Australia's National
Science Agency

Multi-sectoral modelling 2024

David Green, Luke Reedman, Amit Kanudia, Mythili Murugesan, Rosie Dollman, Sam West, Emily Dioguardi, Angus Grant, Martin Nolan, Deepanko Singha, Ro Maxwell, Michael Li and Lisa Havas
Report No. EP2025-1797
May 2025

Citation

Green, D.L., Reedman, L.J., Kanudia, A.*, Murugesan, M., Dollman, R., West, S., Dioguardi, E., Grant, A., Nolan, M., Singha, D.+, Maxwell, R. +, Li, M. +, and Havas, L. 2025. *Multi-sectoral modelling 2024*, CSIRO Report No. EP2025-1797, Australia.

* KanORS-EMR

+ Climateworks Centre

Copyright

Important disclaimer

Contents

Figures

Tables

Acknowledgments

This report has benefited from input from AEMO staff. We also acknowledge internal reviewers from CSIRO for their inputs on previous drafts.

Executive summary

The CSIRO, in collaboration with its partners Climateworks Centre and KanORS-EMR, were commissioned by the Australian Energy Market Operator (AEMO) to assist in producing projections of electricity, fuel consumption, and emissions for the period 2024-25 to 2057-58. This project is an update of the multi-sector modelling that was undertaken by CSIRO and Climateworks Centre in 2022 (Reedman et al., 2022).

Those modelled scenarios were since adapted by AEMO to explore new key contexts such as Australia's potential role in green energy exports. Changes to the modelling methodology include updated assumptions for electrification and energy efficiency uptake, carbon budgets reflecting the most recent climate science, and a land-based sequestration modelling approach that uses an updated cost-curve approach coupled with an emissions sequestration profile of new plantings over time. In addition, the regional scope was extended from the National Electricity Market (NEM) and Western Australia (WA) to include the Northern Territory (NT) for the first time.

The modelling provides insights into the key dynamics and linkages across sectors that may impact the electricity sector under the scenarios provided by AEMO. The AusTIMES model utilised for this project provides a whole-of-economy approach and the ability to cost-optimise across power generation, transport, industry, and buildings sectors to meet the decarbonisation objectives.

The four scenarios defined by AEMO for this modelling are:

Progressive Change: This net zero by 2050 scenario, features slower and weaker economic growth. Global progress towards net zero ambitions progresses in line with currently announced policies and ambitions, including Australia's commitment to a 43% reduction of emissions by 2030.

Step Change: Consumer-led change with focus on energy efficiency, consumer energy resources (CER), digitalisation and increases in global emissions policy ambition. Domestic and international action rapidly increases to achieve the objectives of the Paris Agreement, to limit global temperature rise to well below 2°C compared to pre-industrial levels.

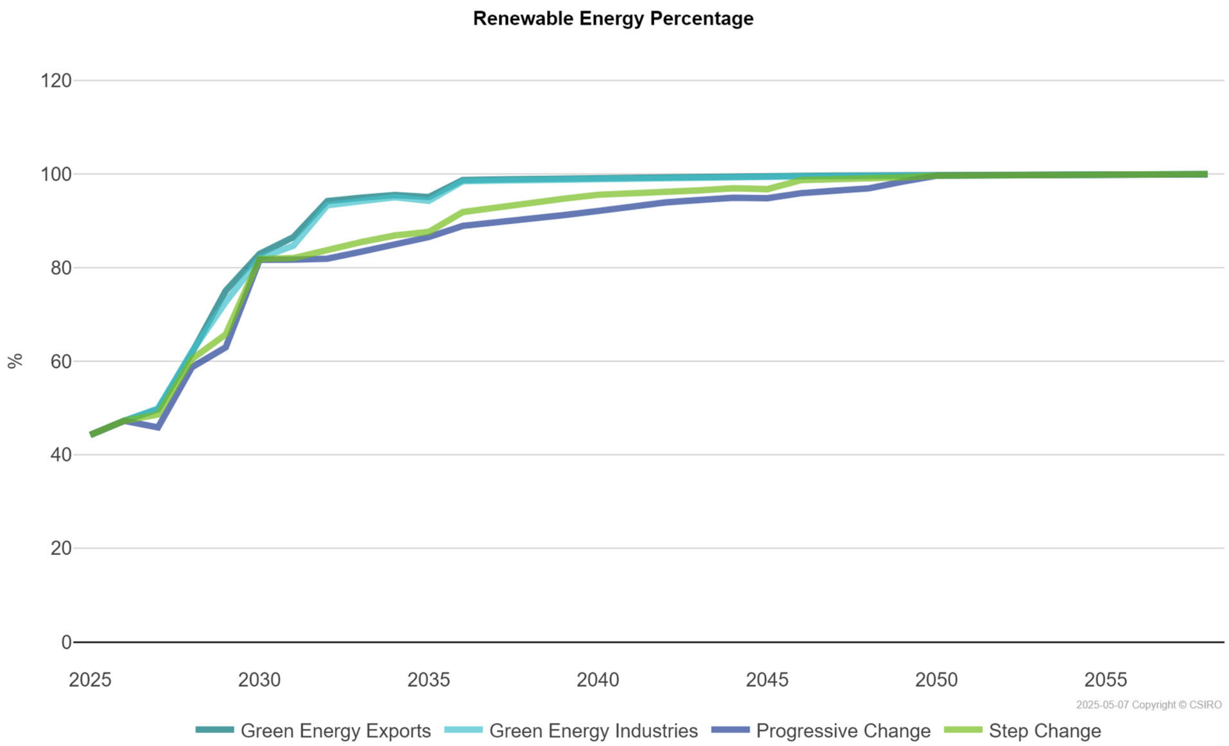
Green Energy Exports: Includes development of a hydrogen industry, focusing on value-add hydrogen products such as green iron and steel, for domestic use and export. Also includes significant opportunity for hydrogen production and associated manufacturing users to develop products for export, including hydrogen as an energy carrier. Strong international decarbonisation objectives lead to faster actions enabling the achievement of the ambition of the Paris Agreement, limiting global temperature rise to 1.5°C above pre-industrial levels.

Green Energy Industries: This scenario has similar scenario settings to Green Energy Exports and represents a world with very high levels of electrification and hydrogen production, fuelled by stronger decarbonisation targets and technology cost improvements. These technology cost reductions improve Australia's capacity to expand its industrial base, supporting stronger domestic economic outcomes relative to other scenarios via the export of green commodities. In contrast to Green Energy Exports, there is no export of hydrogen as an energy carrier.

Key findings from the multi-sectoral modelling are outlined below.

A significant decarbonisation coupled with growth in capacity of the electricity system is central to all modelled cost-effective pathways to meet Australia's renewable energy and emissions reduction targets.

When compared with modelling completed in 2022, this modelling shows that the national renewable target of 82% of renewable electricity and an expanded VRET has led to the share of renewable electricity increases rapidly coinciding with the announced closures of coal-fired generators (Exec Figure 1). The increased proportion of renewable electricity has narrowed the spread in electricity sector emissions across the modelled scenarios.

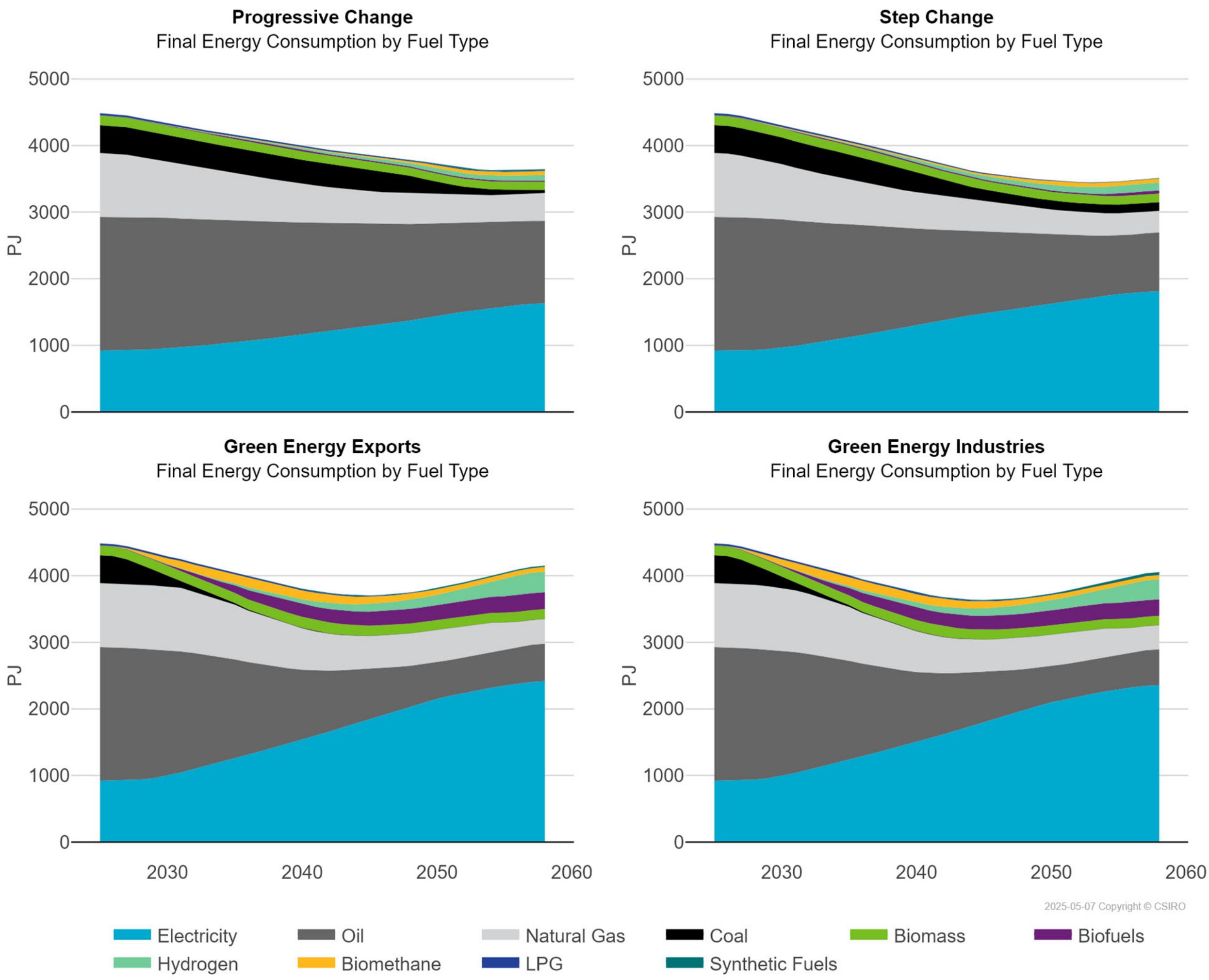


Exec Figure 1 Renewable Electricity Generation Percentage in major grids
Note: Both Green Energy scenarios follow a near identical trajectory.

In the NEM, brown coal transitions out in the mid-2030s with black coal retired by the late 2040s in the Progressive Change scenario. More rapid transition is observed in Step Change with a greater acceleration of renewable deployment given higher activity growth and electrification of end-uses. Brown coal transitions out in the mid-2030s with black coal retired by the mid-2040s in this scenario. This transition is accelerated across the Green Energy scenarios, with a more rapid reduction in coal-fired generation (brown coal exits by 2030 and black coal by 2034).

Across all scenarios, there is a clear decline in fossil fuel consumption, particularly coal, oil, and natural gas, reflecting the shift towards decarbonisation.

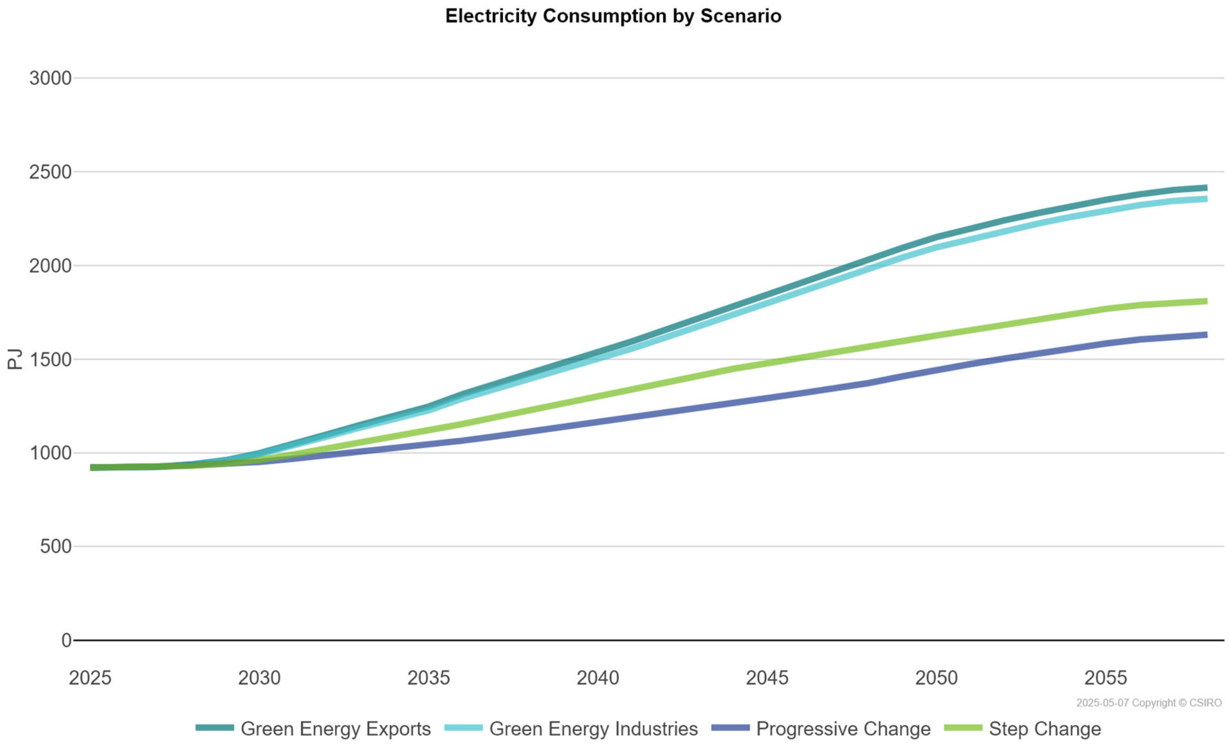
By 2050, natural gas consumption declines between 36 and 59 per cent compared to 2025, while oil consumption drops between 30 and 74 per cent (Exec Figure 2). At the same time, there is a marked increase in electrification, with electricity consumption rising significantly, especially under the Green Energy scenarios where it more than doubles by 2050. Hydrogen emerges as a significant energy carrier, with its uptake varying across scenarios but reaching its highest levels in the Green Energy Exports scenario. Biomethane and synthetic fuels also see substantial growth.



Exec Figure 2 Final energy consumption by fuel type nationally

Electricity consumption increases by between 75 % and 160 % and is driven mostly by the uptake of electric vehicles, and electrification and growth in industry.

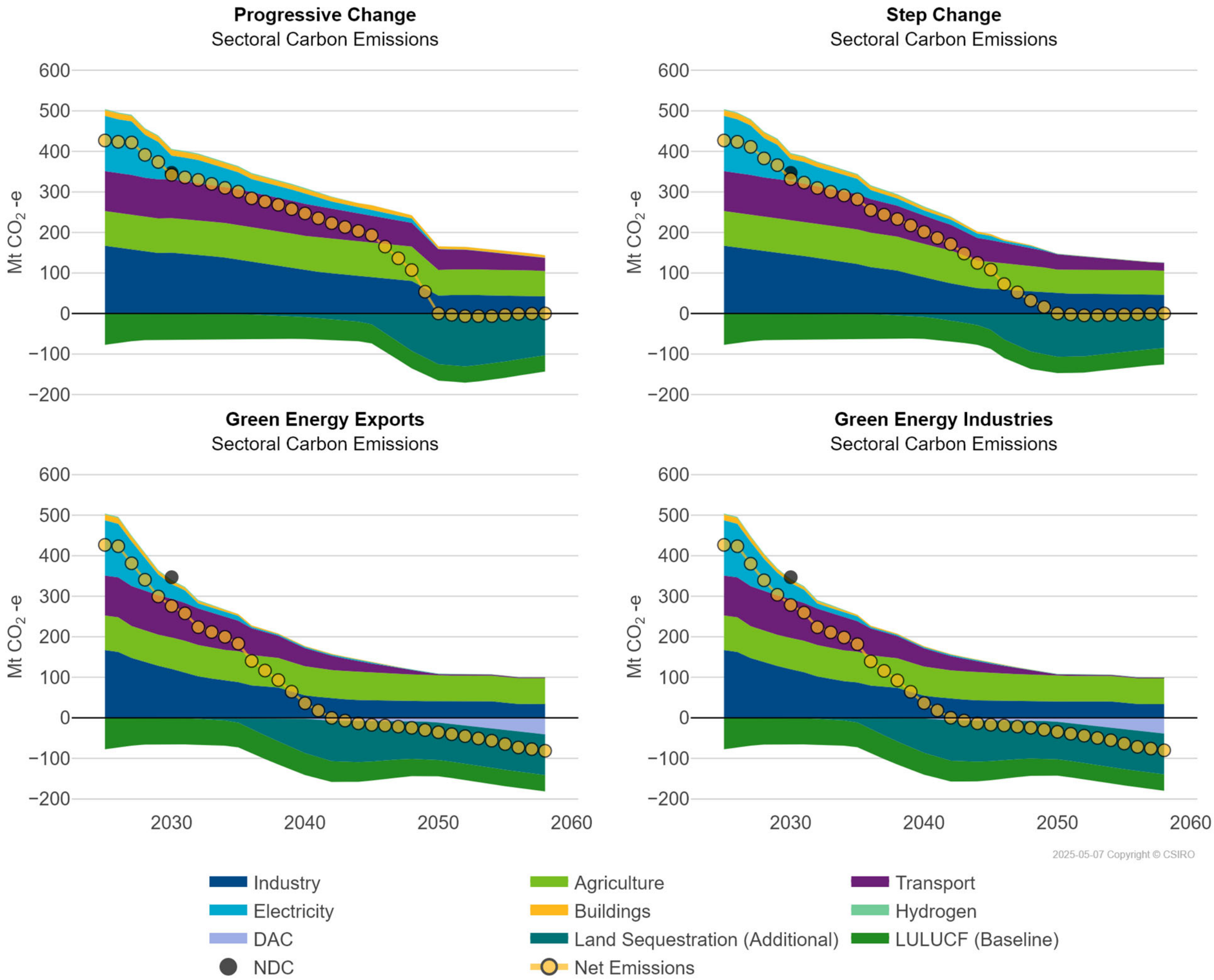
In all scenarios, electricity consumption in buildings increases by at least 40 per cent (from near 500 PJ to more than 700 PJ), but it is industry and transport which drive most of the 75 per cent increase in Progressive Change (160 per cent increase in the Green Energy Scenarios) in overall electricity consumption (Exec Figure 3). In transport this is due to the uptake of electric vehicles, and in industry is the combined result of green commodity production and electrification of the large industrial loads which produce them, such as alumina and iron & steel but also mining and gas extraction/export. This electrification avoids the consumption of between 370 and 500 PJ of natural gas, and energy efficiency improvements reduce overall consumption by between 300 and 700 PJ.



Exec Figure 3 Electricity consumption by scenario nationally

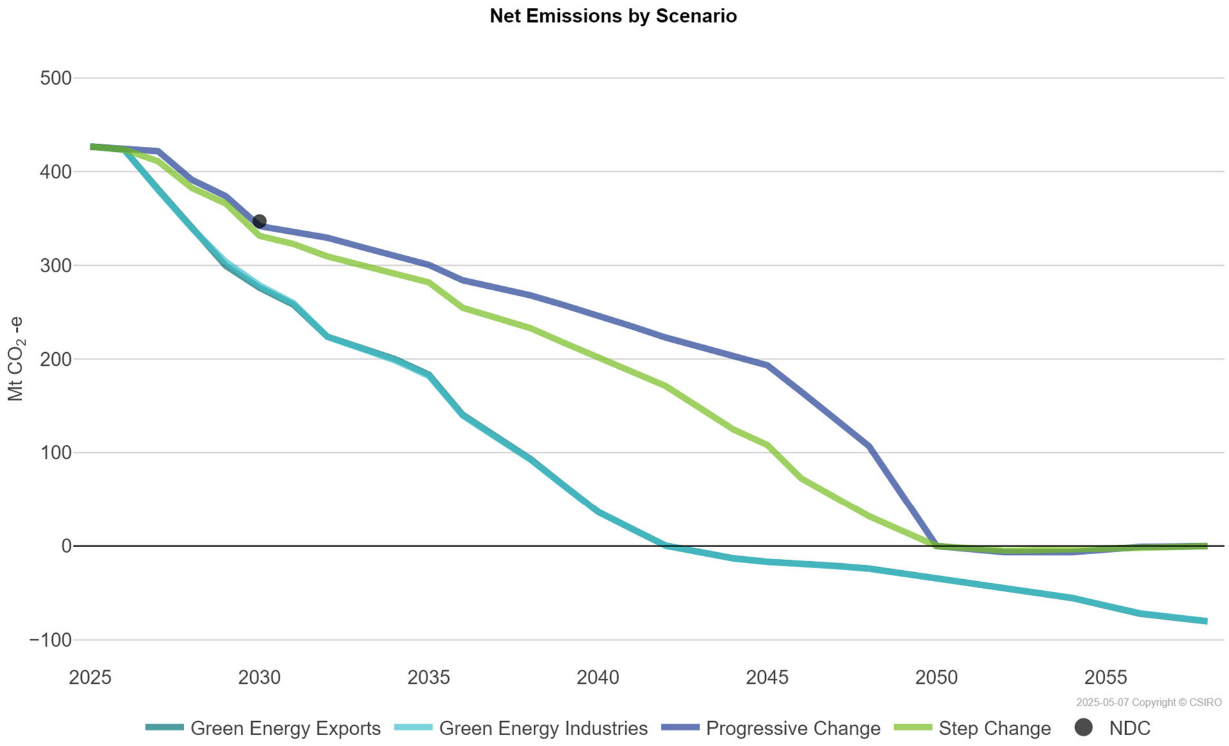
The scale of emissions reduction varies greatly across sectors.

In terms of emissions reduced across the 2025 to 2050 period, the greatest reductions are seen in power generation ("Electricity" in Exec Figure 4), and then in decreasing order, industry, new land-based sequestration (Land sequestration (Additional) in Exec Figure 4), transport, Direct Air Capture (DAC), agriculture, and then buildings. Land-use and land-use change represents the 2024 Commonwealth projections (LULUCF (Baseline) in Exec Figure 4), while new land-based sequestration (environmental plantings and mallee plantings) is based on costings derived from the Land Use Trade-off (LUTO) model.



Exec Figure 4 Sectoral carbon emissions with NDC of 347 Mt of CO2-e in 2030

All scenarios are required to achieve the 2030 Nationally Determined Contribution (NDC) and the legislated net zero target of 2050. Progressive Change and Step Change show a similar emissions reduction trajectory, with Step Change slightly more rapid given the tighter carbon budget. Both scenarios achieve net zero emissions in 2050 (see Exec Figure 5). With a more stringent carbon budget, the Green Energy scenarios feature more rapid decarbonisation in power generation, industry, transport and buildings. There is also earlier deployment of new land-based sequestration and DAC as carbon removal technologies. Both Green Energy Exports and Green Energy Industries achieve net zero emissions in the early 2040s.



Exec Figure 5 Net emissions by scenario

Note: Both Green Energy scenarios follow a near identical trajectory.

1 Introduction

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

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

Progressive Change: This net zero by 2050 scenario features slower and weaker economic growth. Global progress towards net zero ambitions progresses in line with currently announced policies and ambitions, including Australia's commitment to a 43% reduction of emissions by 2030. This scenario is aligned to a global temperature rise of 2.6°C compared to pre-industrial levels.

Step Change: Consumer-led change with focus on energy efficiency, consumer energy resources (CER), digitalisation and increases in global emissions policy ambition. Domestic and international action rapidly increases to achieve the objectives of the Paris Agreement, to limit global temperature rise to well below 2°C, compared to pre-industrial levels.

Green Energy Exports: This scenario represents a world with very high levels of electrification and hydrogen production, fuelled by stronger decarbonisation targets and technology cost improvements than Progressive Change and Step Change. These technology cost reductions improve Australia's capacity to expand its exports of "green commodities" and hydrogen as an energy carrier to global consumers, supporting stronger domestic economic outcomes relative to other scenarios. Strong international decarbonisation objectives lead to faster actions enabling the achievement of the ambition of the Paris Agreement, limiting global temperature rise to 1.5°C, over pre-industrial levels.

Green Energy Industries: This scenario has similar scenario settings to Green Energy Exports and represents a world with very high levels of electrification and hydrogen production, fuelled by stronger decarbonisation targets and technology cost improvements. These technology cost reductions improve Australia's capacity to expand its industrial base, supporting stronger domestic economic outcomes relative to other scenarios via the export of green commodities. In contrast to Green Energy Exports, there is no export of hydrogen as an energy carrier. Strong international decarbonisation objectives lead to faster actions enabling the achievement of the ambition of the Paris Agreement, limiting global temperature rise to 1.5°C, over pre-industrial levels.

These four scenarios were modelled to analyse the effects of multi-sector interactions on regional and sectoral consumptions and emissions for the NEM-connected states and territories (i.e., New South Wales, Australian Capital Territory, Victoria, Queensland, South Australia and Tasmania) and for Western Australia and the Northern Territory for the period 2024-25 to 2057-58.

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

- Section 2 briefly discusses scenario narratives and the key assumptions that do or do not vary by scenario.
- Section 3 outlines the methodology, providing an overview of the AusTIMES model and key aspects of modelling decarbonisation scenarios
- Section 4 discusses NEM, WA and NT level projection results for the four scenarios focussing on emission outcomes, fuel mix changes in the electricity and end-use sectors, hydrogen and biomethane production.

2 Scenario definition

2.1 Scenario overview

The four scenarios modelled in this study are Progressive Change, Step Change, Green Energy Exports and Green Energy Industries. A short narrative for each scenario is provided below with the settings for the key drivers summarised in Table 2-1. The scenario titles and narratives were defined by AEMO, refined by stakeholder feedback, and provided to the CSIRO and its partners to inform the selection of modelling input assumptions.

2.1.1 Progressive Change scenario

This scenario features slower and weaker economic growth than historical trends. These challenging economic conditions lead to the greatest relative risk of industrial load closures. Lesser economic and population growth occurs in the context of lower global investment which slows decline in the cost of low emissions technologies.

Uptake of distributed solar PV and other DER technologies are dampened due to supply chain issues. Renewable energy development trends continue to be driven by jurisdictional developments, and coal capacity features less economic retirement compared to the other scenarios. Uptake of energy efficiency measures is muted across all end-use sectors.

Global progress towards net zero ambitions progresses in line with currently announced policies and ambitions, including Australia's updated commitment to a 43% reduction of emissions by 2030. State emission reduction targets are excluded (see Section B.1).

As with all scenarios, economic utilisation of land-use sequestration offsets may offer a means to address sectors that are harder to decarbonise.

Key features of the Progressive Change Scenario are:

- More insular trade policies and increased protectionism take hold globally. Australia's population growth is relatively lower than other scenarios, with falling birth rates and immigration levels, partly due to sustained impacts on global mobility.
- In search of cost savings, consumers continue to install distributed solar PV, though at lower rates – the reduction partly due to relatively higher costs of panels and inverters due to supply chain issues.
- Similarly, investment in household battery storage and electric vehicles (EVs) does not grow as fast as other scenario forecasts, due to more muted cost reductions, the impact of lower disposable incomes, vehicle supply chain issues, softening in peak demand price signals, and longer vehicle replacement cycles.
- Electrification of heating appliances to transition away from gas is more muted in the near term due to challenging economic conditions.
- Government policy reflects current commitments, particularly the 43% emissions reduction by 2030 and net zero emissions by 2050 (as well as some state-based commitments, excluding

state emission reduction targets), is aligned to a global temperature rise of 2.6°C compared to pre-industrial levels. Lower economic activity reduces total energy requirements.

2.1.2 Step Change scenario

The Step Change scenario assumes moderate global economic growth and improved international coordination in terms of climate change policy. At the domestic level, the Step Change scenario assumes that the demographic and economic drivers of Australia's economy follow a moderate path. This scenario includes a global step change in response to climate change, supported by technology advancements and a coordinated cross-sector plan that tackles the adaptation challenges at a higher level than Progressive Change. Domestic and international action increases to achieve the less stringent temperature goal of the Paris Agreement, to limit global temperature rise to below 2°C compared to pre-industrial levels. Step Change maps to the International Energy Agency's Announced Pledges Scenario and to the Intergovernmental Panel on Climate Change's Representative Concentration Pathway (RCP) 2.6 where relevant.

Rapid transformation of the energy sector is enabled by rapidly falling costs for battery storage and VRE, which enables greater consumer investment in distributed energy resources compared with Progressive Change. The transformation of the transport sector in particular is influenced by a combination of technology cost reductions affecting zero emissions vehicles, and manufacturers eliminating internal-combustion engine vehicles from new vehicle production lines.

Continued advancements in digital technologies enable a greater role for consumers to manage energy use efficiently and provide flexibility to the system compared with Progressive Change. Sustainability has a stronger focus, with consumers, corporations, developers, and government also supporting the need to reduce the collective energy footprint through adoption of greater energy efficiency measures compared with Progressive Change.

This scenario also considers a greater level of technology breakthrough in energy efficiency and fuel switching compared to Progressive Change, which increases the productivity of energy use. Energy efficiency improves by changes in building design, smart appliances, and digitalisation.

As with all scenarios, economic utilisation of land-use sequestration offsets may offer a means to manage sectors that are harder to decarbonise.

Key features of the Step Change Scenario are:

- Moderate growth in the global and domestic economy is observed following recovery from the pandemic.
- Higher levels of awareness towards the impacts of climate change from increasingly energy literate consumers result in a greater degree of individual consumer action to reduce emissions compared with Progressive Change. This is aided by continued advancement in digital technologies, innovation in business models enabling consumer engagement, and market reforms.
- Strong climate action underpins rapid transformation of the energy sector (and broader global economy) to achieve the less stringent temperature goal of the Paris Agreement, limiting global temperature rises to well below 2°C relative to pre-industrial levels.

Domestically, government policy and corporate objectives are aligned with the need to decarbonise the Australian economy, going beyond existing climate policy.

- Currently legislated or materially funded state-based renewable energy policies and targets are achieved, with future electricity sector investments influenced by policy measures that reduce cumulative emissions over time. State emission reduction targets are excluded (see Section B.1).
- This scenario assumes that the scale of hydrogen production connected to the NEM is limited, either technically or economically, such that hydrogen production does not materially impact the NEM's investment or operation.
- The degree of electrification is higher than Progressive Change, particularly from the transport sector, where EVs soon become the dominant form of road passenger transportation. This includes continued innovation in transport services, such as ride-sharing and autonomous vehicles, that may influence charge and discharge behaviours of the EV fleet, including vehicle-to-home discharging trends.
- Consumers also switch from gas to electricity to heat their homes. Stronger electrification from other sectors compared to Progressive Change is expected as a means to decarbonise manufacturing and other industrial activities.
- Overall, the scenario assumes stronger rates of technology cost decline for consumer devices such as DER, and energy efficiency and energy management systems.

2.1.3 Green Energy Exports scenario

This scenario represents a world with higher levels of electrification and hydrogen production than the other three scenarios, fuelled by stronger decarbonisation targets and technology cost improvements. These technology cost reductions improve Australia's capacity to expand its exports of "green commodities" to global consumers, including hydrogen and other energy-intensive products such as green steel, supporting stronger domestic economic outcomes relative to other scenarios.

Strong international decarbonisation objectives lead to faster actions enabling the achievement of the more ambitious goal of the Paris Agreement, limiting global temperature rise to 1.5°C by 2100 over pre-industrial levels. This is matched domestically with strong economy-wide actions in line with global ambition.

Continued improvements in the economics of hydrogen production technologies enable the development of a significant renewable hydrogen production industry in Australia for both export and domestic consumption. Strong global decarbonisation action provides a high level of international demand for this production capacity, supplementing declining exports of traditional emissions-intensive resources in this scenario. In the long-term, technical barriers that prevent high uptake of hydrogen in the gas supply network are also overcome, allowing for up to 100% hydrogen in gas supply distribution networks.

The 1.5°C decarbonisation objective leads to a higher degree of electrification and energy efficiency investments across many sectors than the other three scenarios. Increased access to domestic hydrogen production and refuelling infrastructure increases the competitiveness of hydrogen fuel-cell vehicles in heavy transport.

As with all scenarios, economic utilisation of land-use sequestration offsets may offer a means to manage sectors that are harder to decarbonise.

Key features of the Green Energy Exports scenario are:

- Strong global and domestic action to address climate change and reduce emissions accelerates action to decarbonise. This is enabled through strong economic activity and global investments to meet the preferred objective of the Paris Agreement to limit global temperature rise to 1.5°C.
- Capitalising on significant renewable resource advantages and economic and technological improvements in hydrogen production, Australia establishes strong hydrogen export partnerships to meet international demand for clean energy.
- The export of green hydrogen and other energy-intensive products such as green steel, supports stronger domestic economic outcomes relative to other scenarios, which again causes a higher rate of migration to Australia.
- Both domestic and export hydrogen demand is fuelled, at least in part, by grid-connected electrolysis powered by additional VRE development.
- Strong economy-wide decarbonisation objectives provide significant opportunities to fuel switch towards electricity and hydrogen. The energy transition in Australia is embraced by consumers, as they seek clean energy and energy efficient homes and vehicles.

2.1.4 Green Energy Industries scenario

The Green Energy Industries scenario is identical to the Green Energy Exports scenario except that there is no role for the export of hydrogen as an energy carrier across the forecast period. This presents a diminished export opportunity compared to the Green Energy Exports scenario.

In the Green Energy Industries scenario:

- Australia's population is identical to the Green Energy Exports scenario
- By the end of the forecast period, GDP is forecast to be 0.3% lower compared to the Green Energy Exports scenario but 29% higher than the Step Change Scenario
- Manufacturing industry output is 12% lower in 2057-58 compared to the Green Energy Exports scenario.

