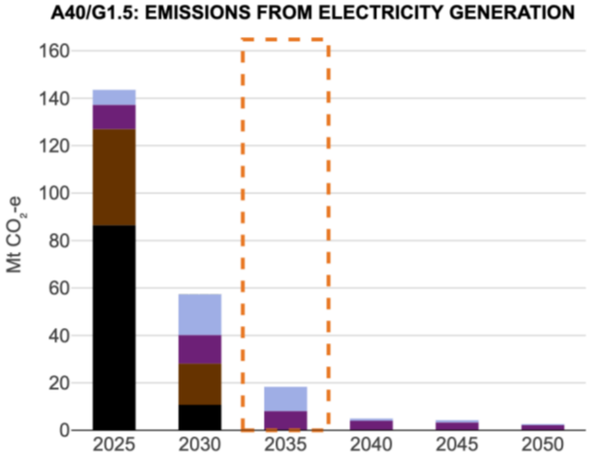
The deployment of utility-scale storage in all scenarios is significant (Figure 11 and Figure 12). In A50/G2 there is a greater share of short-duration storage over the projection period than in A40/G1.5 due to persistence of gas-fired generation. In A40/G1.5 the share of four- and eight-hour batteries is greater from 2040 onwards as there is less gas-fired generation and increased need for energy shifting of renewable energy. There is a notable surge in capacity near the net zero year in all scenarios to mirror the increased deployment of renewable energy.

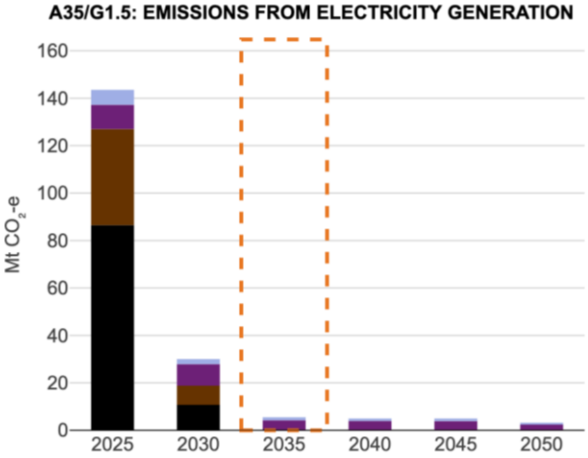

A50/G2: EMISSIONS FROM ELECTRICITY GENERATION


A50/G1.5: EMISSIONS FROM ELECTRICITY GENERATION


A45/G2: EMISSIONS FROM ELECTRICITY GENERATION


A40/G2: EMISSIONS FROM ELECTRICITY GENERATION


A40/G1.5: EMISSIONS FROM ELECTRICITY GENERATION


A35/G1.5: EMISSIONS FROM ELECTRICITY GENERATION

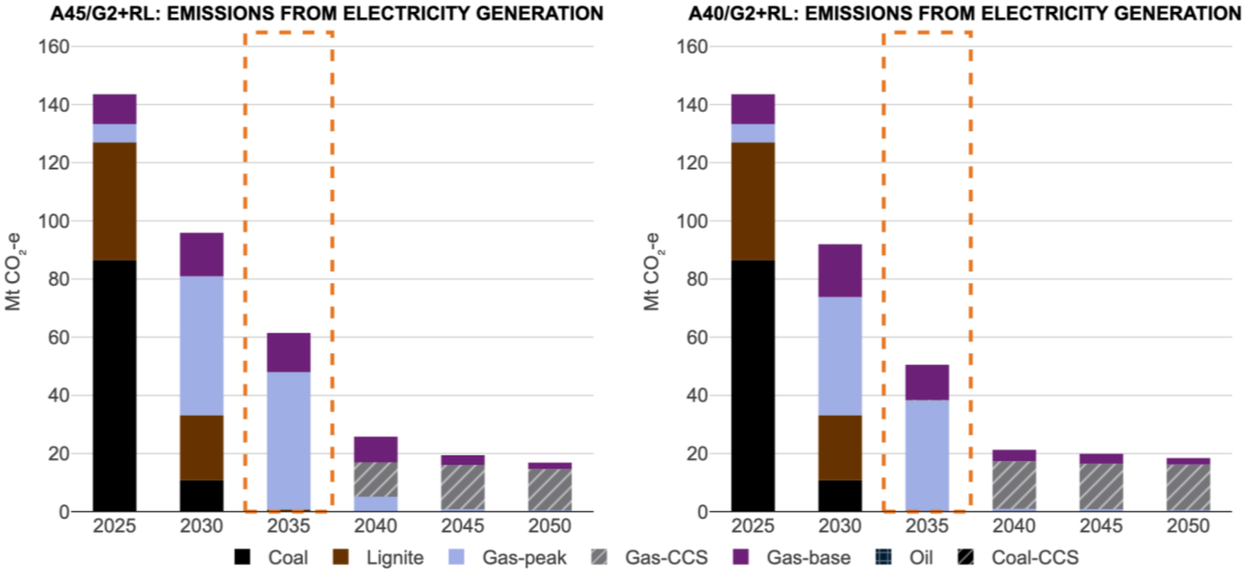


Figure 13 AusTIMES: Emissions from the electricity and energy generation sector

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 13). 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 14). 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. Reflecting the generation mix, emissions are much greater in the two "+RL" sensitivity cases with an additional 35-40 Mt $CO_2$-e in 2030 and 25-30 Mt $CO_2$-e in 2035, respectively, when compared to their core scenarios. Emissions also plateau at a higher level post-2035, at around 20 Mt $CO_2$-e.

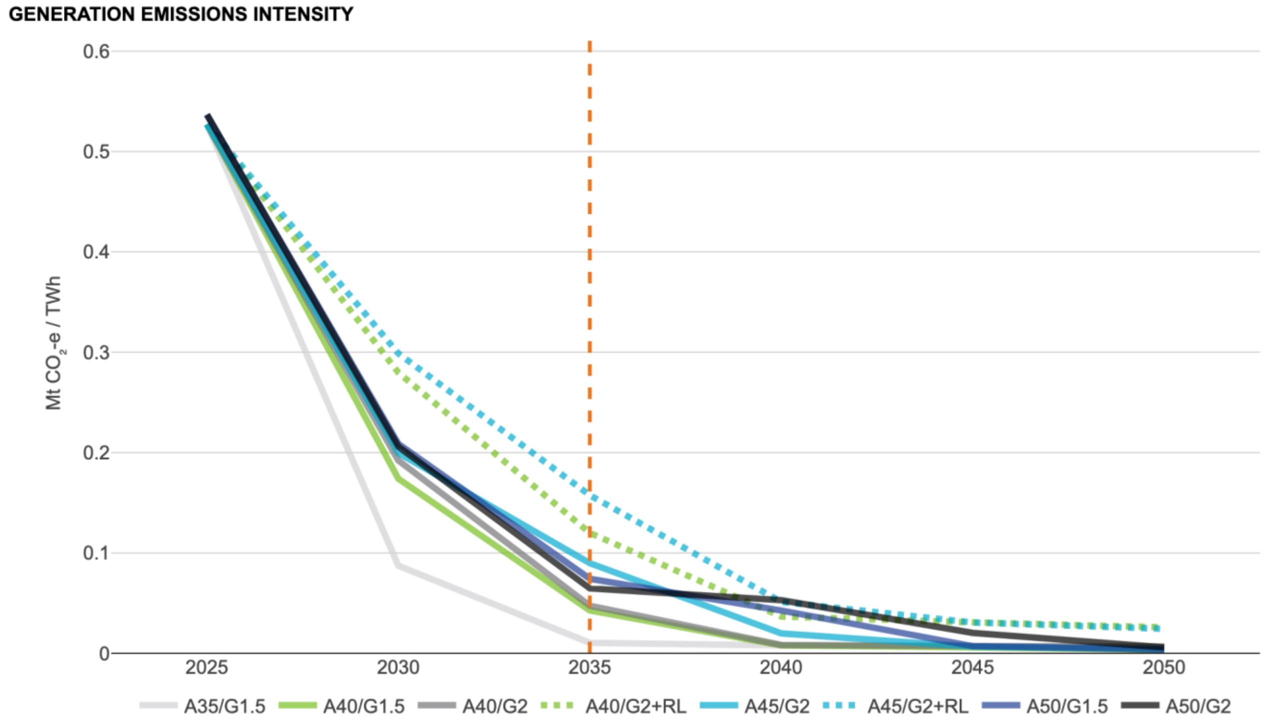


**Figure 14 AusTIMES: Emissions intensity of generation over time**

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 CCS; brown coal gasification with CCS; and SMR without CCS.

In all scenarios, most of the hydrogen production is from electrolysis. Most scenarios also showed a significant fraction of hydrogen production coming from SMR accompanied by the capture and storage of emissions from that process (Figure 14 and Figure 15), with two exceptions. In A50/G2, most SMR production of hydrogen did not include the capture and storage of emissions. In the most stringent scenario, A35/G1.5, SMR did not play a material role. Hydrogen demand is greatest in A40/G1.5 due to the more stringent emissions reduction trajectory and the 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.

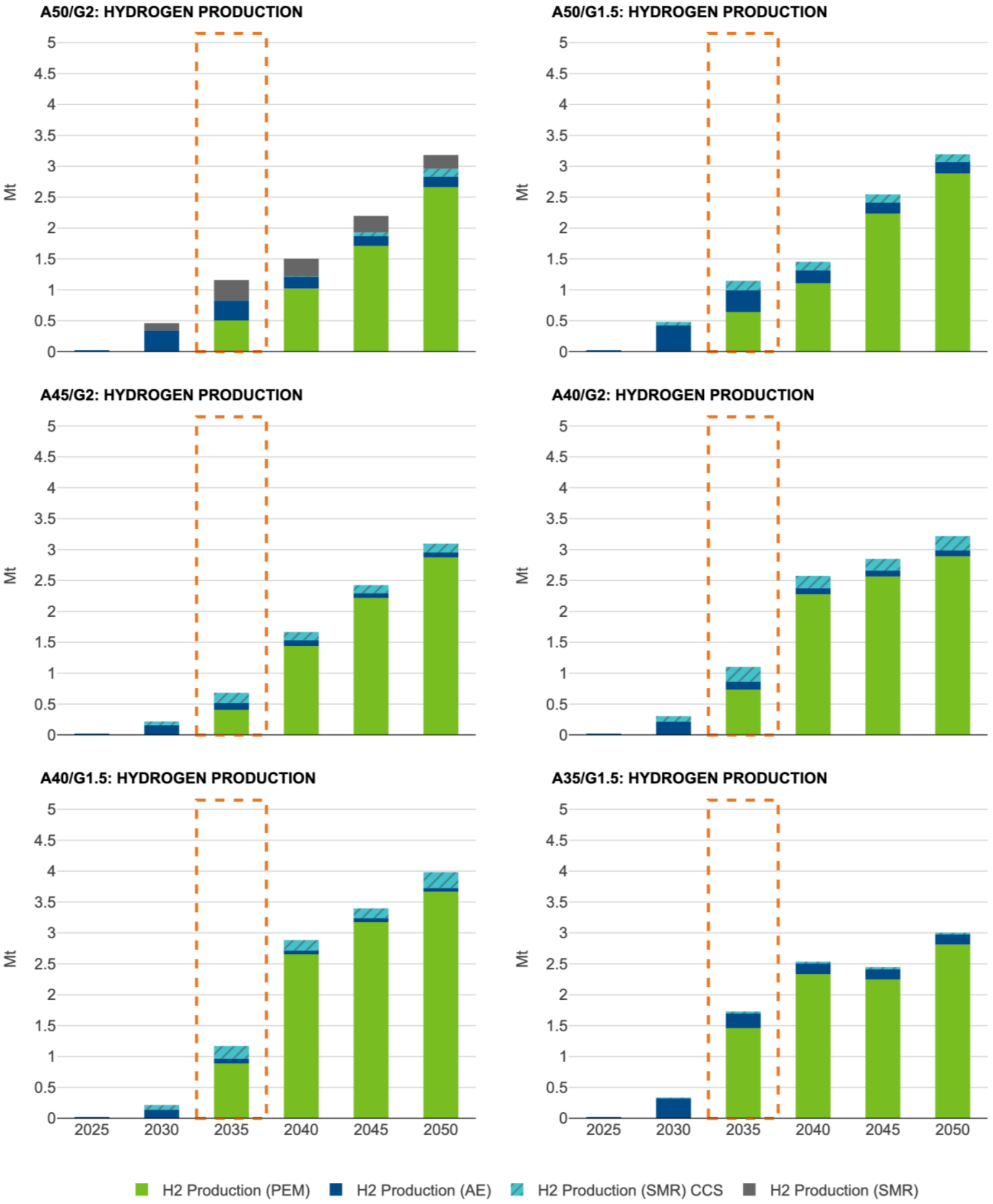


Figure 15 AusTIMES: Hydrogen production by technology

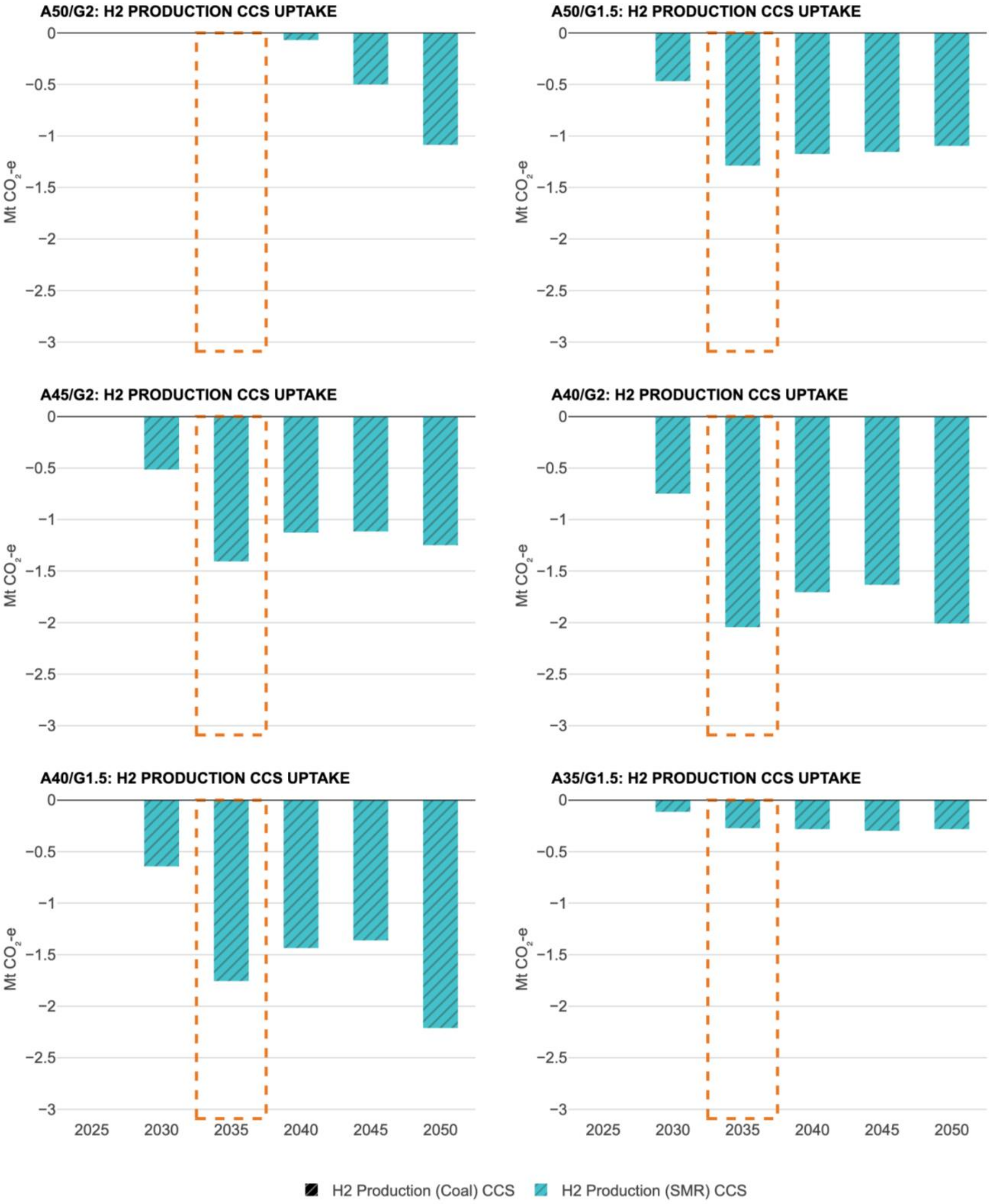


Figure 16 AusTIMES: CCS uptake in H2 production

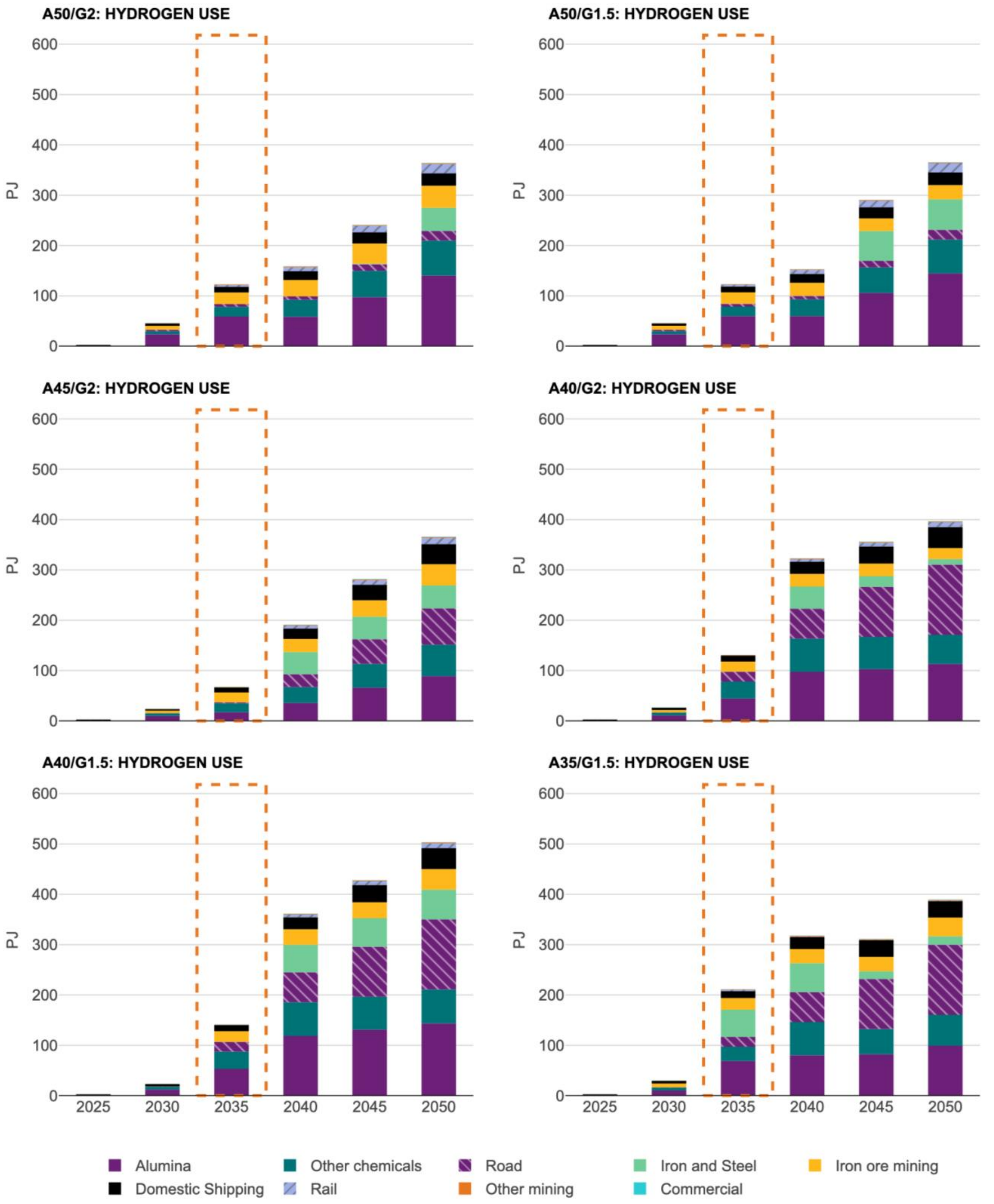


Figure 17 AusTIMES: Hydrogen consumption by sector[8]

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[8] The charted results for hydrogen use for scenarios A50/G2 and A40/G1.5 differ slightly (less than 1%) from those presented in the two-scenario version of this work due to a minor correction to the calculation which applies the energy intensity factors for hydrogen production processes. Although hydrogen production is greater in A50/G2 than A35/G1.5, the hydrogen consumption is less because of hydrogen embedded in synthetic kerosene, not included in energy consumption in Figure 17.