2.1.5 Summary

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

Table 2-1 AEMO scenario definitions

Model Input Assumptions	Progressive Change	Step Change	Green Energy Exports	Green Energy Industries
National decarbonisation target	At least 43% emissions reduction by 2030, Net zero by 2050	At least 43% emissions reduction by 2030, Net zero by 2050	At least 43% emissions reduction by 2030, Net zero by 2050	At least 43% emissions reduction by 2030, Net zero by 2050
Global economic growth and policy coordination	Slower economic growth, lesser coordination	Moderate economic growth, stronger coordination	High economic growth, stronger coordination	High economic growth, stronger coordination
Australian economic and demographic drivers	Lower	Moderate economic growth, with near-term economic growth impacted by current economic challenges[1]	Higher, with near-term economic growth impacted somewhat by current economic challenges	Higher, with near-term economic growth impacted somewhat by current economic challenges
Electrification	Electrification is tailored to meet existing emissions reduction commitments, with slower adoption given weaker economic circumstances	High electrification to meet emissions reduction commitments, with pace of adoption reflecting economic conditions	Higher electrification efforts to meet aggressive emissions reduction objectives, with faster pace of adoption	Higher electrification efforts to meet aggressive emissions reduction objectives, with faster pace of adoption
Emerging commercial loads	Emerging sectors such as data centres experience lower growth as weaker economic circumstances limit technology uptake	Emerging sectors such as data centres match opportunities associated with moderate domestic economic drivers	Emerging sectors such as data centres match opportunities associated with higher domestic economic drivers	Emerging sectors such as data centres match opportunities associated with higher domestic economic drivers
Industrial load closures	Weak economic conditions provide challenging commercial conditions, resulting in load closures across key commercial and industrial facilities	No specific load closures	No specific load closures	No specific load closures
Demand side participation uptake	Lower	Moderate	Higher	Higher
Consumer energy resource investments (batteries, PV and EVs)	Lower	High	Higher	Higher
Coordination of CER (VPP and V2G)	Low long-term coordination, with gradual acceptance of coordination	Moderate long-term coordination, with gradual acceptance of coordination	High long-term coordination, with faster acceptance of coordination	High long-term coordination, with faster acceptance of coordination
Energy efficiency improvement	Moderate	High	Higher	Higher
Hydrogen use and availability	Low production for domestic use, with no export hydrogen	Moderate-low production for domestic use, with minimal export hydrogen	High production for domestic industries, with moderate exports in the short term, and high exports in the longer term	High production for domestic industries, with zero exports as an energy carrier
Renewable gas blending in gas distribution network[2]	Up to 10% (hydrogen), with unlimited blending opportunity for biomethane and other renewable gases	Up to 10% (hydrogen), with unlimited blending opportunity for biomethane and other renewable gases	Up to 10% (hydrogen), with unlimited blending opportunity for biomethane and other renewable gases	Up to 10% (hydrogen), with unlimited blending opportunity for biomethane and other renewable gases

Supply chain strength influencing demand forecasts	Low	Moderate	High	High
Global/domestic temperature settings and outcomes[3]	Aligned to Representative Concentration Pathway (RCP) 4.5 , which is consistent with a global temperature rise of between 2 and 3°C by 2100	Aligned to RCP 2.6, which is consistent with a global temperature rise of ~1.8°C by 2100	Aligned to RCP 1.9, which is consistent with a global temperature rise of ~1.4°C by 2100 (~1.5°C near term temperature rise)	Aligned to RCP 1.9, consistent with a global temperature rise of ~1.4°C by 2100 (~1.5°C near term temperature rise)
IEA 2024 World Energy Outlook scenario alignment	Stated Policies Scenario (STEPS)	Announced Pledges Scenario (APS)	Net Zero Emissions (NZE)	Net Zero Emissions (NZE)

Notes: PV: photovoltaics, EV: electric vehicle, VPP: virtual power plant, V2G: vehicle-to-grid; 1. It is recognised that cost of living challenges have grown since the 2023 IASR. See https://www.abs.gov.au/statistics/economy/price-indexes-and-inflation/selected-living-cost-indexes-; 2. Hydrogen blending into the gas distribution network will need to accommodate the technical requirements of distribution pipelines, as well as the capabilities of connected gas appliances. Higher blends than ~10% by volume are assumed possible for industrial use but may require equipment change and/or shifts to dedicated hydrogen transmission pipelines; 3. RCPs were adopted in the IPCC's first Assessment Report, see https://www.ipcc.ch/report/ar5/syr/

3 Methodology

3.1 AusTIMES model overview

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

The TIMES energy system modelling framework has been used extensively in over 20 countries. TIMES is a successor to the MARKAL energy system model. The model satisfies energy services demand at the minimum total system cost, subject to physical, technological, and policy constraints. Accordingly, the model makes simultaneous decisions regarding technology investment, primary energy supply and energy trade. Extensive documentation of the TIMES model generator is available from the ETSAP website1.

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

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

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

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

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.

3.2 Main structural features

The AusTIMES model has the following structural features:

- Coverage of all states and mainland territories (ACT, NSW, NT, QLD, SA, TAS, VIC, WA)
- Time is represented in annual frequency in financial years (2024-2058)[2]
- End-use sectors include agriculture (8 sub-sectors), mining (11 sub-sectors), manufacturing (21 sub-sectors), other industry (5 sub-sectors), commercial and services (11 building types), residential (3 building types), road transport (10 vehicle segments) and non-road transport (aviation, rail, shipping)
    - Each sector has information regarding energy consumption and assumed efficiency gains, as well as options regarding which primary energy sources can be consumed, additional costed fuel switching or efficiency improvements, options for avoiding non-energy emissions and potential for carbon capture and storage (CCS)
- Representation of fuel types across the end-use sectors:
    - Industry and agriculture: Oil (mainly diesel), black coal, brown coal, natural gas, hydrogen, biomethane, electricity and other bioenergy (e.g., bagasse in existing applications, biodiesel)
    - Residential buildings: Natural gas, liquid petroleum gas, hydrogen, biomethane, wood and electricity
    - Commercial buildings: Oil (as reported in Australian Energy Statistics), natural gas, hydrogen, biomethane and electricity
    - Transport: Oil (mainly petrol, diesel, kerosene, fuel oil), biofuels (ethanol, biodiesel), liquid petroleum gas, natural gas, electricity, hydrogen.
- Electricity sector (more details in Appendix A.2)
- Multiple hydrogen production pathways including two electrolysis pathways: proton exchange membrane (PEM); and alkaline electrolysis (AE); steam methane reforming (SMR); SMR with CCS; brown coal gasification with CCS; by-product hydrogen produced in the chemicals industry.

3.3 Model calibration and inputs

The AusTIMES model for this study has been calibrated to the latest state/territory level energy balance that was available upon commencement of this modelling (DISER, 2024a), the most recent national inventory of greenhouse gas emissions[3], stock estimates of vehicles in the transport

---

[2] Note that the model solution was approximately every two years over the model horizon (sometimes yearly) and for years where there is no explicit model solution, linear interpolation was used.

[3] https://www.greenhouseaccounts.climatechange.gov.au [accessed 16 April 2025]

sector (BITRE, 2023), data on the existing power generation fleet (AEMO, 2024; Australian Energy Council, 2024), and installed capacity of distributed generation (Graham and Mediwaththe, 2024).

For this particular work, additional inputs were sourced from AEMO and its third-party consultants regarding economic activity, population growth, distributed energy resources, capital costs of generation technologies, projected uptake of CER (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). The assumptions applied based on these parallel consultancies are outlined in Section 3.7.

3.4 Objective function

TIMES is formulated as a linear programming problem. The objective function of total discounted system costs over the projection period (inter-temporal optimisation) is minimized while adhering to specific constraints. TIMES 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 (the equations of the model) which express the physical and logical relationships that must be satisfied to properly depict the energy system. Details on the constraints are available in Part I of the TIMES model documentation.[4]

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

3.5 Implementation of decarbonisation objectives in AusTIMES

Several approaches are available to implement decarbonisation objectives in AusTIMES:

1. Impose an annual carbon price trajectory
2. Specify one or more yearly net emission targets
3. Specifying a cumulative emissions constraint across a certain period.

The modelling for all scenarios in this report used a combination of the second and third options. Annual emissions targets in line with Australian Government commitments under the Paris Agreement (43% reduction on 2005 levels by 2030 and net zero emissions by 2050) are specified, and a cumulative emissions constraint is applied. Specific settings are discussed in Section 3.6.

[4] https://iea-etsap.org/docs/Documentation_for_the_TIMES_Model-Part-I.pdf [accessed 16 April 2025]

3.6 Carbon budgets and cumulative emissions constraints

Cumulative emissions constraints were set for all four scenarios, which represented the total cumulative emissions allowed between 2027-2060[5]. The cumulative emissions constraints (as opposed to the national point target constraints at 2030 and 2050) span the full range of emissions pressure, for example, for Progressive Change the carbon budget does not drive model outcomes as the pressure is insufficient, while in the Green Energy scenarios the carbon budget is sufficiently tight as to represent the most ambitious decarbonisation rate. The carbon budget for the Green Energy scenarios was determined by solving the model at increasingly tighter budgets until it was unable to find a solution. The tightest budget (see Table 3-1) maps to a 1.5 degree at 43% likelihood overshooting to 30% likelihood - similar to the A40/G1.5 scenario published by CSIRO and the Climate Change Authority[6] (Verikios et al., 2024; Climate Change Authority, 2024). The Step Change scenario carbon budget lies somewhat midway between the minimum and maximum emissions pressure budgets specified by those of Progressive Change and the Green Energy scenarios and maps to a 1.8 degree with 67% likelihood global temperature rise. The 2027-2060 budget values are listed in Table 3-1 as well as an approximate mapping from domestic carbon budget to global temperature target[7]. The methodology for the mapping from budget to temperature is described in Section 3.6.1.

Table 3-1 National cumulative and point emissions targets and mapping to temperature increase[8]

	2023-2060 Cumulative Emissions [$GtCO_2$-e]		**2030 % Reduction over 2005**		**2050 % Reduction over 2005**		**Mapped Global Temperature Target [Temp. @ Likelihood]**	
Scenario	Target	Achieved	Target	Achieved	Target	Achieved	Goal	Achieved
Progressive Change	<= 14.9	7.7	>= 43%	44%	>= 100%	100%	2.6 deg @ 83%	2 deg @ 80%
Step Change	<= 6.8	6.8	>= 43%	46%	>= 100%	100%	1.8 deg @ 66%	1.8 deg @ 66%
Green Energy Exports	<= 3.8	3.8 (4.6)	>= 43%	55%	>= 100%	106%	1.5 deg @ 43%	1.5 deg @ 43% (30%)
Green Energy Industries	<= 3.8	3.8 (4.6)	>= 43%	54%	>= 100%	106%	1.5 deg @ 43%	1.5 deg @ 43% (30%)

[5] The application of the carbon budget through till 2060 (as opposed to 2058) is due to the model time horizon being through to 2060, that is, one additional two-year time step beyond the range of interest as is the standard way AusTIMES is run. The carbon budget must also be applied through to the end of the model time horizon (rather than the range of interest) to avoid post-budget constraint rebound effects.

[6] For the A40/G1.5 scenario published by CSIRO and the Climate Change Authority, the mapping to temperature was 1.5 degrees @ 51% (31%), i.e., 51% likelihood with overshoot which maps to 31% likelihood with some of the main differences being that in this work there is a significantly updated model for land-based sequestration availability and rate of sequestration and high growth of green commodities.

[7] The mapping from a global temperature target to a domestic carbon budget relies on a series of assumptions (as detailed in Section B.2) and only applies should the rest of the world match the climate ambition indicative in the domestic scenario.

[8] Note that the model solution was approximately every two years over the model horizon (sometimes yearly) and for years where there is no explicit model solution, linear interpolation is used for the cumulative emissions calculations in Table 6.

Notes: Percentage values are the typical “likelihood” notation as used in climate scenario science. Note that all scenarios are fixed to the model solution for Progressive Change through to 2026, after which the scenario dependent settings are applied. Figures in parentheses indicate limited overshoot of the carbon budget, i.e., the carbon budget is exceeded, and net-negative emissions return the cumulative emissions to the constrained budget over the period between the net-zero year and 2060. The values in parentheses are those if using the maximum value of the cumulative emissions curve for the calculations (as opposed to the final value at 2060). For this work, only the Green Energy scenarios exhibit overshoot (of 0.8 $GtCO_2$-e) which maps to a 1.5 degree at 43% likelihood overshooting to 30% likelihood - similar to the A40/G1.5 scenario published by CSIRO and the Climate Change Authority[9] (Verikios et al., 2024; Climate Change Authority, 2024).

For the set of assumptions in this work (which include high growth green commodity levels), 1.5 degrees at 43% likelihood was only achievable when overshoot of the carbon budget is allowed, i.e., while the carbon budget constraint is met by 2060, the maximum in the cumulative emissions curve is higher than the budget, and is subsequently reduced to meet the budget between the net-zero year and 2060 via net negative emissions. That “overshoot” is constrained to 35% of the budget and is only taken up in the Green Energy scenarios. For those scenarios, we additionally impose a net-zero year of no later than 2042 as while the combination of carbon budget and limited overshoot constraints do drive ambitious decarbonisation, without the additional 2042 constraint emissions reach very low values in the early 2040s but do not actually reach net-zero. As such, the additional 2042 target yields a more canonical net-zero year while only minimally impacting the model solution.

3.6.1 Mapping from global temperature target to domestic carbon budget

The mapping from national carbon budget to global temperature rise is based on the method used by Meinshausen (2019) and updated by Nicholls and Meinshausen (2022). This approach involves the conversion of a global carbon budget into an Australian-specific budget by considering:

- The translation of a global carbon dioxide budget into a carbon dioxide-equivalent budget including other GHG emissions (Meinshausen, 2019)
- An assumption that Australia’s ‘fair share’ of the global carbon budget is 0.97% (consistent with the modified contraction and convergence approach from Garnaut 2008; Meinshausen et al., 2019)
- Subtraction of historical emissions up to 2023.

The full methodological approach including interim calculations and specific carbon budgets for each scenario are documented in Appendix B.2.

3.7 Link to other consultancies

In parallel to the multi-sectoral modelling, AEMO has commissioned consultants to provide other modelling which can form inputs into the multi-sectoral modelling (see Table 3-2).

[9] For the A40/G1.5 scenario published by CSIRO and the Climate Change Authority, the mapping to temperature was 1.5 degrees @ 51% (31%), i.e., 51 % likelihood with overshoot which maps to 31% likelihood with some of the main differences being that in this work there is a significantly updated model for land-based sequestration availability and rate of sequestration and high growth of green commodities.

Table 3-2 Links to other consultancies

Consultancy	Outputs	Inputs to AusTIMES
Economic and population forecasts (Deloitte)	Population growth Gross State Product (GSP) growth Industry Gross Value Added (GVA) growth	Activity driver for industry, transport and residential
Energy efficiency forecasts (SPR)	Energy efficiency uptake by sector	Rates of autonomous energy efficiency improvements are aligned. These improvements have no associated cost in AusTIMES, however, in SPR forecasts they are considered market led (requiring no additional policy actions), and are not necessarily zero cost.
Consumer Energy Resources (CER) projections (CSIRO)	Capacity of rooftop solar photovoltaic (PV), behind-the-meter batteries	CER capacity
EV projections (CSIRO)	Electric vehicle (EV), fuel cell electric vehicles (FCEV) and hybrid numbers of vehicles	Transport demand Shares of hybrids, EVs and FCEVs in vehicle kilometres travelled
Natural gas price projections (ACIL)	Wholesale gas prices	Input for fuel costs for end-use sectors Generator fuel costs
Biomethane price curves (ACIL)	Cost/quantity functions for biomethane from different feedstocks	Input for fuel costs for end-use sectors
Hydrogen export, green commodities (ACIL)	Hydrogen export volumes, green commodities production	Hydrogen export and feedstock hydrogen volumes for green commodities production
Hydrogen delivery costs (ACIL)	Delivery and storage costs to end-users	Delivery and storage costs to end-users

As AusTIMES is calibrated to historical data, a key input into the model are activity drivers which change the demand for energy over the projection period. The economic and population forecasts provide activity drivers for industry and commercial sectors (projections of changes in gross value added), residential buildings (population growth), passenger transport demand (population growth), freight transport demand (population and economic growth).

Uptake of energy efficiency can reduce the growth in energy demand. AusTIMES accounts for uncosted autonomous energy efficiency improvement (AEEI) as well as costed (and endogenously determined) energy efficiency measures (see Appendix B.3). The energy efficiency forecasts from SPR use the same AEEI assumptions as AusTIMES. However, in SPR forecasts they are considered market led (requiring no additional policy actions), and are not necessarily zero cost.

The uptake of rooftop solar PV, behind-the-meter batteries, and alternative-drivetrain vehicles (electric vehicles, fuel cell electric vehicles, plug-in hybrid electric, and hybrid vehicles), can also be determined within AusTIMES. Recognising that the uptake of these technologies have economic and non-economic drivers, and to ensure consistency, the uptake of these technologies by scenario was used as an input into AusTIMES for the multi-sectoral modelling. Projections of Consumer Energy Resources (CER) provided by CSIRO are a direct input into AusTIMES based on the capacity projections of rooftop solar PV and batteries. For hybrid, electric and fuel cell vehicles, the kilometre shares of these vehicles are direct input into AusTIMES.

Natural gas price projections are a key input into AusTIMES to ensure scenario consistent input fuel costs for end-use sectors and gas-fired power generators. Similarly, cost-quantity functions for biomethane from different feedstocks provide input fuel costs for industry and buildings as a substitute to natural gas, assuming end-users face similar network use of system charges to natural gas.

Volumes of green commodities for alumina, ammonia, methanol, and iron for either domestic consumption or export imply production of green hydrogen as part of their production process. Similarly, export volumes of hydrogen are also imposed.

4 Projection results

4.1 Underlying electricity demand

Underlying electricity demand here refers to end-use demand for electricity in all sectors, which could be met by either grid or off-grid electricity, and has taken into account the increase in electricity consumption due to electrification (see Section 4.7.1). Electricity consumption increases from just under 1000 petajoules (PJ) to over 1500 PJ in Progressive Change by the end of the projection period (Figure 4-1). This scenario features modest electrification in different end-users, the lowest uptake of electric vehicles, and modest growth in economic activity. Growth in electricity consumption is higher in Step Change (reaching around 1800 PJ by 2058) reflecting increased electrification in different end-uses (more so in buildings and agriculture), greater uptake of electric vehicles, and generally increased growth in economic activity. This is accelerated in the Green Energy scenarios (reaching around 2500 PJ by 2058) which feature the highest levels of electrification in all sectors, including industry, and the uptake of electric vehicles.

Interpreting multi-sectoral modelling results

It is important to keep in mind how the multi-sector modelling results are intended to be interpreted. The AusTIMES modelling does not intend to predict the future. It provides a internally-consistent view (in a least-cost sense) of the energy system under the set of assumptions which define the scenarios.

Furthermore, while the modelling includes process-level representations of many subsectors at a granular regional level, interpreting results at that fine scale granularity requires more detail than what is found in this publication. As such, this modelling is best utilised to examine trends rather than the small-scale detail within any given result.

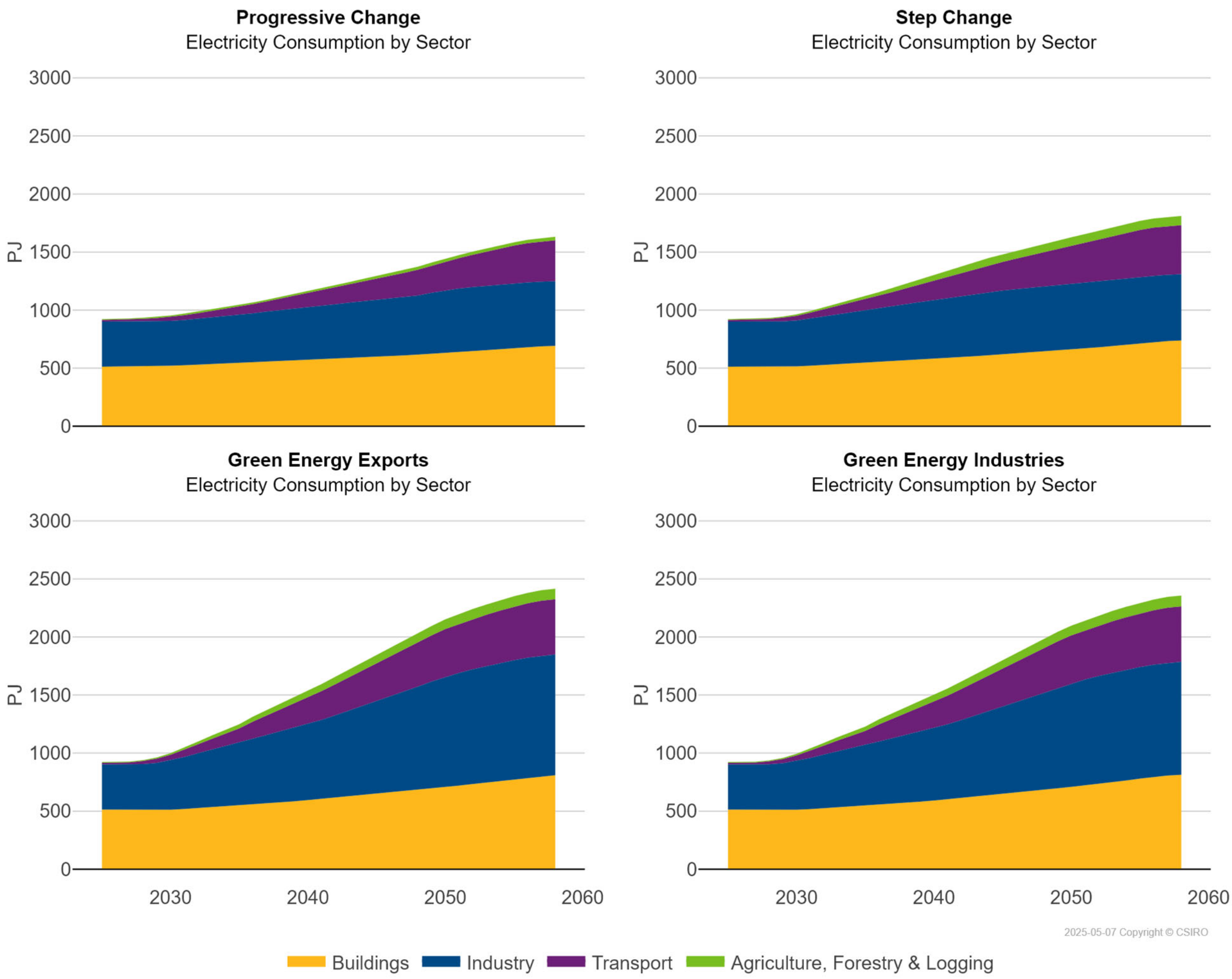


Figure 4-1 Electricity consumption by sector nationally

For the small wedge of electricity consumption in Agriculture, Forestry & Logging, the electrification increases are in transport for Forestry & Logging (up to 54% of subsector energy use), and for Agriculture, it is assumed that motors, onsite transport and machinery can be electrified (in ranges from 18% - 43% of subsector energy use depending on subsector).

The trends for the NEM (Figure 4-2) are broadly similar to the national picture, with buildings accounting for a greater proportion of electricity consumption as the NEM encompasses the most populous states with the majority of commercial activity. By the end of the projection period, electricity consumption equals around 1260 PJ in Progressive Change, around 1430 PJ in Step Change, and around 1770 PJ and 1730 PJ in the Green Energy Exports and Green Energy Industries scenarios, respectively.

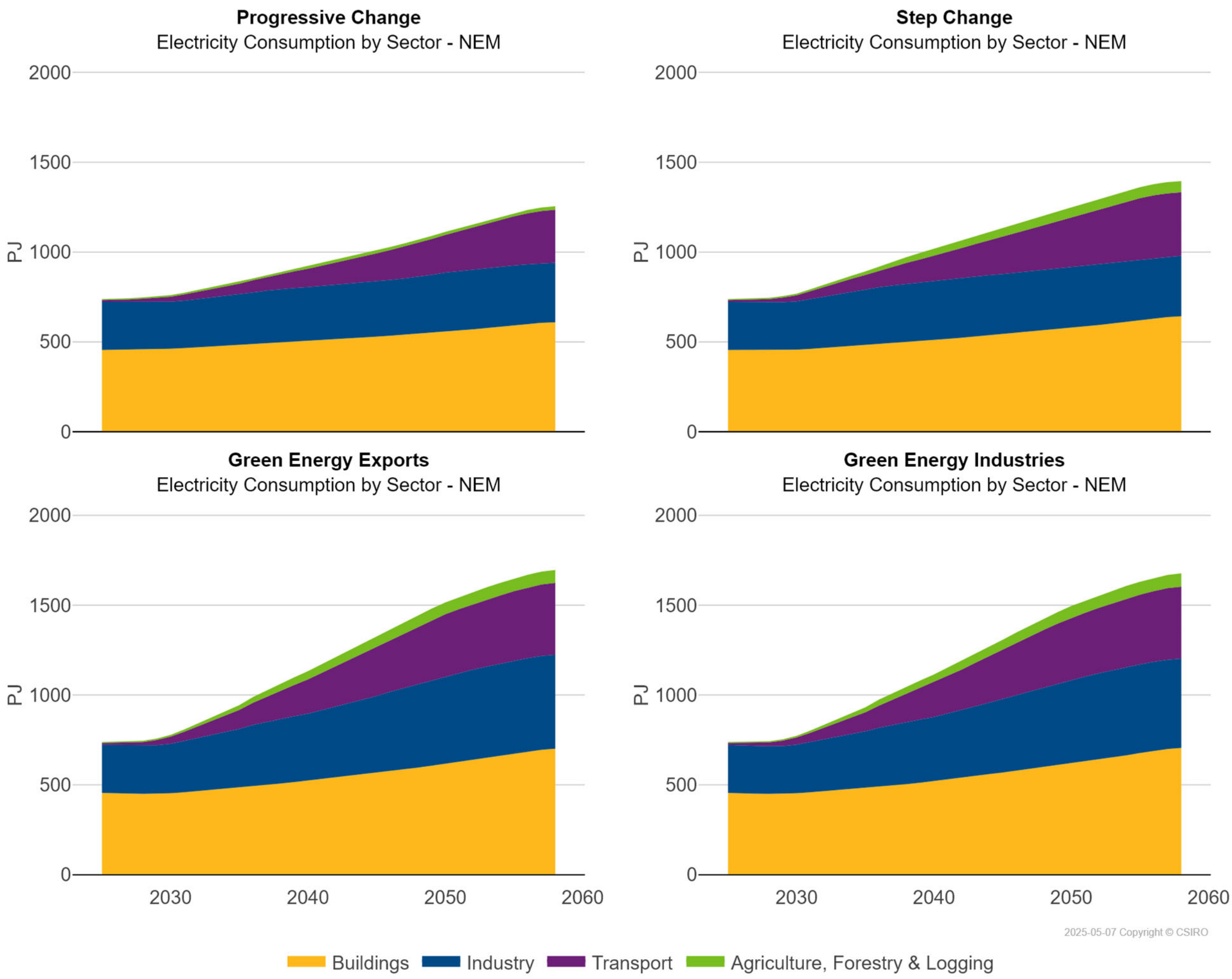


Figure 4-2 Electricity consumption by sector in the NEM

The trends for Western Australia (Figure 4-3) show that industry accounts for a greater proportion of electricity consumption compared to the NEM, due to the presence of energy-intensive industries and lower population (which impacts buildings and transport). It also shows that industry growth, especially Iron & Steel and Alumina, in the Green Energy scenarios has a larger impact on overall electricity consumption compared to the NEM. By the end of the projection period, electricity consumption equals around 315 PJ in Progressive Change, around 360 PJ in Step Change, and around 620 PJ and 595 PJ in the Green Energy Exports and Green Energy Industries scenarios, respectively.

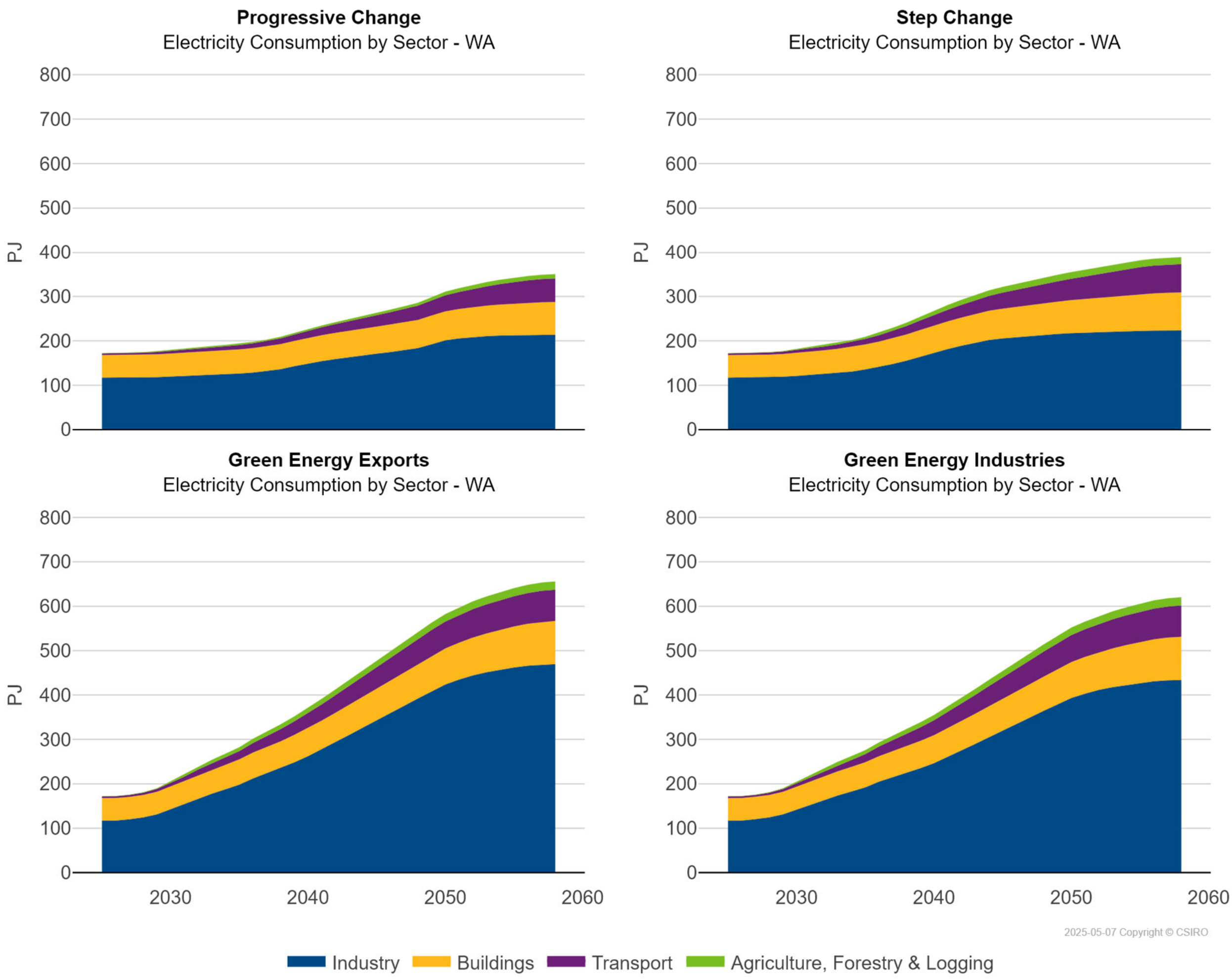


Figure 4-3 Electricity consumption by sector in Western Australia

In contrast, electricity consumption in the Northern Territory is currently dominated by buildings reflecting limited consumption of natural gas and significant cooling loads (Figure 4-4). Growth in electricity consumption shows similar trends to the NEM in the Progressive Change and Step Change scenarios. Similar to WA, higher industry growth in the Green Energy scenarios results in nearly a ten-fold increase in industrial electricity consumption. By the end of the projection period, electricity consumption equals around 25 PJ in Progressive Change, around 30 PJ in Step Change, and around 65 PJ and 60 PJ in the Green Energy Exports and Green Energy Industries scenarios, respectively.

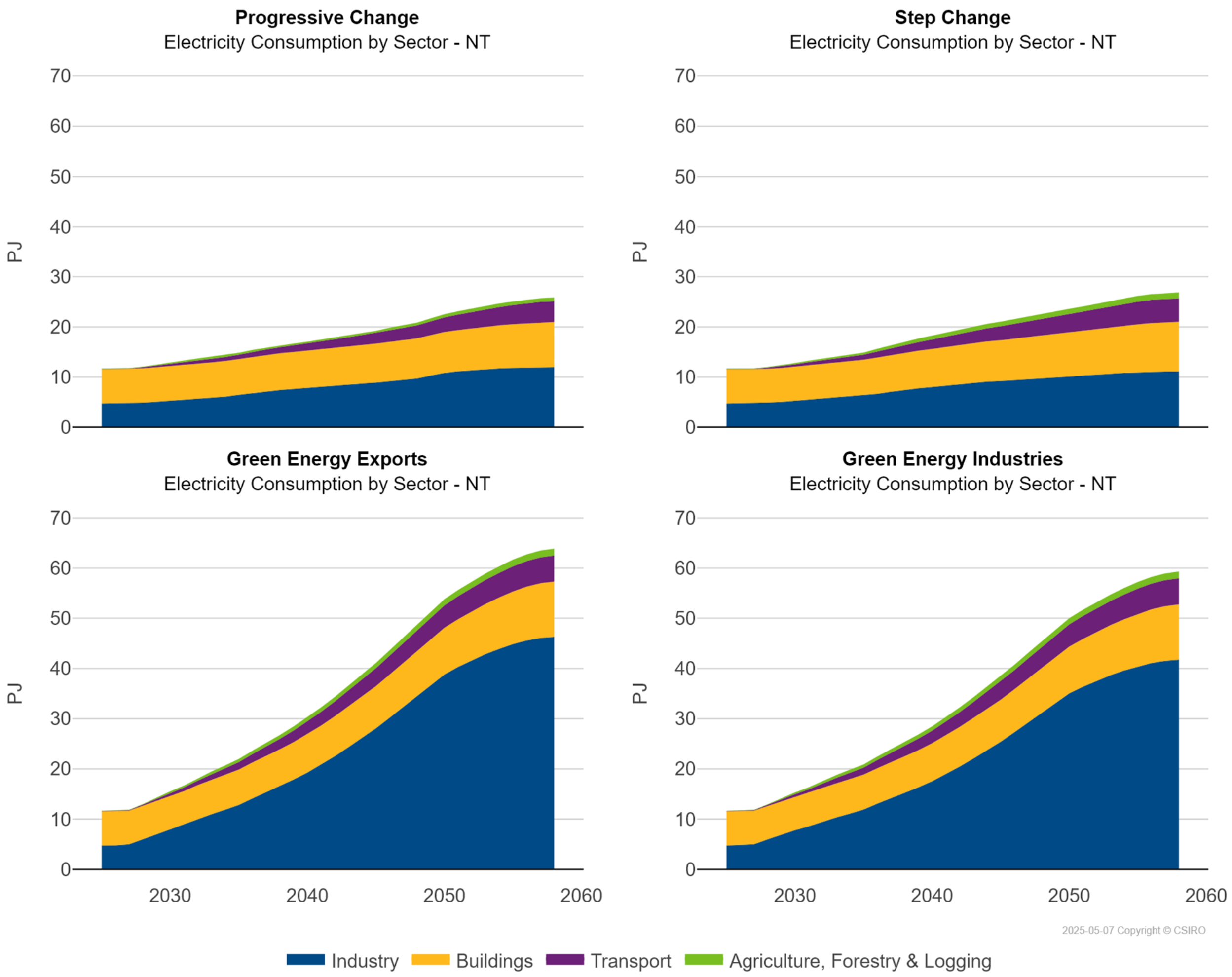


Figure 4-4 Electricity consumption by sector in the Northern Territory

4.2 Emissions

Australia's total net GHG emissions were around 433 Mt of CO_2-equivalent (Mt CO_2-e) emissions in 2021-22[10]. The modelled gross and net emissions by sector are shown in Figure 4-5. In 2022, the Australian Government announced an updated target of a 43% reduction in emissions by 2030 compared to 2005 levels (Albanese, 2022). Based on the latest National Greenhouse Gas Inventory (NGGI), this equates to a Nationally Determined Contribution (NDC) of 347 Mt CO_2-e by 2030 (black dot marked "NDC" in Figure 4-5).

[10] 432.6 Mt CO_2-e in 2021-22 according to Australia's National Greenhouse Accounts: https://greenhouseaccounts.climatechange.gov.au/ [accessed 13 February 2025].

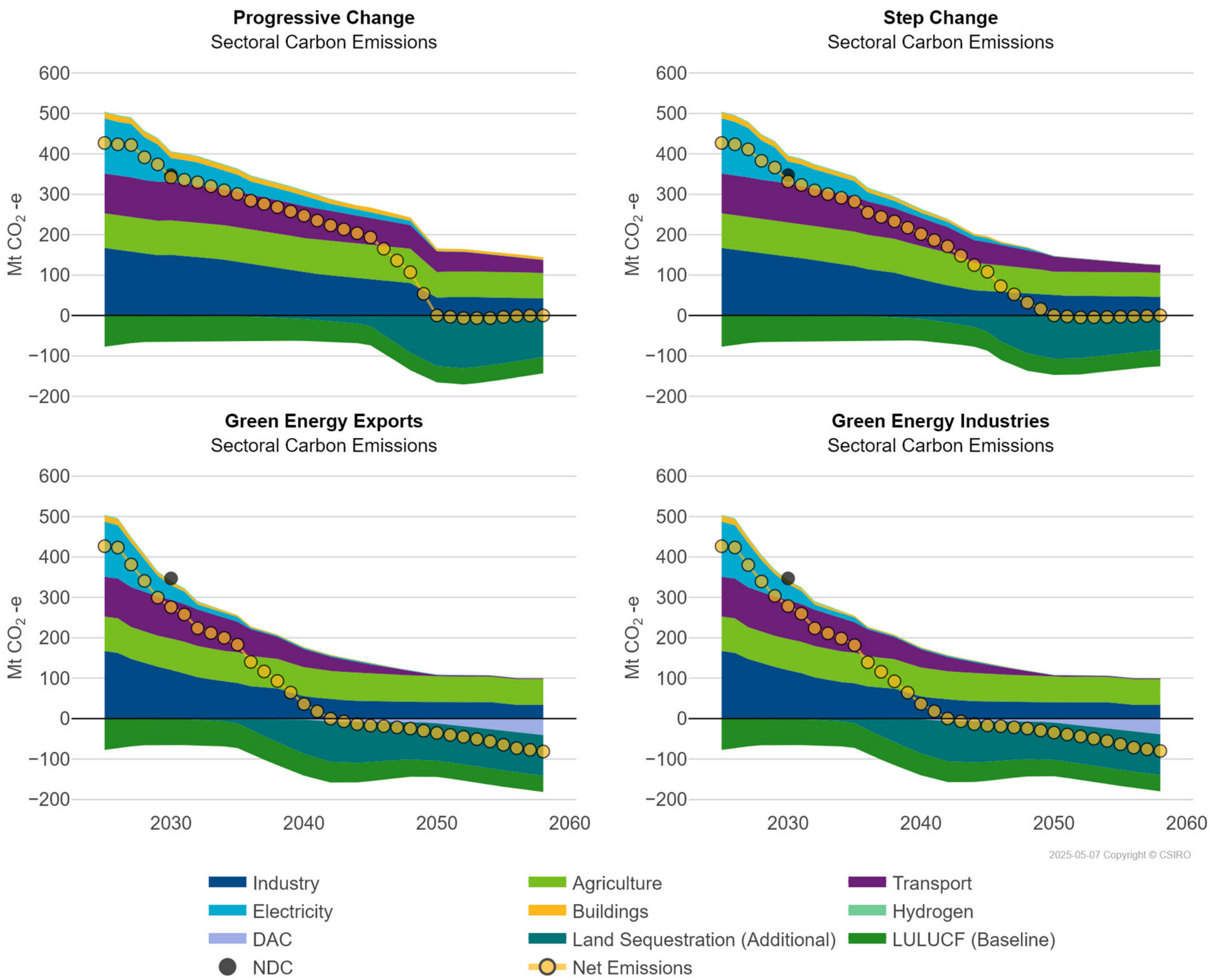


Figure 4-5 Sectoral carbon emissions with NDC of 347 Mt of CO2-e in 2030

All scenarios overachieve on the 2030 target. Progressive Change only slightly overachieves (around 342 Mt CO_2-e) when compared to Step Change (around 332 Mt CO_2-e). This contrasts with the Green Energy scenarios which reduce emissions more rapidly consistent with a 1.5-degree carbon budget: around 276 Mt CO_2-e and around 279 Mt CO_2-e in 2030, in the Green Energy Exports and Green Energy Industries scenarios, respectively.

The scale of emissions reduction varies greatly across sectors. In terms of emissions reduced across the 2025 to 2050 period, the greatest reductions are seen in power generation ("Electricity" in Figure 4-5), and then in decreasing order, industry, new land-based sequestration (Land sequestration (Additional) in Figure 4-5), transport, Direct Air Capture (DAC), agriculture, and then buildings. Land-use and land-use change represents the 2024 Commonwealth projections (DCCEEW, 2024e) (LULUCF (Baseline) in Figure 4-5), while new land-based sequestration (environmental plantings and mallee plantings) is based on costings derived from the Land Use Trade-off (LUTO) model (see Appendix B.9).

All scenarios are required to achieve the 2030 NDC and the legislated net zero target of 2050. Progressive Change and Step Change show a similar emissions reduction trajectory, with Step Change slightly more rapid given the tighter carbon budget. Both scenarios achieve net zero emissions in 2050. With a more stringent carbon budget, the Green Energy scenarios feature more rapid decarbonisation in power generation, industry, transport and buildings. There is also earlier deployment of new land-based sequestration and DAC as carbon removal technologies. Both Green Energy Exports and Green Energy Industries achieve net zero emissions in the early 2040s.

4.3 Emissions sequestration

Emissions sequestration (or negative emissions) is required for the economy to meet net zero emissions while residual emissions are still occurring. Land-based emissions sequestration, direct air capture (DAC) and carbon capture & storage (CCS) are the primary methods considered in AusTIMES. All sequestration in AusTIMES is assumed to occur domestically within Australia – the use of international offsets is not considered.

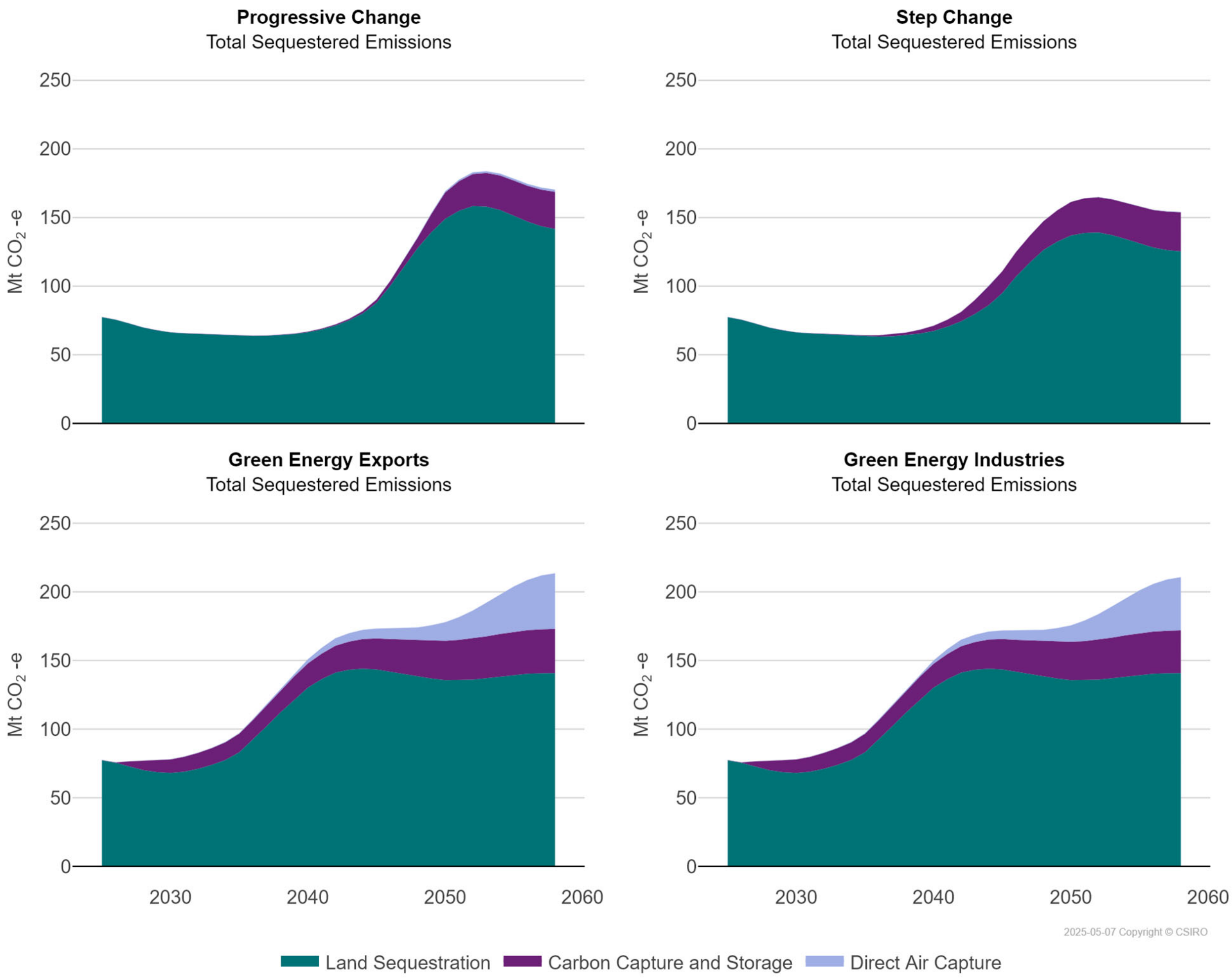


Figure 4-6 Total emissions sequestered

The initial emissions sequestration in all scenarios equates to the land-use and land-use change (LULUCF) from the most recent Commonwealth projections (DCCEEW, 2024e). Compared with the baseline scenario from the 2023 DCCEEW projections, the LULUCF sink is projected to be 7 Mt CO_2-e larger in 2030 and 5 Mt CO_2-e larger in 2035. This is driven by lower projected land clearing emissions, reflecting the continued trend to decrease land clearing observed in recent years (DCCEEW, 2024e). In Step Change, new land-based sequestration and deployment of CCS in industry (in Cement and Aluminium) leads to additional offsets from the late 2030s, increasing into the 2040s. These dynamics are more delayed in Progressive Change, emerging in the mid-2040s and increasing nearer the net zero year of 2050. The need for carbon removals after 2050 in both Progressive Change and Step Change is reduced as industry and transport emissions continue to decline. In contrast, the Green Energy scenarios feature more rapid deployment of CCS and new land-based sequestration in the 2030s, along with DAC around 2040. Once sufficient decarbonisation has occurred in other sectors the need for more sequestration plateaus during the 2040s but then increases from 2050 with increased removals from the operation of DAC plants, with minimal increases in removals from new land-based sequestration (reaches upper bound near the net zero year in all scenarios).

4.4 Electricity sector emissions

It was noted in Section 4.2, that over the 2025 to 2050 period, the greatest reductions in emissions are from power generation (Figure 4-7). The electricity sector is a relatively low-cost abatement sector of the economy and assists other sectors to decarbonise. It is a typical finding in an economy-wide emissions reduction target that the power sector does more than its fair share of economy-wide abatement.

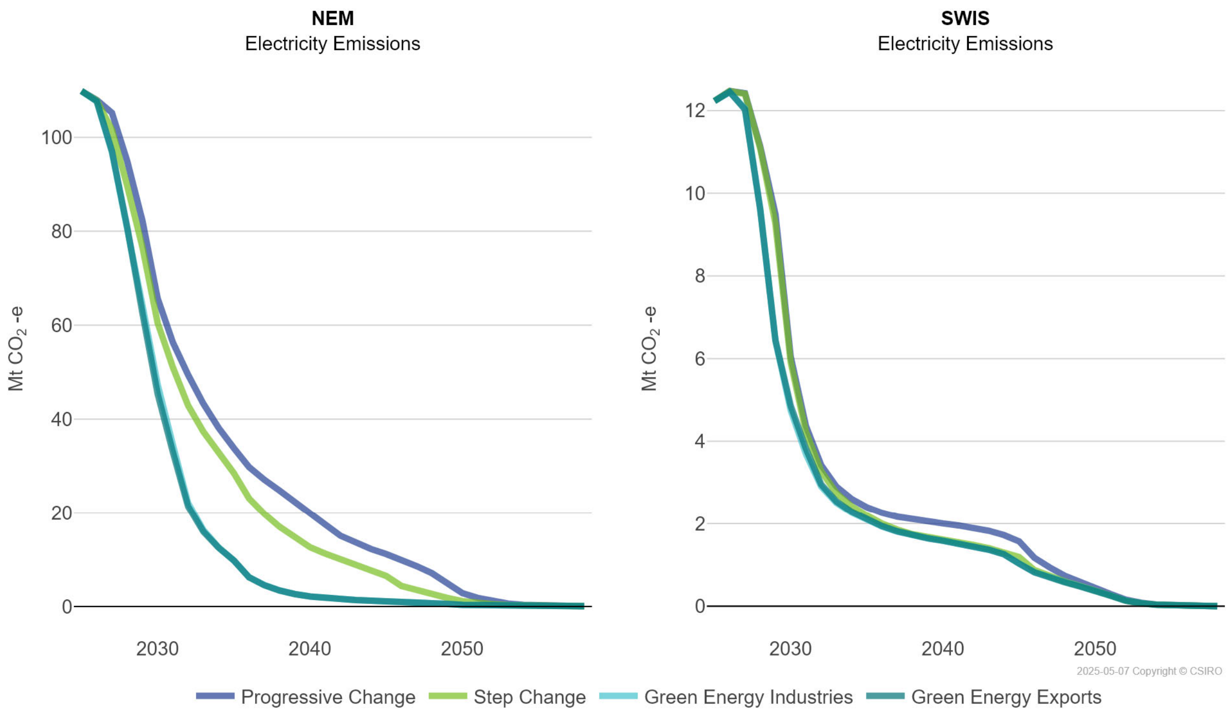


Figure 4-7 Electricity sector emissions

Note the vertical axes have different scales.

For the NEM, emissions decline rapidly from the reduced operation and retirement of coal-fired generators and the existing suite of state/territory renewable energy targets. The retirement is accelerated in the Green Energy scenarios. Power sector emissions in the NEM stabilise at a low level in the Green Energy scenarios of around 1 Mt by the mid-2030s with a more gradual reduction in Progressive and Step Change (see Section 4.5.1 for discussion of technology mix changes).

For the South-west Interconnected System (SWIS) in Western Australia, there is also a transition away from coal-fired generation with non-state-owned coal-fired generation persisting to 2031 in the Progressive Change and Step Change scenarios. In all scenarios it is assumed that all state-owned coal-fired generators are retired by 2030 in line with the WA Government announcement in August 2022[11]. The modelled results are also consistent with the WA Government commitment that no new gas-fired generators are commissioned after 2030 (see Section 4.5.1 for discussion of technology mix changes).

4.5 Electricity generation

4.5.1 Electricity generation

Historically, power generation in Australia has relied on coal- and gas-fired generation for grid power, and predominantly diesel generation in off-grid systems. Despite the historical dominance of non-renewable centralised electricity generation, there has recently been significant growth in the deployment of distributed rooftop solar photovoltaic (PV) systems, especially on residential buildings, followed by large-scale renewable generation (primarily onshore wind and solar PV). Australian Energy Statistics report that in FY2023, electricity generation was around 274 terawatt-hours (TWh), of which 47 per cent was coal-fired, followed by non-hydro renewables at 28 percent, natural gas at 18 per cent, hydro at 6 per cent, and oil (mainly diesel) at around 2 per cent (DCCEEW, 2024b).

[11] https://www.wa.gov.au/government/announcements/state-owned-coal-power-stations-be-retired-2030-move-towards-renewable-energy [accessed 16 April 2025]

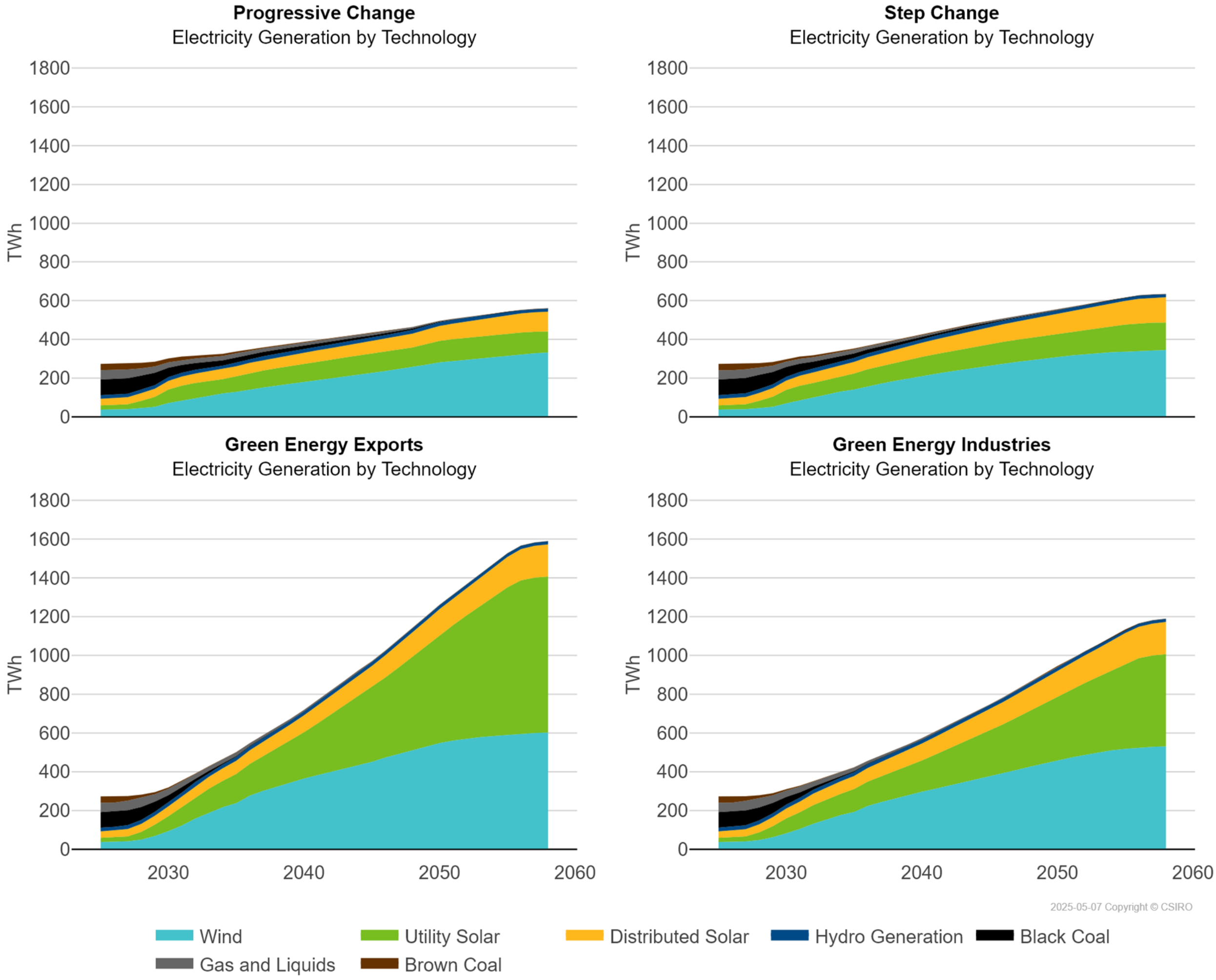


Figure 4-8 Electricity generation by technology nationally

Under all four scenarios, the projected national generation mix in Figure 4-8 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 the announced closures of coal-fired generators. Over the longer-term, the assumed continued declines in the costs of renewable generation and storage technologies, an ageing coal generation fleet, and the cost competitiveness of electrification in a future with strong emissions reduction targets are the key drivers to an increasing share of variable renewable energy (VRE), mainly in the form of utility-scale and distributed (rooftop) solar PV and wind farms over the projection period.

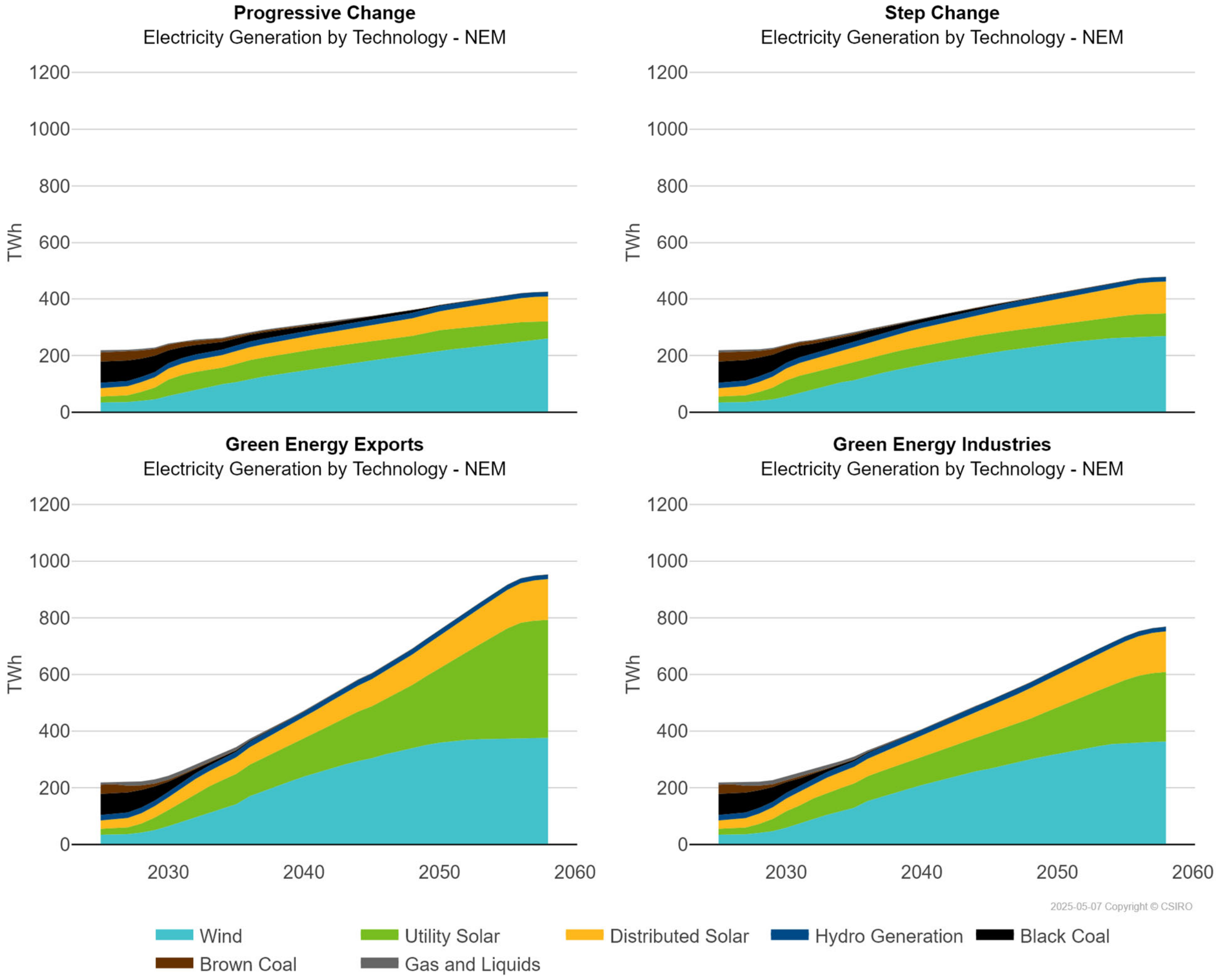


Figure 4-9 Electricity generation by technology in the NEM

The projected generation mix shows significant change for the NEM from its current level of around 53% of coal-fired generation (Figure 4-9). Similar dynamics to the national generation mix are evident. In Progressive Change, moderate growth in demand in conjunction with national (82% renewables in main grids by 2030) and state renewable energy targets (QRET, TRET, VRET and *NSW Electricity Infrastructure Roadmap*), transitions the NEM away from coal-fired generation to an increasing share of VRE, mainly in the form of onshore wind farms and utility-scale and distributed solar PV. Brown coal transitions out in the mid-2030s with black coal retired by the late 2040s in this scenario. Total generation reaches around 425 terawatt hours (TWh) by the end of the projection period.

More rapid transition is observed in Step Change with a greater acceleration of renewable deployment given higher activity growth and electrification of end-uses. Brown coal transitions out in the mid-2030s with black coal retired by the mid-2040s in this scenario. Total generation reaches around 480 TWh by the end of the projection period. This transition is accelerated across the Green Energy Exports and Green Energy Industries scenarios, with a more rapid reduction in coal-fired generation (brown coal exits by 2030 and black coal by 2034), coupled with higher growth in electricity demand resulting from higher levels of economic activity, electrification and need to produce hydrogen for green commodities.

Although there is some uptake of new peaking gas-fired generation in the scenarios, there is no uptake of coal- or gas-fired generation coupled with carbon capture and storage (CCS), or of nuclear. Based on the cost assumptions used in the modelling (see Appendix B.5, the bulk of capacity additions are renewable technologies – mainly onshore wind generation, utility-scale and rooftop solar PV – coupled with storage technologies, especially dispatchable storage including utility-scale and behind-the-meter batteries and pumped storage hydro.

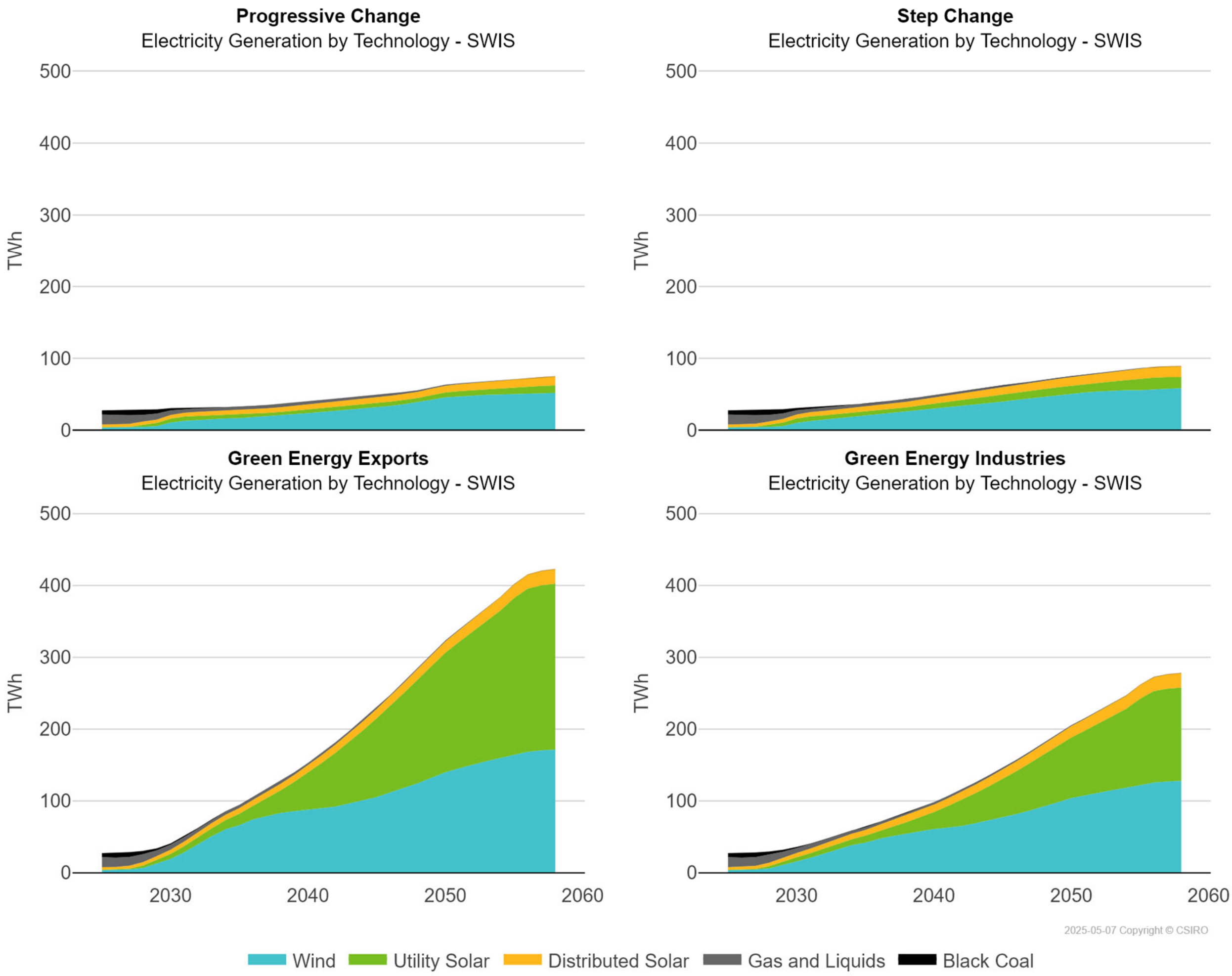


Figure 4-10 Electricity generation by technology in the SWIS

For the SWIS in Western Australia, there is also a transition away from coal-fired generation with the retirement of all state-owned coal-fired generators by 2030, in line with the WA Government announcement in August 2022. Privately owned coal-fired generation persists to 2031 in the Progressive Change and Step Change scenarios and the late 2020s in the Green Energy scenarios (Figure 4-10). The modelled results are also consistent with the WA Government commitment that no new gas-fired generators are commissioned after 2030.

Gas-fired generation persists in all scenarios, however the transition to a high-VRE system is similar across all scenarios to that observed for the NEM. Overall, the scale of the transformation in the SWIS is more pronounced due to relatively high electrification (see Section 4.7.1) and significant production of hydrogen (see Section 4.8), especially in the Green Energy Export, and to a lesser extent, the Green Energy Industry scenario.

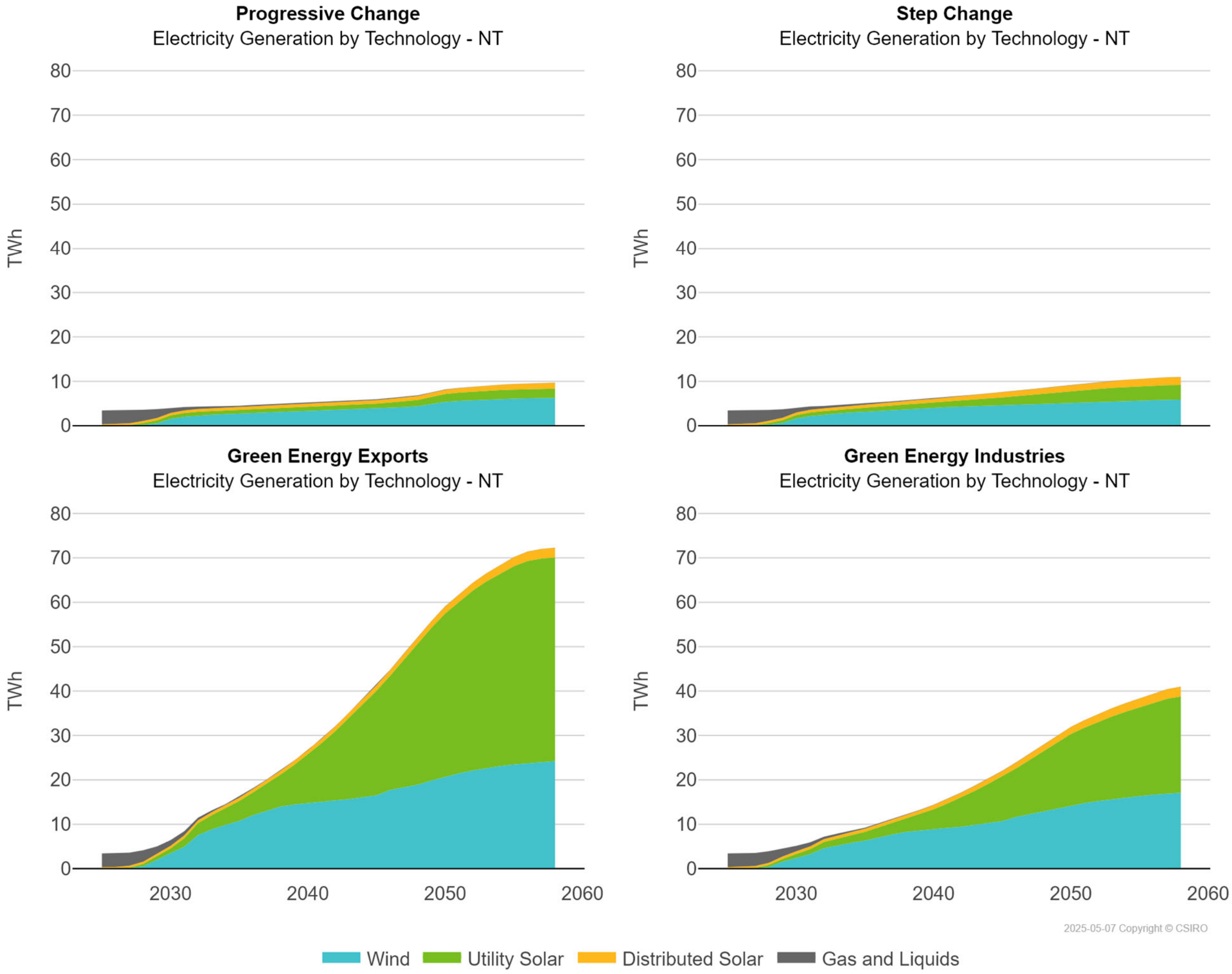


Figure 4-11 Electricity generation by technology in the DKIS

For the Darwin-Katherine Interconnected System (DKIS) in the Northern Territory, there is a transition away from gas- and diesel-fired generation towards renewables over the projection period in all scenarios (Figure 4-11). The scale of the transformation is less in Progressive Change and Step Change as the overall demand growth is lower (mainly industry growth). In the Green Energy scenarios, similar to the NEM and SWIS, the production of hydrogen requires a significant increase in renewable generation, especially utility-scale solar.