## 2.3 Industry and Resources

### 2.3.1 Industry Sector Output

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

Industries that exhibit negative growth are coal mining, gas extraction, gas export, oil mining, and petroleum refining (Figure 18). Gas export levels vary greatly by scenario, with the A40/G1.5 and A35/G1.5 showing transient positive growth. This reflects assumptions regarding gas output, which are constant across all G1.5 scenarios and based on IEA projections. This causes transient positive growth in exports depending on the speed with which the economy moves to net zero emissions.

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

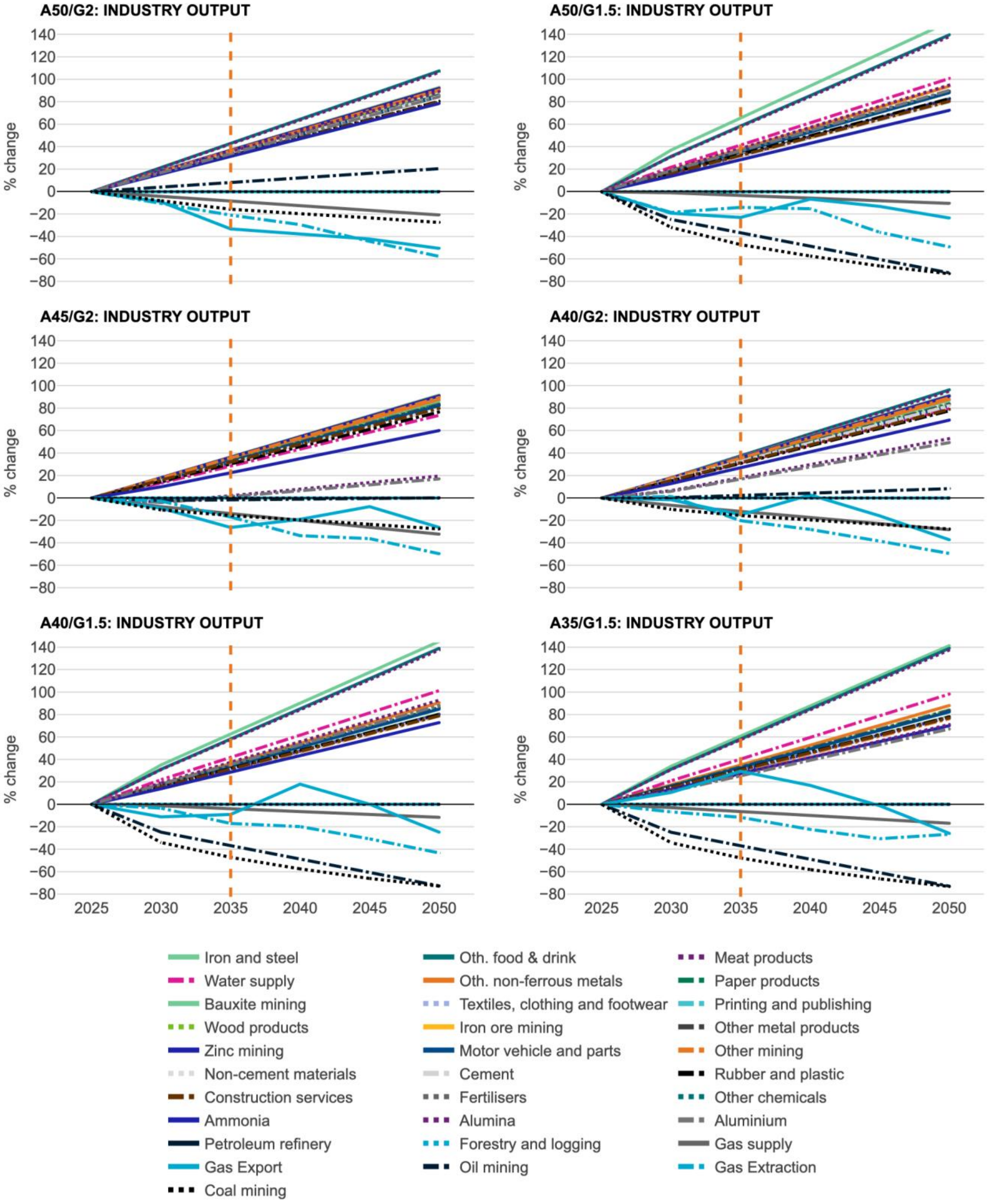

Figure 18 GTEM and AusTIMES: Growth in the volume of industry output

### 2.3.2 Industry Sector Energy Consumption and Intensity

Despite overall industry growth through to 2050, energy consumption remains largely flat, i.e., energy efficiency improves. The 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 and represents the largest of the technology adoptions across the industry sector. The specific industries that 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 (liquified natural gas (LNG), via compressor electrification and waste heat recovery), ammonia (via feedstock substitution of natural gas for hydrogen[10]), and cement (via material substitution of Portland cement).[11]

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 over a range of timelines from near 2045 in A50/G2 through 2035 for A35/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.

### 2.3.3 Industry Sector Emissions Reduction and Intensity

Emissions are reduced to approximately one-third (around 55 Mt $CO_2$-e) of their 2025 levels by the net zero year for the A50/G2, A50/G1.5, and A45/G2 scenarios (see Figure 21). The remaining scenarios achieve net zero emissions earlier, with emissions falling to around 60 Mt $CO_2$-e by those years. 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).

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 exhibit a smaller relative emissions reduction (see Section 2.3.5 for further breakdown).

Carbon capture and uptake of emissions-reducing technologies (e.g., material substitution and process improvements) play a significant role in achieving emissions reductions across the industry sector and in all 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. The uptake of these costed abatement measures is driven to earlier years for scenarios with more ambitious net-zero years.

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

[11] While the model may sometimes show smooth changes in capacity for production technologies, in reality these shifts typically occur as step changes when industries or facilities switch to new technologies.

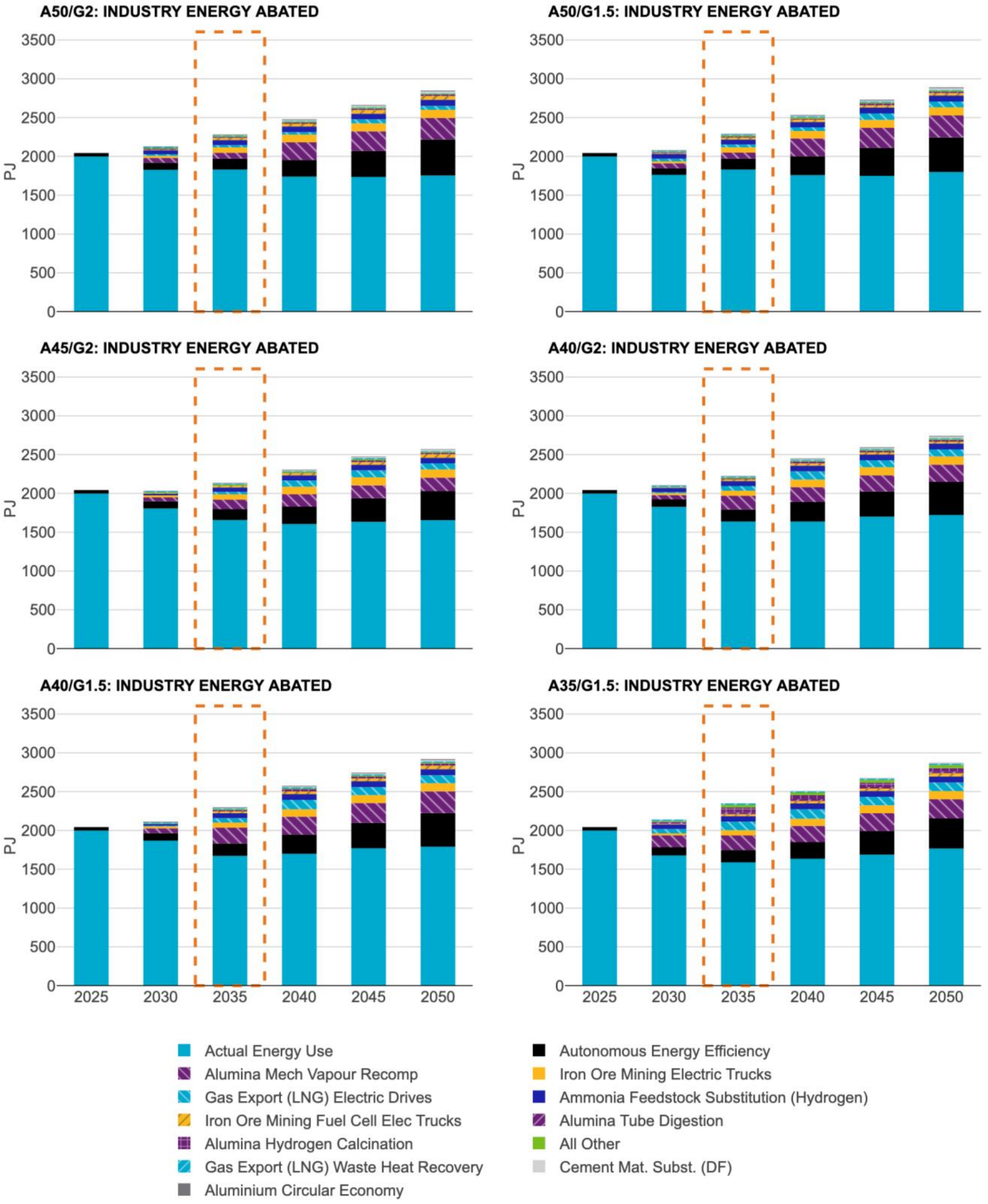

**Figure 19 AusTIMES: Industrial energy abated compared to counterfactual energy efficiency**

**This figure shows how the energy efficiency, process improvements, material substitution, and new technology adoptions contribute to a reduced energy demand over the counterfactual, which assumes no uptake of emissions capture or abatement related process improvements.**

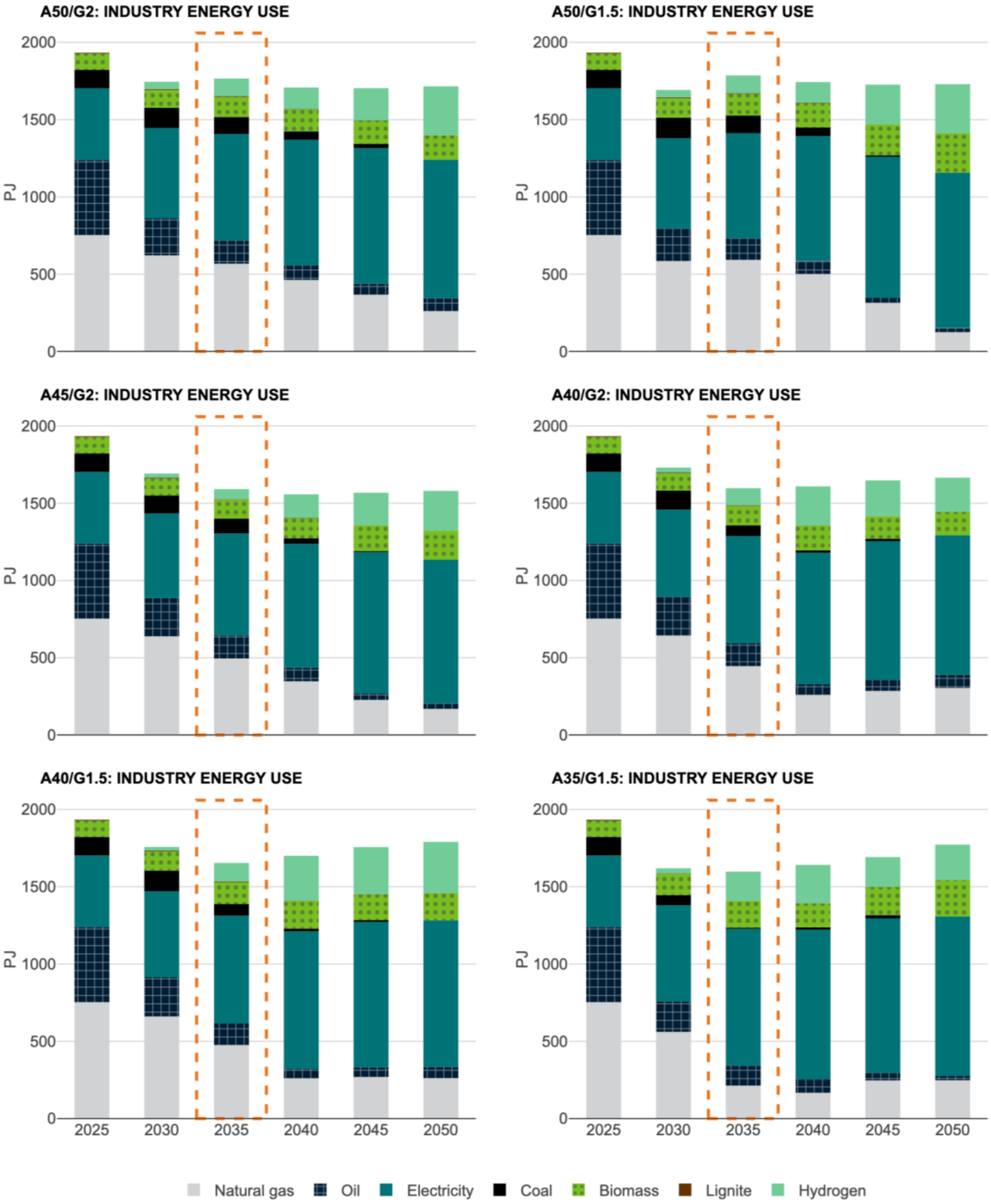

**Figure 20 AusTIMES: Industry energy use by fuel type**

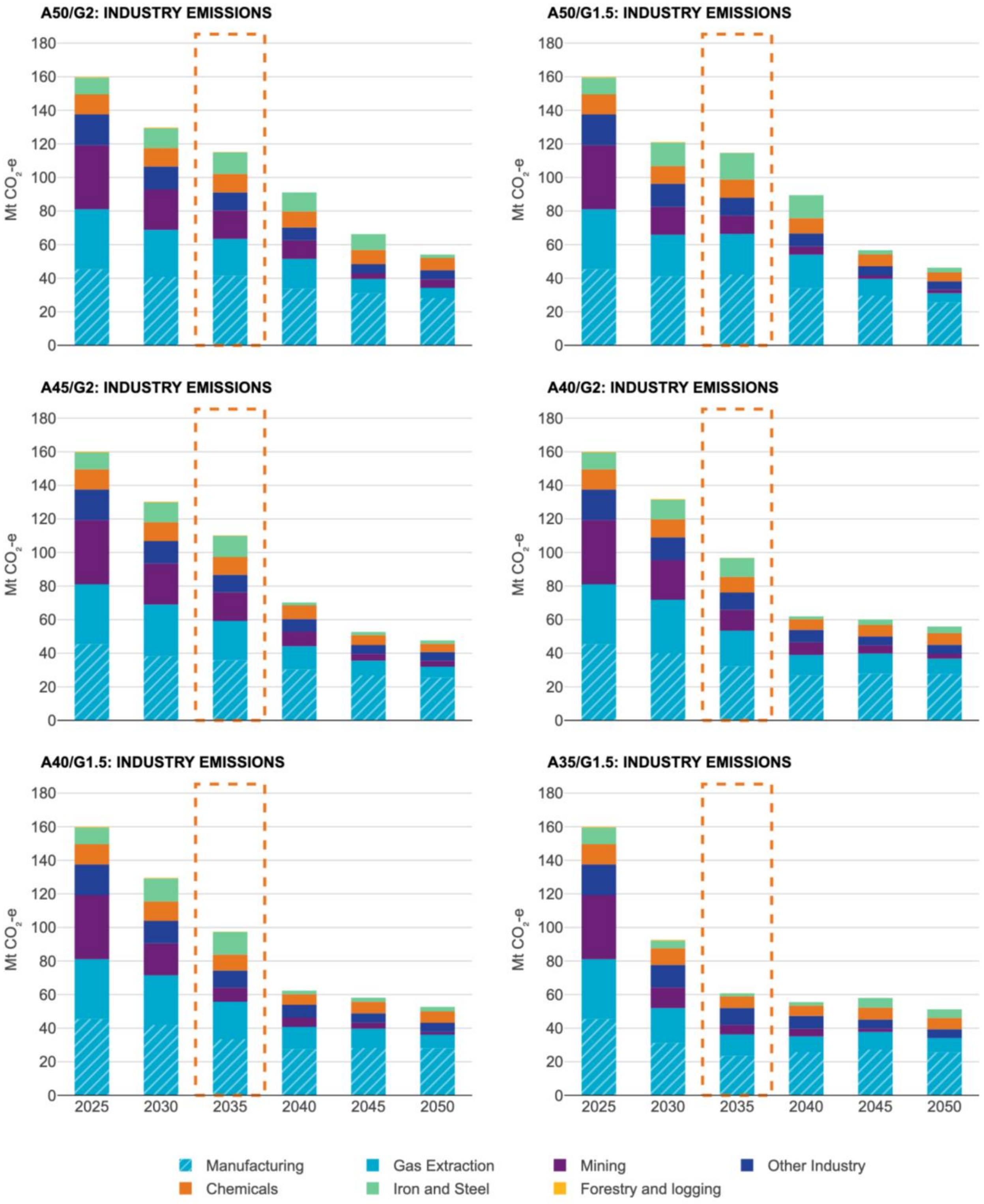

Figure 21 AusTIMES: Industry emissions by subsector

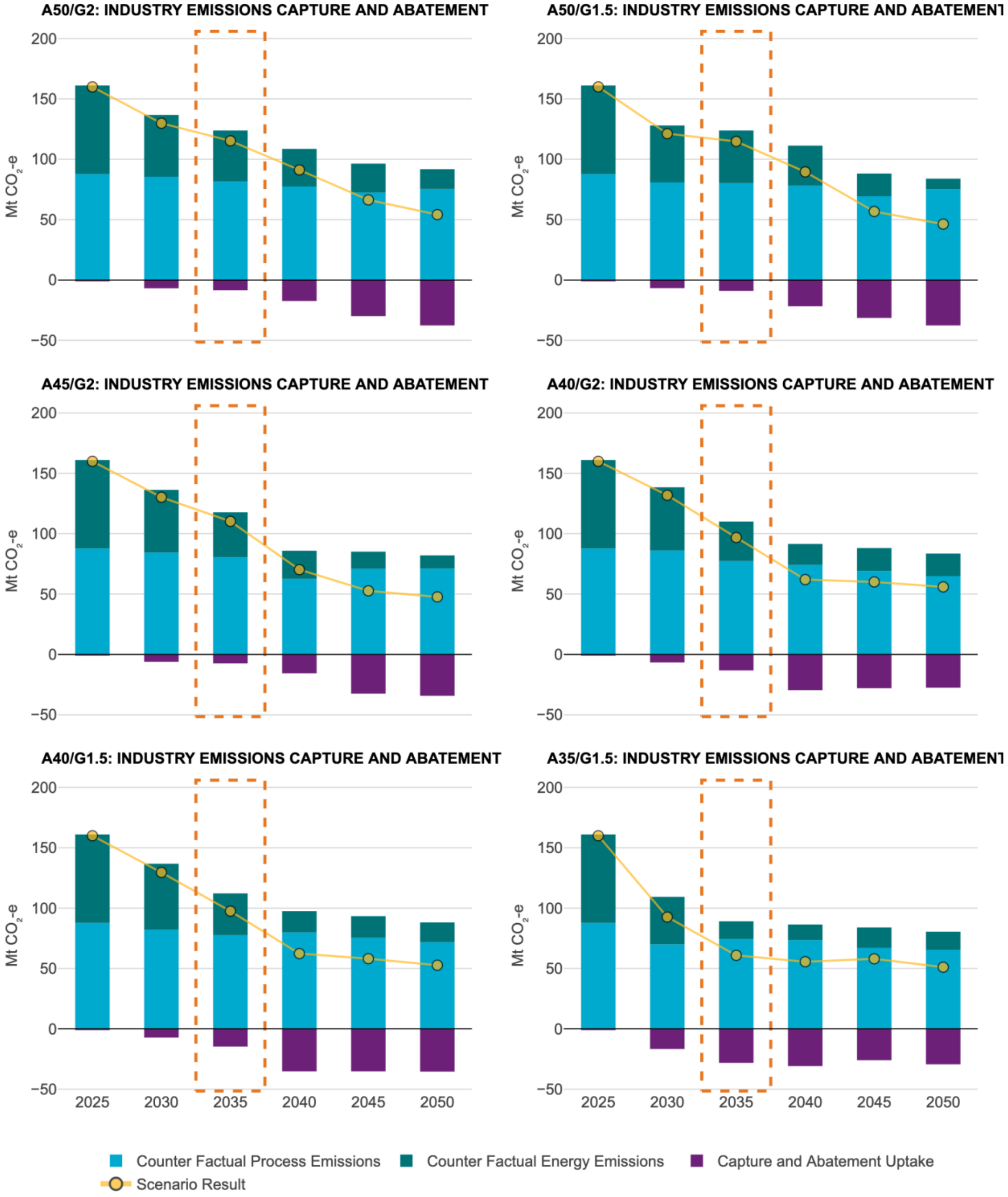

**Figure 22 AusTIMES: Industry sector abatement technology and process uptake**

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

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

The energy use in fossil fuel extraction (not including that used for gas export) is shown in Figure 23, with coal, gas, and oil all declining.