4.5.2 Electricity capacity

The transformation of the electricity system is also significant from a capacity standpoint. For Australia, electricity generation increases from just under 100 gigawatts (GW) to around 240 GW by the end of the projection period (Figure 4-12) in the Progressive Change scenario. The evolution of capacity in Step Change is similar to Progressive Change but increases to a higher level of around 275 GW reflecting more electrification and higher activity growth. Electricity generation capacity increases six-fold and nearly five-fold in the Green Energy Exports and Green Energy

Industry scenarios, respectively. This reflects the higher activity growth in both these scenarios but also the significant production of hydrogen from electrolysis to produce green commodities.

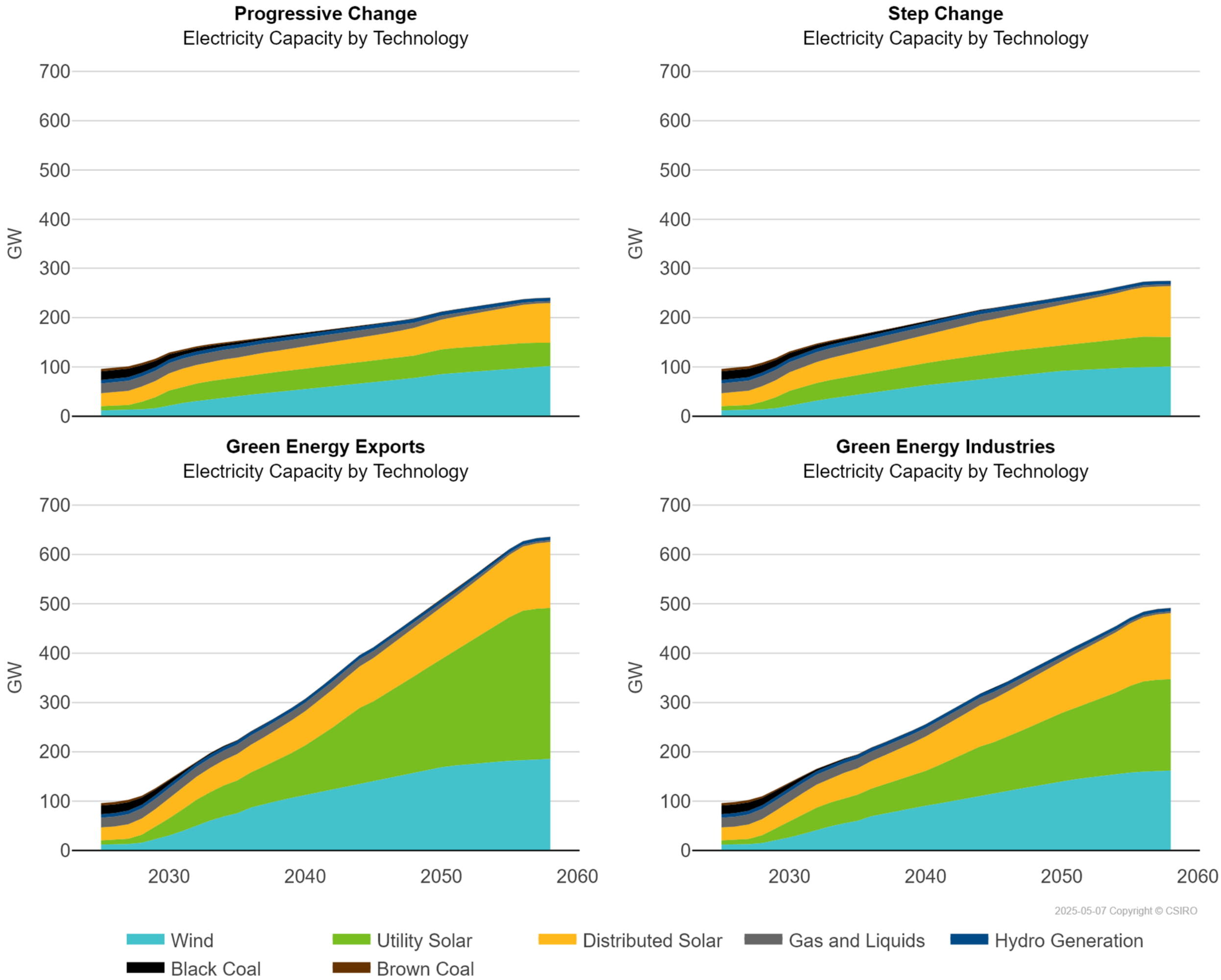


Figure 4-12 Electricity capacity by technology nationally

Similar transformation in capacity occurs in the NEM. Electricity generation capacity more than doubles in Progressive Change to around 185 GW by the end of the projection period (Figure 4-13). This is eclipsed in Step Change (215 GW). The Green Energy Exports and Green Energy Industries scenarios feature a similar pattern to the national picture, but to a lower level of four-fold and slightly under four-fold increase by 2058. The lower order of magnitude capacity increase in the NEM reflects the much greater demand growth for industry overall and green commodity production in Western Australia compared to the Eastern states.

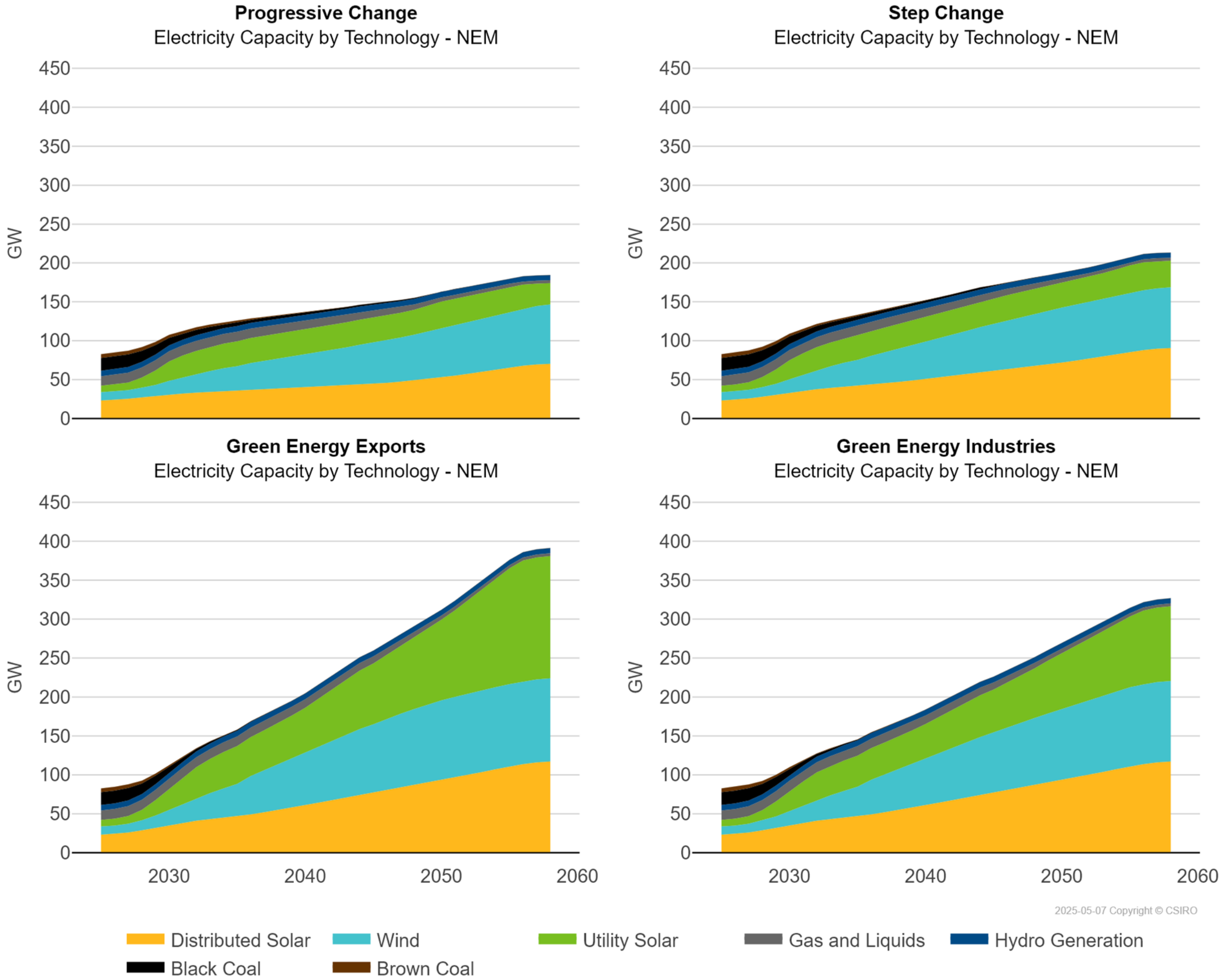


Figure 4-13 Electricity capacity by technology in the NEM

In the SWIS, electricity generation capacity increases three-fold in both the Progressive Change to and Step Change scenarios from around 10 GW in the near-term to around 30 GW by the end of the projection period (Figure 4-14). The scale of transformation of capacity is much more significant in the Green Energy Exports and Green Energy Industry scenarios, with a fifteen-fold and ten-fold increase, respectively. This reflects the higher industrial activity and population growth in both these scenarios but also the significant production of hydrogen from electrolysis to produce green commodities. It should be noted that most of the electricity to produce green hydrogen is not grid-connected in the SWIS (see Section 4.8).

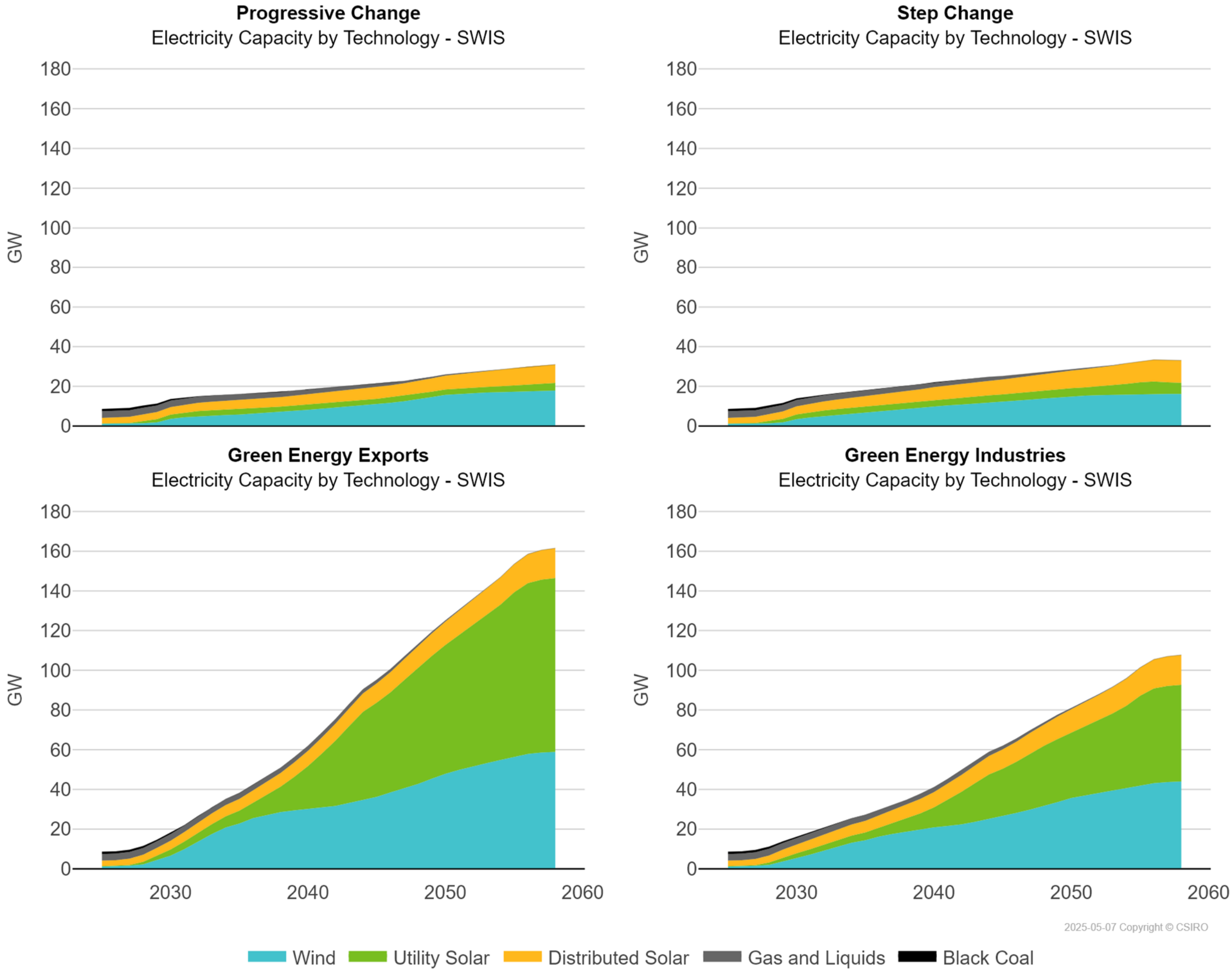


Figure 4-14 Electricity capacity by technology in the SWIS

In the DKIS, similar patterns are observed to the SWIS, with a much greater transformation in the Green Energy Exports and Green Energy Industry scenarios (Figure 4-15) with a twenty-five-fold and fifteen-fold increase, respectively. The same drivers of higher industrial activity and population growth in both these scenarios but also the significant production of hydrogen from electrolysis are present.

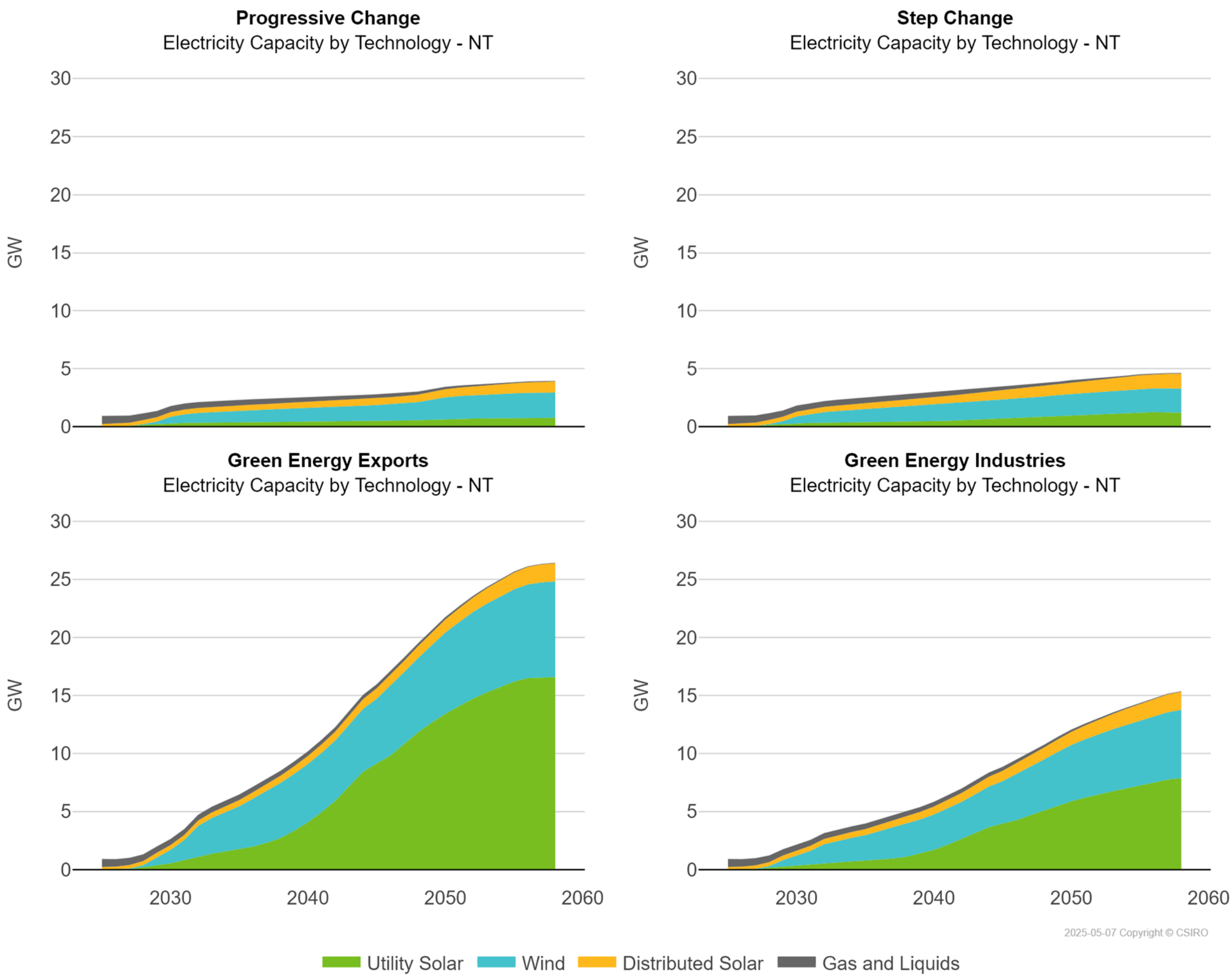


Figure 4-15 Electricity capacity by technology in the DKIS

4.5.3 Electricity storage capacity

The near-term state/territory and national renewable energy targets to 2030, combined with energy storage targets, means that under all scenarios there is significant deployment of utility storage, particularly utility batteries. For Australia, utility-connected battery storage capacity increases from just under 2 GW currently, to around 12 GW by 2030, and 42 GW by the end of the projection period, in the Progressive Change scenario (Figure 4-16). Distributed storage capacity increases from around 3 GW to 13 GW over the same period. The Step Change scenario features a slightly greater increase in capacity. The Green Energy scenarios feature a doubling to 2030 compared to Progressive Change, with a similar ratio observed for Green Energy Exports in the long-term. The growth from 2030 is more muted than the growth in renewable energy generation capacity reflecting lower utilisation factors for electrolysers in the long run, reducing the need for storage to support hydrogen production.

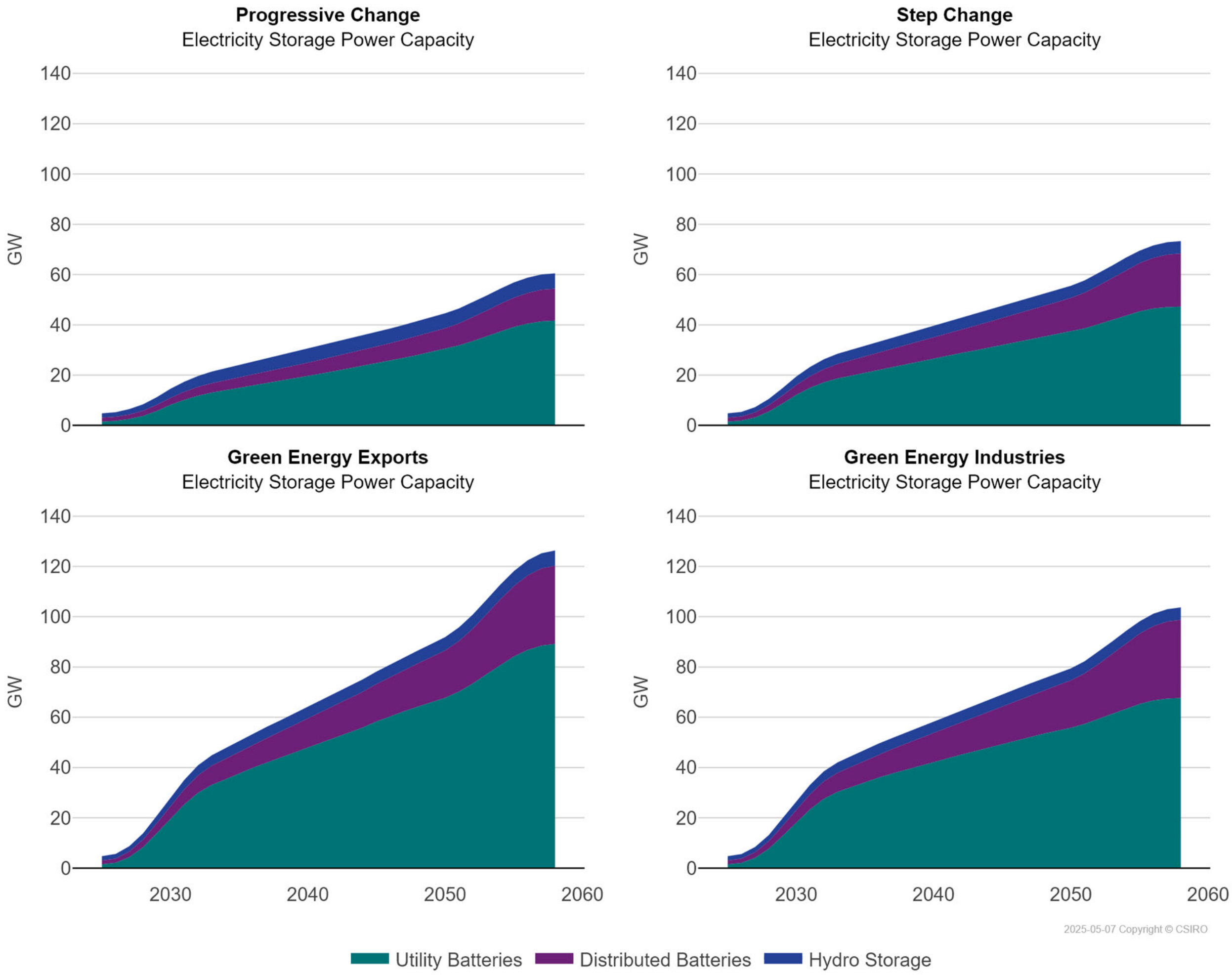


Figure 4-16 Energy storage capacity nationally

Similar growth patterns of storage capacity are observed in the NEM (Figure 4-17).

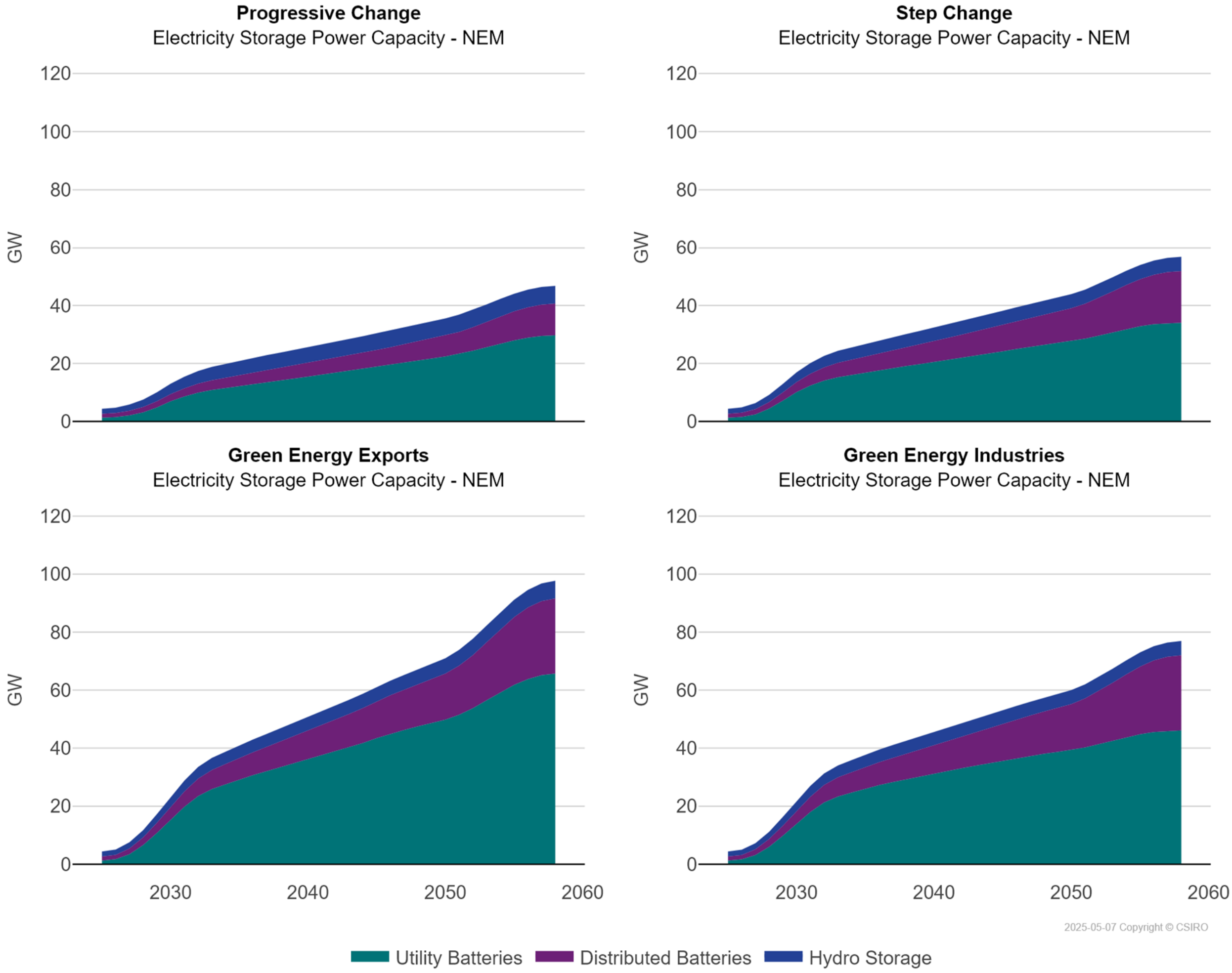


Figure 4-17 Energy storage capacity in the NEM

For the SWIS, there is steady growth in utility battery storage capacity in the near- to medium-term in Progressive and Step Change scenarios (Figure 4-18). There is accelerated deployment in the long-term reflecting greater update of utility scale solar PV. This growth is more pronounced and earlier in the Green Energy scenarios reflecting increased utility scale solar PV deployment due to higher demand growth.

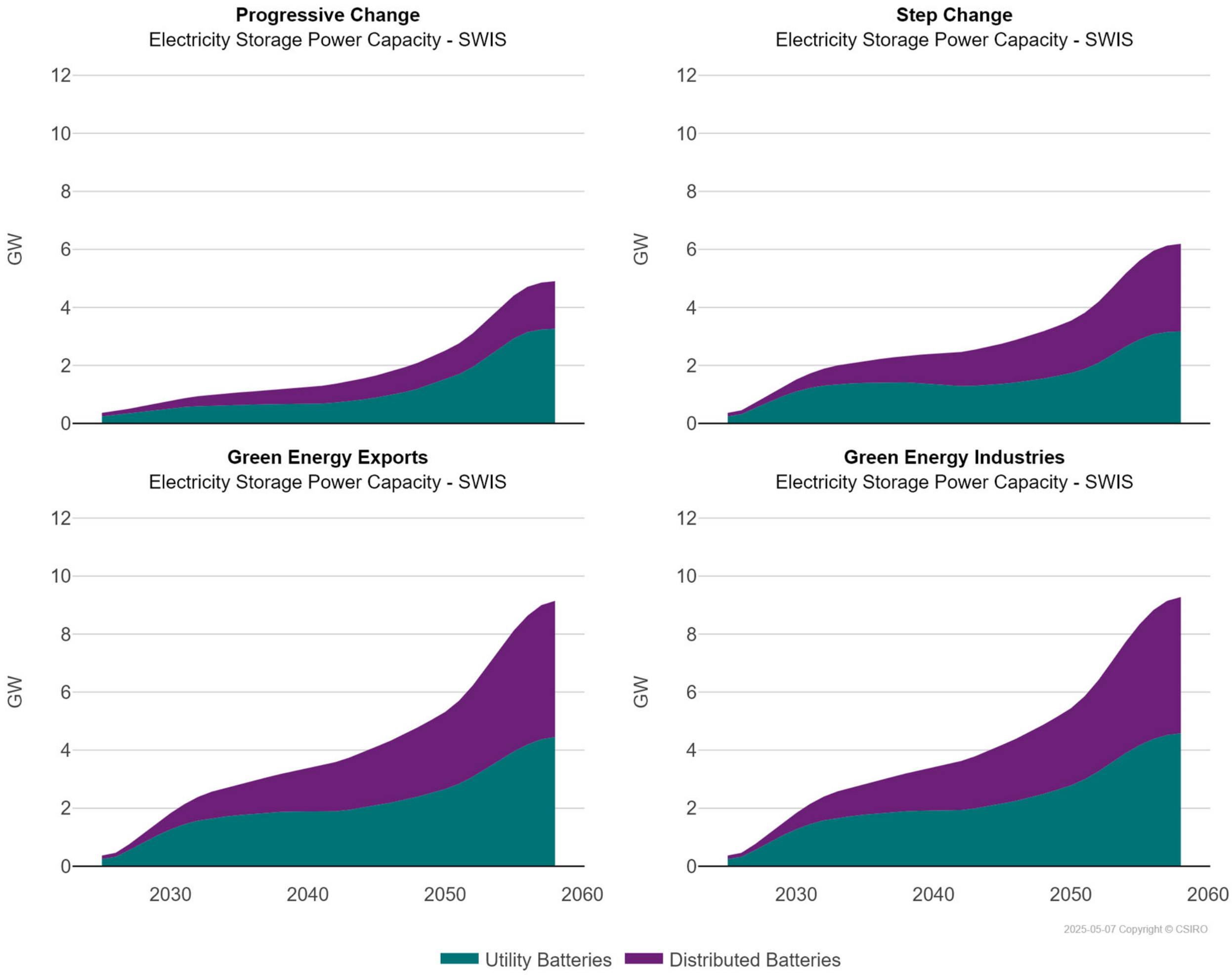


Figure 4-18 Energy storage capacity in the SWIS

Similar trends are observed for DKIS at a reduced scale given the overall level of demand (Figure 4-19).

Figure 4-19 Energy storage capacity in the DKIS

4.6 Gaseous fuel demand and production

This section examines the demand for natural gas, hydrogen, and biomethane in sectors excluding power generation. Figure 4-20 below shows that the overall demand for gaseous fuels (together with electricity for context) declines in Progressive and Step Change, while in the Green Energy scenarios, the demand is somewhat flatter due to growth in green commodity production via the use of natural gas in the earlier years, and then hydrogen post 2040.

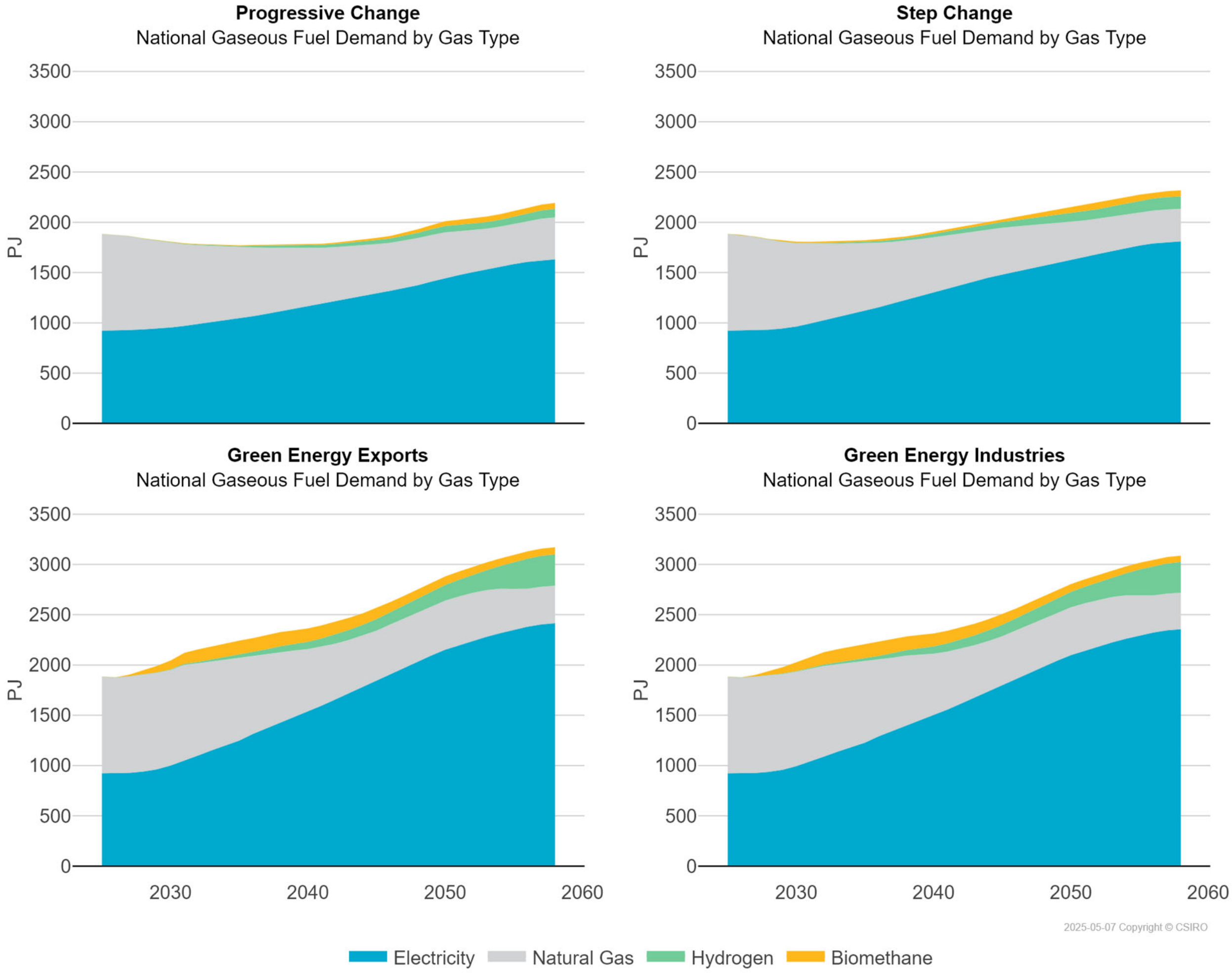


Figure 4-20 National gaseous fuel demand by gas type (with electricity for context)

Note: Hydrogen in this figure excludes hydrogen for feedstock

4.6.1 Demand for Natural Gas

Natural gas demand declines across all scenarios, with electrification and fuel-switching being partially responsible as indicated in Figure 4-21 below. For the Step Change and Green Energy scenarios, nearly half of the counterfactual demand for natural gas is replaced by electrification and switching to biomethane. Figure 4-21 also shows that natural gas consumption is mostly driven by industry and then residential buildings. The further breakdown of the sources of fuel switching can be seen in Figure 4-22.

The gas ban policies of ACT[12] and Victoria[13] are also factors for the reduction in demand. Victoria has phased out gas connections for new residential buildings from 2024. From that year onward, all new residential buildings have 100% electrification potential (noting that this ignores the lag

[12] See Powering Canberra: Our Pathway to Electrification - Chief Minister, Treasury and Economic Development Directorate

[13] See Victoria's Gas Substitution Roadmap

between legislation and planning approvals). In the ACT, no new gas connections for residential buildings are allowed from 2024, with a complete transition to renewable energy for all residential and commercial buildings—both new and existing—by 2045. This implies 100% electrification potential for new buildings from 2024, and for all buildings by 2045.

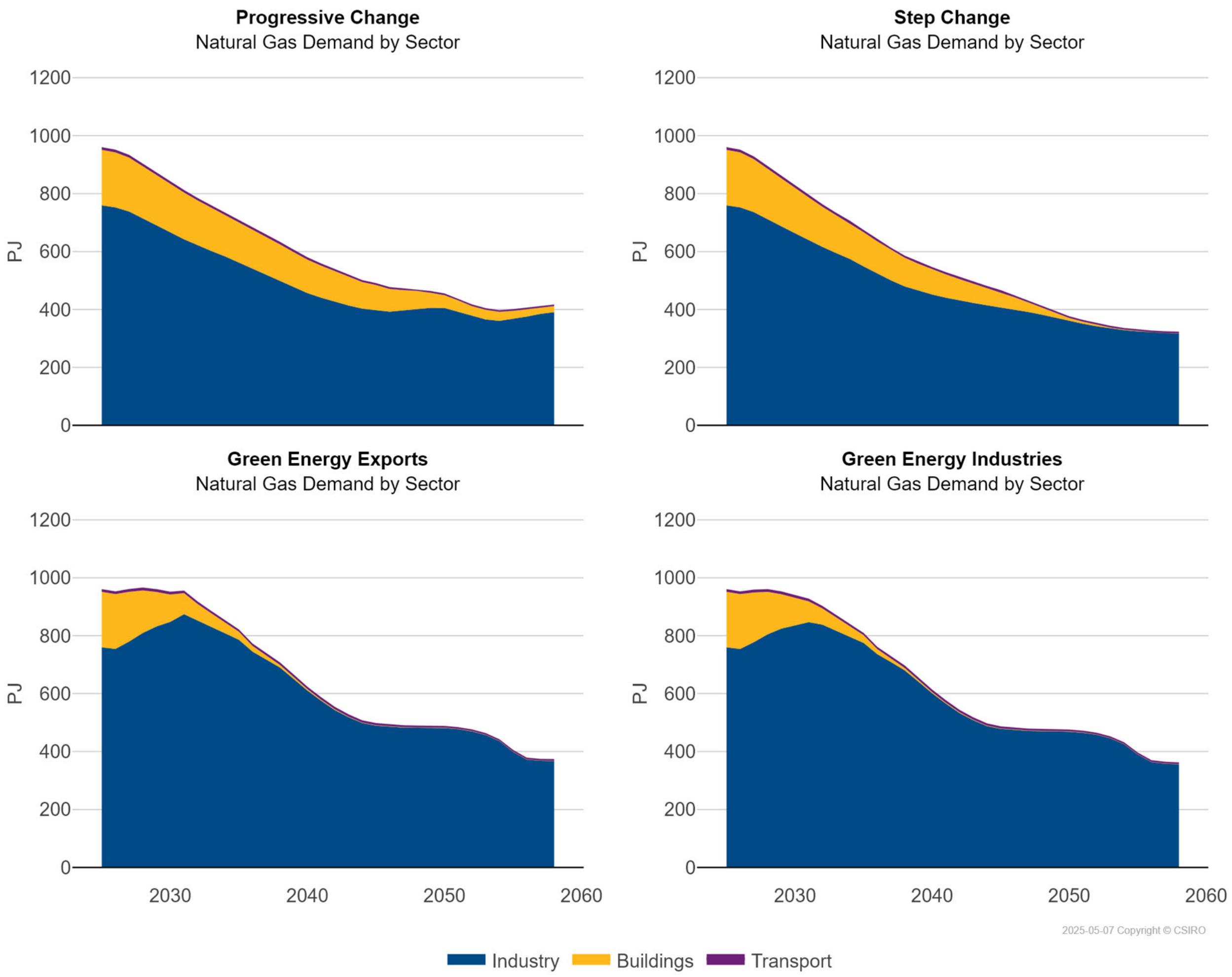


Figure 4-21 National natural gas demand by sector

Figure 4-22 National fuel-switching and electrification away from natural gas by "to-fuel"

Note these are in units of energy of the fuel being switched away from, and that the figure does not include switching to natural gas from other fuels (mostly coal to natural gas) such that Figure 4-21 and the remaining-consumption here are not directly comparable

4.6.2 Demand for hydrogen

The National Hydrogen Strategy (DCCEEW, 2024c) identified several demand sectors that are more likely to support the hydrogen sector to scale up, contribute to domestic decarbonisation, or reduce emissions overseas from large-scale export of green commodities. These include:

- a clean source of industrial process heat to the refining of mineral resources and enable the export of green metals, such as iron and alumina;
- a viable pathway to decarbonising current ammonia production, essential to the manufacture of fertilisers and explosives. Ammonia is also a vehicle to transport hydrogen and may play a role as a fuel in decarbonising the maritime industry;
- the production of low-carbon liquid fuels in the decarbonisation of the long-haul road transport, aviation and shipping sectors.

Green commodity estimates were provided at a state/territory level for all the scenarios (ACIL Allen, 2024), and these were subsequently scaled by AEMO. The resulting national totals of commodity volumes, by scenario for selected years (Mt) is shown in Table 4-1.

Table 4-1 Summary of national commodity volumes, by scenario for selected years (Mt)

Scenario	Commodity/use case	2030	2040	2050
Progressive Change	Hydrogen exports	0	0	0
	Ammonia (green)	0	0	0
	Methanol	0	0	0
	Green iron	0	0	0.1
	Green steel	0	0	0
	Alumina	18.2	18.2	18.2
Step Change	Hydrogen exports	0	0	0
	Ammonia (green)	0.1	0.8	2.5
	Methanol	0	0	0
	Green iron	0	0	0.7
	Green steel	0	0	0.1
	Alumina	18.2	18.2	18.2
Green Energy Exports	Hydrogen exports	0	0.6	1.2
	Ammonia (green)	0.8	13.7	33.4
	Methanol	0	0.2	0.7
	Green iron	0.8	22	78.3
	Green steel	0.2	4.7	16.7
	Alumina	18.2	18.2	18.2
Green Energy Industries	Hydrogen exports	0	0	0
	Ammonia (green)	0.1	0.8	2.5
	Methanol	0	0	0
	Green iron	0.8	22	78.3
	Green steel	0.2	4.7	16.7
	Alumina	18.2	18.2	18.2

Note: Volume of hydrogen exports is the volume of hydrogen itself. For all other commodities the volume shown is the volume of the commodity produced. Iron and steel volumes exclude existing production at integrated (coal-based) steelworks. Source: Updated version of Table 3.1 from ACIL Allen (2024), with AEMO scaling applied.

It was noted in Section 3.7 that although the uptake of alternative-drivetrain vehicles is also determined within AusTIMES, the uptake of these technologies by scenario was an exogenously imposed input into AusTIMES for the multi-sectoral modelling. This leverages the parallel consultancy that used adoption curve modelling to provide uptake rates based on economic and non-economic drivers. Accordingly, the kilometre shares of fuel cell vehicles in road transport are imposed as a direct input. AusTIMES then determines the hydrogen consumption outcome based on the vehicle kilometres travelled of fuel cell vehicles.

Endogenous uptake of hydrogen in AusTIMES is limited to fuel switching in residential and commercial buildings (up to blending limits imposed by scenario – see Table 2-1), fuel switching for process heat in industrial sectors, uptake in non-road transport (e.g., shipping, rail and aviation), and power generation.

Demand for hydrogen for commodities in Progressive Change is limited to green iron. In Step Change, green iron and ammonia are green commodity demands (Figure 4-23). Additionally in these scenarios, there is modest uptake in other industry sectors and road transport (mainly freight) and shipping. There is minimal uptake of hydrogen in residential and commercial buildings, with a preference for biomethane and electrification based on cost.

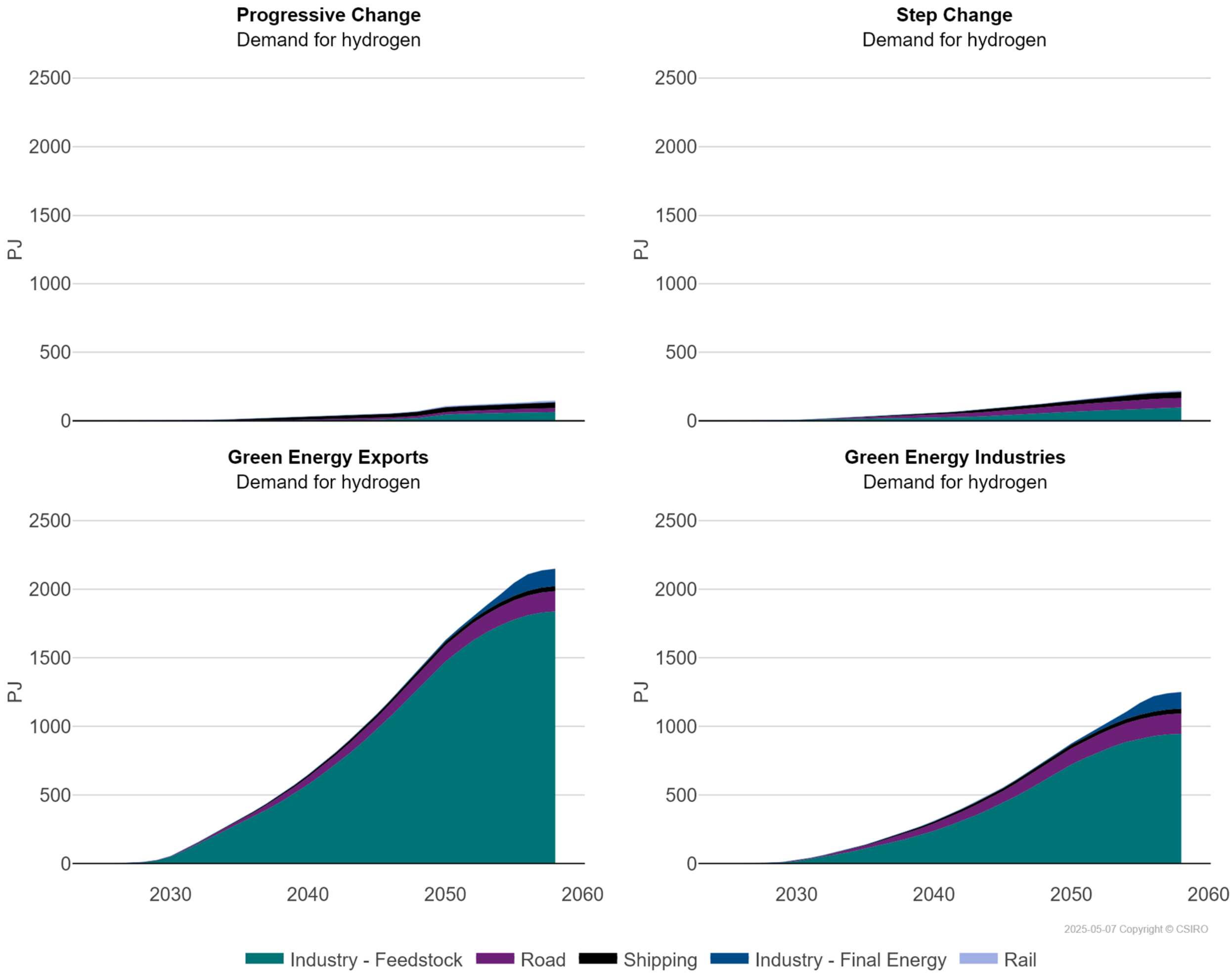


Figure 4-23 National demand for hydrogen

Note that this figure does not include the export demand for hydrogen.

4.6.3 Demand for biomethane

Biomethane (also known as “renewable natural gas”) is near-pure methane produced either by “upgrading” biogas (a process that removes any CO_2 and other contaminants present in the biogas) or through the gasification of solid biomass followed by methanation. Accordingly, biomethane is indistinguishable from natural gas and so can be used without the need for any changes in transmission and distribution infrastructure or end-user equipment (IEA, 2022).

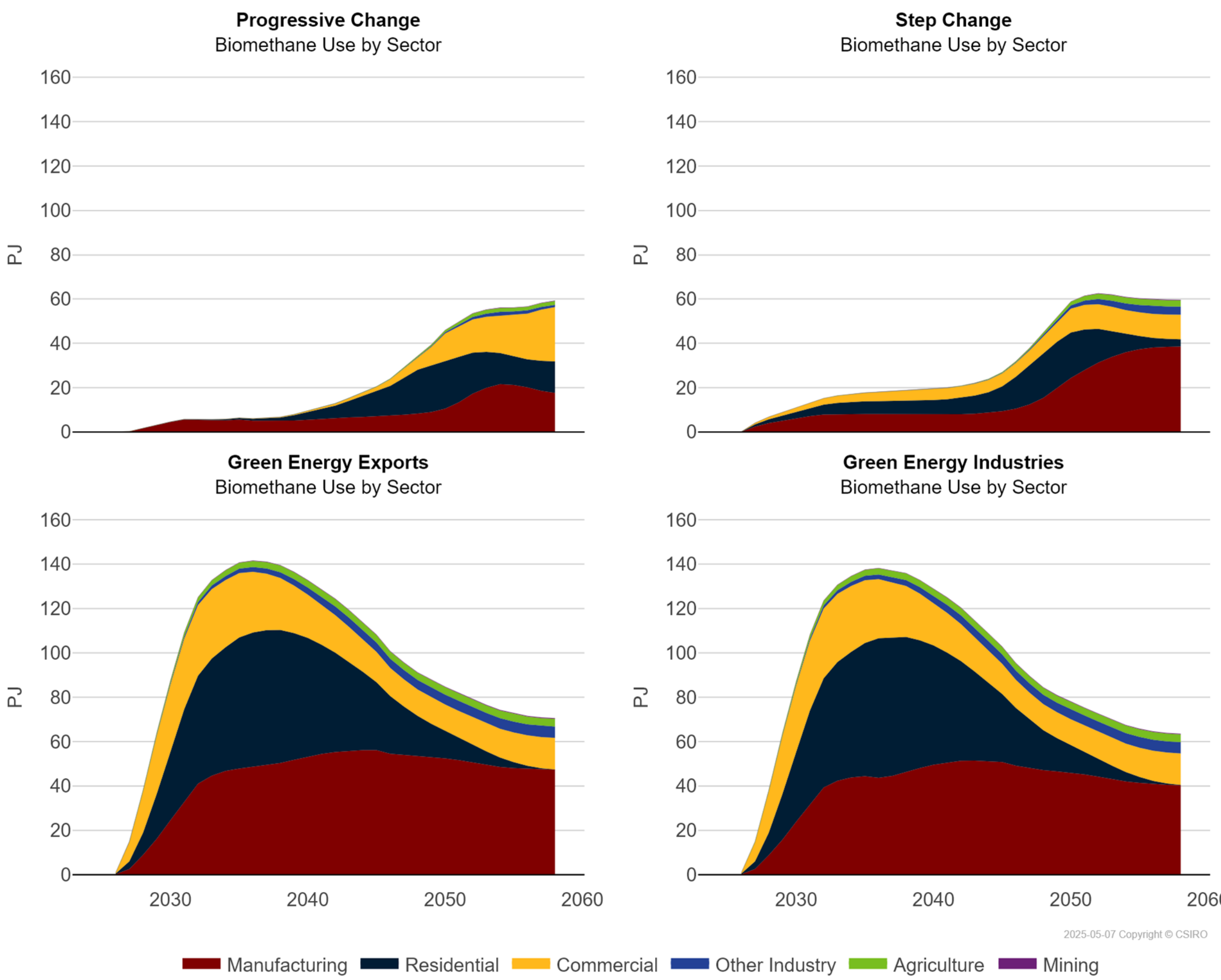


Figure 4-24 National biomethane consumption by sector

Uptake is greatest in the Green Energy scenarios, especially in the near-term, as a means to decarbonise the use of natural gas in existing processes and buildings. This is especially the case for residential buildings which then has increased electrification in the medium- to long-term as new buildings increase their share of overall energy use. Biomethane use in industry mostly occurs in food manufacturing and petroleum refining and other manufacturing.

4.7 Energy consumption by Sector

The final energy consumption by fuel type across all sectors is shown in Figure 4-25. Across all scenarios, there is a clear decline in fossil fuel consumption, particularly coal, oil, and natural gas, reflecting the shift towards decarbonisation. Note that final energy consumption excludes feedstocks such as natural gas and hydrogen that are used to manufacture chemicals and commodities.

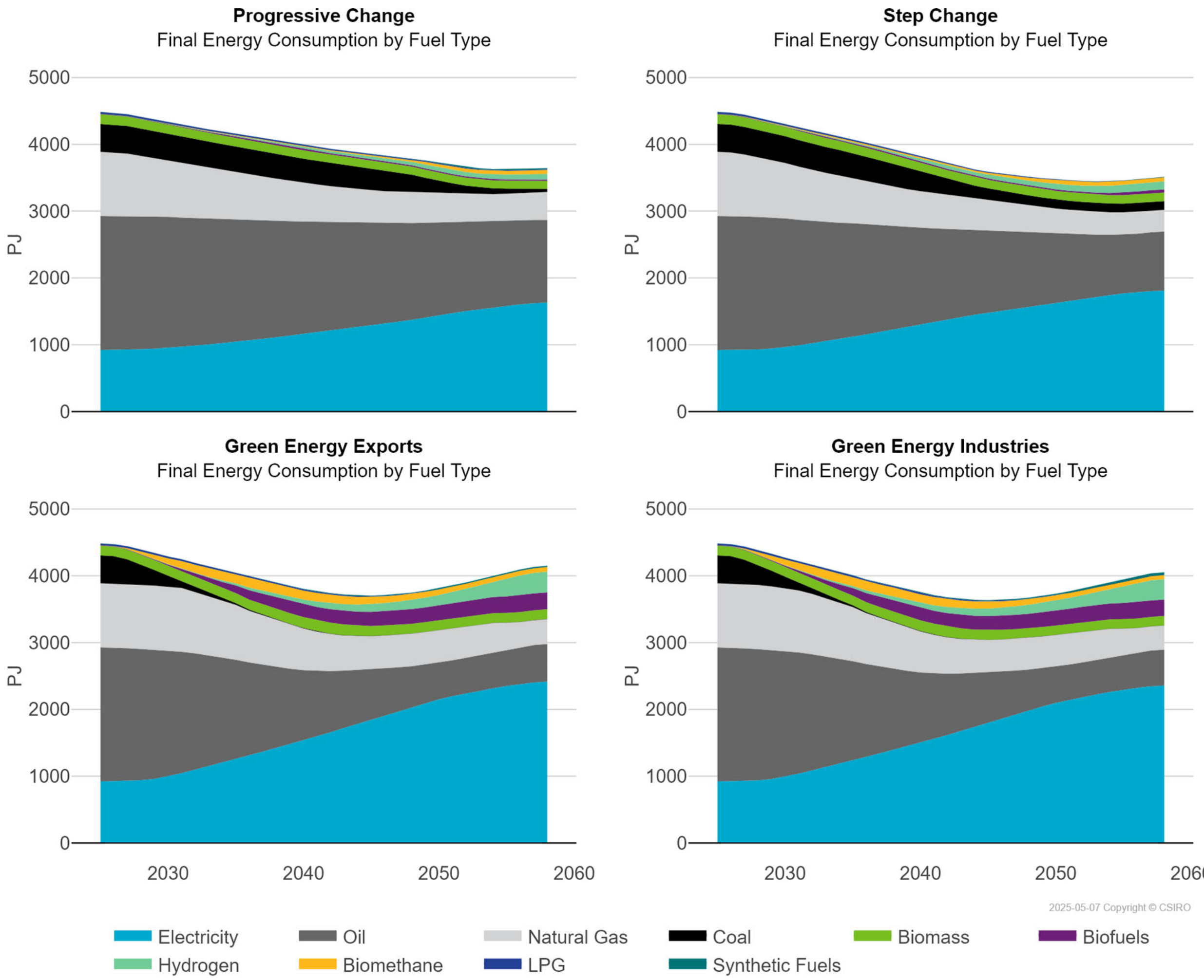


Figure 4-25 National final energy consumption by fuel type

By 2050, natural gas consumption declines between 36% and 59% compared to 2025, while oil consumption drops between 30% and 74%. At the same time, there is a marked increase in electrification, with electricity consumption rising significantly, especially under Green Energy Industries, where it more than doubles by 2050. Hydrogen emerges as a significant energy carrier, with its uptake varying across scenarios but reaching its highest levels in the Green Energy Exports scenario. Biomethane and synthetic fuels also see substantial growth. In the following sub-sections, the electrification and energy efficiency aspects are examined further, as are the individual sectors.

4.7.1 Electrification, fuel switching, and energy efficiency in buildings and industry

Final electricity demand in end-use sectors is influenced by various factors, with energy efficiency improvements, electrification, and fuel-switching to fuels other than electricity playing a pivotal role in driving energy consumption patterns. As industries, households, and businesses transition toward low-carbon energy solutions, advancements in technology and market dynamics can influence the overall energy demand. Energy efficiency measures reduce total energy consumption by improving the performance of appliances, equipment, and industrial processes, while electrification shifts energy use from fossil fuels to electricity. A high level view of the fuel switching aspect of this is shown in Figure 4-26 and for the endogenous and autonomous components of energy efficiency savings in Figure 4-37 and Figure 4-39 respectively.

Figure 4-26 National fuel switching and electrification

Fuel switching refers to switches to any fuel other than electricity, and electrification refers to switching from any fuel to electricity. Remaining consumption refers to energy consumption unrelated to switching, and the energy units for the fuel switching and electrification series in this chart are in the from-fuel basis.

There have been several updates to electrification and energy efficiency assumptions since the previous modelling was undertaken (detailed in Appendix B.11). The amount of electrification and energy efficiency allowed in each scenario is scaled down from a baseline maximum amount using IEA WEO scenarios. This scaling has been updated to use the 2024 WEO scenarios, rather than 2021, which has reduced the overall amount of electrification and energy efficiency allowed in the Progressive Change and Step Change scenarios. This reduction is due to relative changes between the IEA WEO scenarios, where the most ambitious scenario moves further away from the other scenarios, as well as the re-mapping of Step Change scenario to the IEA Announced Pledges scenario (rather than the Sustainable Development scenario, which is no longer being updated by the IEA). The baseline maximum amount of electrification has also been revised for the 2024 MSM, which has led to a reduction in electrification potential in the short-term (by 2030) for industry.

Electrification

For electrification (the switch from other fuels to electricity), Figure 4-27 shows the scale of switching for each fuel type in units of the fuel being switched away from. By 2060, coal-to-electricity is near 200 PJ and natural-gas-to-electricity switching ranges from 380 PJ in Progressive Change to 500 PJ in the Green Energy scenarios. In comparison, LPG remains between roughly 6 PJ and 11 PJ, while oil consistently contributes less than 3 PJ in all scenarios.

The sub-sectoral breakdown is shown in Figure 4-31. For Step Change and Progressive Change, the sectors with the largest contributions to electrification are (in descending order of contribution) alumina production, residential buildings, agriculture, LNG export, commercial buildings, mining, manufacturing, and then iron & steel. For the Green Energy scenarios, the main difference is that iron & steel plays a more significant role, matching alumina as the largest contributor.

The technology switches driving this electrification are as follows:

- Alumina: Electrification is replacing coal when switching from traditional calcination to electric around 2040 (2030 for Green Energy scenarios) and is responsible for the notable uptick in electrification in Progressive Change.
- Residential Buildings: Electrification replaces gas, and in order is dominated by the end uses of heating, cooking, and hot water.
- Agriculture: Electrification is due to replacing liquid fuels, mostly in agricultural services, sheep and cattle, grains, and dairy (onsite transportation, and machinery, e.g., pumping, refrigeration, and irrigation systems).
- Gas Export: Electrification is via the switch to electric drives for LNG production.
- Commercial Buildings: Gas is being replaced (in decreasing order of gas reduction) across the commercial types of offices, public buildings, and then retail. This relates to gas-based heating and hot water systems that are being replaced with electric alternatives.

- Mining: Electrification is dominated by the replacing of liquid fuels in coal mining haulage and excavation. In gas mining, there is a reduction in the total PJ of gas avoided in the mid-2050s as domestic gas consumption declines due to uptake of hydrogen in the Green Energy scenarios.

  Manufacturing: The bulk of electrification in manufacturing by 2058 occurs in Alumina (see first bullet point), and Iron and Steel through replacing coal via the switch to hydrogen-based direct reduction iron production (DRI), and then in other manufacturing including the replacing of liquid fuels in petroleum refining, mostly via electrification of boilers, and less so the electrification of low temperature furnaces.

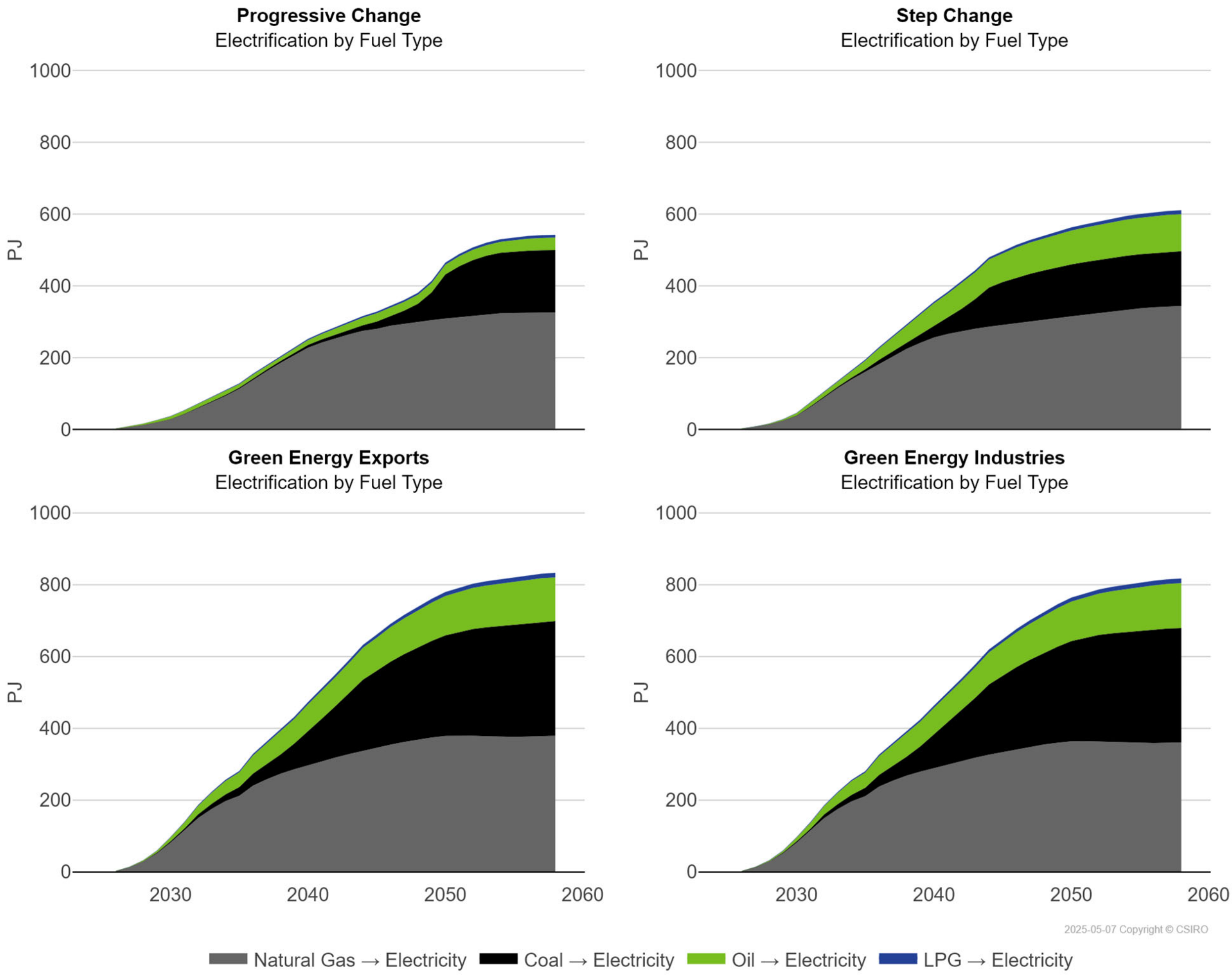


Figure 4-27 National electrification by fuel type in from-fuel basis

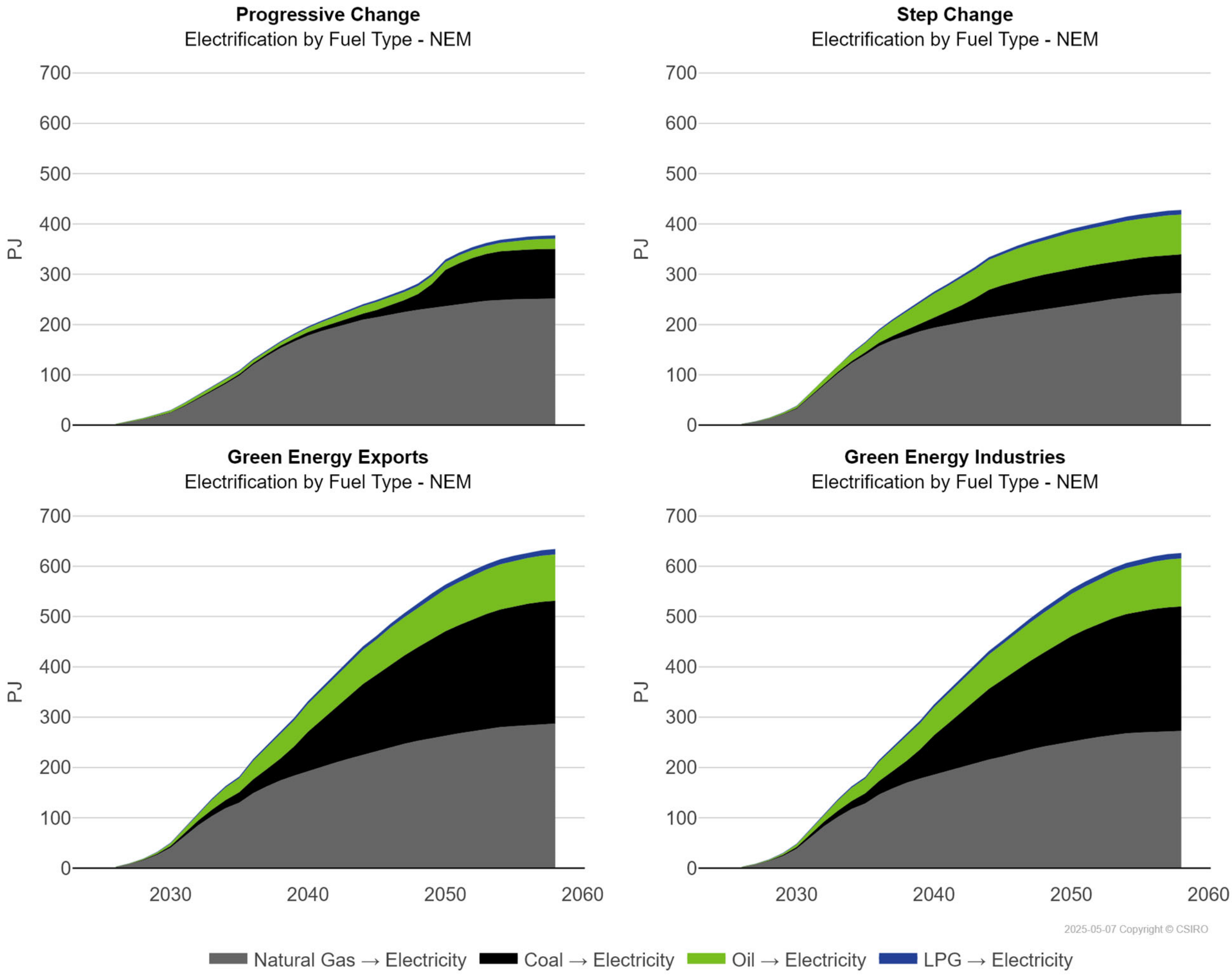


Figure 4-28 Electrification by fuel type in from-fuel basis for the NEM

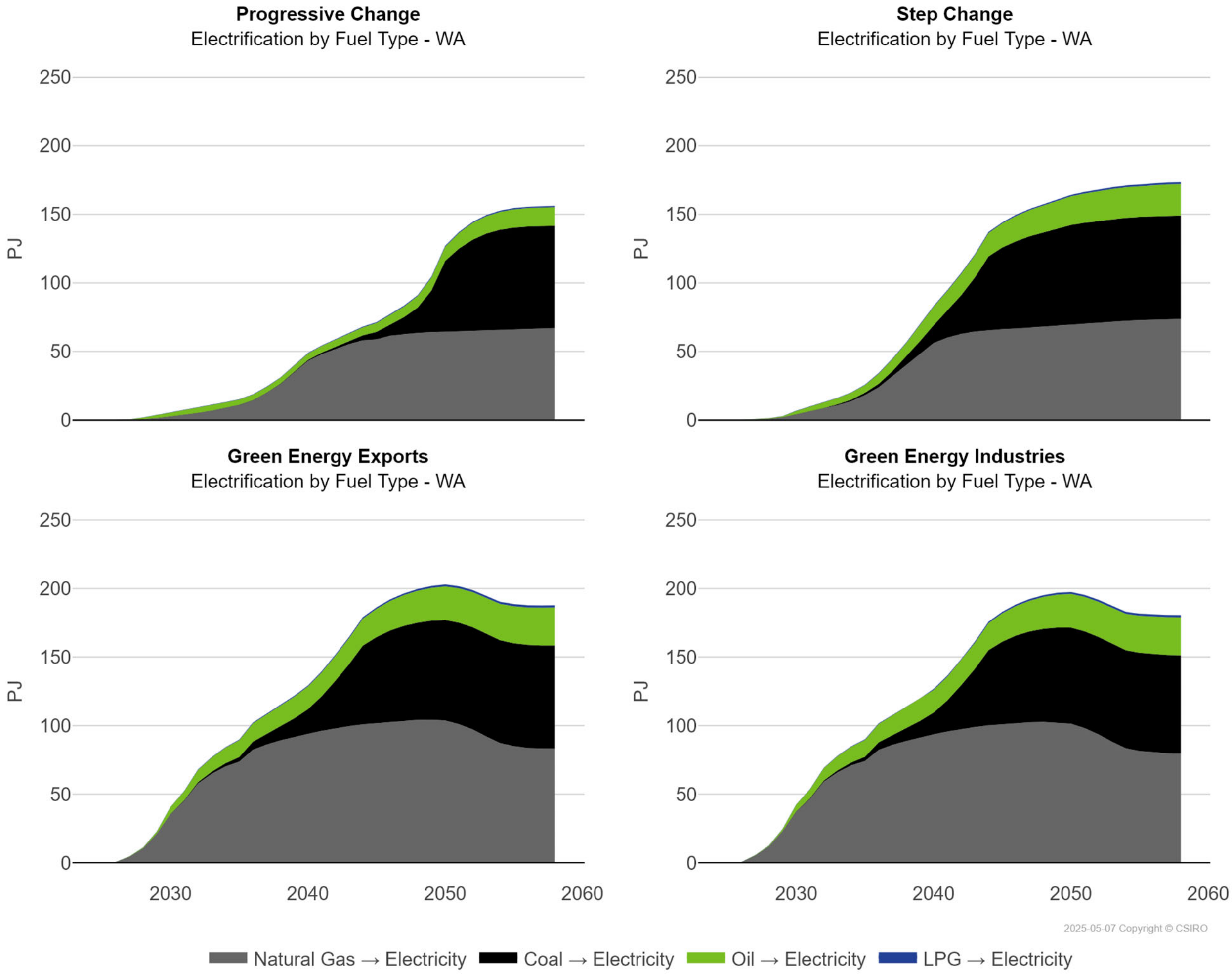


Figure 4-29 Electrification by fuel type in from-fuel basis for Western Australia