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 transient increase in gas export in A40/G1.5 and A35/G1.5 is driven by the faster global decarbonisation under that scenario and the subsequent higher demand for gas as a near term interim fuel.

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 26 further details the technology and process uptake driving the reduction in emissions, which shows more aggressive uptake of these methods with increasing scenario ambition. In addition to replacing diesel engines in heavy machinery and transportation with electric or fuel cell drivetrains, methane-fugitives-reducing methods in coal mining, CCS in gas and oil extraction, and the carbonation of mine waste rock (tailings) are taken up in both nickel and bauxite mining (small negative emissions in Figure 26). In the gas export industry, further leak detection and repair (LDAR) and the centralisation of gas supply networks also contribute to lower emissions.

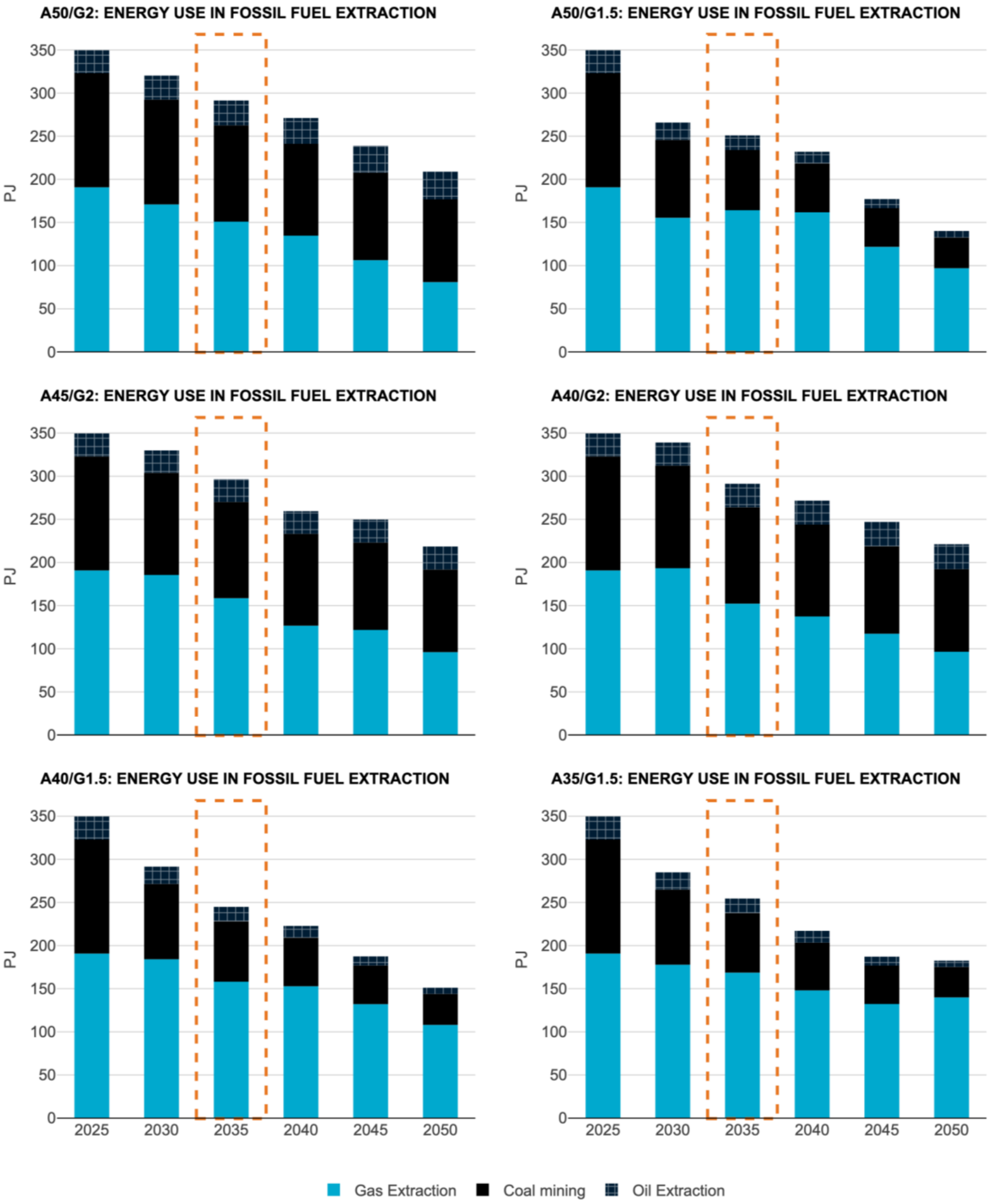

Figure 23 AusTIMES: Energy use in fossil fuel extraction

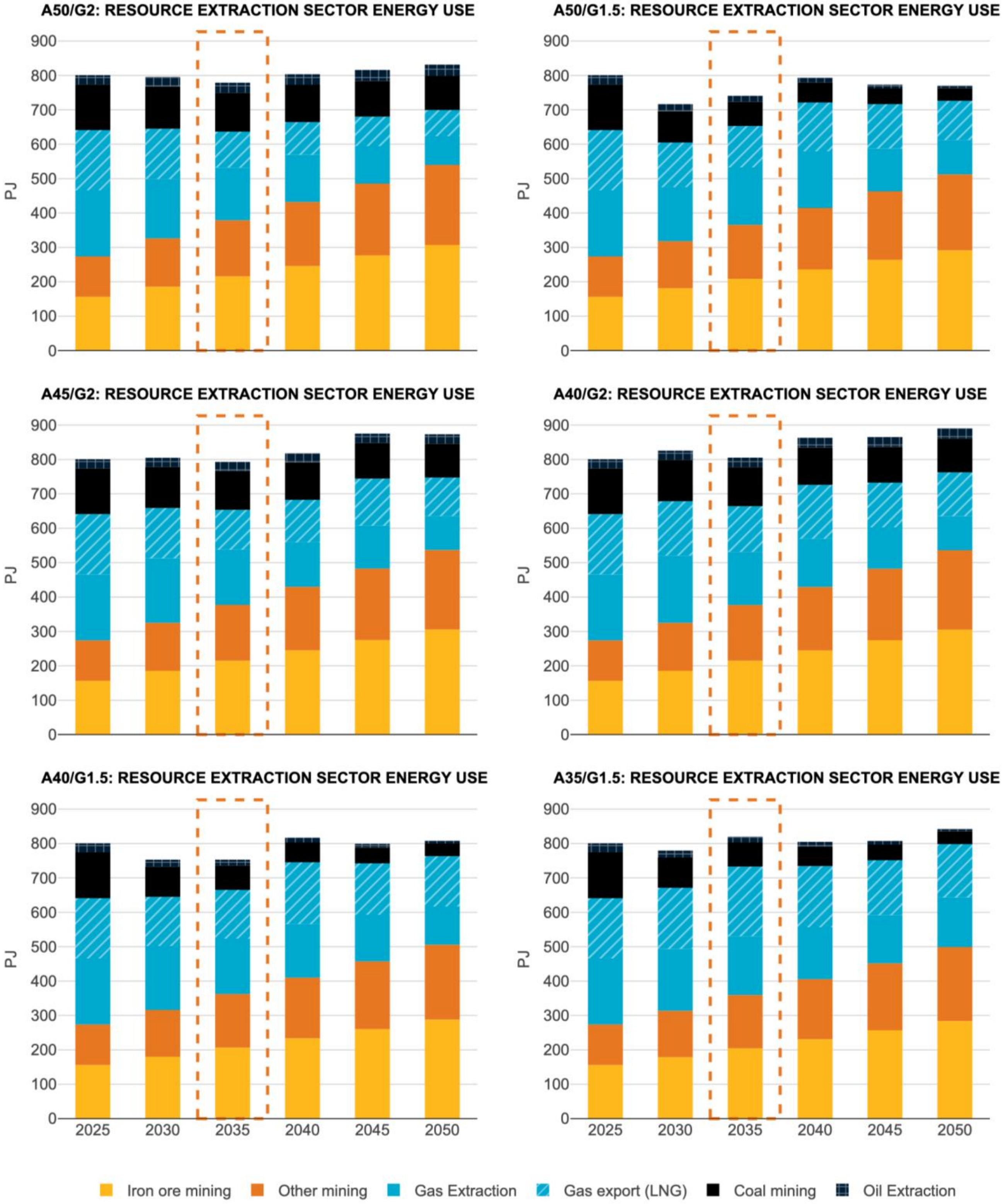

**Figure 24 AusTIMES: Energy use by resource extraction (mining, gas extraction and export industries)**

**Gas extraction is endogenous to the AusTIMES model to meet domestic and export demand. Gas export (LNG) is the liquefaction process to convert extracted gas to exportable LNG.**

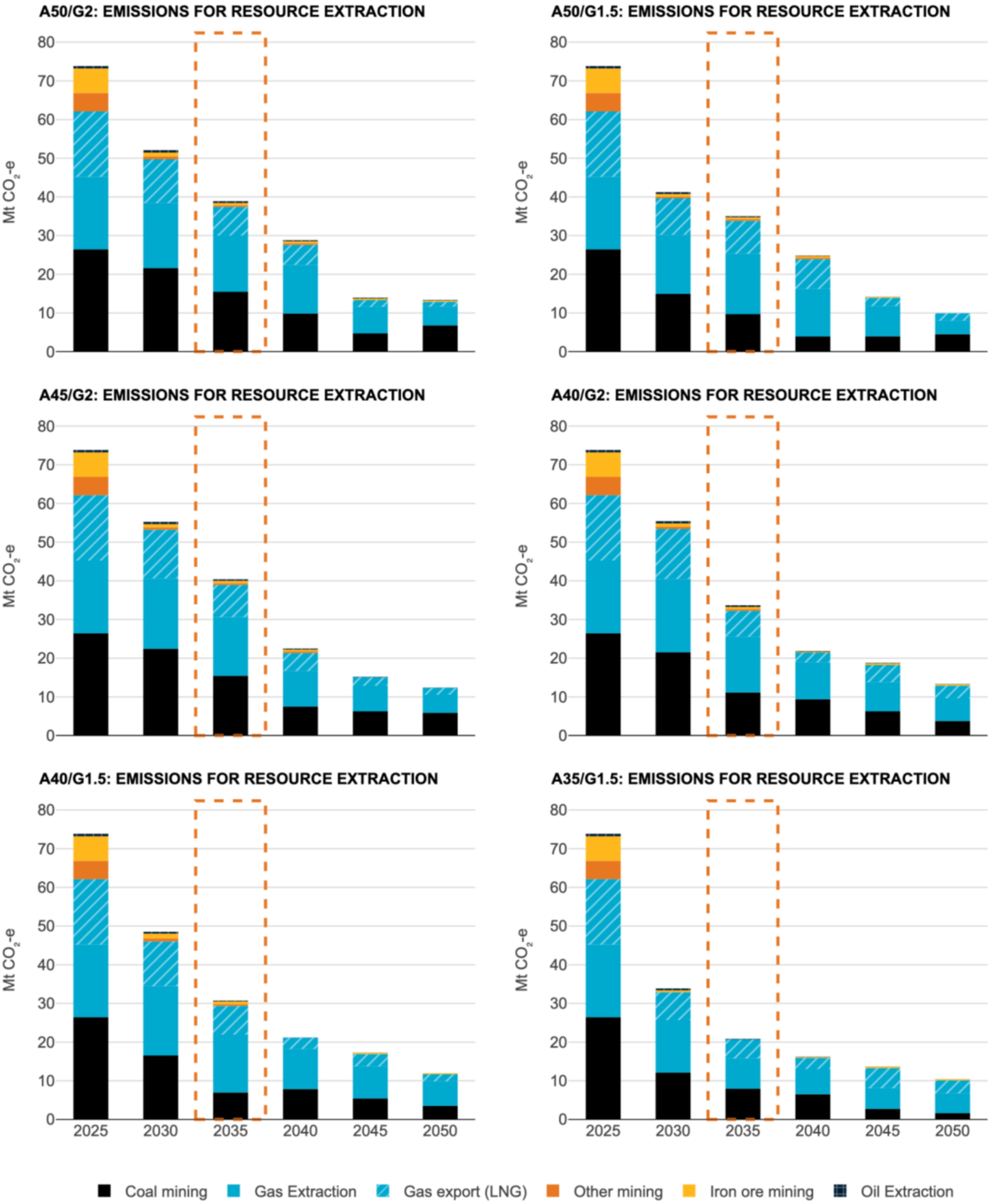

Figure 25 AusTIMES: Resource extraction (mining plus gas extraction) emissions

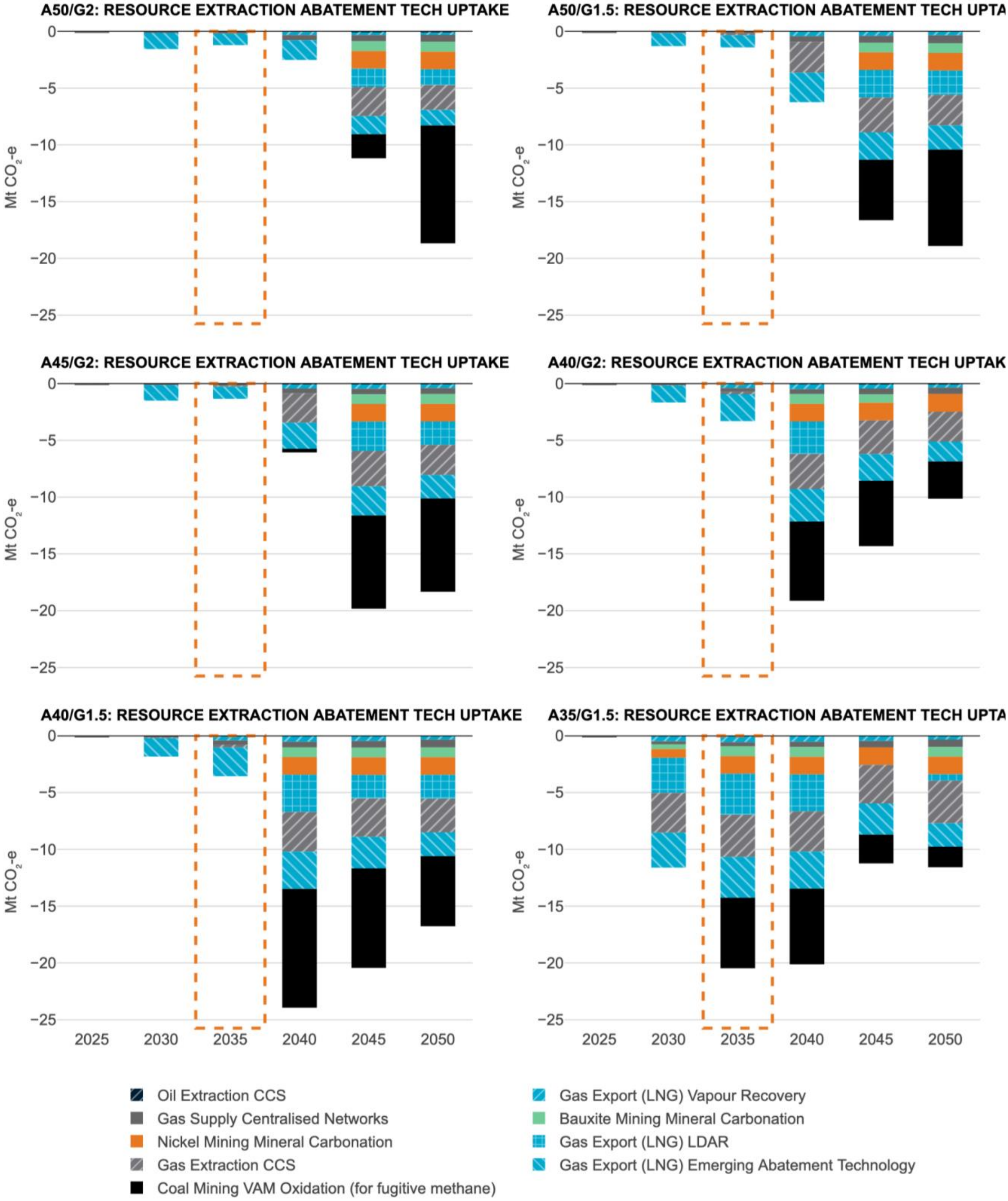

**Figure 26 AusTIMES: Resource extraction (plus Gas Supply) sector uptake of CCS and other emissions reducing processes and technologies.**

### 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 that can be taken up.[12] 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. For A35/G1.5, the switch to MBOF occurs earlier (in 2030) and uses natural gas as its fuel source before switching to hydrogen in 2035.

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

For the A40/G2 and A35/G1.5 scenarios, Figure 28 shows a switch back to natural gas from hydrogen in the post net-zero years. This is due to a combination of two constraints being simultaneously imposed on the model. The first is the overall net emissions pathway, including the net zero emissions year, which in these cases are 2035 or 2040. The second is the negative emissions pathway reflecting land-based sequestration and direct air capture. The model solves only for the remaining abatement method uptake (e.g., CCS, process improvements, material substitution, etc.) and gross emissions subject to these previous constraints. For these two scenarios, there is a steep pathway to net zero, and a correspondingly steep decrease in positive emissions to meet those net zero years. However, after the net zero year, the constraints require relatively large growth on negative emissions, which allows for an increase in positive emissions as long as net emissions do not exceed the overall emissions pathway constraint. Therefore, in sectors such as iron and steel, where the cost of conventional technologies is still lower than the cost of mitigation technologies, emissions increase to reach the least-cost outcome. It is likely that this is not a realistic outcome, and that hydrogen would continue to be used.

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[12] The appearance of DRI in iron and steel in 2025 is not historical capacity, but rather initial uptake of that technology as it is first available to the model starting 2025. This is related to the 2025 gas consumption by iron and steel as the uptake of gas-based DRI sees an increase of near 9 PJ of natural gas as a feedstock. The increase of 9 PJ natural gas is associated with the decarbonisation of existing facilities (rather than new production capacity). In addition, green iron projects are in the pipeline that plan to use natural gas until hydrogen is ready.

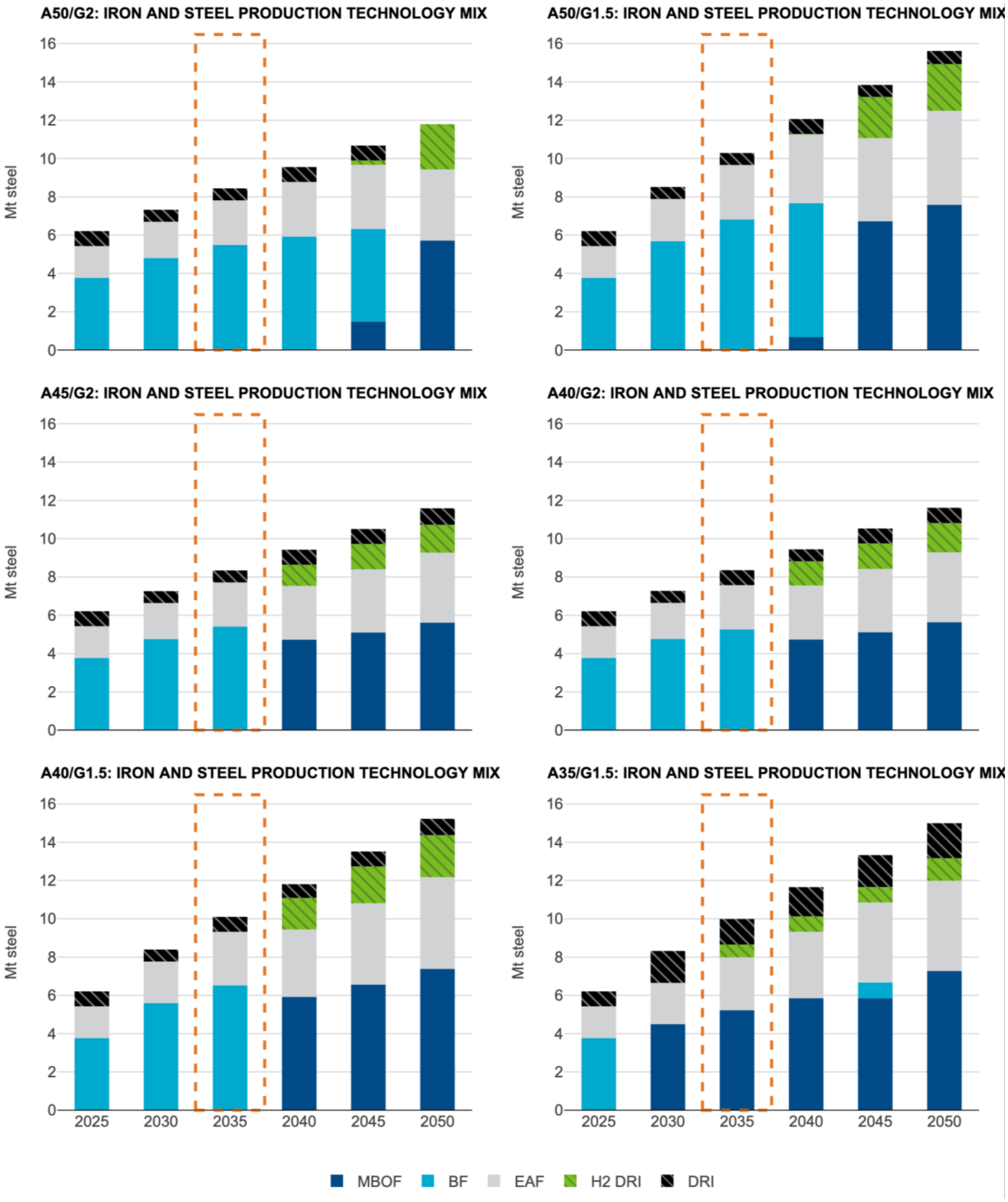

Figure 27 AusTIMES: Iron and steel production technology mix[13]

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[13] In the AusTIMES model, the DRI process can use natural gas or hydrogen, whereas the H2-DRI process can only use hydrogen.

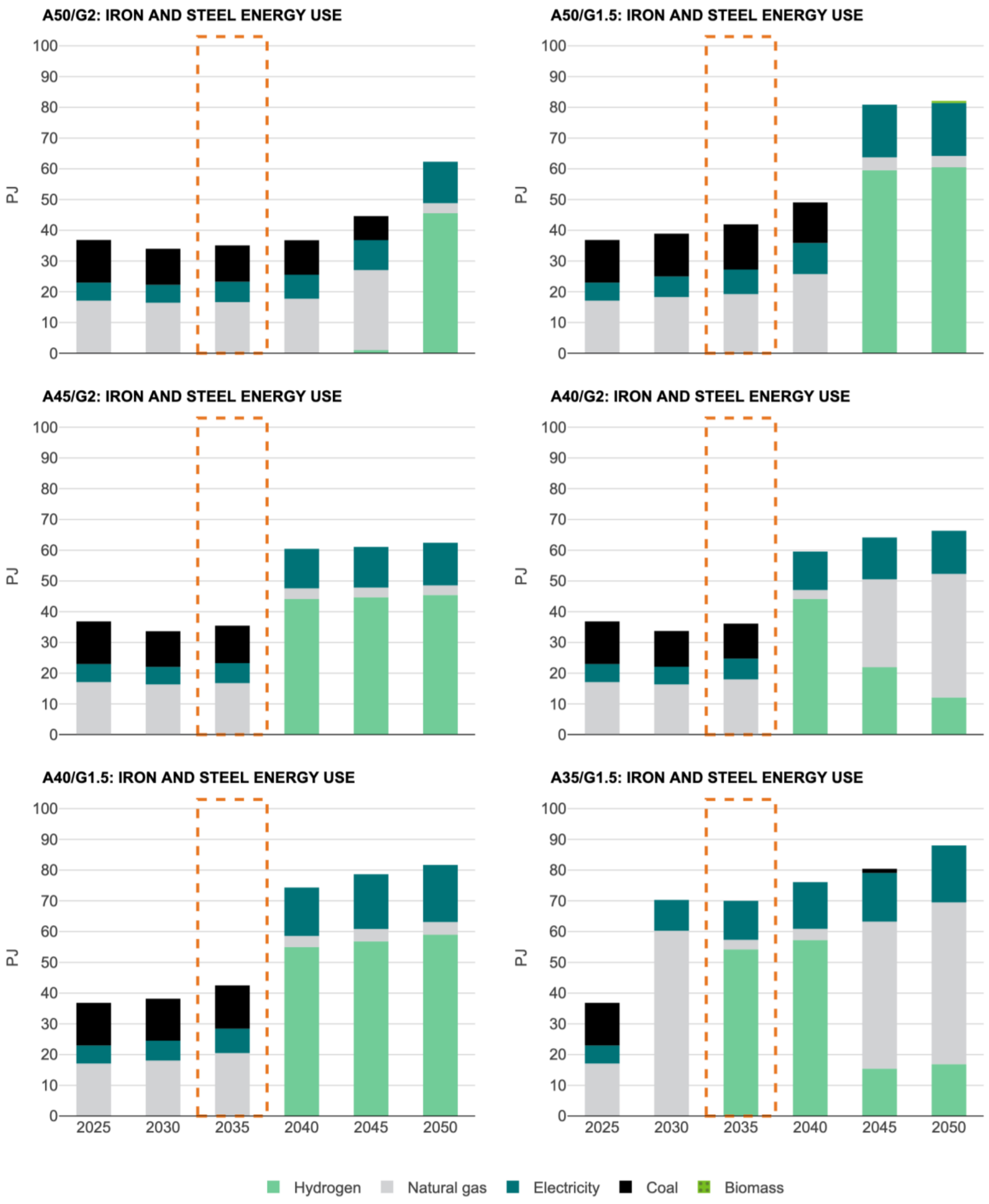

**Figure 28 AusTIMES: Iron and steel energy use by fuel type**

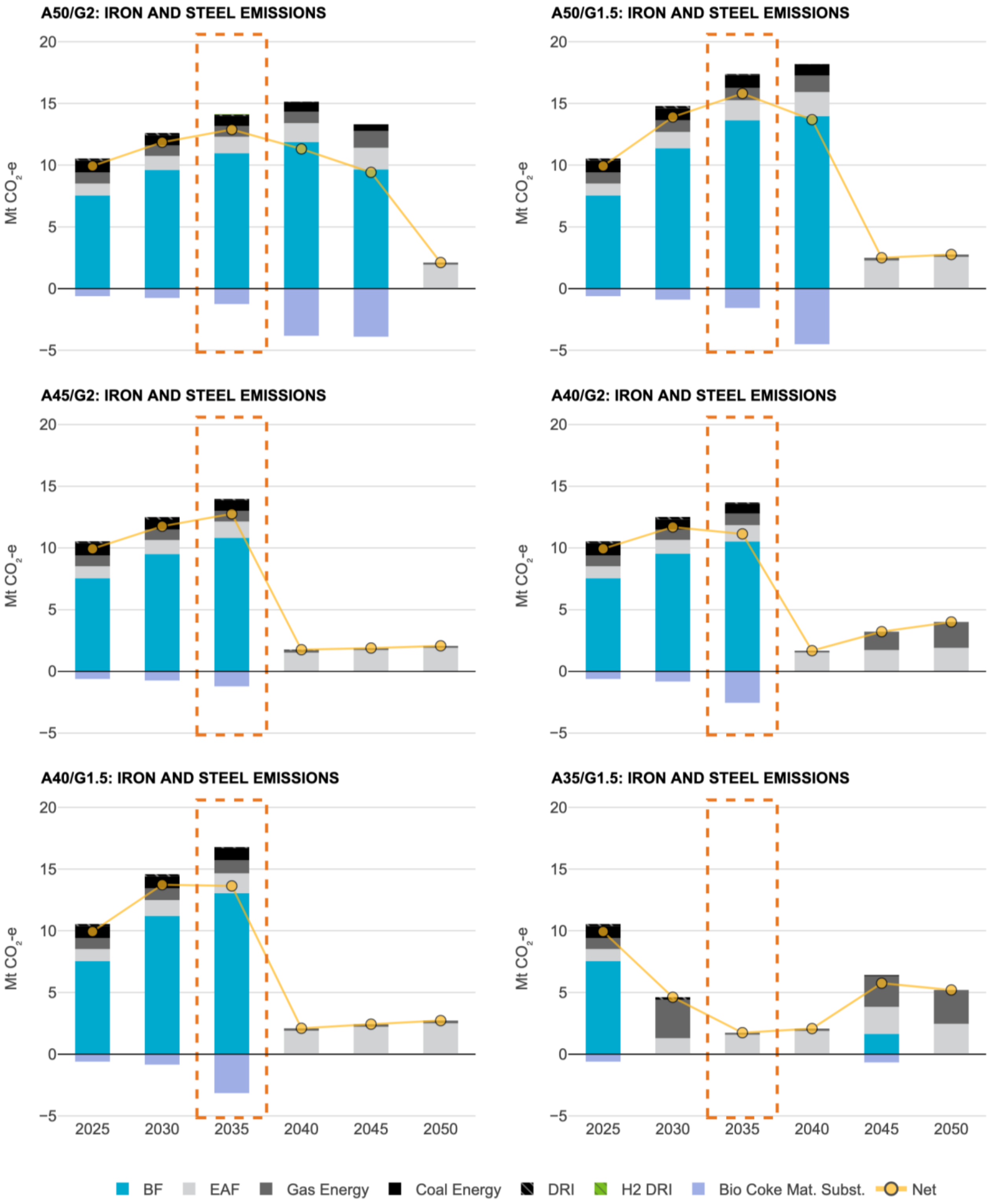

Figure 29 AusTIMES: Iron and steel emissions by technology

### 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).

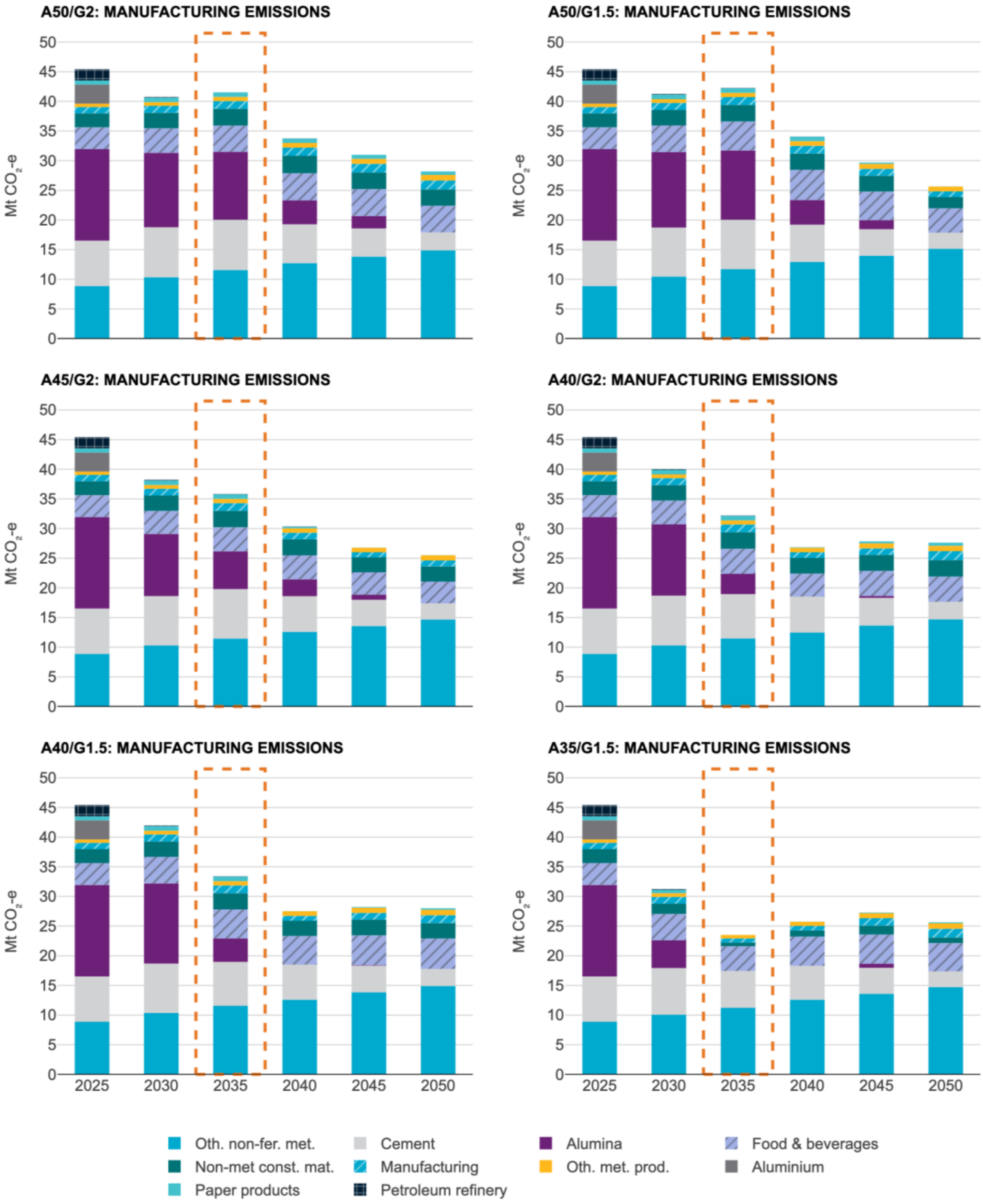

Figure 30 AusTIMES: Manufacturing emissions by industry

The emissions reductions observed in the manufacturing sector are primarily illustrated in Figure 31, where contributions from the aluminium industry (through inert anode adoption[14]), the cement industry (through CCS and material substitution), and the iron and steel industry (through bio-coke material substitution) are highlighted.

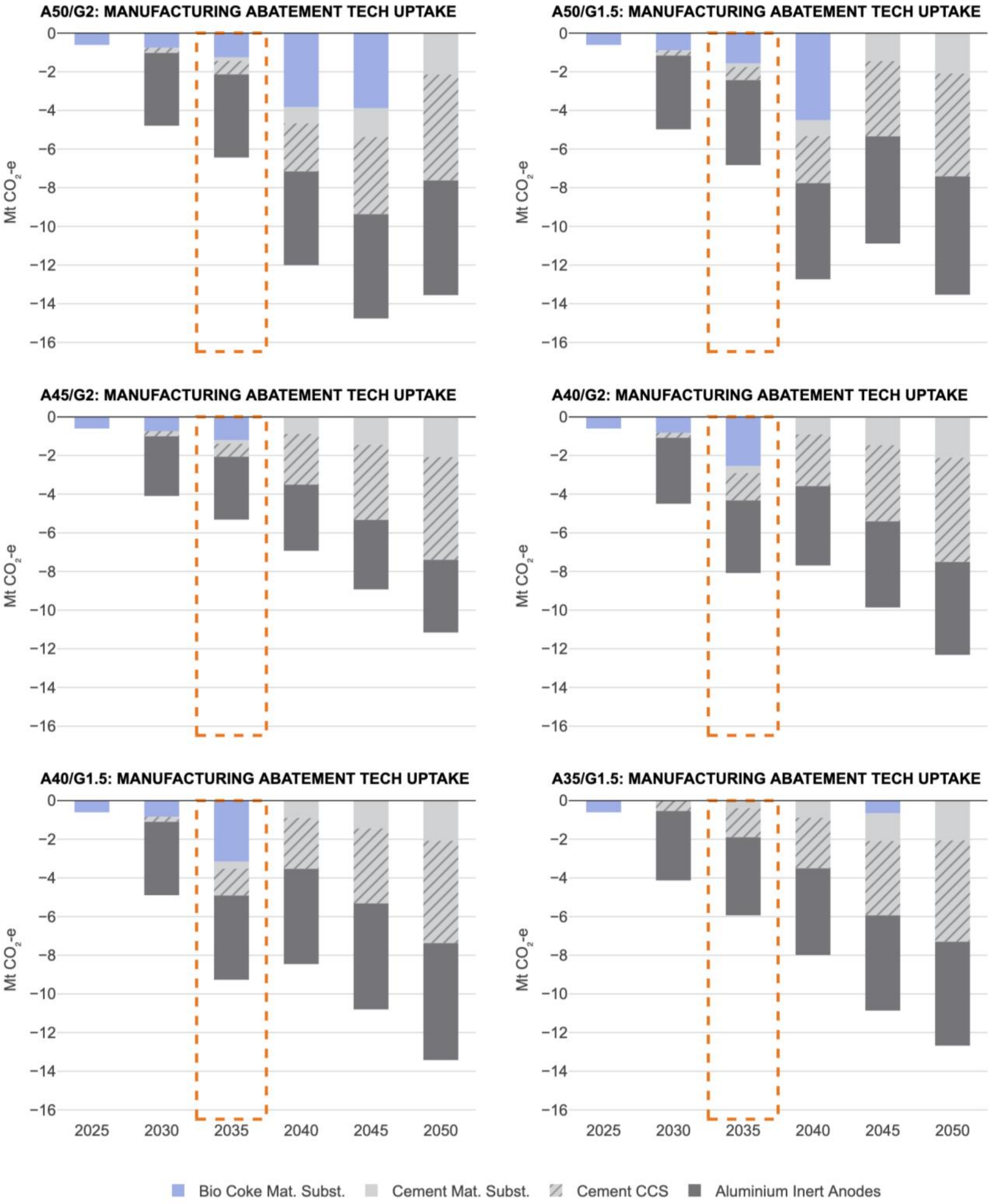

Figure 31 AusTIMES: Manufacturing uptake of CCS and other emission reducing technologies and processes

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[14] The start date for various new technologies can be uncertain, e.g., for inert anodes for the decarbonisation of Aluminium production the model assumes this to be 2030, but a later start date of 2035 would be only one time point difference in this 5-yearly model.

Since the reductions seen in Figure 30 for Alumina are driven by reduced energy consumption from fuel switching, 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.

The reductions seen (in Figure 21) in the chemicals industry emissions are shown in 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).

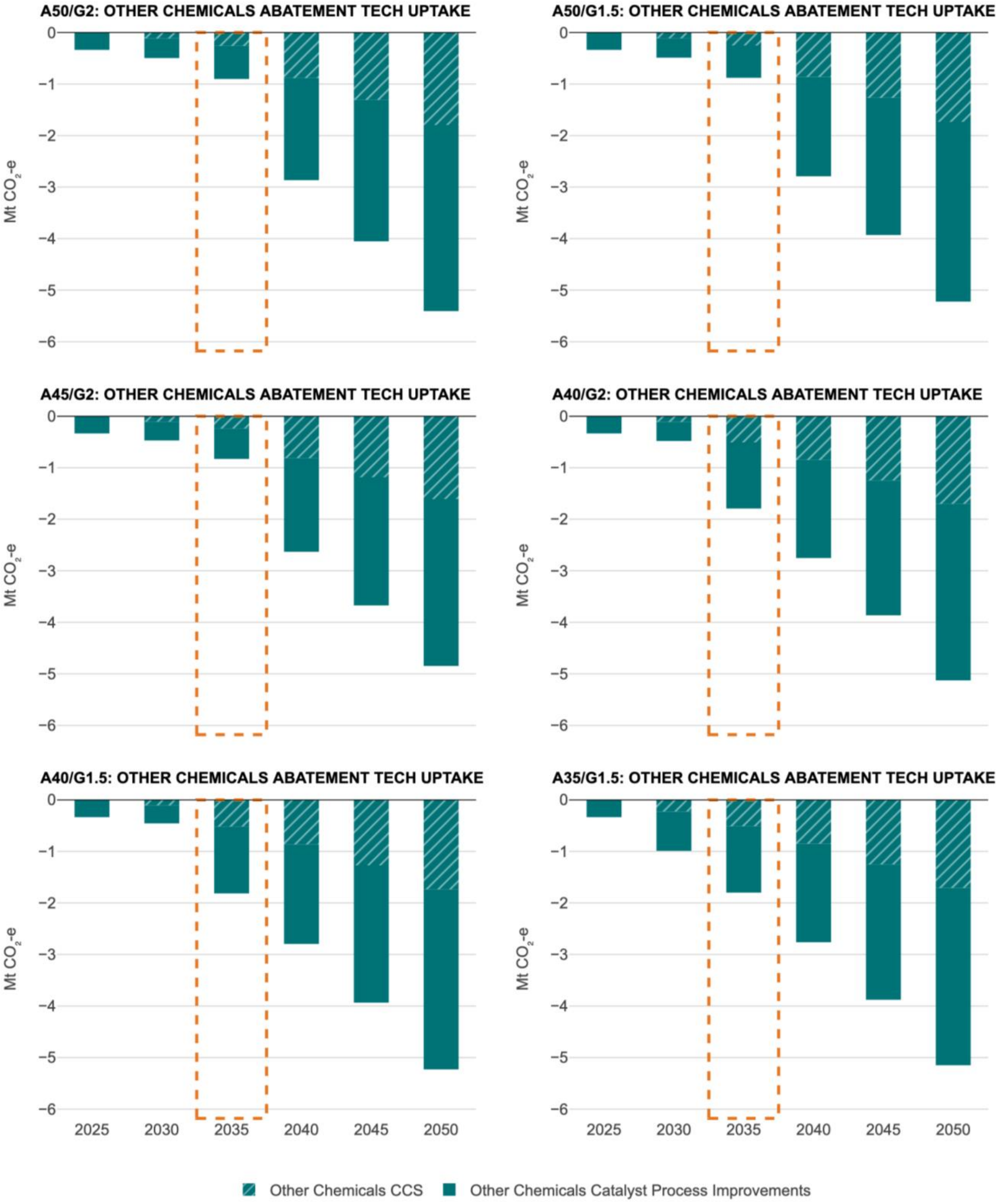

Figure 32 AusTIMES: Other Chemicals abatement technology and process uptake

## 2.4 Transport sector

Over the period 2025 to 2050, emissions from the transport sector decline by more than 75% in A50/G2 and more than 98% in A35/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 they account for the vast majority of vehicle fleet. Over time, there is greater deployment of electric vehicles (EV) especially in the A40/G1.5 scenario to meet the more stringent emissions reduction requirement. There is also modest uptake of fuel cell EV in freight applications in the A40/G2, A40/G1.5 and A35/G1.5 scenarios. The portion of the fleet made up of internal combustion engine vehicles drops to less than 10% in A50/G2, and to near zero in A40/G1.5 and A35/G1.5, by 2050.