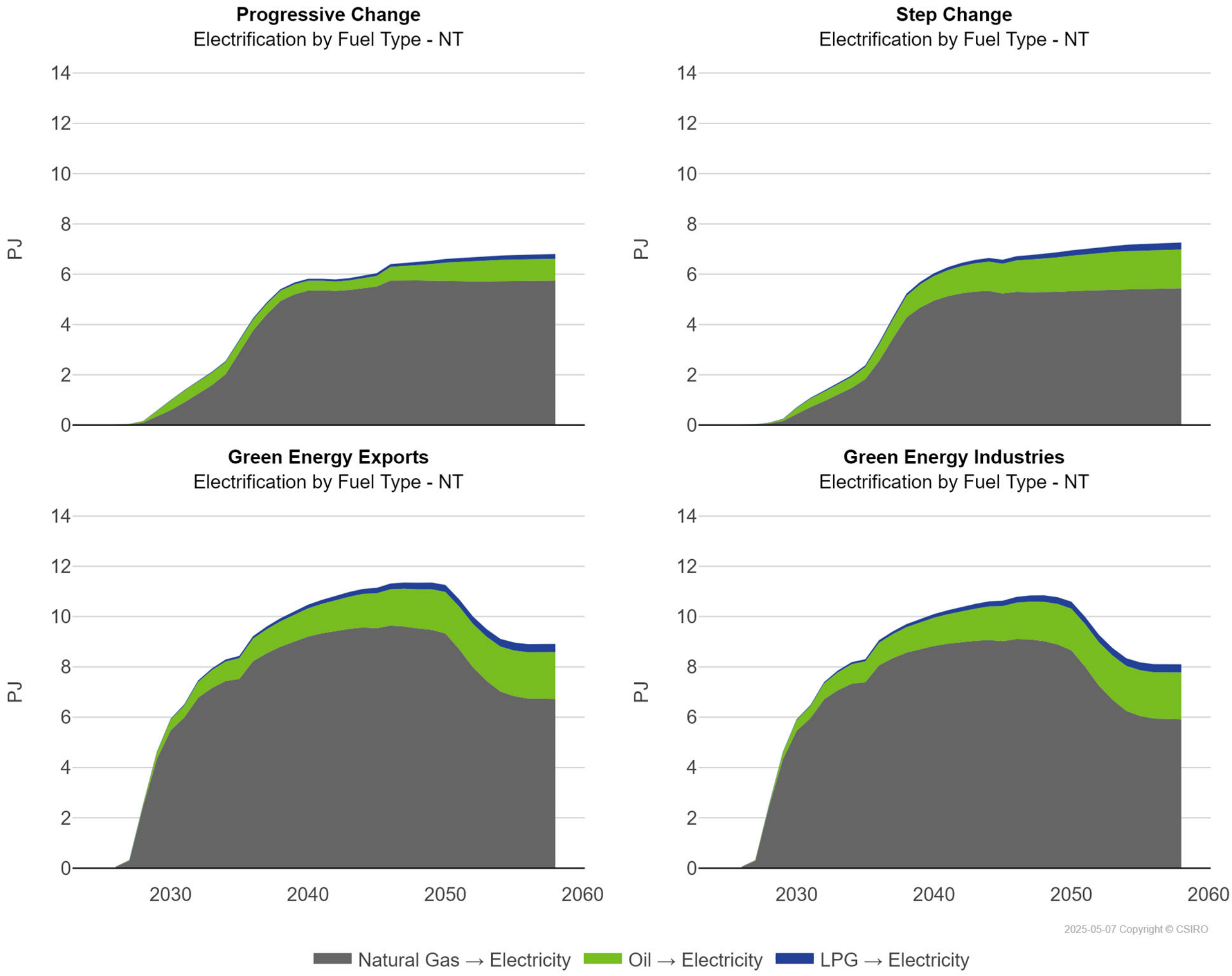


Figure 4-30 Electrification by fuel type in from-fuel basis for the Northern Territory

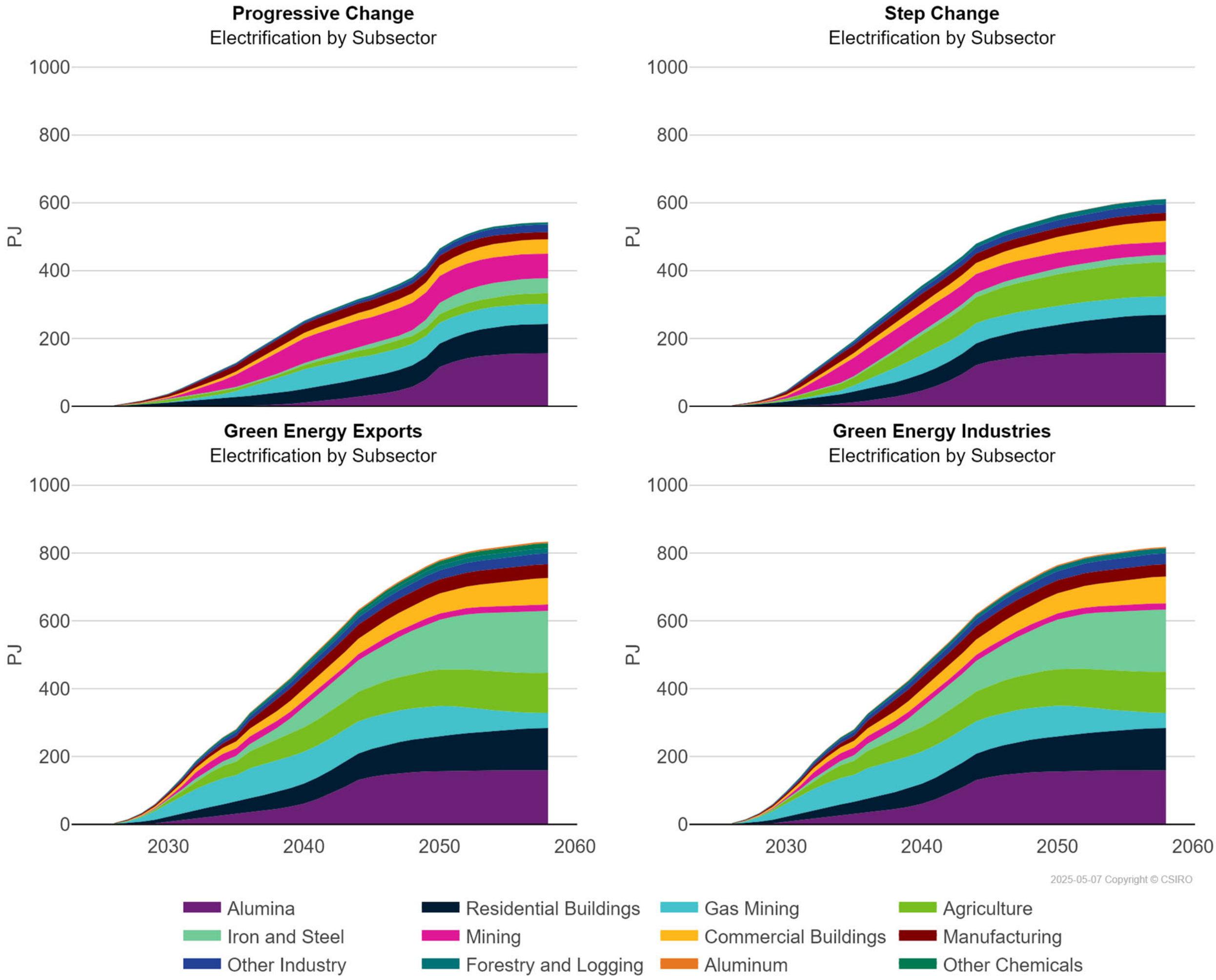


Figure 4-31 National electrification by sub-sector in from-fuel basis

Fuel Switching

For the switching away from fossil fuels to fuels other than electricity (refered to as "fuel switching" here), the two dominant components are coal to natural gas and natural gas to biomethane. In Progressive Change, the switch from coal to gas occurs mid 2040's, then late 2030's in Step Change, and from 2027 in the Green Energy scenarios. This is driven by Alumina (in Bauxite mining) in Progressive Change, Iron and Steel in Step Change (via the switch to natural gas based DRI), and a combination of those subsectors in the Green Energy scenarios (via the near term switch to gas in blast furnace operation in Iron and Steel, and the calcination process in Alumina). The switch from gas to biomethane in Progressive and Step Change are driven by Other Industry (including petrolium refining) and buildings (about an equal split across residential and commercial). In the Green Energy scenarios, residential buildings exhibit almost double the switch to biomethane of commercial, and industry sitting between them (again being Other Industry, but also Other Manufacturing including food production). The Green Energy scenarios also exhibit the switch from coal to hydrogen in the mid 2050's driven by mostly by the Alumina subsector (in bauxite mining and the Bayer process), with contributions from Iron and Steel, Aluminium, Cement, and Ammonia, all for high temperature process heat.

The regional breakdowns are shown in Figure 4-32 through Figure 4-35, with the NEM largely reflecting the above, while WA is dominated by switching from coal to gas in alumina calcination, and coal to gas also in the NT (for ammonia production).

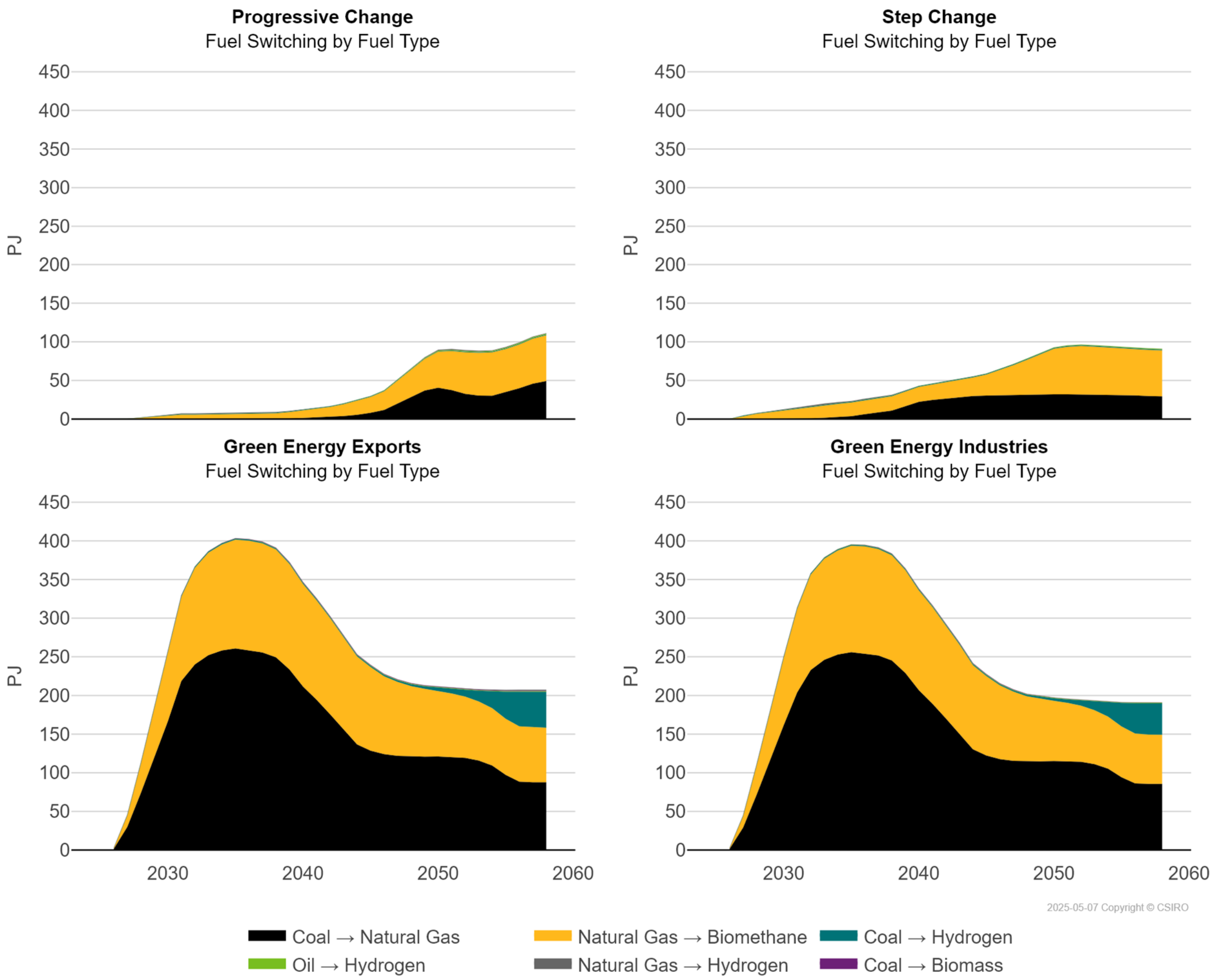


Figure 4-32 National fuel switching by fuel type in from-fuel basis

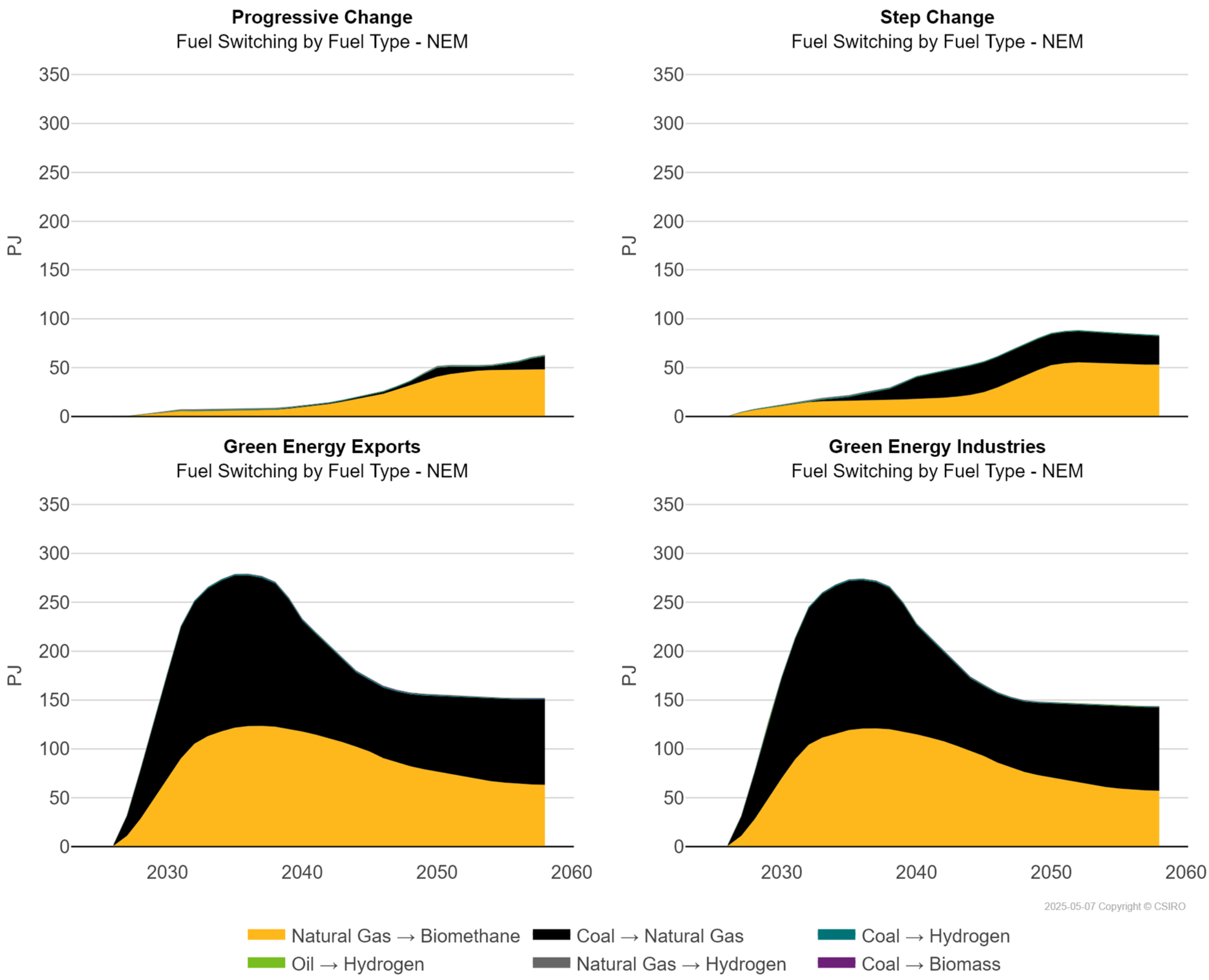


Figure 4-33 Fuel switching by fuel type in from-fuel basis for the NEM

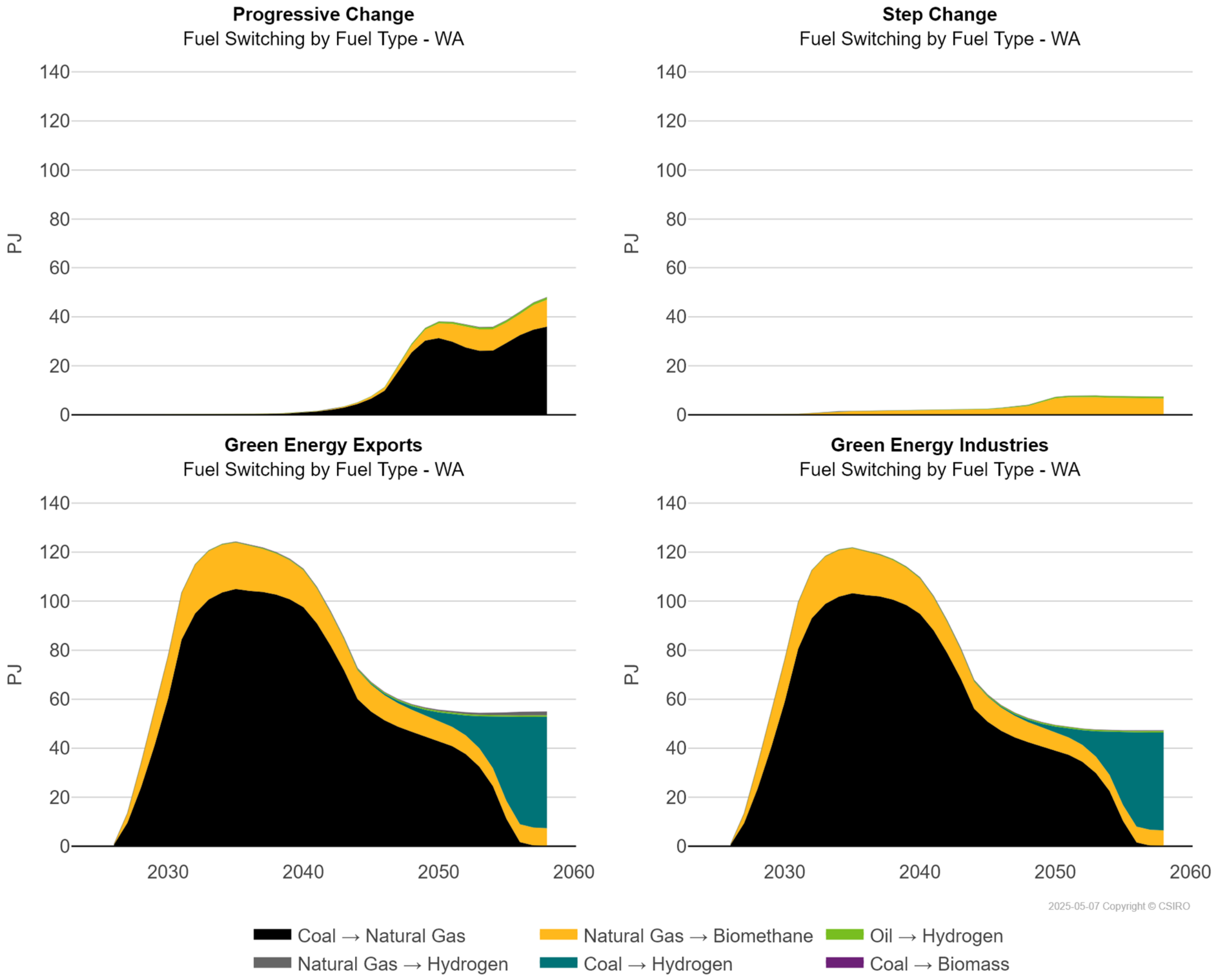


Figure 4-34 Fuel switching by fuel type in from-fuel basis for Western Australia

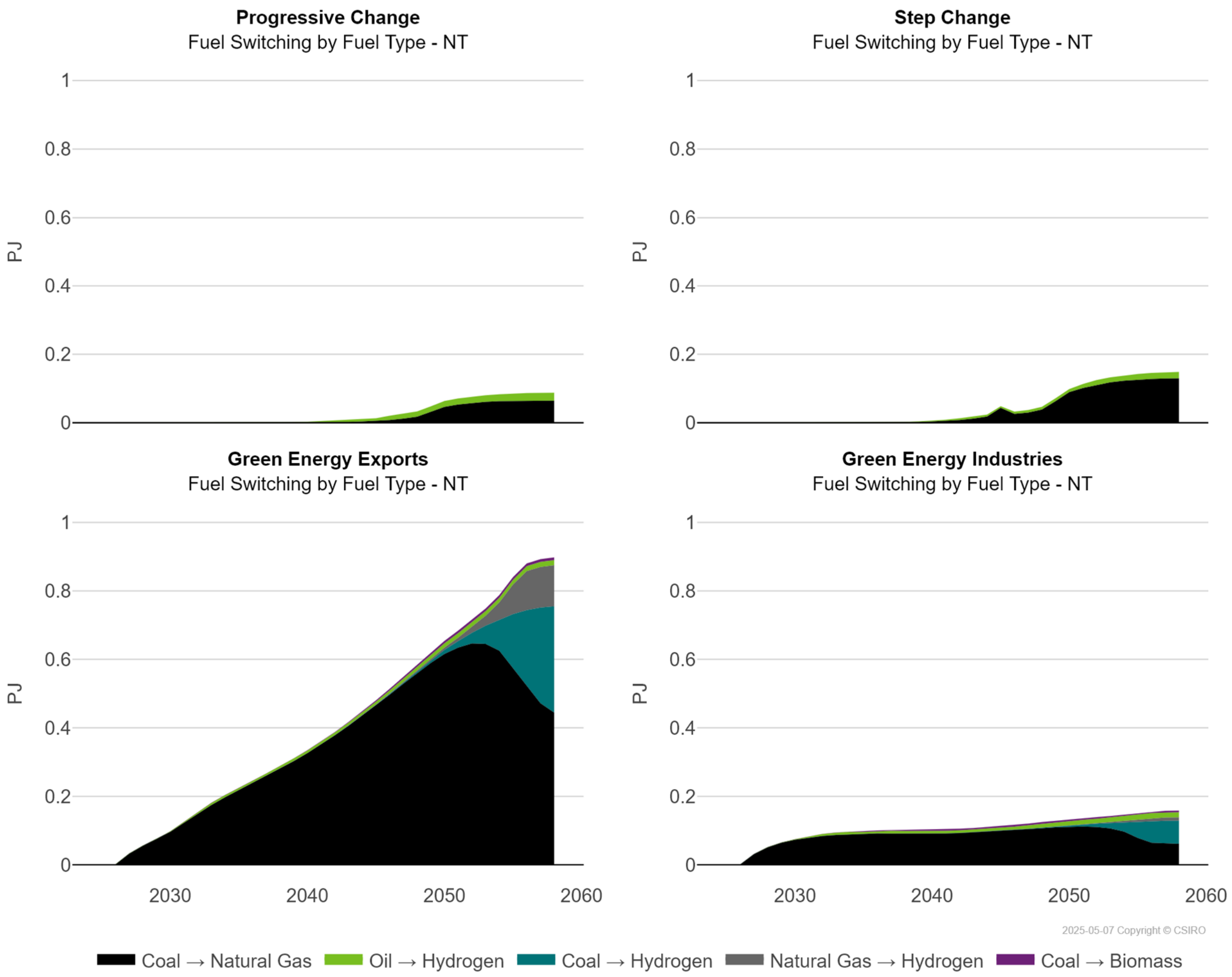


Figure 4-35 Fuel switching by fuel type in from-fuel basis for the Northern Territory

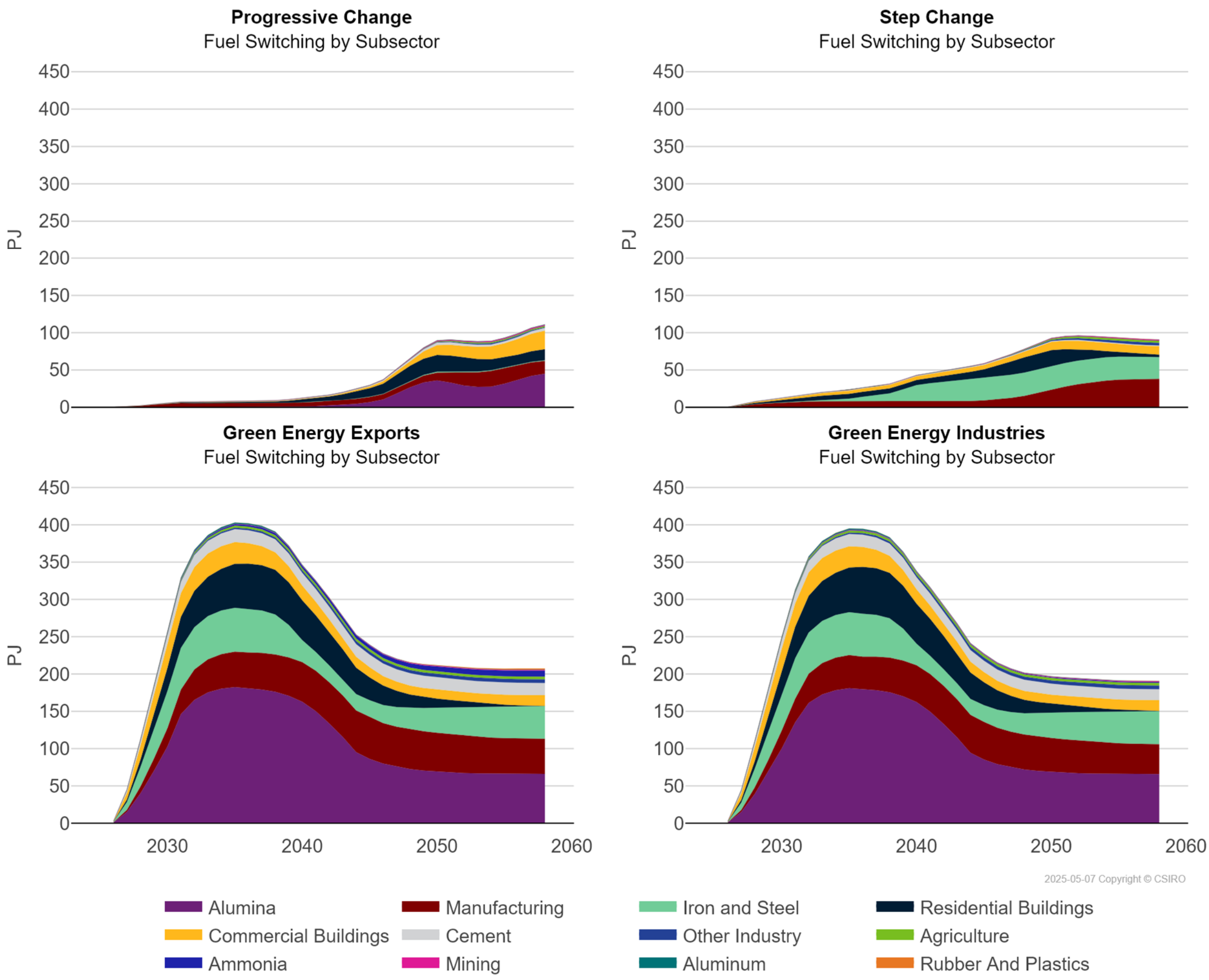


Figure 4-36 National fuel switching by subsector in from-fuel basis

The national level view of total fuel switching (to fuels other than electricity) by sector is shown in Figure 4-36 where Alumina is shown to dominate via the nearer term switching from coal to natural gas to reduce emissions in the calcination process.

Energy Efficiency

Energy efficiency plays a vital role in reducing energy demand, cutting emissions, and improving the overall sustainability of energy systems. In AusTIMES, energy efficiency improvements are typically categorised into autonomous energy efficiency improvements (AEEI), endogenous energy efficiency (EEE), and exogenous energy efficiency (Reedman et al., 2022). However, the exogenous energy efficiency assumptions are not used in this project due to the limited availability of cost data and the non-costed options that account for emissions reductions for innovative, but uncertain, technologies[14]. The details of autonomous and endogenous energy efficiency are

[14] In the buildings sector these included: stack ventilation, Trombe walls, phase change materials, variable air volume systems, chilled beams, indirect evaporative cooling, thermal energy storage systems, cool roofs, motorized shading design, occupancy detection & zoning, daylight dimming, proportional band economizer control, water-side chillers, HVAC optimization, Cool Biz, and air source heat pumps. In industry these included: material substitution (e.g., timber buildings, geopolymer cement, bio-coke), material efficiency (e.g., better building design, 3D printing), circular economy strategies (e.g., plastic recycling, metal recycling), and automation/artificial intelligence.

outlined in Appendix B.3 as both play a significant role in shaping future energy consumption trends. To assess their impacts on the energy system across the scenarios, energy efficiency outcomes are reported in terms of avoided energy consumption, as shown in Figure 4-37 for EEE and Figure 4-39 for AEEI. These figures highlight the respective contributions of technological advancements and cost-driven efficiency improvements in reducing energy demand over time.