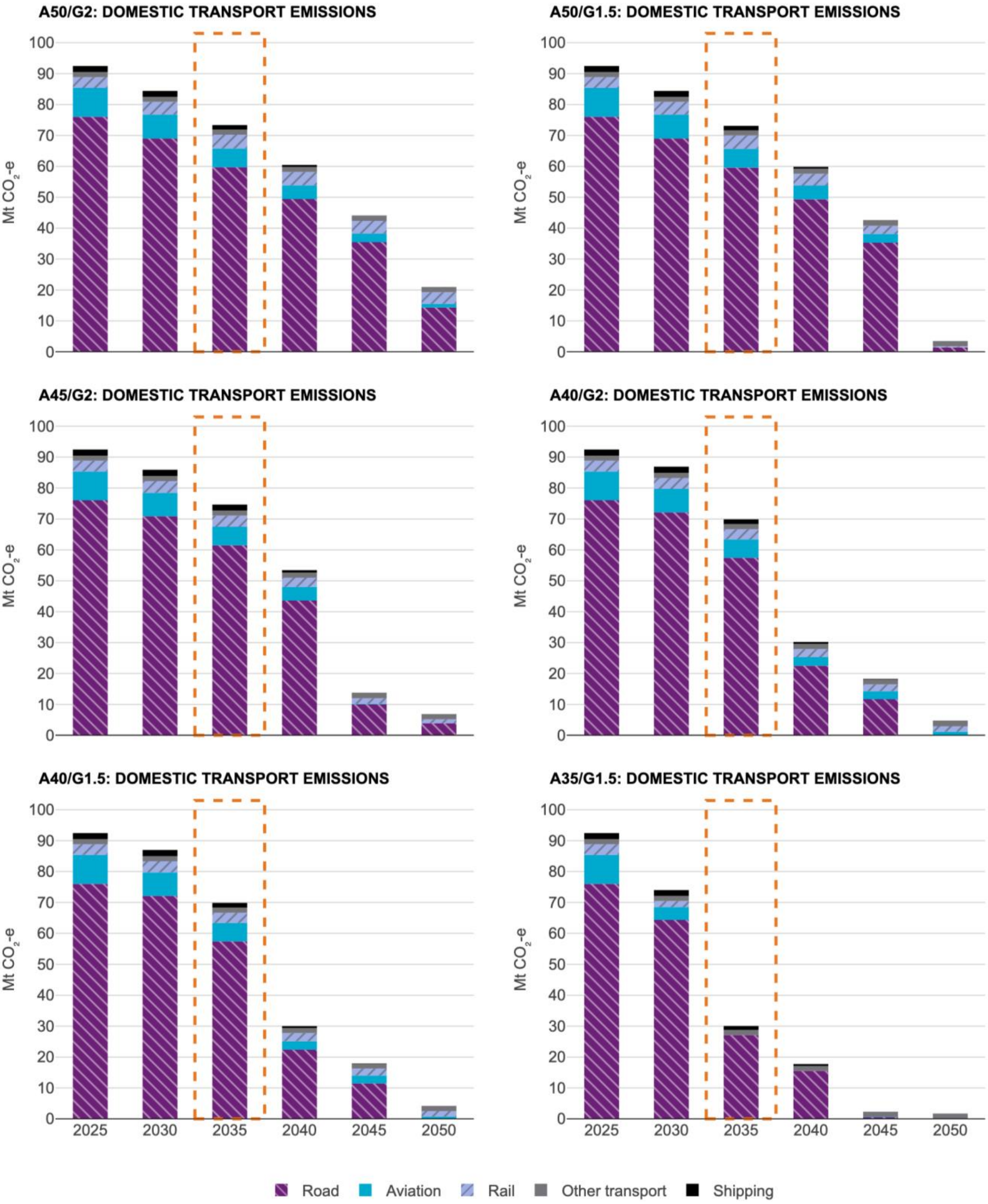

Figure 33 AusTIMES: Transport sector emissions by transport mode

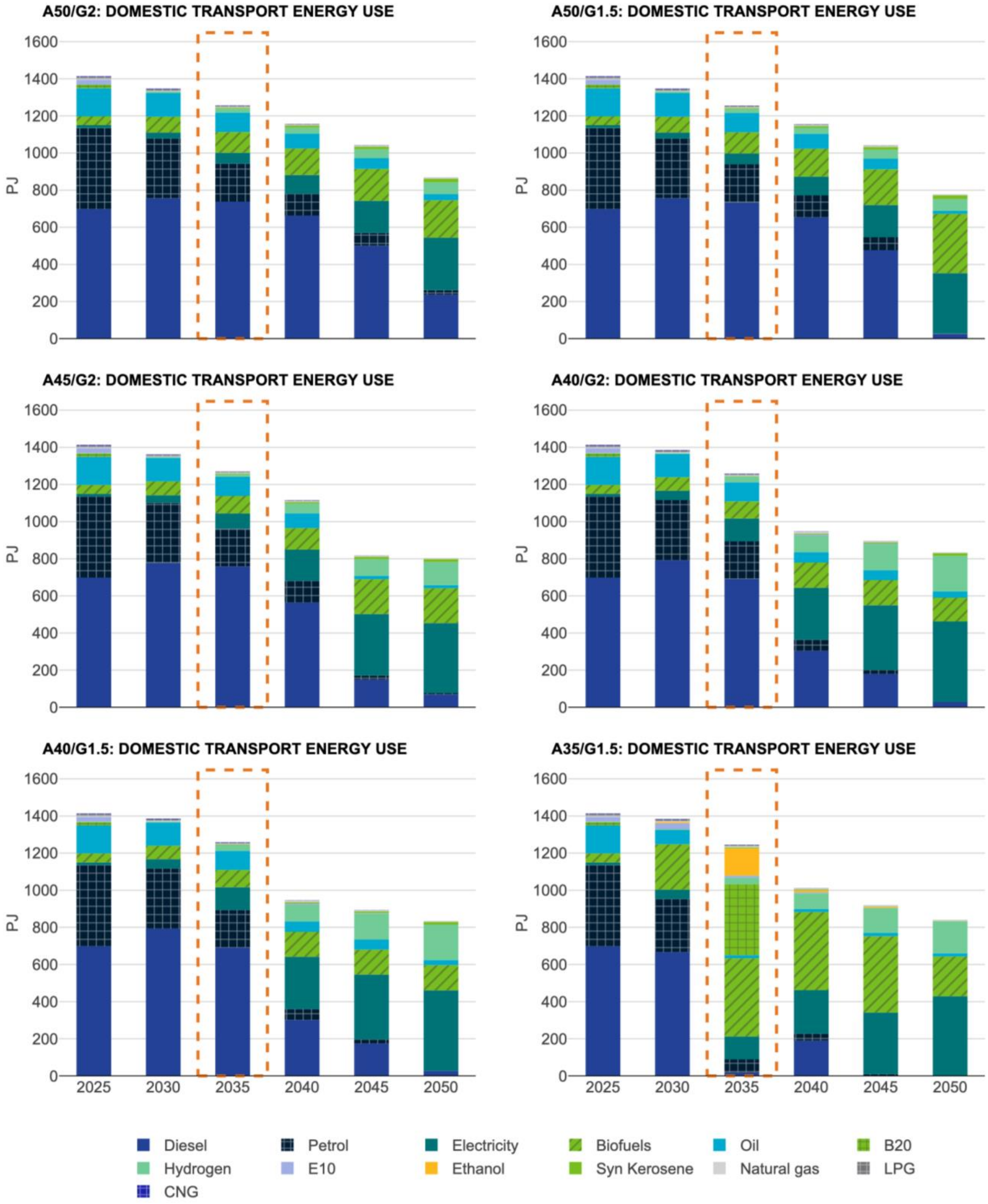

Figure 34 AusTIMES: Domestic transport energy consumption by fuel type[15]

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[15] This figure retains the native AusTIMES fuel type granularity, as opposed to aggregating petrol, B20, E10, ethanol, and biodiesel into oil and biofuels as was done in the 2-scenario version of this report.

At the beginning of the projection period, most of the 1400 PJ energy consumption in 2025 is from oil derived fuels of petrol and diesel in road transport (light and heavy vehicles) and kerosene (part of oil) in domestic aviation (Figure 34). The biofuel consumption is mainly low-blend ethanol (E10) in some eastern states and biodiesel consumption due to mandates in New South Wales and Queensland. 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.

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. The exception is A35/G1.5. Due to more aggressive emissions reduction, there is significant uptake of biodiesel in 2035 that persists for a decade as a means to reduce emissions from near-zero carbon “drop-in” fuels in existing vehicles. 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.

Fuel consumption for transport is currently dominated by road transport, but with the accelerated uptake of EV 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 EV 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[16] is dominated by oil-derived kerosene. In all 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 constraints. 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 pre-2050 net zero scenarios (A45/G2, A40/G2, A40/G1.5, A35/G1.5) in the long-term is much less than 2050 net zero scenarios (A50/G2, A50/G1.5). This reflects some mode switching away from aviation and stronger fuel efficiency improvements (reduction of 1% per year).

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[16] Table F of the Australian Energy Statistics splits fuel consumption out for domestic and international aviation (DCCEEW, 2023b). Under the Paris Agreement rules neither inbound nor outbound international aviation emissions are included in Australia's (or any other countries') national emissions, and thus only domestic aviation energy and emissions are presented in this report.

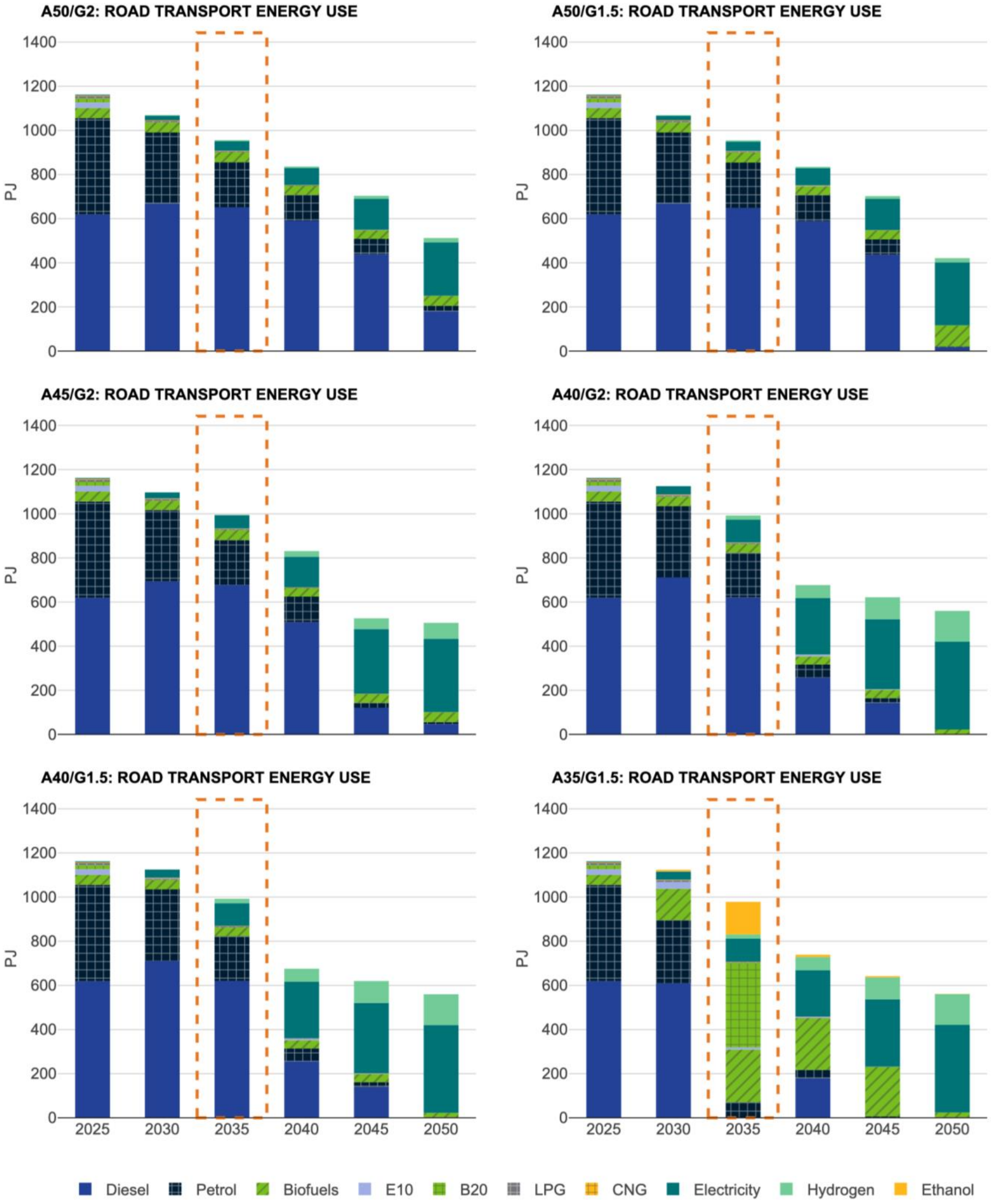

Figure 35 AusTIMES: Energy consumption in road transport by fuel type

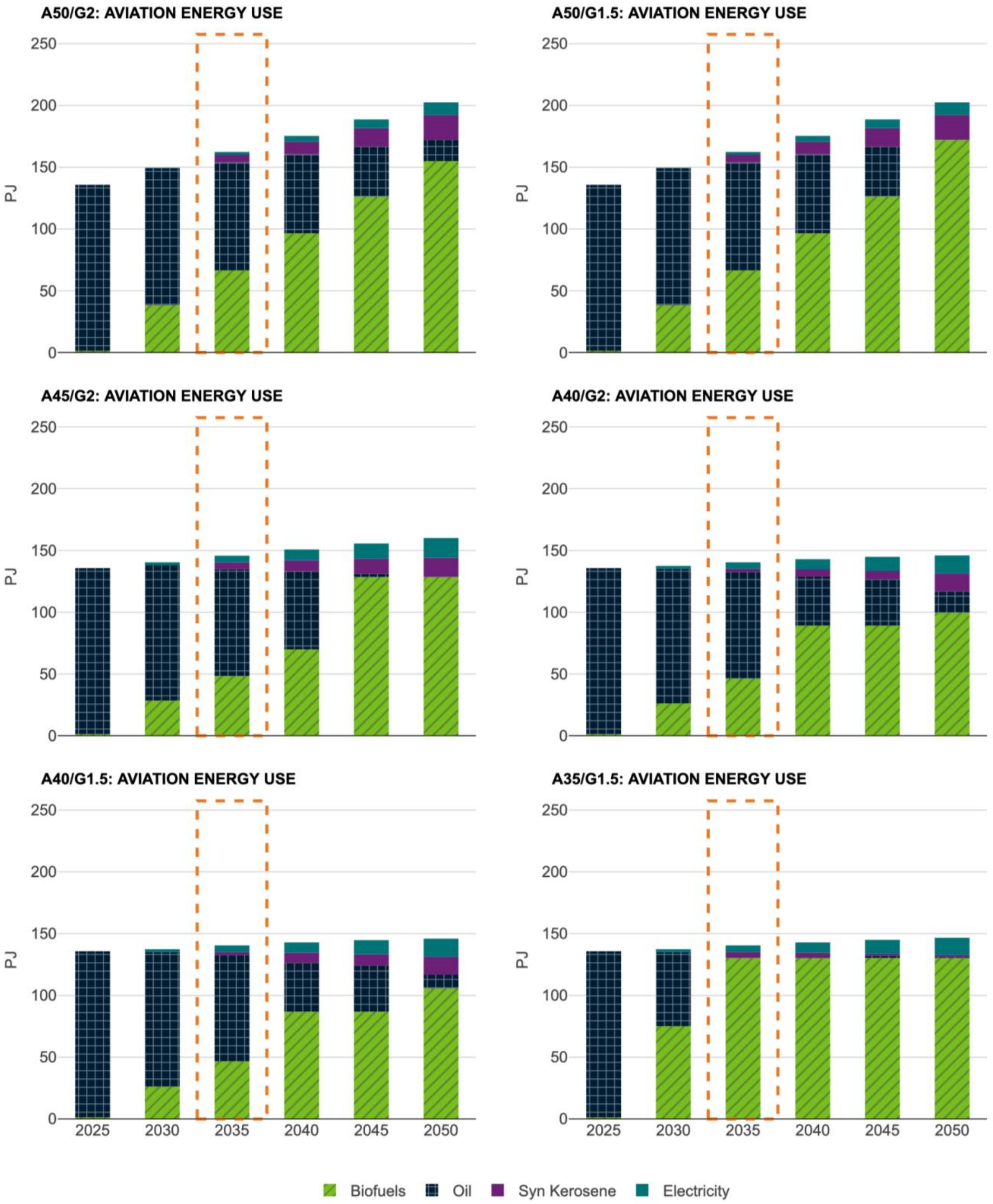

Figure 36 AusTIMES: Domestic aviation energy use

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 also 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 all scenarios, see 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 pre-2050 net zero scenarios (A45/G2, A40/G2, A40/G1.5, A35/G1.5) in the long-term is much less than the 2050 net zero scenarios (A50/G2, A50/G1.5). This reflects some mode switching away from rail to road and stronger fuel efficiency improvements (2.3% per annum).

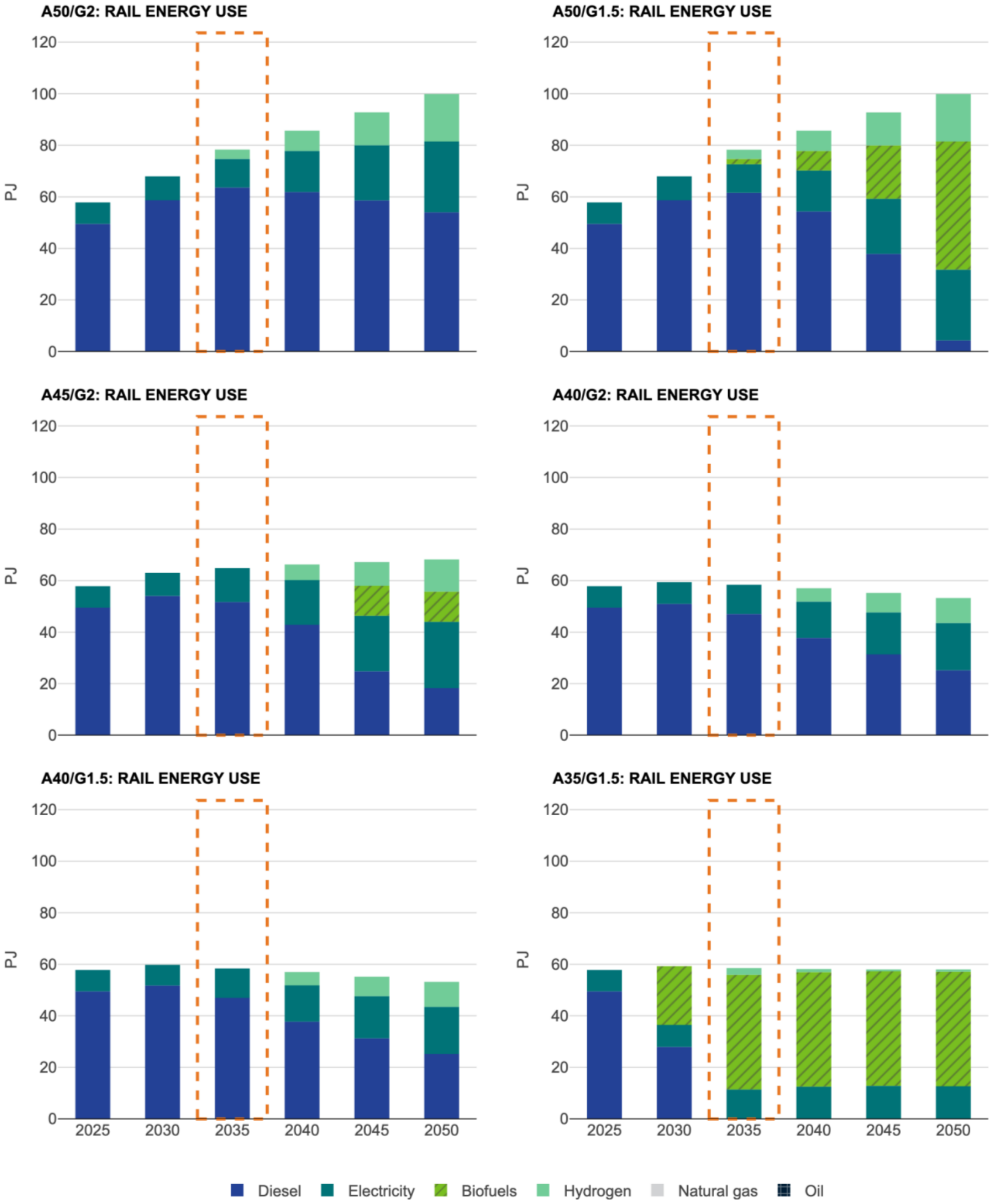

Figure 37 AusTIMES: Energy consumption in domestic rail by fuel type

## 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; Strategy Policy Research, 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 buildings, and the Commercial Building Energy Consumption Baseline Study for commercial buildings (Strategy Policy Research, 2022).

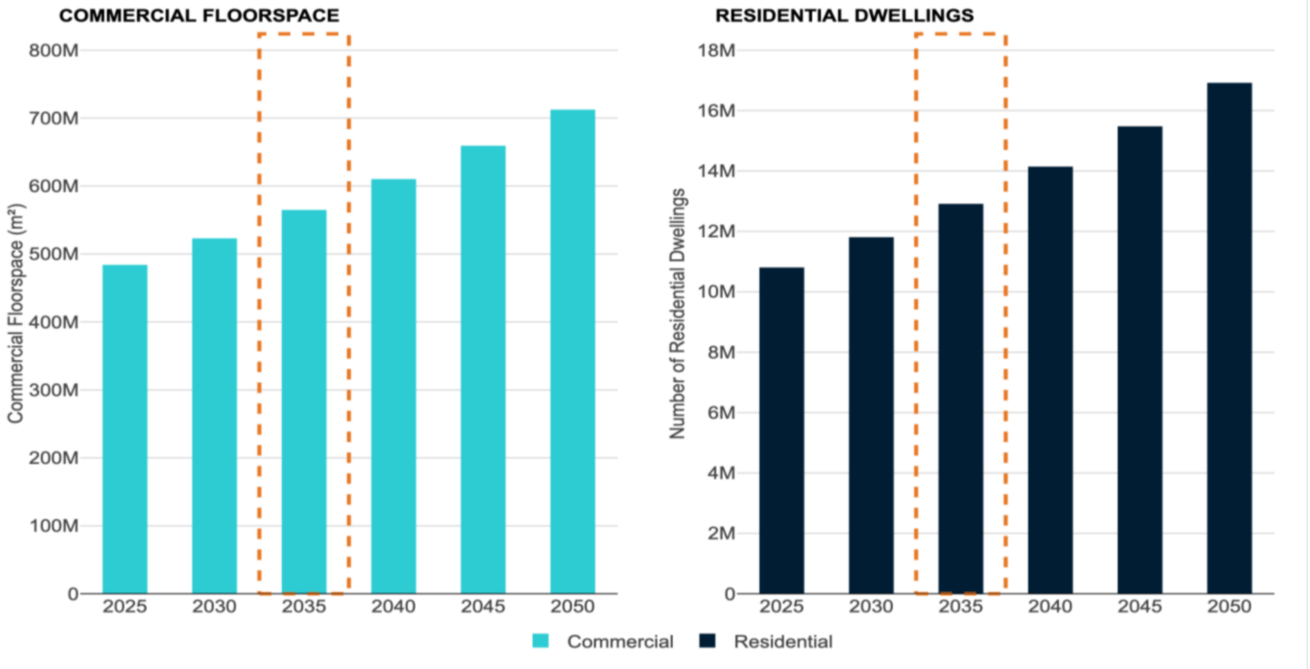

**Figure 38 AusTIMES: Built environment (residential and commercial) growth**

The modelling results shows that the emissions from the built environment sector (both commercial and residential buildings) in 2025 amount to 13.5 Mt $CO_2$-e. These emissions primarily result from direct, on-site combustion of fossil fuels for heating and cooking, which can be managed and controlled through building operations. A sharp reduction in emissions from this sector can be observed: residential emissions fall by 19% to 25% by 2030 and nearly reaching zero by 2050; commercial emissions fall by 15% by 2030 and drop to very low levels by 2050 (Figure 39). Energy efficiency and electrification technologies have an impact on emissions but the sharp fall in emissions is not accompanied by a sharp corresponding decline in energy consumption; this is examined in more detail in Figure 40.

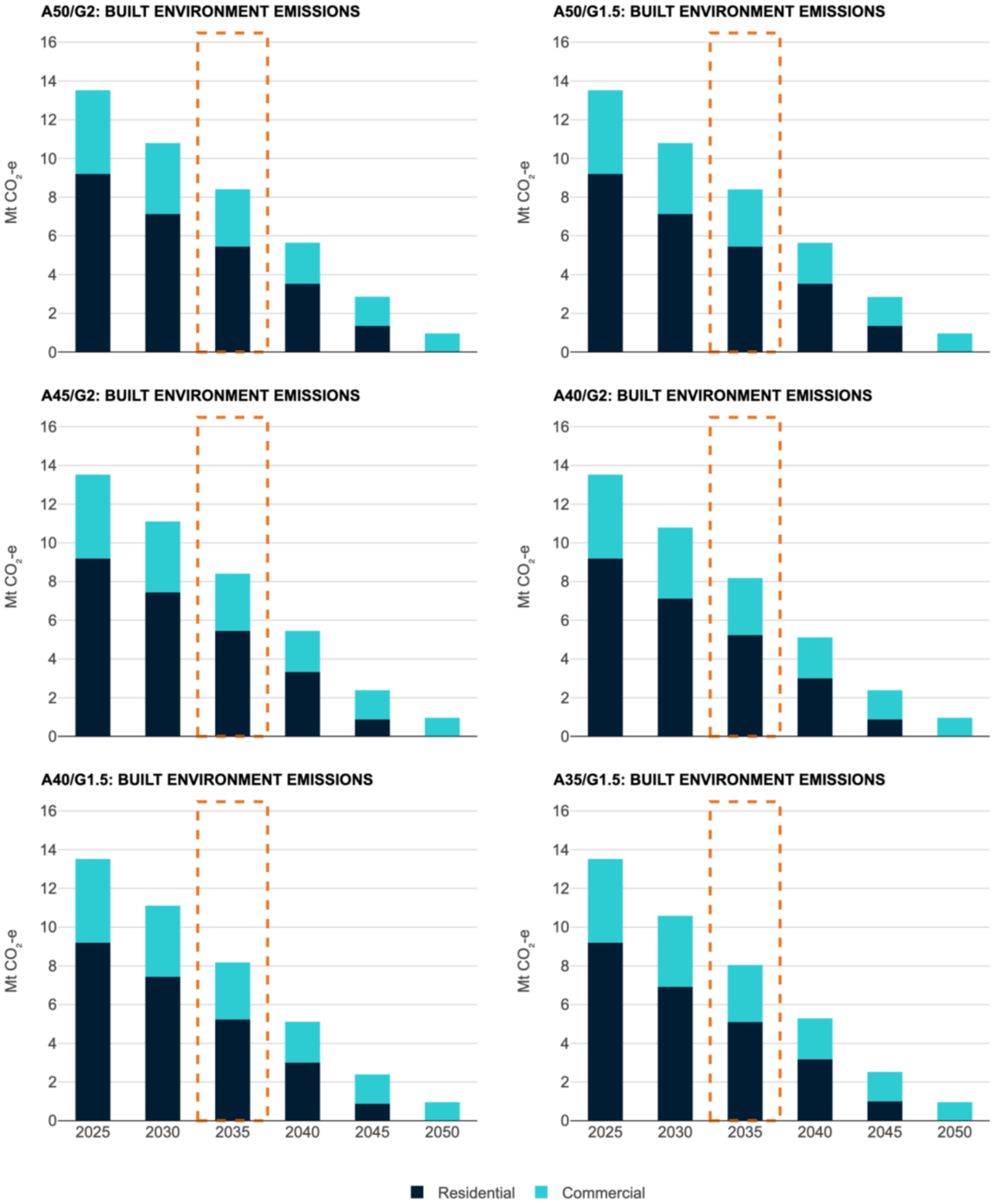

Figure 39 AusTIMES: Built environment sector emissions

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% to 12%, while commercial consumption has fallen by 15% to 21% across all scenarios.

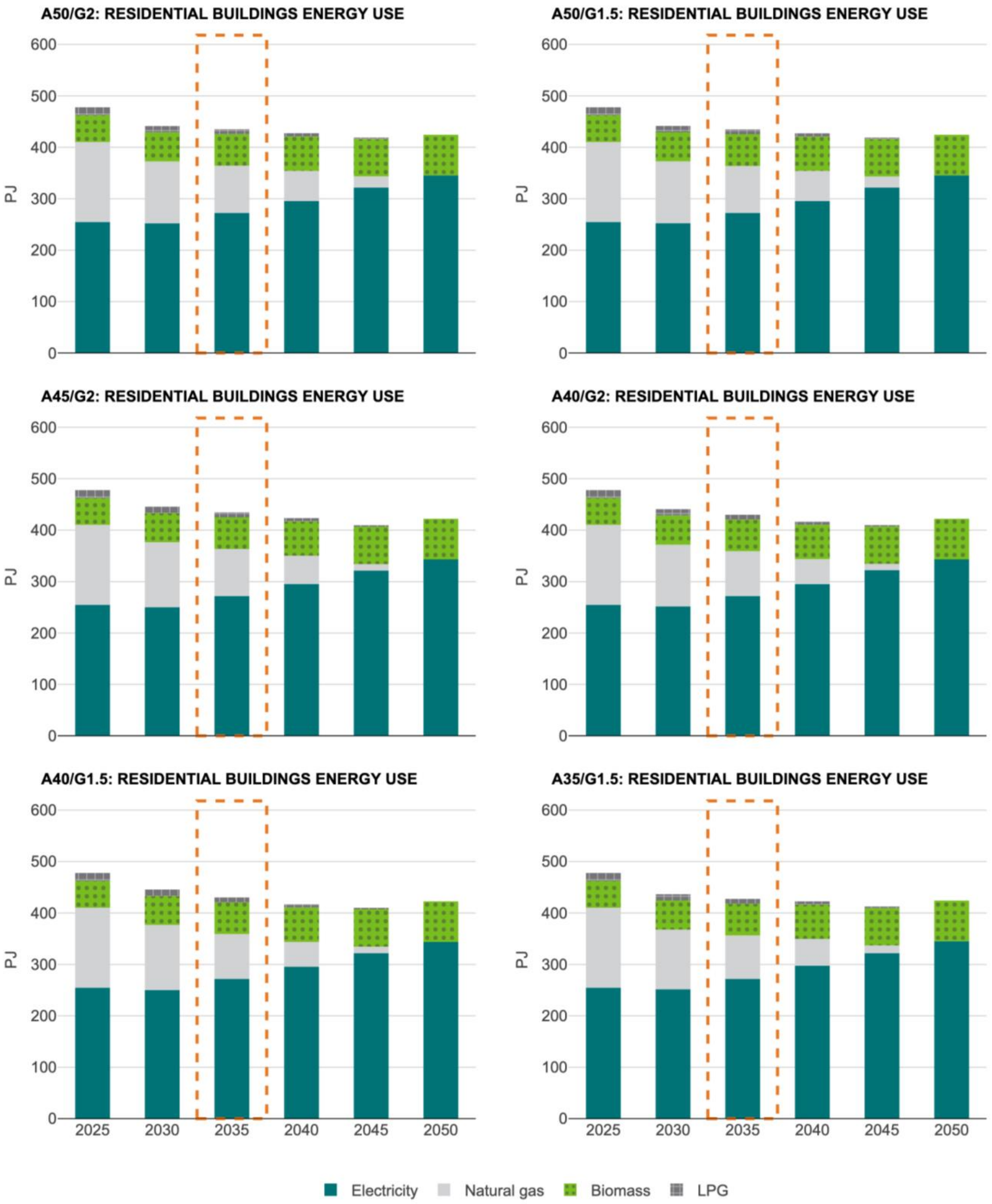

Figure 40 AusTIMES: Residential buildings energy consumption by fuel type

In residential buildings, electricity consumption is projected to increase by 35% to 36% by 2050 whereas natural gas and LPG consumption is expected to be phased out by 2050 across all scenarios. In contrast, in commercial buildings (Figure 41), electricity consumption is forecast to remain relatively constant with a slight fall of 3% and 4% by 2050 in A50/G1.5 and A50/G2, no change in the A45/G2, and slight rise of 1% to 5% by 2050 in the other three scenarios. The largest fall in consumption is in oil of around 91% followed by natural gas of around 68%, although consumption persists in both fuels until 2050, and natural gas is not completely phased out as it is in the residential sector.

Figure 41 AusTIMES: Commercial buildings energy consumption by fuel type

While the model has the option to blend hydrogen up to 10% by volume into the natural gas supply by 2050, there is no hydrogen uptake in either residential or commercial sectors. Biomethane is also an option to blend into the gas supply. However, due to its cost, no biomethane uptake is observed in any of the six scenarios for residential and commercial sectors.

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 all scenarios which is consistent with the long run trend and ABARES projections (ABARES, 2023). Forestry and logging are also flat in energy terms.

As shown in Figure 42, 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, the A40 and A35 (see right panel of Figure 42) results show more than double the sequestration compared to the A50 results in most years. This is a result of the higher carbon price under those scenarios[17], 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.

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

Figure 42 AusTIMES: Land and agriculture emissions by subsector[18]

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[18] The sequestration from land-use and land-use change (LULUCF) represents that from the existing inventories as reported in the 2023 Australian Government projections (DCCEEW, 2023a) (held flat through 2050 beyond the end of those projections). The Land seq. (Future) represents sequestration from additional new plantings and resulting from the coupling of the GTEM and LUTO models.

Figure 43 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 all 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. In these results they are not deployed until after 2035 in most scenarios, the exception being the A35/G1.5 scenario.

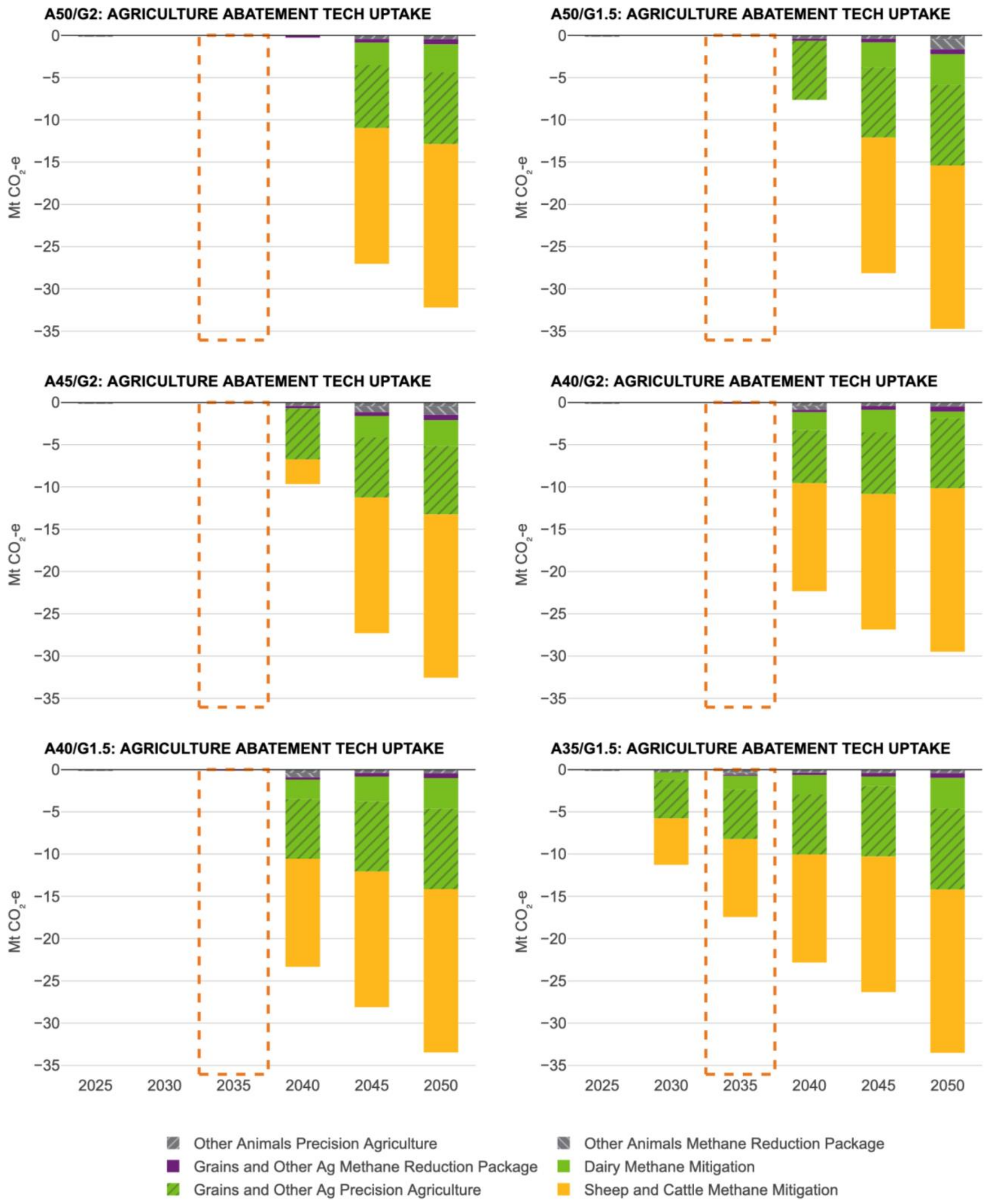

Figure 43 AusTIMES: Agriculture emissions reductions technology and process uptake

# Appendix A Technical supplement

## A.1 Model framework and integration

This appendix describes the three models and their integration in this exercise. Readers should note that all models (including those applied here) are reduced-form representations of reality and as such are designed to provide insights without the complexity of reality. In the current exercise the models provide insights on the trade-offs across emission pathways under different global settings. The insights do not necessarily include definitive representations of how the economy will evolve in any particular scenario.

### 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 establish the economic context (i.e., export and import demand and prices, primary factor demands and prices, etc) and explore the economic impacts in each scenario.
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)[19]. 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.

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

CSIRO's GTEM model[20] 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-of-economy emissions trajectory and trading conditions drawn from GTEM, taking into account the land use change emissions drawn from LUTO.