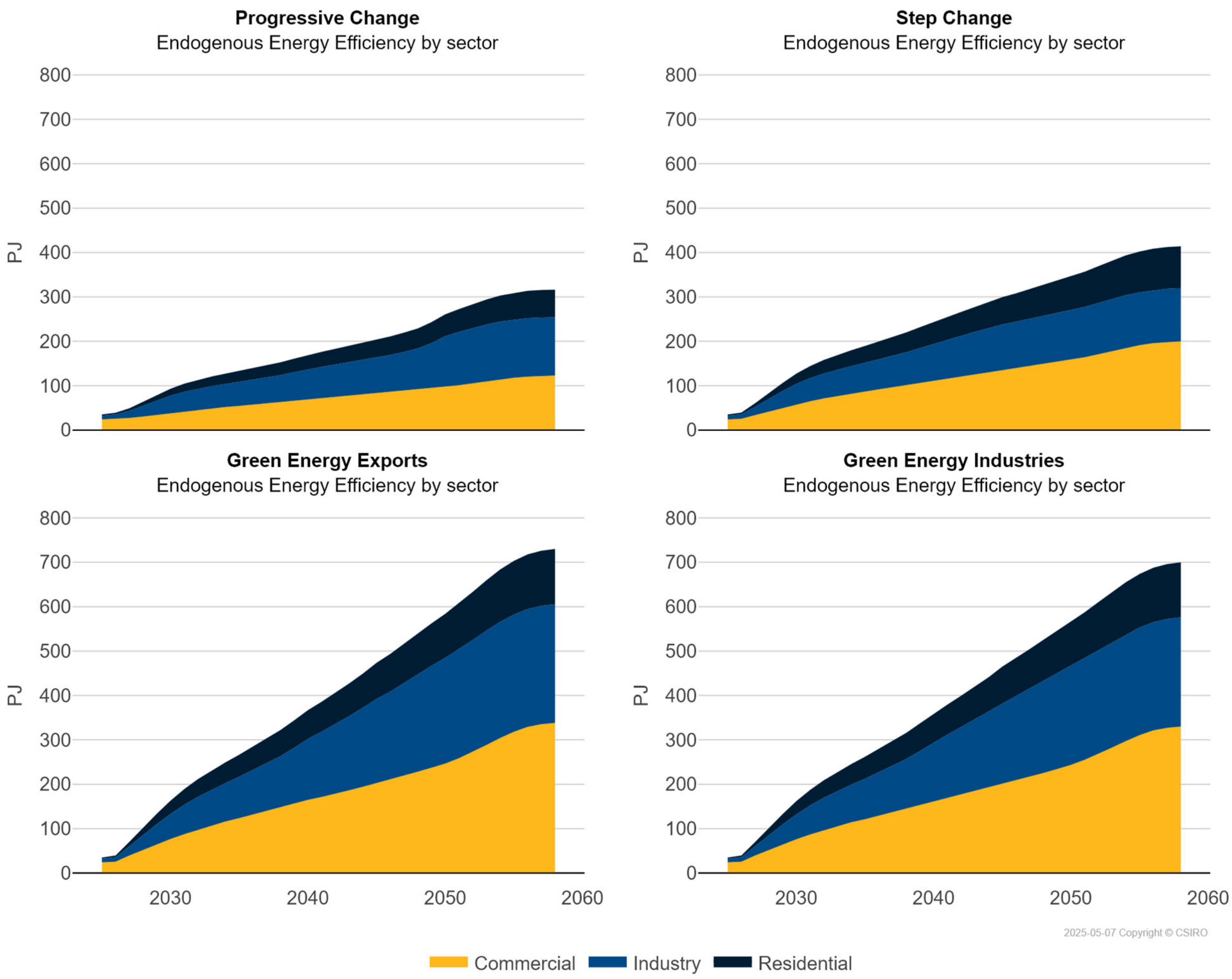


Figure 4-37 National endogenous energy efficiency by sector

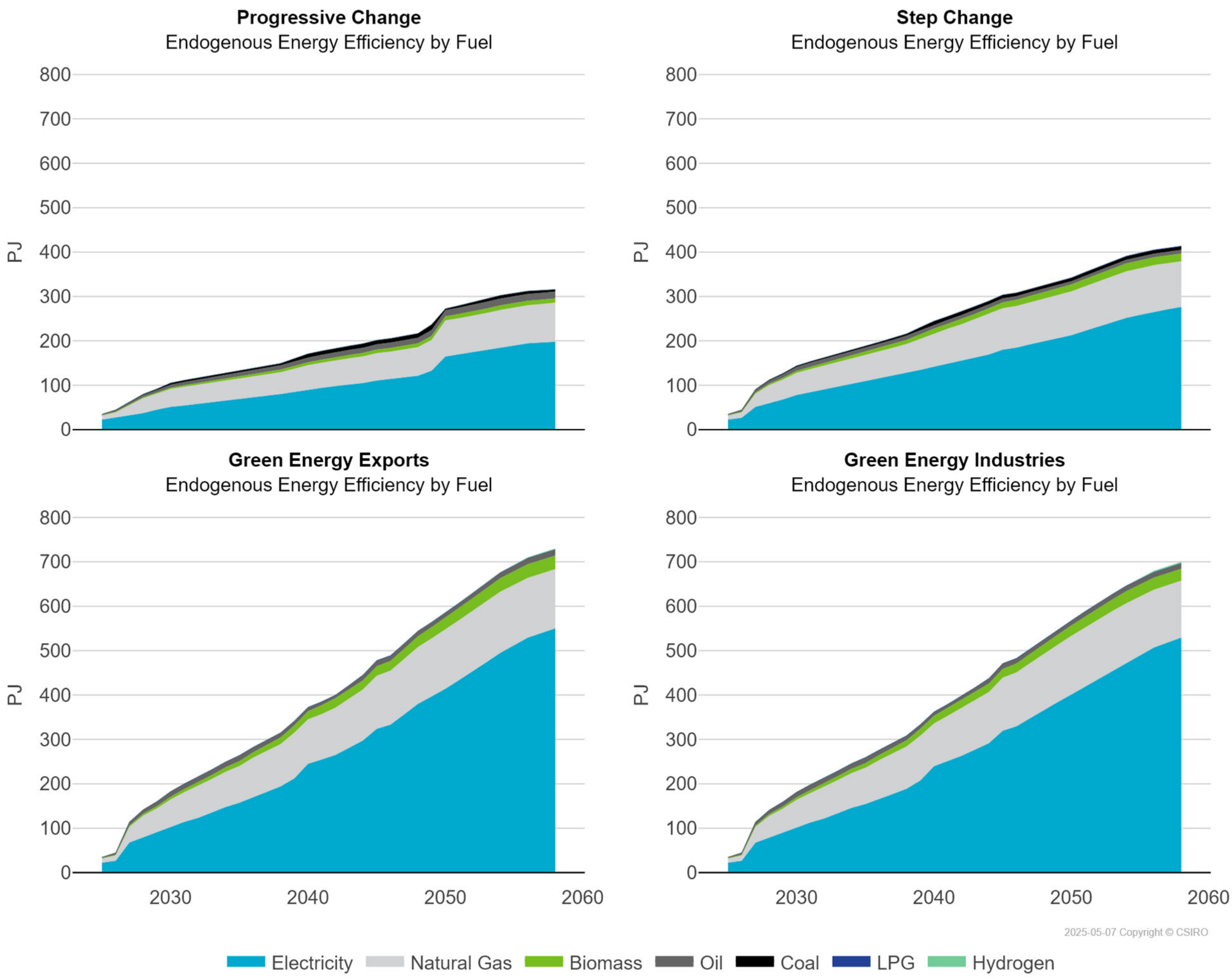


Figure 4-38 National endogenous energy efficiency by fuel

The adoption of 'endogenous' energy efficiency measures in buildings and industry is driven by technological advancements that support ambitious decarbonisation objectives. Due to the energy-intensive nature of industrial processes, especially in manufacturing (notably in Food and Beverages, Alumina, and Iron & Steel sub-sectors), even minor efficiency improvements can result in significant absolute energy savings. By 2058, the highest uptake of EEE across buildings and industry sectors is observed in the Green Energy Exports scenario, with 470 PJ of avoided energy in buildings and 266 PJ in industry across Australia, aligning with its strong decarbonisation focus. The Green Energy Industries scenario follows, with 467 PJ of avoided energy in buildings and 245 PJ in industry, reflecting greater uptake of energy efficiency in the 1.5 degree aligned scenarios. In contrast, the Progressive Change scenario (186 PJ in buildings, 130 PJ in industry) and the Step Change scenario (297 PJ in buildings, 122 PJ in industry) exhibit lower levels of energy efficiency improvements, indicating a more limited role for efficiency in their respective narratives.

Regional energy savings trends show that the NEM regions account for the majority of avoided energy consumption, representing 88 per cent of total building energy savings, with WA contributing 11 per cent and the NT approximately 1 per cent across all scenarios by 2058. Similarly, for industrial sector's energy savings, the NEM regions contribute between 75 per cent and 90 per cent, while WA accounts for 9–23 per cent. The NT's contribution remains negligible in

Green Energy scenarios and approximately 1–2 per cent in Progressive Change and Step Change scenarios.

The breakdown of energy savings from endogenous energy efficiency uptake at the national level by fuel type is shown in Figure 4-38. The majority in all scenarios is for electricity, and most of that in buildings. For Step Change, around 250 PJ is in buildings, and most of the remaining (near 20 PJ) being in industry. For the Green Energy scenarios this rises above 400 PJ for buildings and industry increases to near 150 PJ of savings. For natural gas, the savings are dominated by industry, with near 60 PJ saved in industry and 40 PJ for buildings in Step Change. For the Green Energy Scenarios these are closer to 85 and 55 PJ respectively. The savings for electricity in buildings are (in descending order) cooling, lighting, appliances, IT and equipment, then water heating. For natural gas in buildings, the largest end use savings (again in descending order) are through heating and domestic hot water. For industry, these gas savings are primarily found in the oil and gas extraction (including LNG production) and manufacturing.

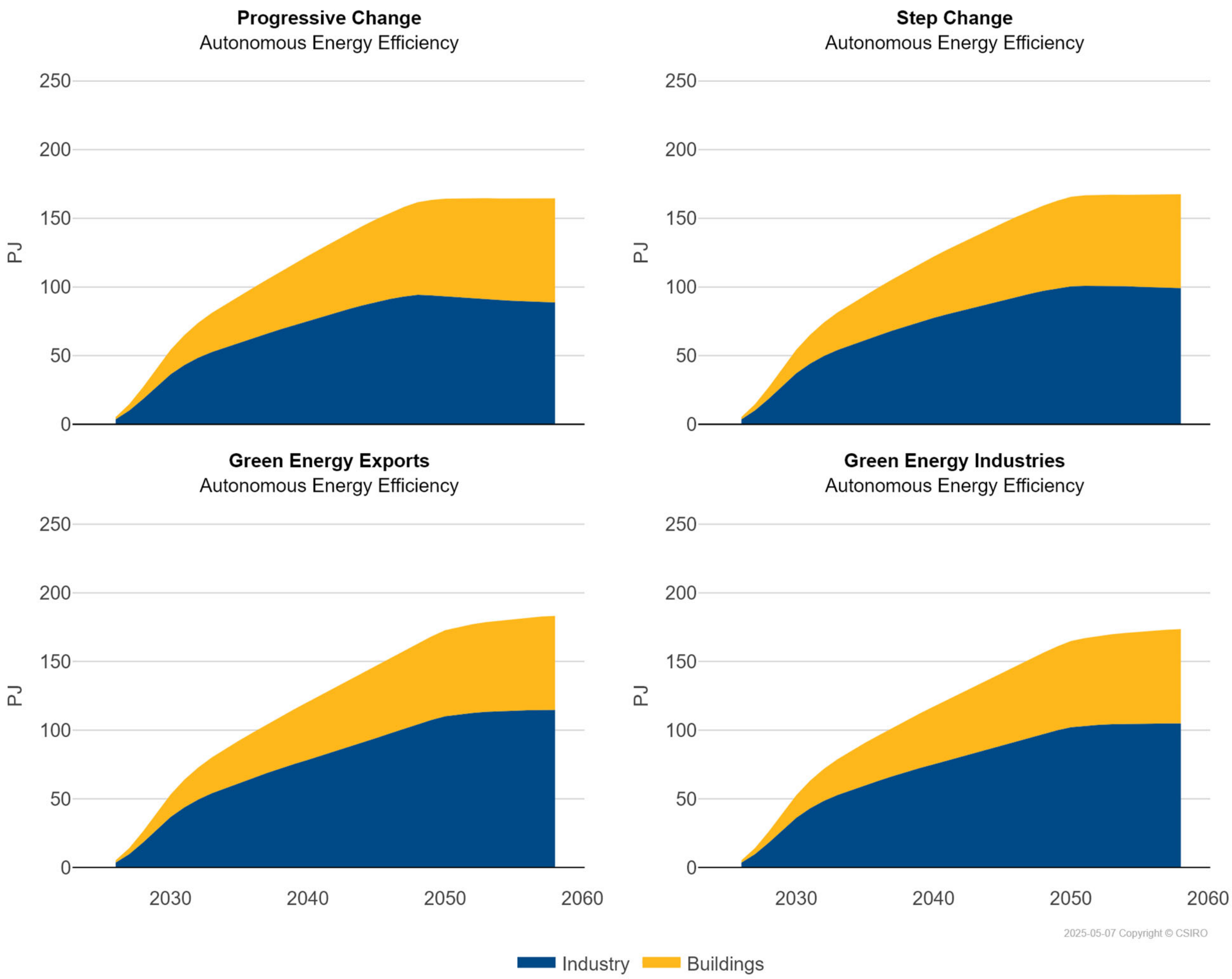


Figure 4-39 National autonomous energy efficiency

Note that for this work autonomous energy efficiency savings were not disaggregated by fuel type as they were for endogenous savings.

Energy savings from AEEI vary across sectors and scenarios. Figure 4-39shows a rapid increase in energy efficiency savings in buildings and industry from 2030 to 2050. Beyond 2050, these savings plateau as energy intensity stabilises, reflecting constant rates of energy efficiency improvement. In the Green Energy Exports scenario, industrial energy savings are the highest, reaching 114 PJ by 2058, aligned with its strong decarbonisation objectives and greater industrial activity. In all other scenarios, industrial energy savings range between 88 PJ and 104 PJ across Australia. In contrast, the highest AEEI savings in buildings is observed in the Progressive Change scenario, reaching 76 PJ, while in all other scenarios, building energy savings remain 74 PJ in 2058 due to more natural gas in the Progressive Change scenario. Regionally, the majority of building energy savings occur in the NEM regions, accounting for 89% to 90% of total energy savings. WA contributes 9% to 10%, while the NT accounts for approximately 1% of total energy savings in 2058. Similarly, most industrial sector energy savings are also concentrated in the NEM regions, making up 63%–73% of total savings, while WA contributes 26%–36%. In the Green Energy Export scenario, the NT accounts for 1% of industrial energy savings, whereas in all other scenarios, its contribution is negligible by 2058.

As outlined in Appendix B.3, the energy efficiency assumptions for buildings and industry across the scenarios are based on the 2022 Multi-Sector Modelling (MSM) project with adjustments to maximum energy efficiency uptake rates for better alignment with the outcomes of various IEA World Energy Outlook 2024 scenarios. As a result, there are some differences in the final energy efficiency uptake and the overall profile of efficiency improvements in this year's scenarios compared to those in 2022 MSM modelling results. Notably, the current modelling results show greater energy savings in industrial subsectors compared to buildings, particularly in the Alumina and Iron & Steel industries.

4.7.2 Fuel mix in Industry

The fuel consumption by industry is the largest of all the sectors and, as indicated below in Figure 4-40, varies strongly with scenario. In Progressive Change, the sum of natural gas and electricity consumption vary only a little, with some natural gas being replaced via electrification (seeFigure 4-41) in mining and manufacturing (mostly Alumina). Oil (diesel) use declines and coal use is pinched (and displaced by gas and some electricity) to meet the 2050 net-zero target. In Step Change there is slightly more electrification (mostly in Agriculture). Coal consumption shows a decline after 2040, and diesel consumption dropping by more than 85% of its present value. In the Green Energy scenarios, there is an increase in natural gas consumption through the late 2030s to reduce emissions by replacing coal, and later in the mid 2050's some of that gas is displaced by hydrogen to further bring down emissions (see Figure 4-43 for a breakdown of industry hydrogen consumption). The overall increase in fuel consumption in those scenarios is driven by the large green commodity demand which defines those scenarios.

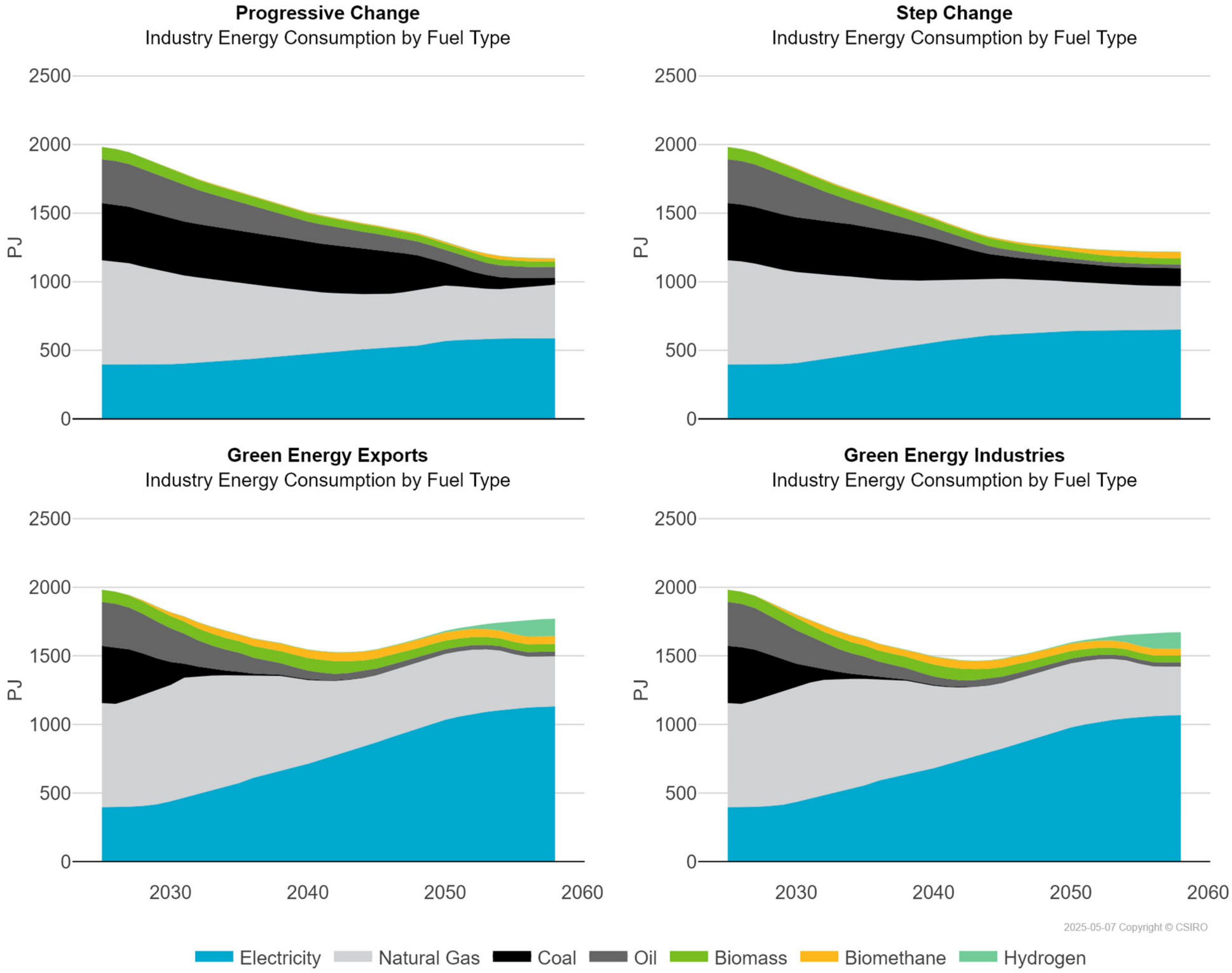


Figure 4-40 National industrial fuel consumption by fuel type

Focusing on natural gas, across all four scenarios and as shown in Figure 4-42, the overall use of natural gas in industry is approximately halved from 2025 to 2050 (representing around 300 PJ), although for the Green Energy scenarios, the usage increases almost 100 PJ from 2025 through 2030. The largest single subsector decrease is in Oil and Gas Extraction, mostly via the electrification of LNG, but also contributions from waste heat recovery in the LNG processes and the decline in LNG export from 2030 through 2035. The increase in gas consumption by the Manufacturing sub-sector in the Green Energy scenarios through to 2040 is due to fuel switching away from coal in Alumina production (calcination, Bayer, and open-pit mining of bauxite processes), which is subsequently replaced by hydrogen in Bayer and open-pit mining and electrification in calcination from around 2040. The Iron and Steel sub-sector shows a significant increase in consumption starting in the late 2030's in Progressive and Step Change, and from 2027 in the Green Energy scenarios. This is due to the fuel switch from coal to gas in the blast furnace, pelletizing (straight grate and DRI), and coke ovens.

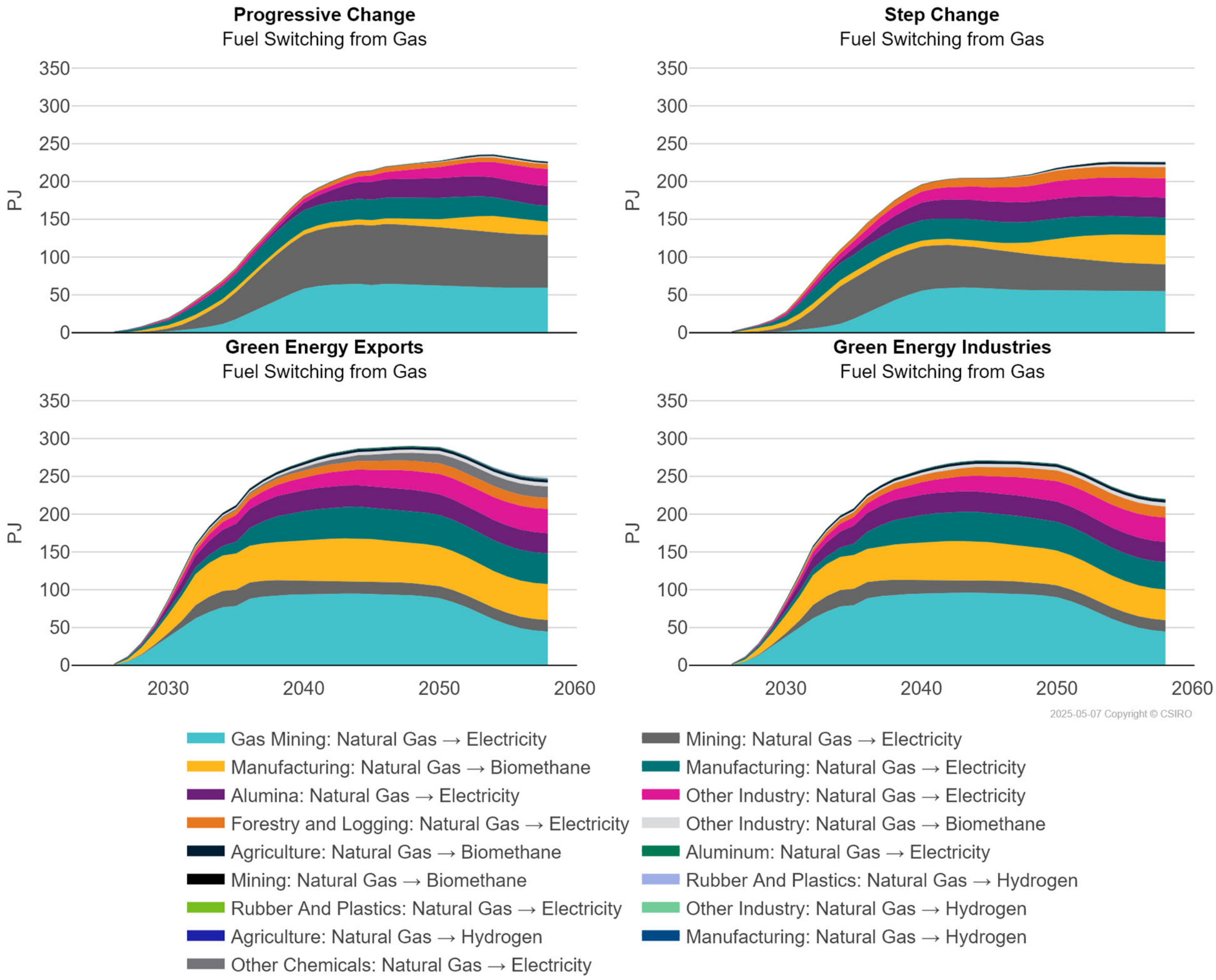


Figure 4-41 National industrial fuel-switching and electrification away from natural gas by sub-sector

Figure 4-41 shows that in all scenarios around two thirds of the reduction in gas consumption is due to electrification, and the other third of the switch to biomethane. The reduction in Gas Mining (and near half of the industrial gas consumption reduction overall) is due to the electrification of LNG production. Other significant electrification of gas occurs in Alumina, Mining, and Other Industry. The remainder of the switch to biomethane is various sub-sectors of manufacturing including petroleum refining, non-cement/non-construction materials, and other food products.