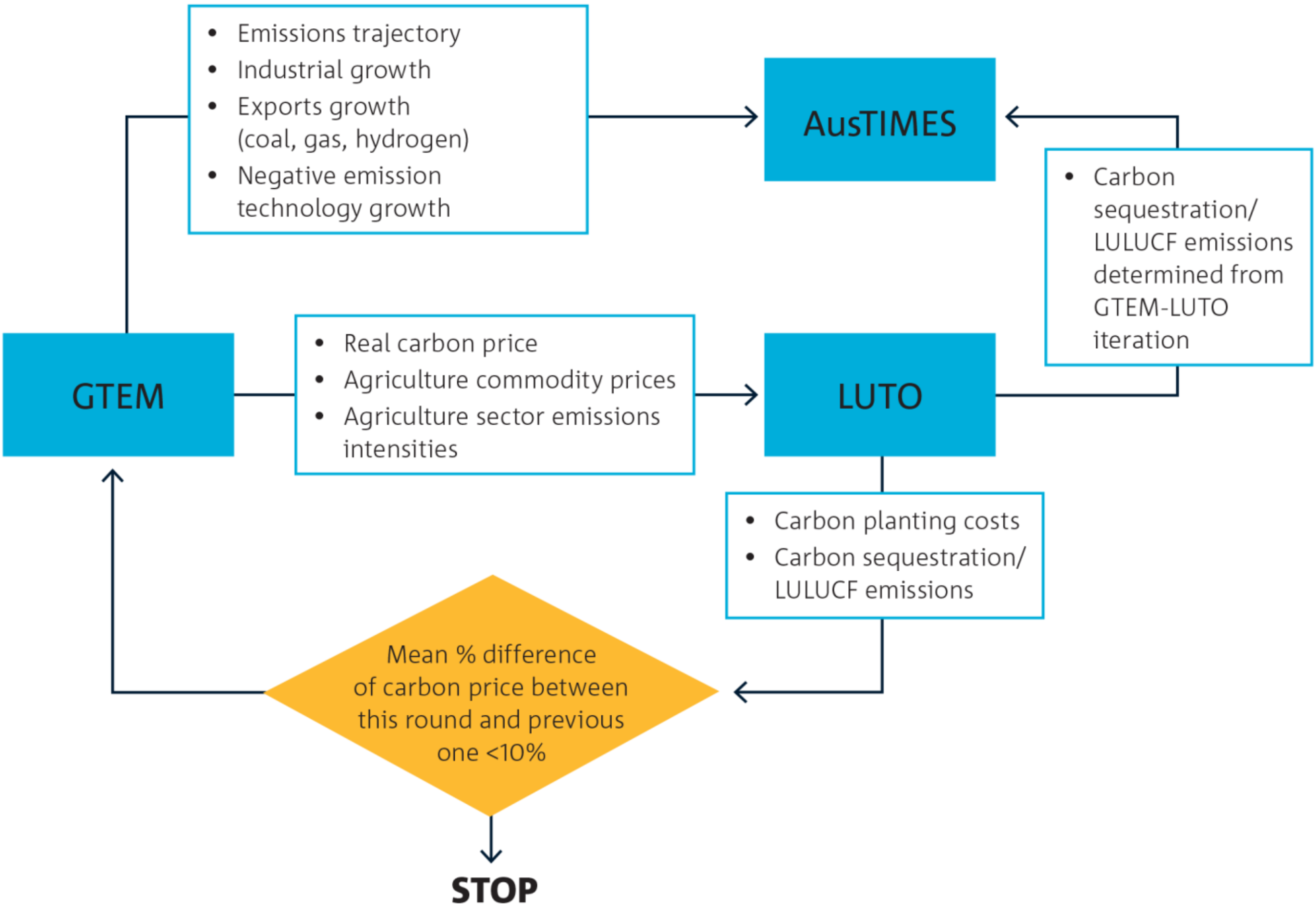

**Figure 44 An overview of the interrelationship of input sources across the model suite**

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

### 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 GHG 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.

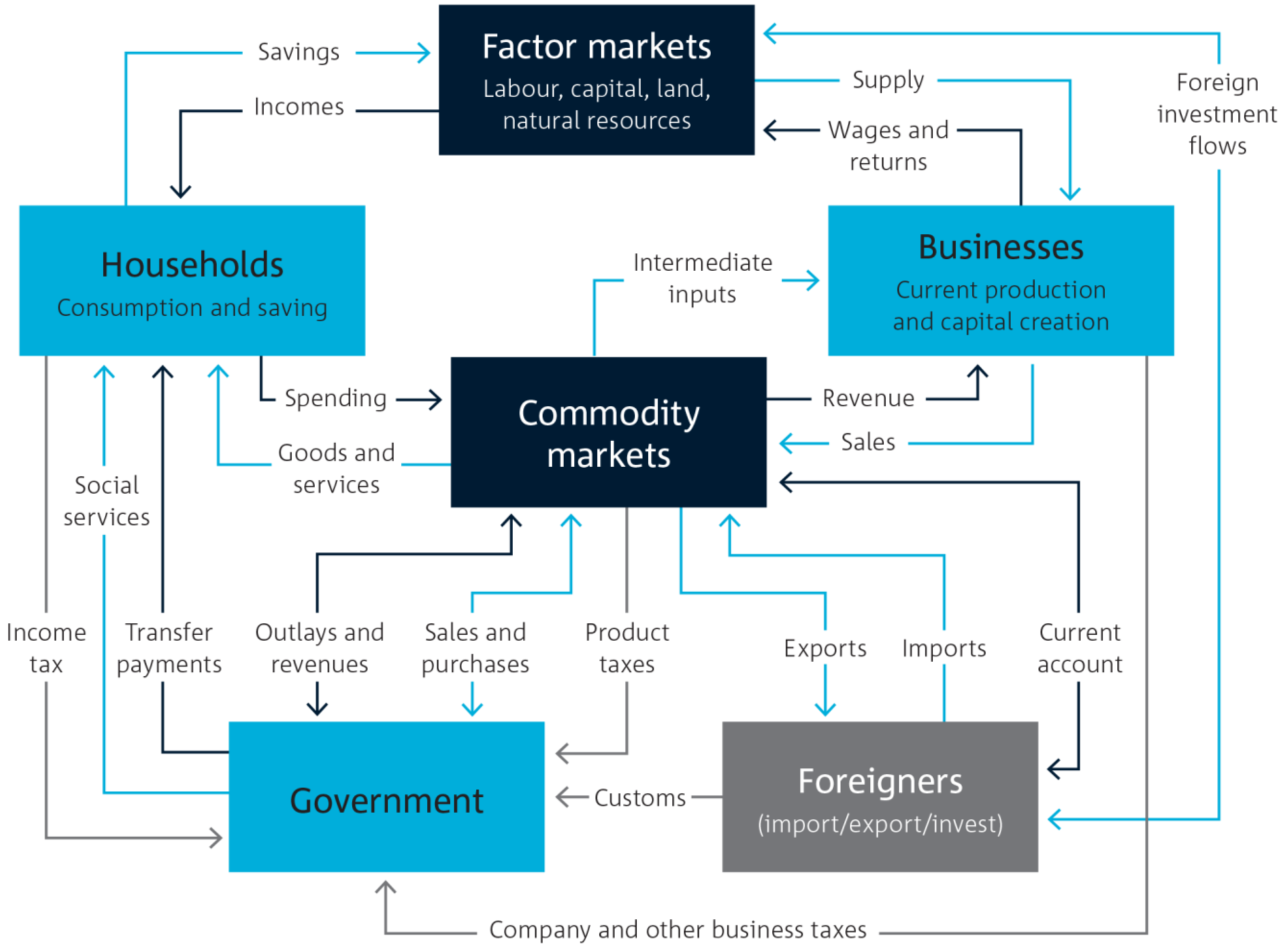


**Figure 45 GTEM: Interactions between agents within a given aggregate region**

**Source**: Whitten et al (2022).

## Firms and production

### Technology bundle industries

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

There are three TB industries in GTEM as implemented in this study: electricity, iron and steel, and land transport (i.e., road and rail transport). Here we focus on the treatment of electricity. Electricity generation accounts for a large fraction of 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 46 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 47). At the top nest, industrial output is a Leontief function of a fuel-factor composite and other intermediate inputs. The fuel-factor composite is a Leontief or CES function of the fuel composite and the primary factor composite, allowing different levels of substitutability between fuel and other inputs. The fuel composite is a CRESH aggregate of coal, gas, petroleum, electricity and gas distribution. The CRESH inter-fuel substitution parameters are set to 0.2. This value falls within the range of the literature (Stern, 2012).

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

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

### The regional household

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

Figure 48 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.

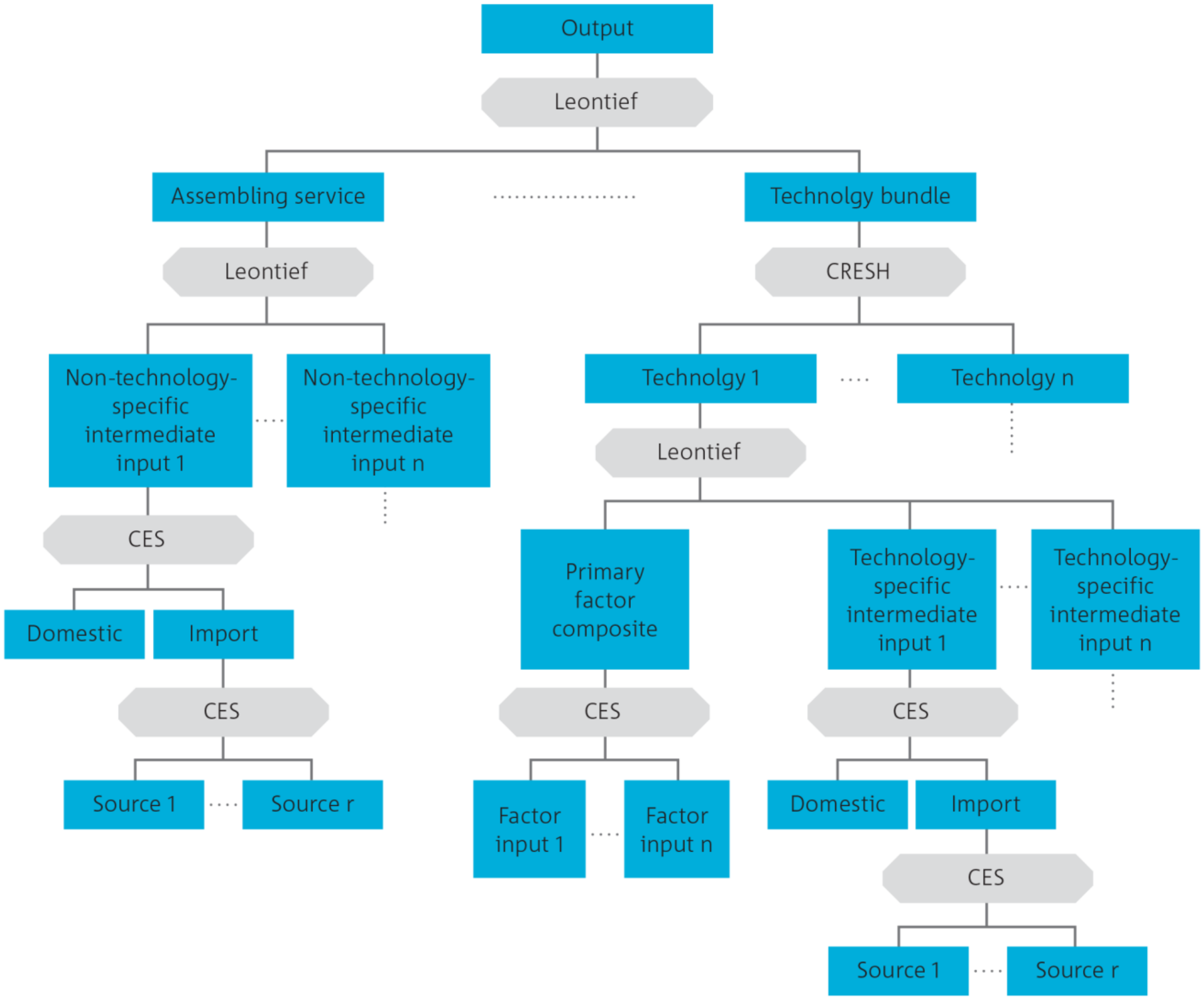


Figure 46 GTEM: Production structure of a technology bundle industry

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).

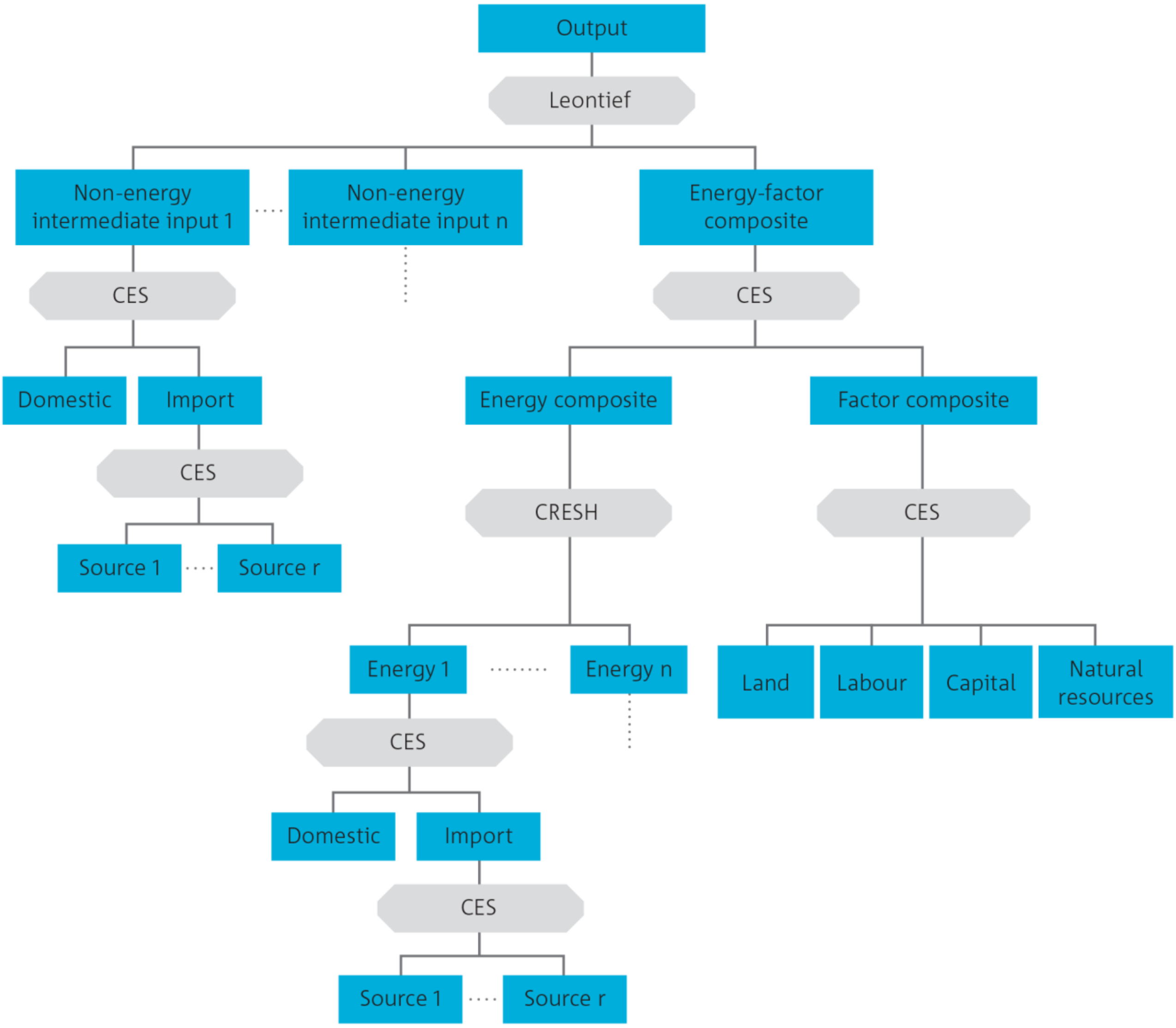


**Figure 47 GTEM: Production structure of a non-technology-bundle industry**

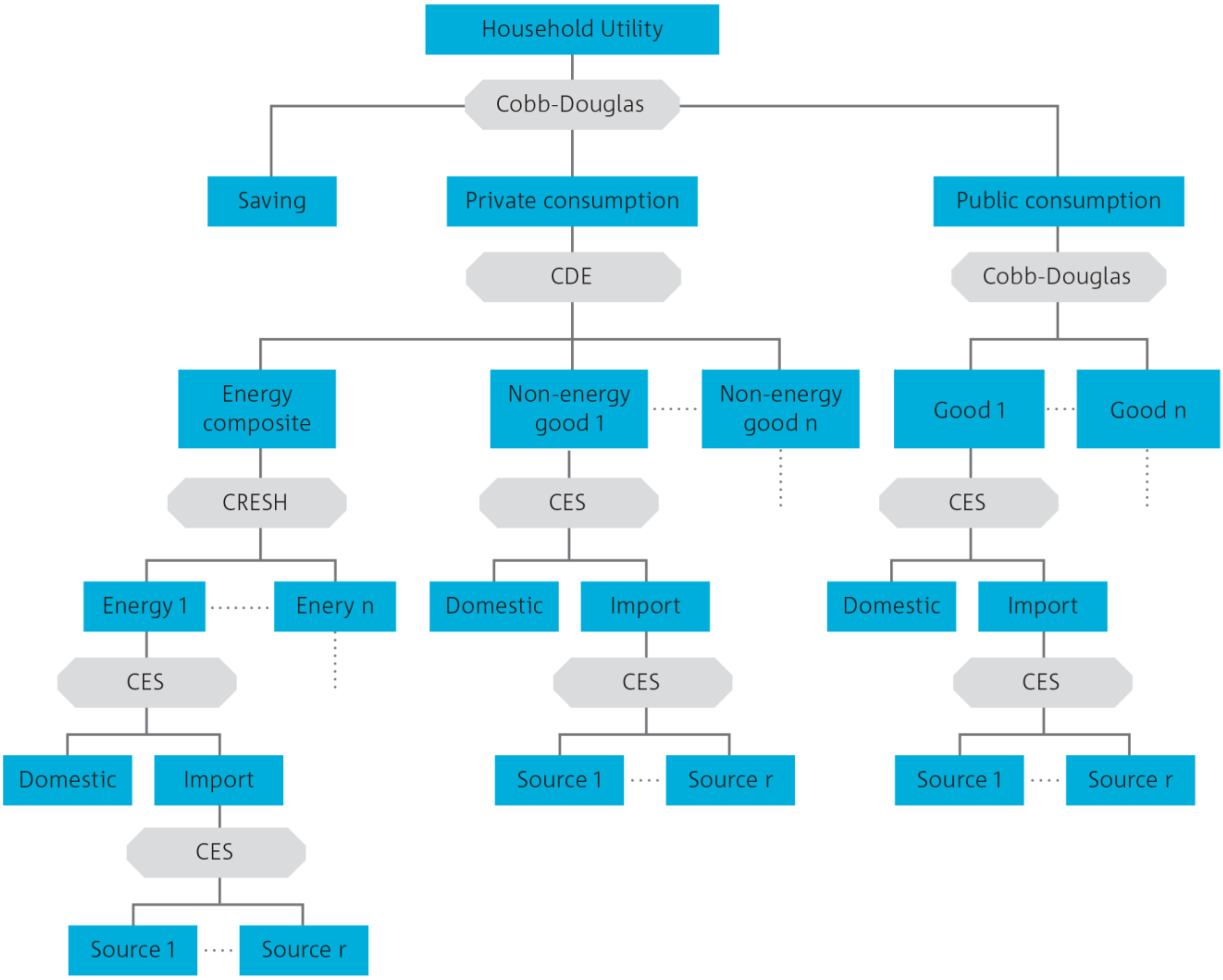


Figure 48 GTEM: Utility structure of the regional household

### 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 GHG 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., 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 GHG 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 13). 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 5 GTEM: Sectoral and regional aggregation**

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

### (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 49).

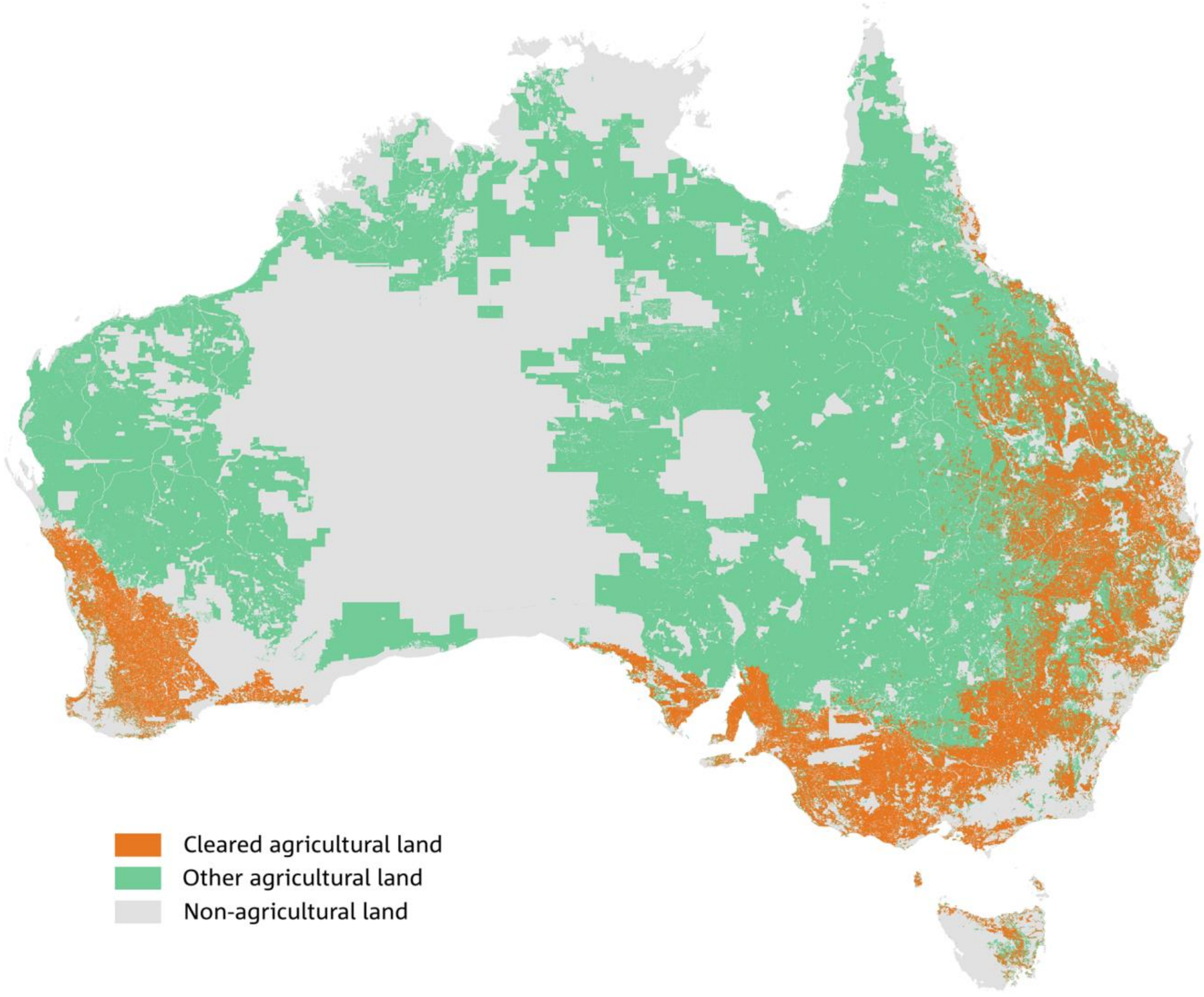


Figure 49 LUTO: Agricultural zones defined for modelling

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 an annual expenditure of $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 50) which was calculated using the pre-European vegetation layer from the NVIS (NVIS, 2020).

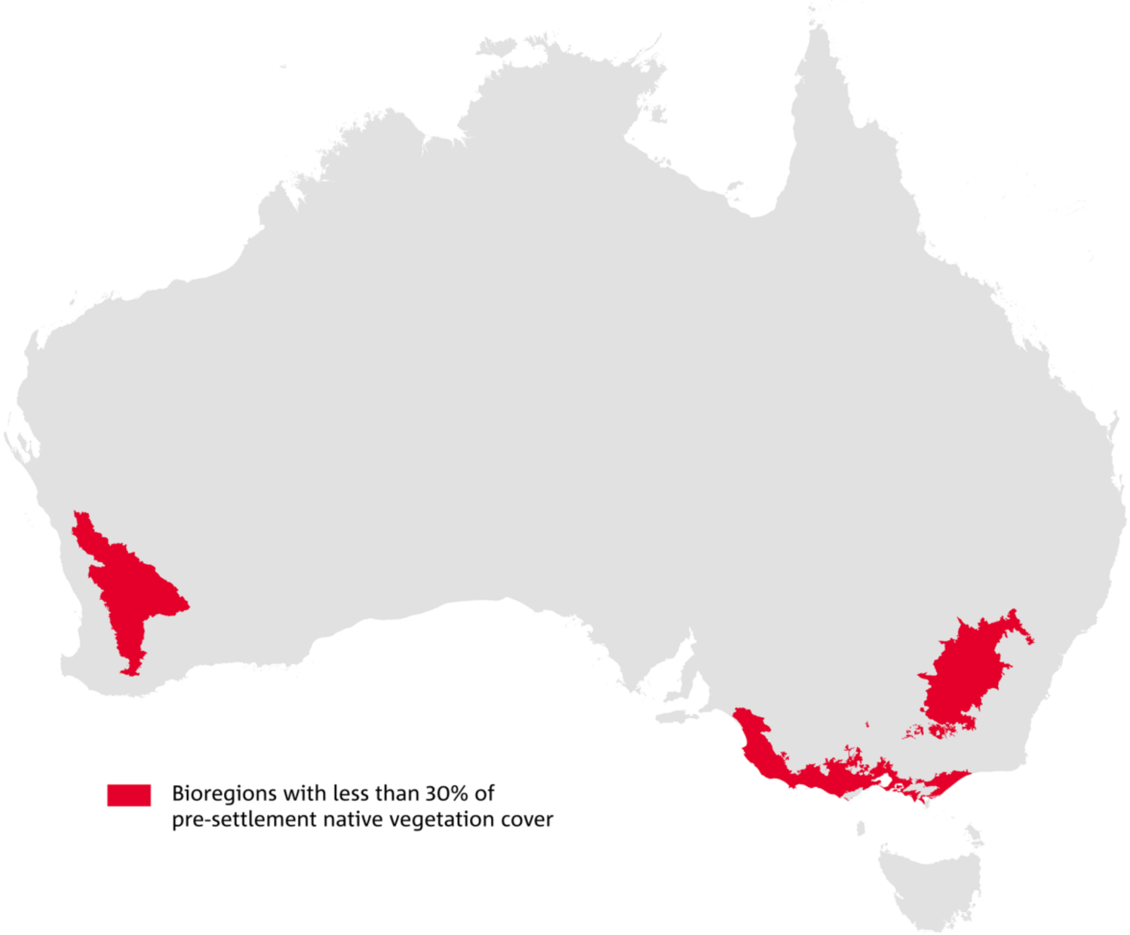


**Figure 50 LUTO: Bioregions where only environmental plantings allowed**

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 6, and mapped in Figure 51. The cap operates as follows:

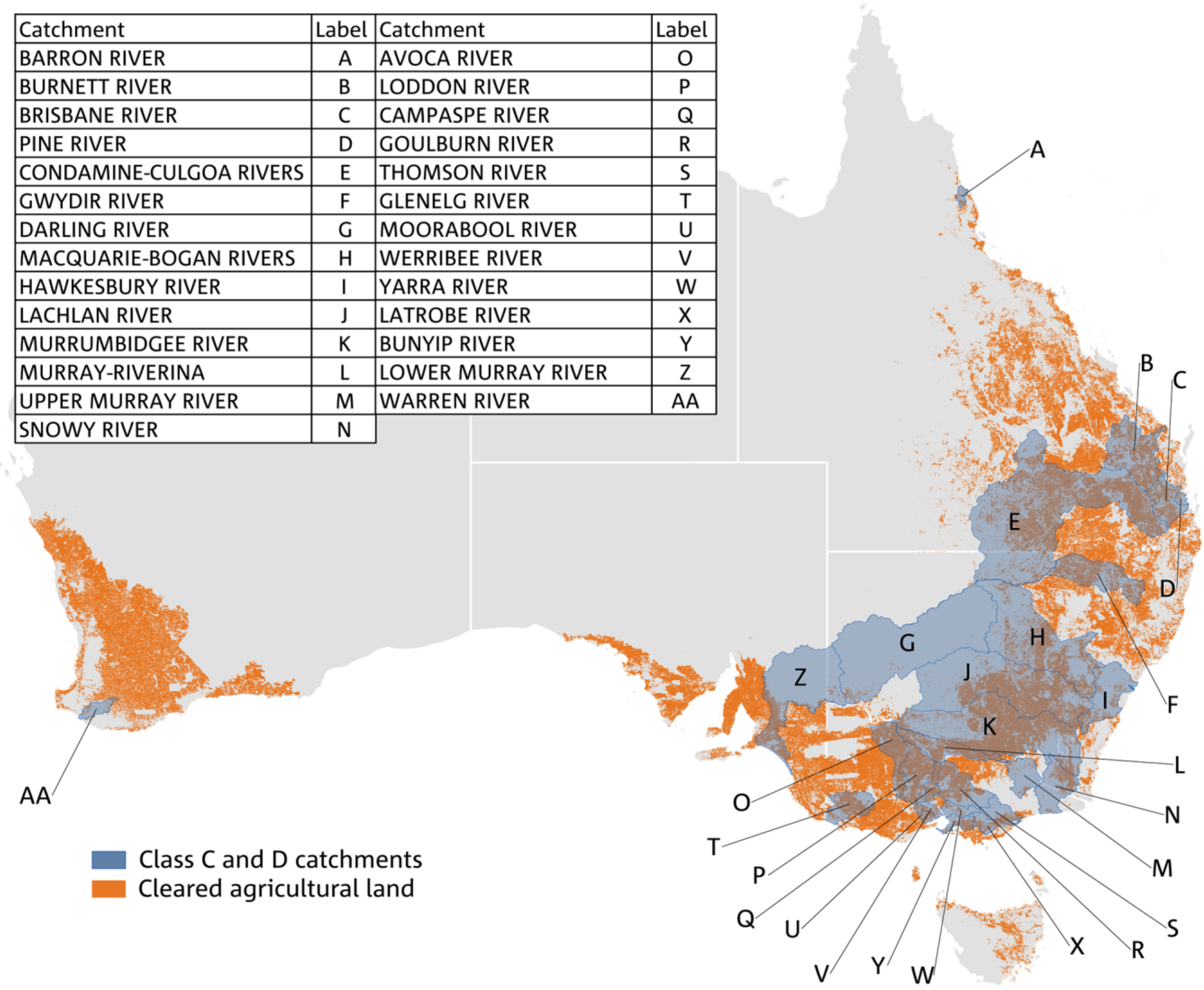
1. Current total agricultural water use for a stressed catchment is calculated and used as the basis for the cap for that catchment.
2. Plantations and agriculture within a catchment then compete for this water. A location will only switch to carbon plantings if carbon plantings is more profitable at 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 600 mm 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 6 LUTO: 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<br>• Likely moderate risk of overuse/overallocation<br>• 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<br>• Likely high risk of overuse/overallocation<br>• 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 51 LUTO: 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 five-year time steps (2015, 2020, …, 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 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 GHG 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 constraints 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 constraints 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 7 AusTIMES: Mapping to ANZSIC (2006) industry subsectors

| AusTIMES 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 and 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 8).

Table 8 AusTIMES: Mapping to ANZSIC agriculture subsectors

| AusTIMES 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, 2023a), 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 9).

Table 9 AusTIMES: Road transport segments, vehicle classes, and fuel categories

| Market segments | Vehicle types | Fuels |
|---|---|---|
| Motorcycles<br>Small, medium, and large passenger<br>Small, medium, and large light commercial vehicles<br>Rigid trucks<br>Articulated vehicles<br>Buses | Internal combustion engine<br>Hybrid/internal combustion engine<br>Plug-in Hybrid/internal combustion engine<br>Short-range electric vehicle<br>Long-range electric vehicle<br>Autonomous long-range (private) electric vehicle<br>Autonomous long-range (ride-share) electric vehicle<br>Fuel cell electric vehicle | Petrol<br>Diesel<br>Liquefied Petroleum Gas (LPG)<br>Compressed or Liquefied Natural gas<br>Petrol with 10% ethanol blend (E10)<br>Diesel with 20% biodiesel blend (B20)<br>Ethanol<br>Biodiesel<br>Hydrogen<br>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, 2023a), 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 10).

Table 10 AusTIMES: Non-road transport market segments and fuels

| Market segments | Fuels |
|---|---|
| Rail | Diesel<br>Electricity<br>Biofuel<br>Hydrogen |
| Aviation – domestic | Avgas<br>Kerosene<br>Biofuel<br>Electricity<br>Synthetic kerosene<br>Hydrogen |
| Shipping – domestic | Fuel oil<br>Diesel<br>Biofuel<br>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 11).

Table 11 AusTIMES: Residential building types, end-use service demands and fuel types

| Building types | End-use service demands | Fuel types |
|---|---|---|
| Detached (separate houses)<br>Semi-detached (townhouses, duplexes)<br>Apartments | Space heating<br>Space cooling<br>Cooking<br>Water heating<br>Appliances<br>Lighting | Electricity<br>Natural gas<br>Hydrogen<br>Biomethane<br>LPG<br>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 12).

Table 12 AusTIMES: Commercial building types, end-use service demands and fuel types

| Building types | End-use service demands | Fuel types |
|---|---|---|
| Hospital<br>Hotel<br>Office<br>Public building<br>Retail<br>School<br>Aged care | Space heating<br>Space cooling<br>Water heating<br>Appliances<br>Lighting<br>Equipment | Electricity<br>Natural gas<br>Biomethane<br>Oil<br>Hydrogen |

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 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) (IEA, 2021a) 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 13 GTEM: Treatment of key variables

| 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 NIGEM baseline with population and GDP forecasts from Oxford Economics as reported in the IEA's *Net Zero by 2050 report*<br>Regional debt-to-GDP ratios are stabilised by 2050 (IEA, 2021b) | Movements in regional population and regional debt-to-GDP ratios match the CSP scenario<br>Movements in regional labour supply, regional GDP, regional employment and the global CPI are endogenously determined within GTEM | G1.5 Scenario<br>Movements in regional population and regional debt-to-GDP ratios match the CSP scenario<br>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 constraints | Endogenously responds to emissions constraints |
| **Emissions** | Global and selected regional $CO_2$ emissions pathways via shifts in emission intensity<br>Global and selected regional electricity $CO_2$ emissions pathways, including Australia emissions updated to the latest *National Greenhouse Gas Inventory (December 2022)*<br>Global $CO_2$ emissions pathways for selected industries – basic chemicals, iron and steel, land transport, water transport, and air transport<br>Global and regional AFOLU $CO_2$-e emissions pathways from GLOBIOM (Frank et al., 2021), using Australia's *NGGI*'s 2023 | Consistent with IMP_Ren scenario carbon budget in the *IPCC sixth Assessment Report*:<br>Global net GHG emissions budget of 827 Gt (IPCC, 2022) | Consistent with IPCC IMP_GS scenario's carbon budget the *IPCC sixth Assessment Report*:<br>Global net GHG emissions budget of 1,110 Gt (IPCC, 2022) |

| Variable | CSP scenario | G1.5 scenario | G2 scenario |
|---|---|---|---|
| | June Quarterly Update for historical data till 2023 and apply DCCEEW's *2023 Australian Emissions Projections* for the period of 2024-2035.<br>Source: IEA Stated Policies scenario from *IEA World Energy Outlook 2021* (IEA, 2021a) | | |
| **Electricity output and technology mix** | Global and regional electricity output pathways<br>Global electricity technology mix pathway<br>Source: IEA Stated Policies scenario from *IEA World Energy Outlook 2021* (IEA, 2021a)<br>Australia's electricity output and technology mix pathway is consistent with AusTIMES' latest projection<br>Source: AusTIMES (CSIRO) | Global electricity output pathway<br>Global electricity technology mix pathway<br>Source: IEA NZE scenario from *IEA World Energy Outlook 2021* (IEA, 2021a) | Global electricity output pathway<br>Global electricity technology mix pathway<br>Source: IEA APS scenario from *IEA World Energy Outlook 2021* (IEA, 2021a) |
| **Fossil fuel output** | Global coal, oil and gas output pathways from IEA Stated Policies scenario (IEA, 2021a) | Global coal and gas output pathways from IEA NZE scenario (IEA, 2021a) | Global coal and gas output pathways from IEA APS scenario (IEA, 2021a) |
| **Energy efficiency** | 1.5% annual energy efficiency improvement for households and firms<br>Extra 0.5% annual energy efficiency improvement for iron and steel, non-ferrous metals, and all transport sectors | 1.5% annual energy efficiency improvement for households and firms<br>Extra 0.5% annual energy efficiency improvement for iron and steel, non-ferrous metals, and all transport sectors<br>Extra 0.5%-1% annual efficiency improvement in use of fossil fuels | 1.5% annual energy efficiency improvement for households and firms<br>Extra 0.5% annual energy efficiency improvement for iron and steel, non-ferrous metals, and all transport sectors<br>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 13mentions 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 14, Table 15 and Table 16 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 14 GTEM: 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 15 GTEM: 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 $CO_2$) | | | | |
| **Fossil fuels and processes** | 39 | 1,325 | na | 5,650 |
| **Direct air capture** | 0 | 70 | na | 630 |
| **Bioenergy** | 1 | 255 | na | 1,475 |

Table 16 GTEM: 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 | 4 | 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 $CO_2$)** | | | | |
| **Fossil fuels and processes** | 39 | 1,325 | na | 5,245 |
| **Direct air capture** | 0 | 70 | na | 630 |
| **Bioenergy** | 1 | 255 | na | 1,380 |

Table 17 GTEM: 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 |

| | 2020-2030 | 2030-2040 | 2040-2050 |
|---|---|---|---|
| **Population* (average annual %-change)** | | | |
| **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 18 AusTIMES: Treatment of key variables

| Variable | A50/G2, A50/G1.5 | A45/G2 | A40/G1.5, A40/G2, A35/G1.5 |
|---|---|---|---|
| **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 "Step 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 Post 2050" 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 "Step Change" scenario in 2022 CSIRO projections | Consistent with "Export Superpower" scenario in 2022 CSIRO projections |
| **Transport Sector** | Progressive Change scenario (higher growth in transport demand) | Step Change scenario (moderate 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 | High propensity for uptake of electrification and energy efficiency measures |

### A.2.2 Carbon emissions pathway assumptions

Table 19 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 19 Australia's emissions pathways imposed under the GTEM domestic scenarios

| Year | A50/G2 (Mt $CO_2$-e) | A45/G2 (Mt $CO_2$-E) | A40/G2 (Mt $CO_2$-e) | A50/G1.5 (Mt $CO_2$-e) | A40/G1.5 (Mt $CO_2$-e) | A35/G1.5 (Mt $CO_2$-e) |
|---|---|---|---|---|---|---|
| **2020** | 473 | 473 | 473 | 473 | 473 | 473 |
| **2021** | 465 | 465 | 465 | 465 | 465 | 465 |
| **2022** | 465 | 465 | 465 | 465 | 465 | 465 |
| **2023** | 460 | 460 | 460 | 460 | 460 | 460 |
| **2024** | 445 | 445 | 445 | 445 | 445 | 445 |
| **2025** | 430 | 430 | 430 | 430 | 430 | 430 |
| **2026** | 415 | 415 | 415 | 415 | 415 | 387 |
| **2027** | 400 | 400 | 400 | 400 | 400 | 344 |
| **2028** | 385 | 385 | 373 | 385 | 373 | 301 |
| **2029** | 370 | 370 | 342 | 370 | 342 | 258 |
| **2030** | 355 | 355 | 311 | 355 | 311 | 215 |
| **2031** | 337 | 331 | 280 | 337 | 280 | 172 |
| **2032** | 319 | 307 | 249 | 319 | 249 | 129 |
| **2033** | 301 | 284 | 218 | 301 | 218 | 86 |
| **2034** | 284 | 260 | 187 | 284 | 187 | 43 |
| **2035** | 266 | 236 | 156 | 266 | 156 | 0 |
| **2036** | 248 | 213 | 124 | 248 | 124 | Hold gross emissions (excl. LULUCF emissions) constant till 2050 |
| **2037** | 230 | 189 | 93 | 230 | 93 | |
| **2038** | 213 | 165 | 62 | 213 | 62 | |
| **2039** | 195 | 142 | 31 | 195 | 31 | |
| **2040** | 177 | 118 | 0 | 177 | 0 | |
| **2041** | 160 | 95 | Hold gross emissions (excl. LULUCF emissions) constant till 2050 | 160 | Hold gross emissions (excl. LULUCF emissions) constant till 2050 | |
| **2042** | 142 | 71 | | 142 | | |
| **2043** | 124 | 47 | | 124 | | |
| **2044** | 106 | 24 | | 106 | | |
| **2045** | 89 | 0 | | 89 | | |
| **2046** | 71 | Hold gross emissions (excl. LULUCF emissions) constant till 2050 | | 71 | | |
| **2047** | 53 | | | 53 | | |
| **2048** | 35 | | | 35 | | |
| **2049** | 18 | | | 18 | | |
| **2050** | 0 | | | 0 | | |

These emissions reduction constraints 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 20.

Table 20 Additional assumptions

| Model | Assumptions/constraints |
|---|---|
| **GTEM** | Australia does not participate in global emissions trading.<br>Australia's coal and gas outputs in G1.5 group of scenarios and G2 group of scenarios are no higher than that in the G1.5 and G2 scenarios, respectively.<br>Australia's coal output in G2 is capped to a linear decrease to a maximum of 70% of initial levels in 2050.<br>Australia's livestock sectors (Cattle and Raw Milk) outputs are kept at 2020 levels till 2050 as a proxy for constant herd cattle numbers.<br>DACCS and BECCS technology starts to take up after 2030.<br>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.<br>GFDL-ESM2M global climate used to model agricultural and plantation climate impacts<br>Agricultural GHG 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.<br>Hydrogen and biomethane fuels are incorporated into the model as a decarbonisation option for buildings and industry.<br>Land and technical (LULUCF and DAC) sequestrations are imposed exogenously in this realisation of AusTIMES. CCS is solved for endogenously.<br>Energy efficiency and electrification are assumed to reduce carbon footprint and offer cost savings for homeowners.<br>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. |

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