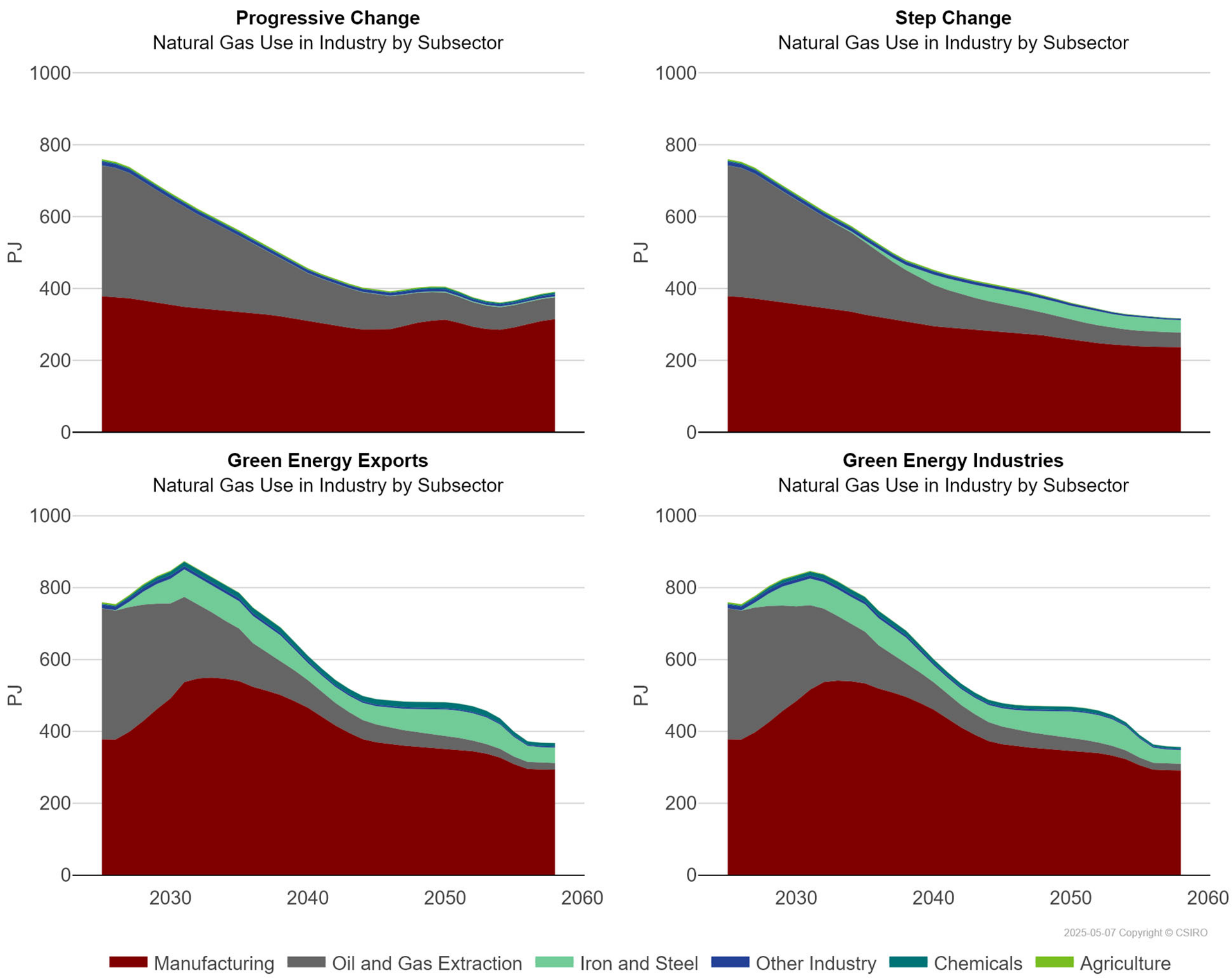


Figure 4-42 National industrial natural gas consumption by sub-sector

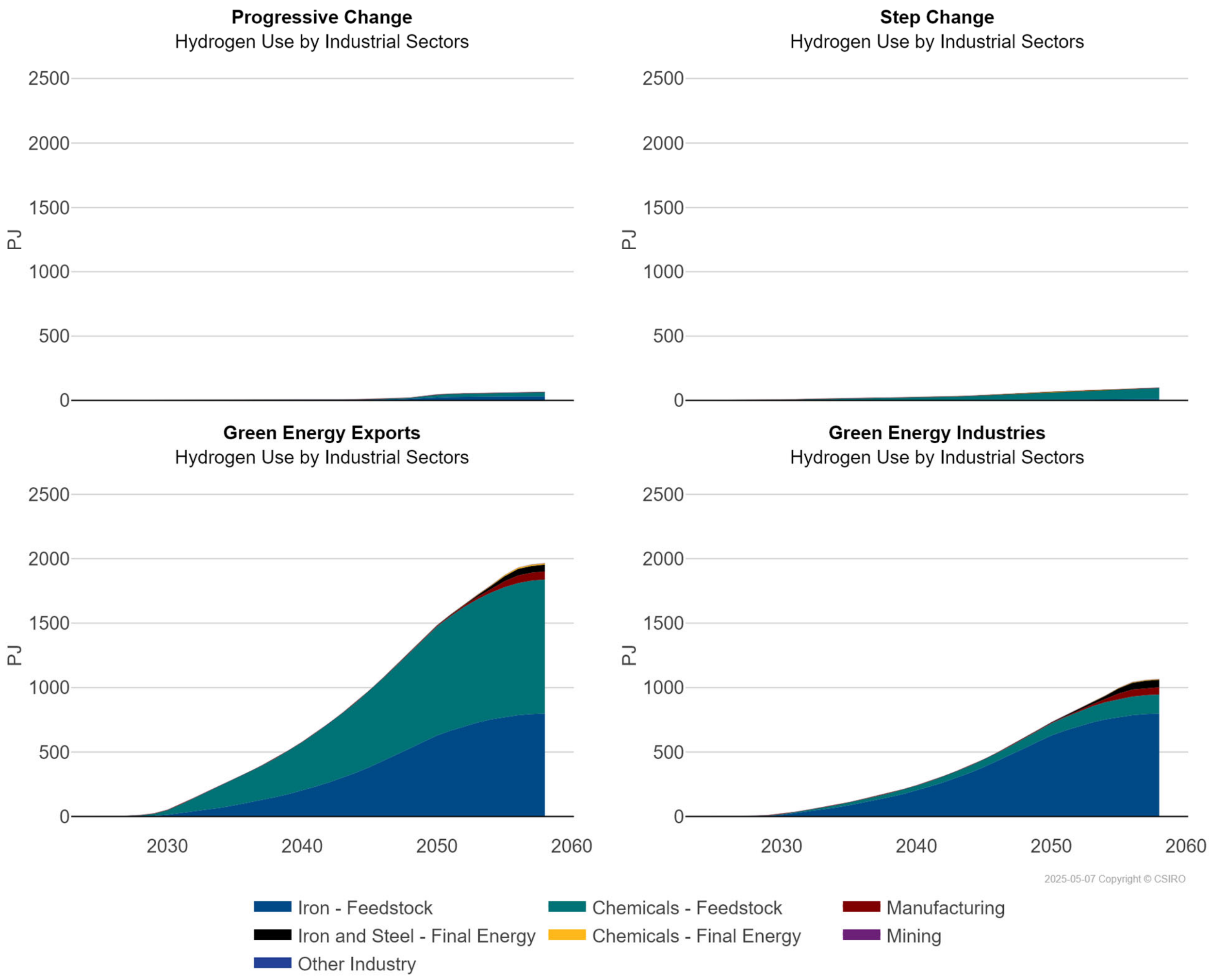


Figure 4-43 Hydrogen use by industrial sectors, nationally

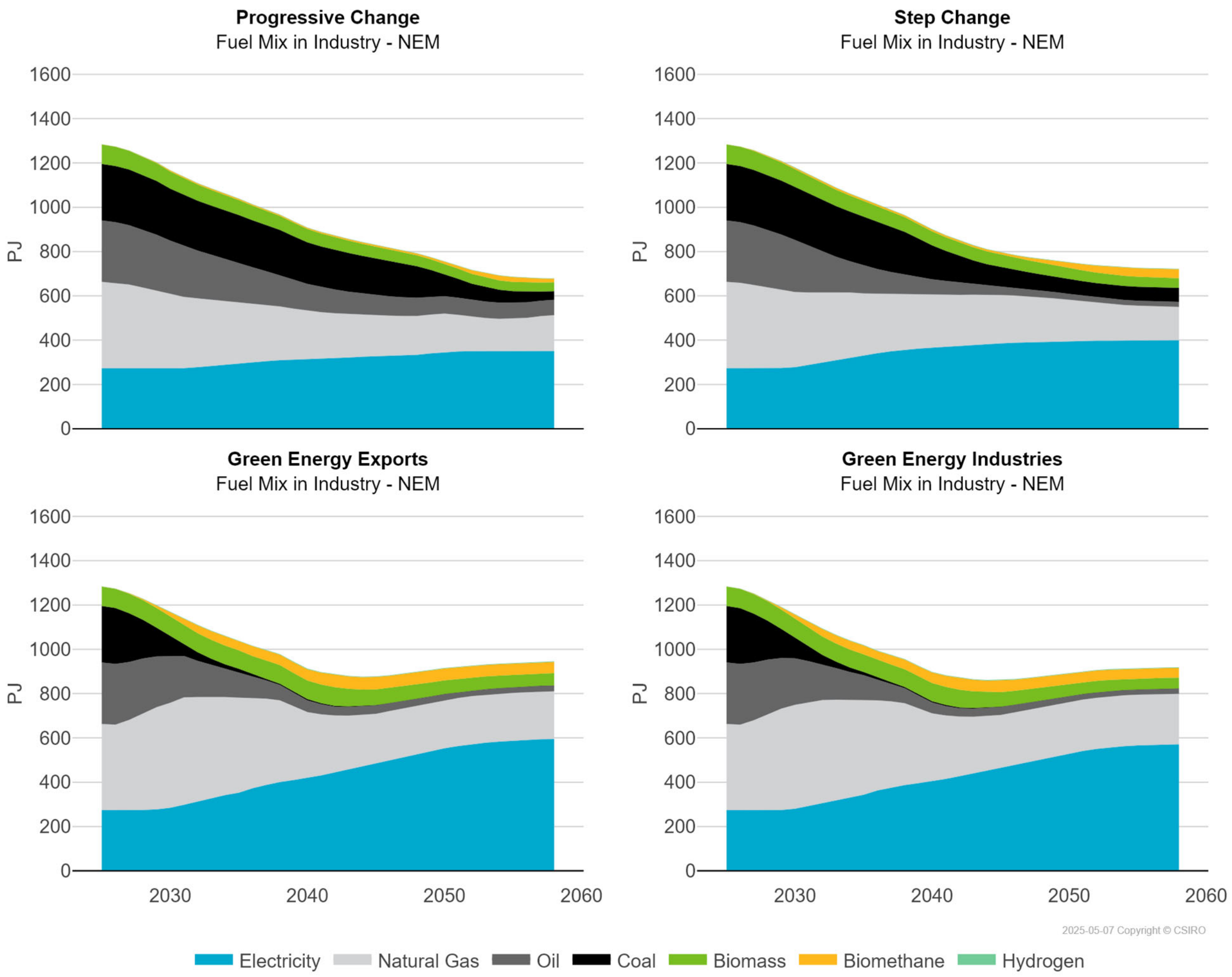


Figure 4-44 Fuel mix in industry in the NEM

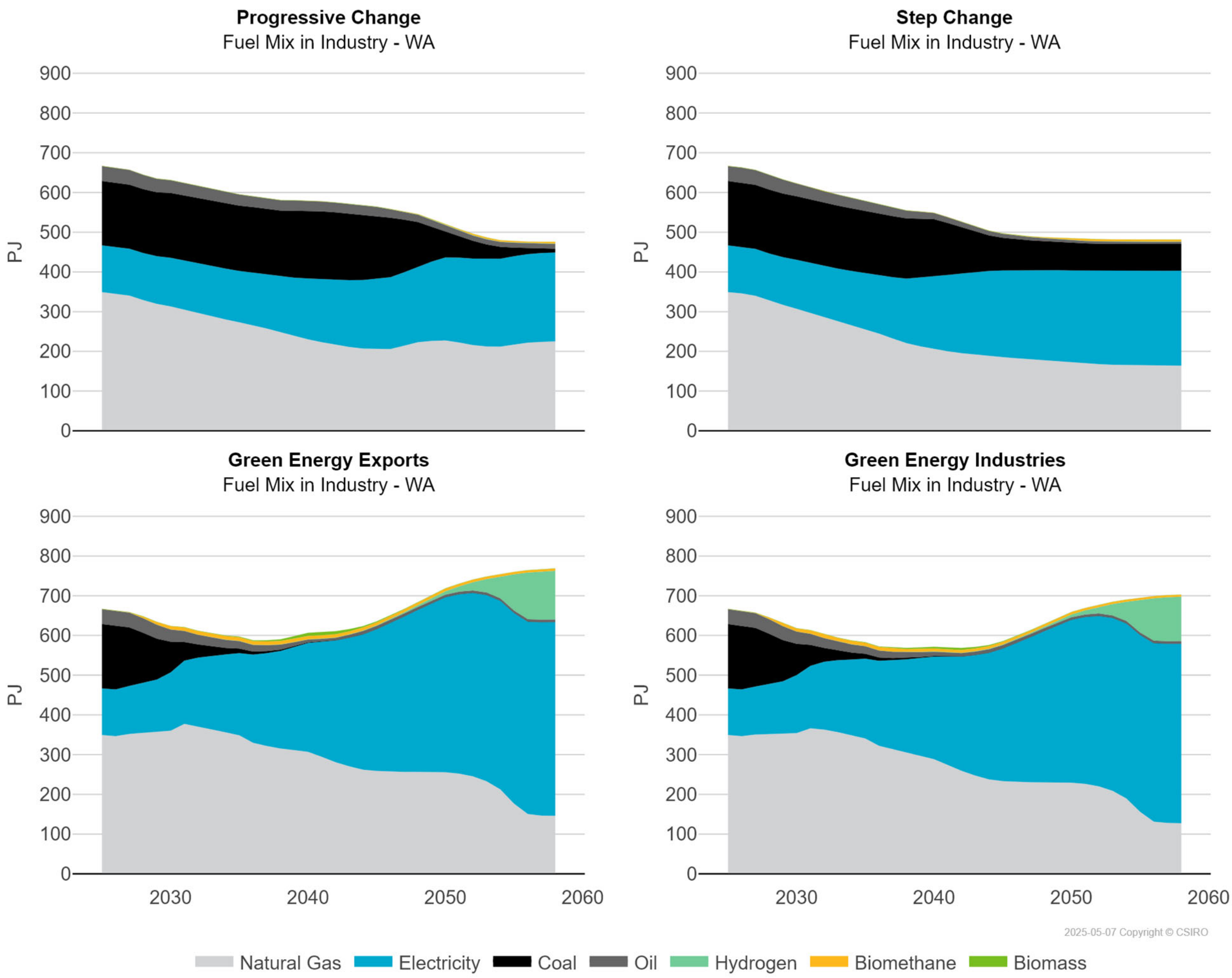


Figure 4-45 Fuel mix in industry in Western Australia

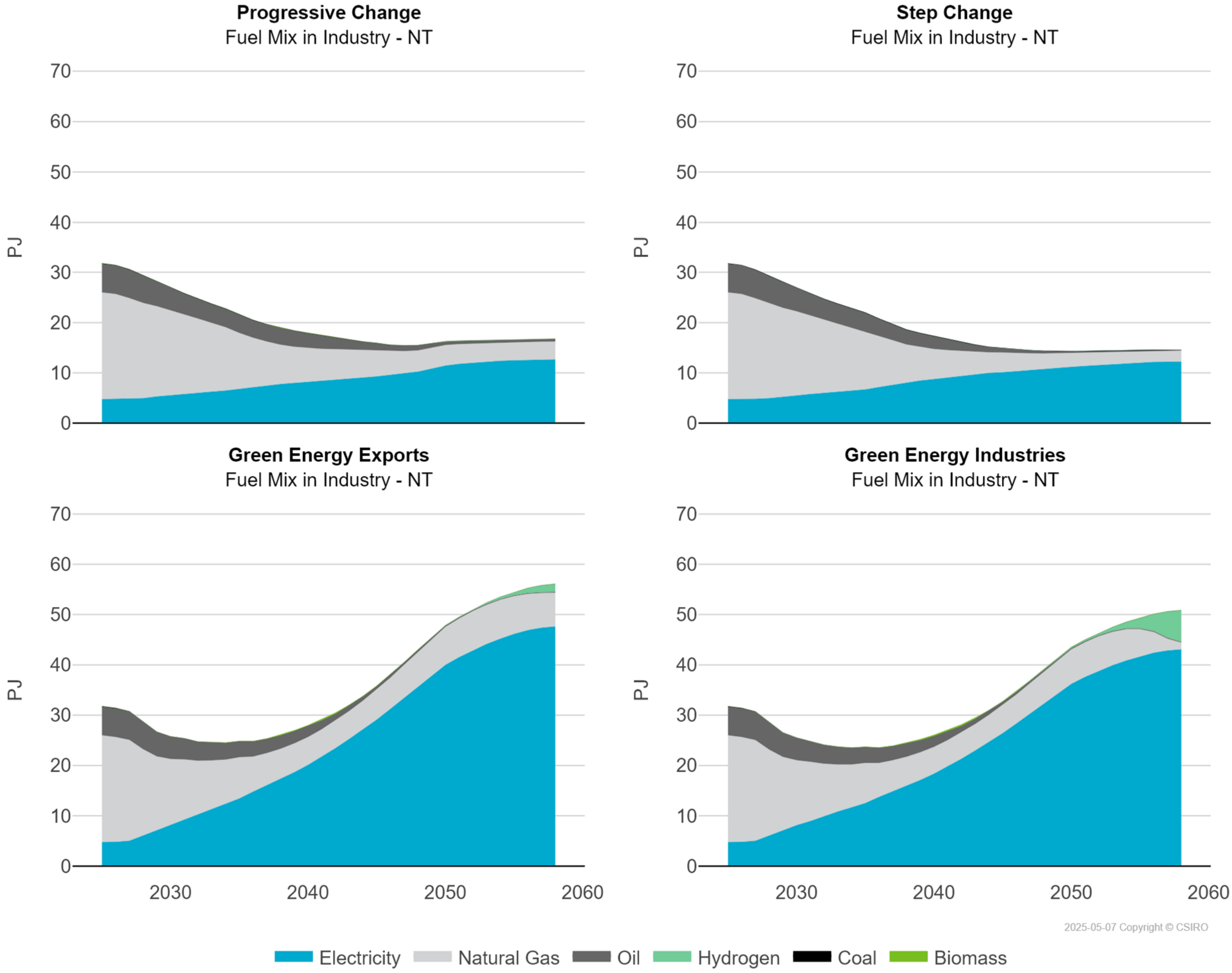


Figure 4-46 Fuel mix in industry in the Northern Territory

4.7.3 Fuel consumption, switching, and technology choice in large industry

For six of the large industrial sub-sectors (alumina, aluminium, cement, and iron and steel), the modelling examined the fuel switching and electrification resulting from changing technology choices due to emissions constraints. Here these switching results are detailed.

Alumina

As shown in Figure 4-47, alumina output is almost constant at near 21 Mt per year. However, Figure 4-48 shows that emissions from that sub-sector drop by about half, mostly due to the switch from the traditional calcination process to electric. In Progressive and Step Change, the calcination process relies on coal through till the early 2040s and then switches to electric, whereas in the Green Energy scenarios, there is an intermediate switch from coal to natural gas for heat in traditional calcination starting in 2027 and fully displacing coal in the early 2030s. This intermediate switch to natural gas is also responsible for the drop in emissions seen through until the early 2030s from the calcination process. The natural gas is again displaced by electric calcination by the mid-2040s. In terms of the fuel switching shown in Figure 4-41, in addition to the switching to natural gas for calcination, open-pit bauxite mining similarly shows a switch from coal to natural gas over the 2027 through early 2030s, whereas the Progressive and Step Change scenarios have that switch delayed till the late 2040s. For the low temperature Bayer component of Alumina production, there is a switch from coal to natural gas in the late 2040s in Progressive Change, while in Step Change the switch is to hydrogen in the early 2050s, and for the Green Energy scenarios, the switch from coal to natural gas starts in 2027, which subsequently begins to be displaced by hydrogen in the early 2040s, and uptake of electric boilers (replacing gas) starting in 2027. The Green Energy scenarios also show a later switch from natural gas to hydrogen in the mid-2040s for low-temperature Bayer, dry beneficiation, and open-pit mining.

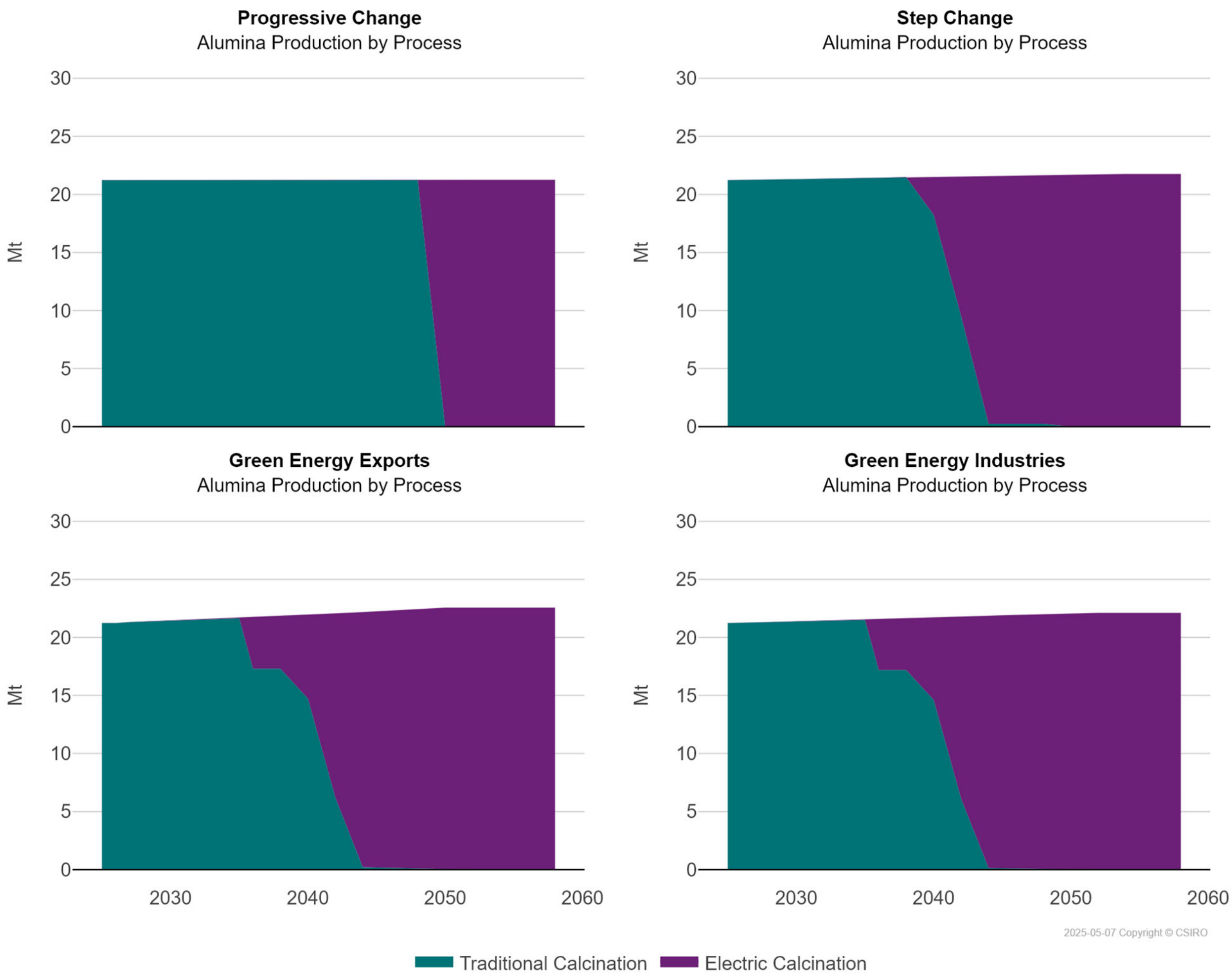


Figure 4-47 Alumina production by process

Figure 4-48 Alumina emissions by process

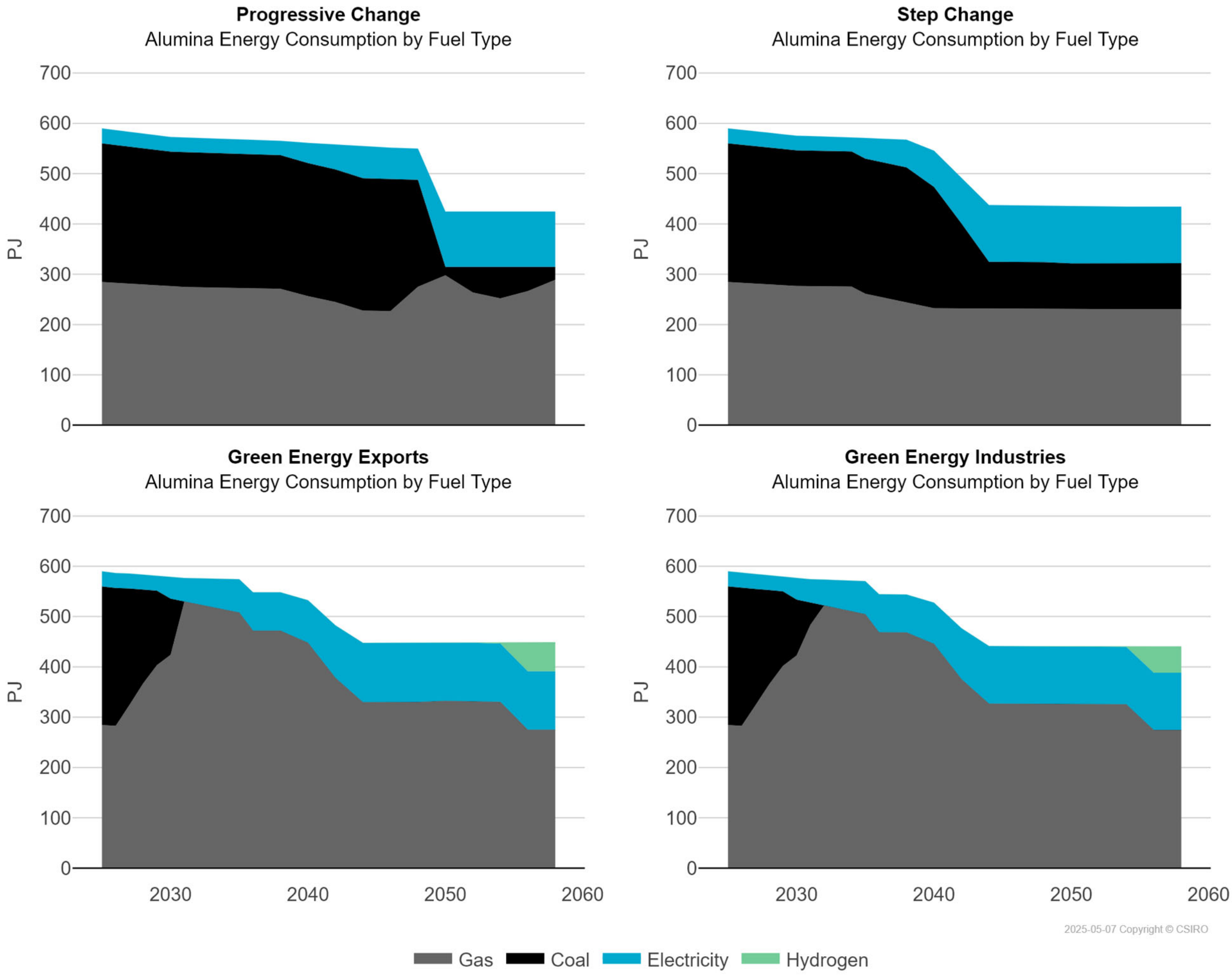


Figure 4-49 Alumina energy consumption by fuel type

Aluminium

The aluminium production varies weakly by scenario, with the Green Energy scenarios increasing to more than 2 Mt of aluminium per year (up from 1.5 Mt), whereas in Progressive Change that production is closer to flat and Step Change only increasing to near 1.8 Mt. Of that production, the Green Energy scenarios show uptake of inert anodes from 2027 reaching more than 80% of production by 2040, and CCS for the Hall-Heroult (with prebaked anode) process for the remaining production. The CCS captures about equal parts combustion and process emissions and reaches approximately 0.2 $MtCO_2$-e per year. As shown by Figure 4-51, this results in near an 80% reduction in emissions. Figure 4-52 shows the energy consumed by aluminium production by fuel type, and of the between 85 and 115 PJ per year, all but 6 PJ of that is electricity in the Hall-Heroult process. Of the remaining consumption, about 2 PJ is calcination, which starts out using coal, and is replaced by switching to natural gas by 2030 in the Green Energy scenarios, and significant switching in Progressive and Step Change at or after 2050. The Green Energy scenarios see up to 0.4 PJ of hydrogen for heat in calcination and prebaked anode production. Prebaked anode production (close to 1 PJ per year) also switches from coal to natural gas in the Green Energy scenarios.

Figure 4-50 Aluminium production by process

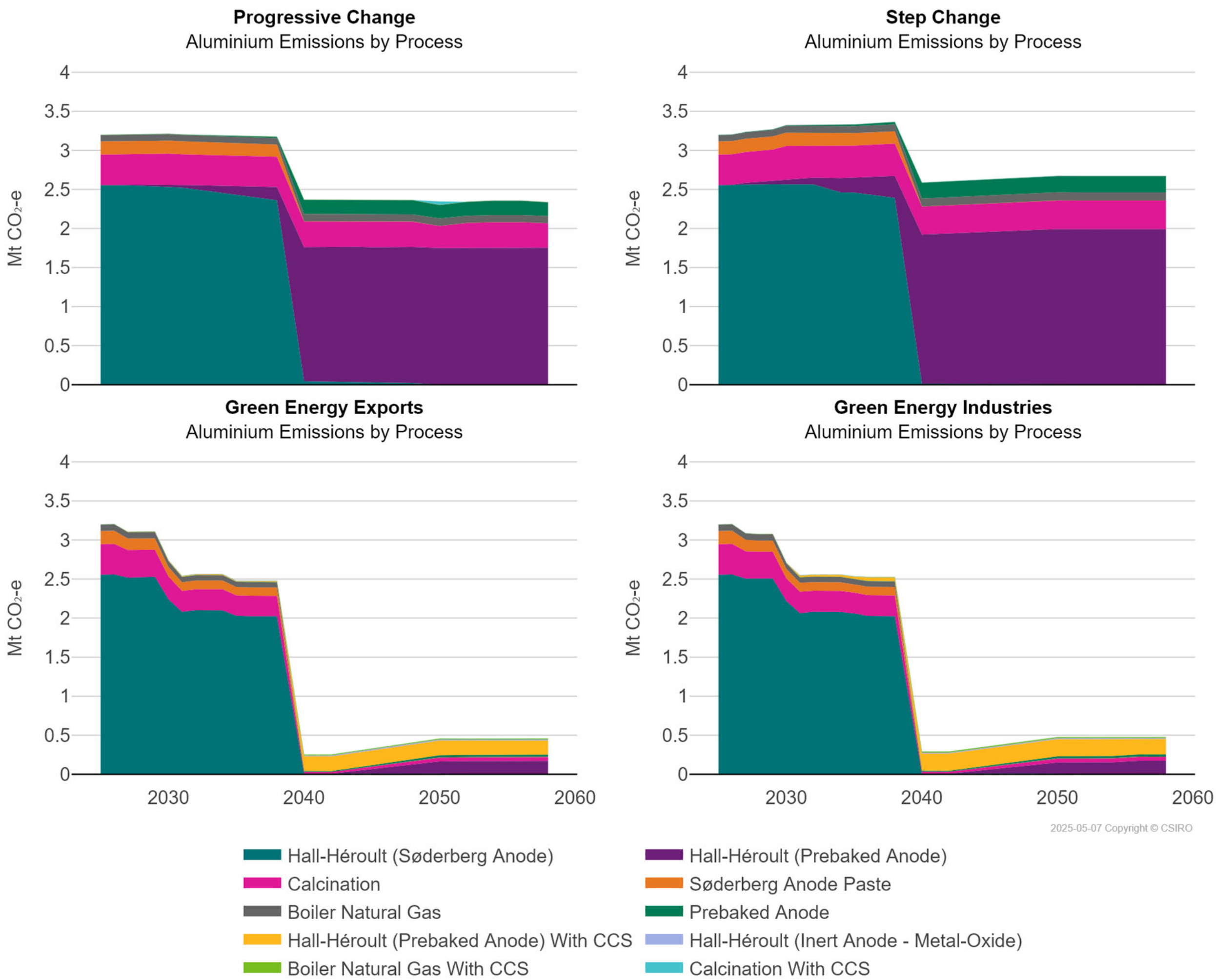


Figure 4-51 Aluminium emissions by process

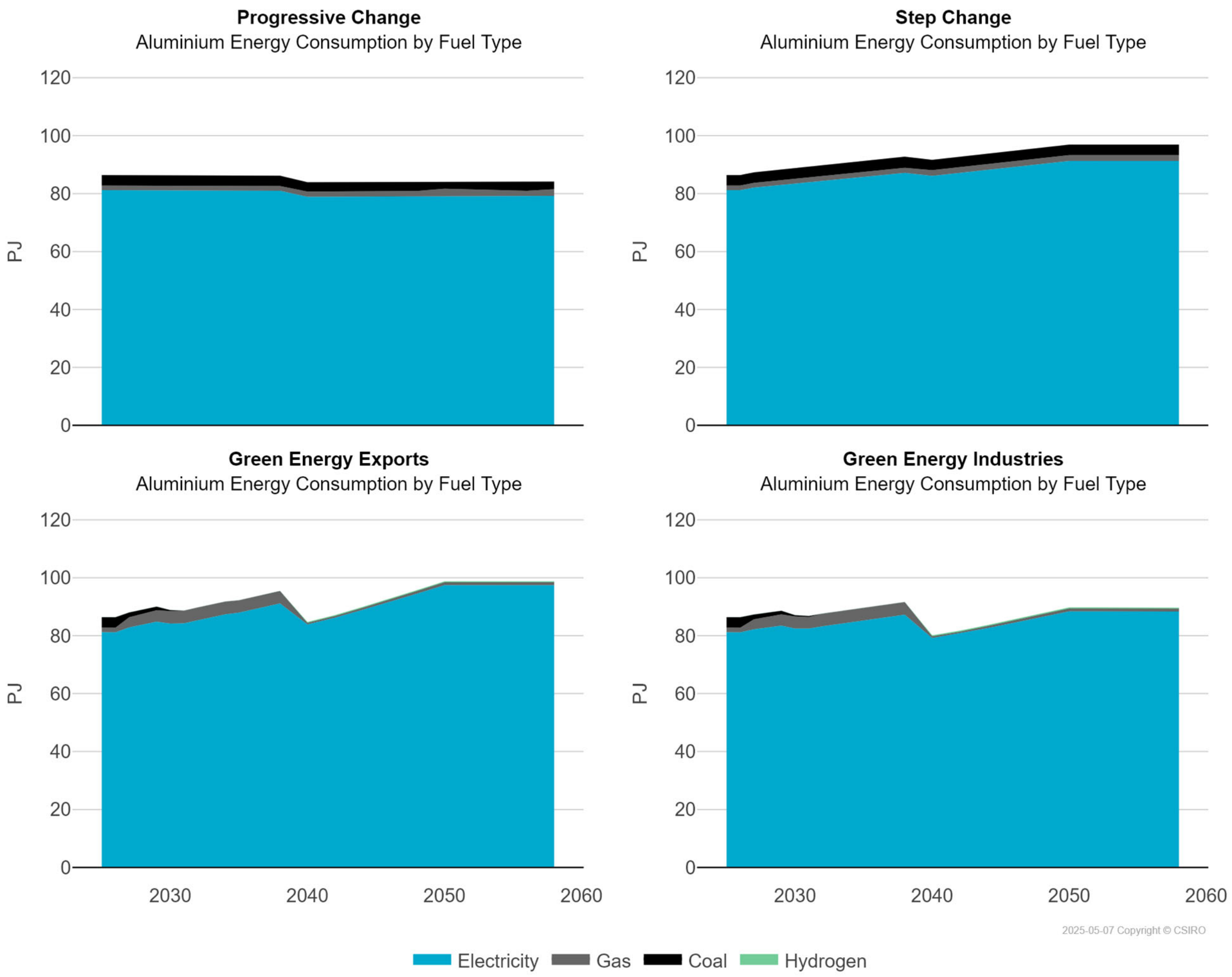


Figure 4-52 Aluminium energy consumption by fuel type

Cement

Emissions reductions in cement are mostly on the energy side, i.e., by changing the fuels burnt to provide heat, or by capturing emissions once produced. The pre-calcination and dry kiln stages show switches from coal to natural gas starting in 2027 in the Green Energy scenarios, and near 2050 in Progressive Change. A small uptake of hydrogen to further displace coal and reduce emissions in all scenarios starts in 2027, and then more significant uptake of hydrogen in the Green Energy scenarios in the mid-2050s. For those Green Energy scenarios, an alternative fuel (biomass) kiln option is selected starting 2035 but is limited at less than 10% in fuel terms. There is also uptake of CCS on pre-calcination and dry kiln stages post 2040 amounting to capturing near 5% of emissions. Combining these, the high-level view of emissions reductions is that fuel switching results in approximately a 10% reduction in the emissions intensity, and then post 2040, the addition of CCS increases that to around a 15% reduction in the overall emissions intensity. While Figure 4-54 shows between 50 and 60% reduction in emissions for cement production over the 2025 through the mid-2050s period, much of that is driven by the reduced demand for cement (as indicated by the between 15 and 30% reduction in overall production in Figure 4-53). In the Green Energy scenarios, a sharp uptake of hydrogen to displace gas for heat drives emissions further lower.

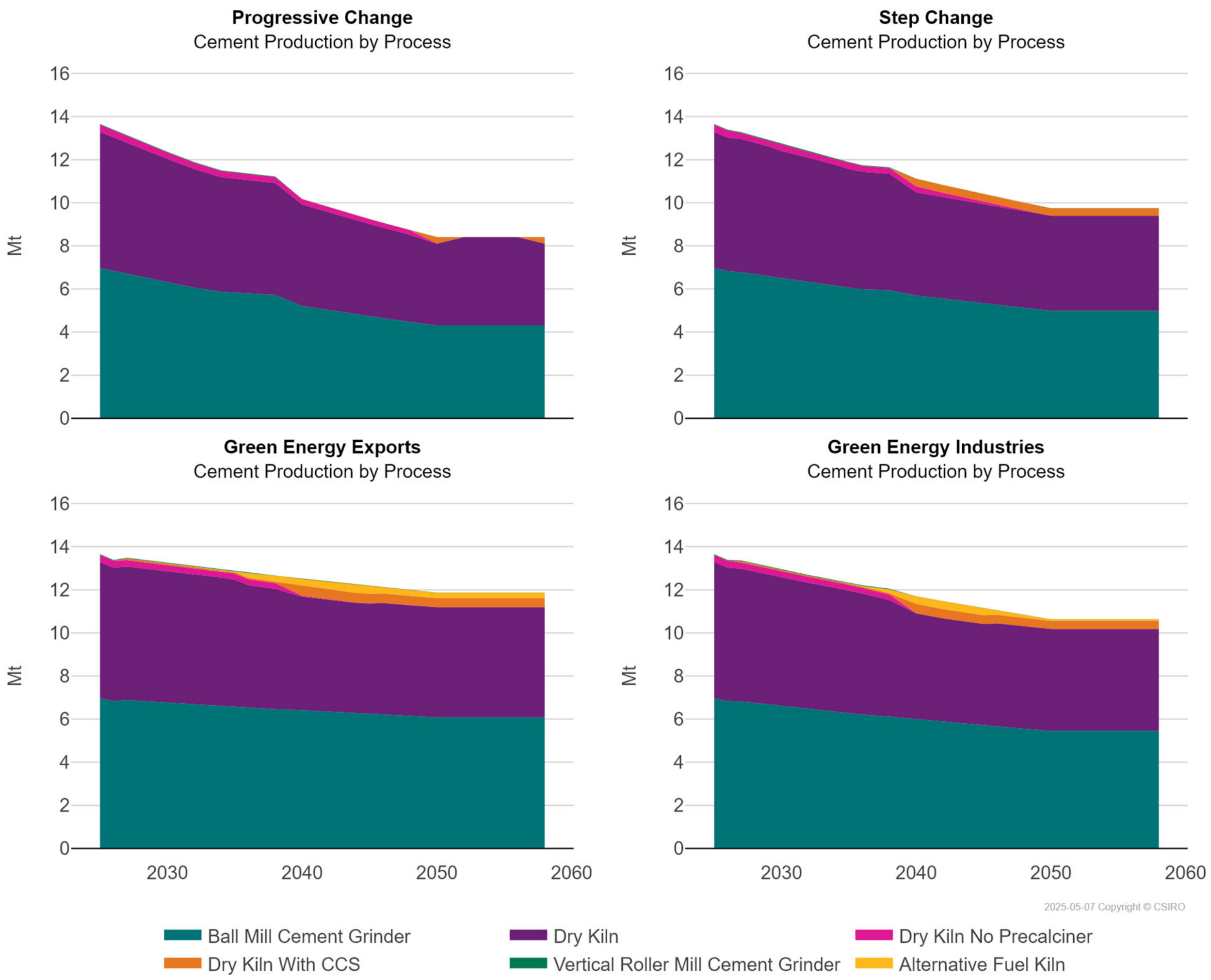


Figure 4-53 Cement production by process

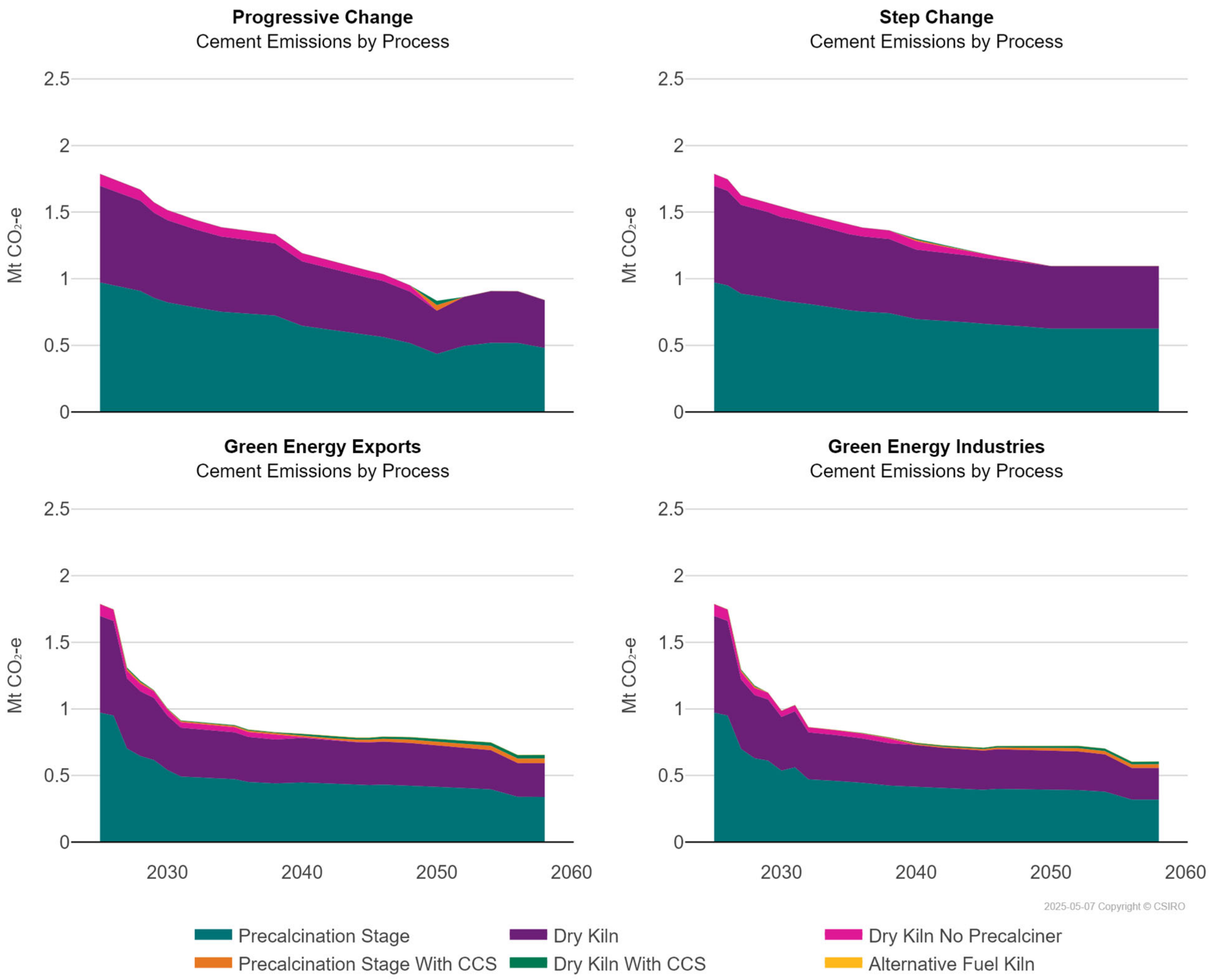


Figure 4-54 Cement emissions by process

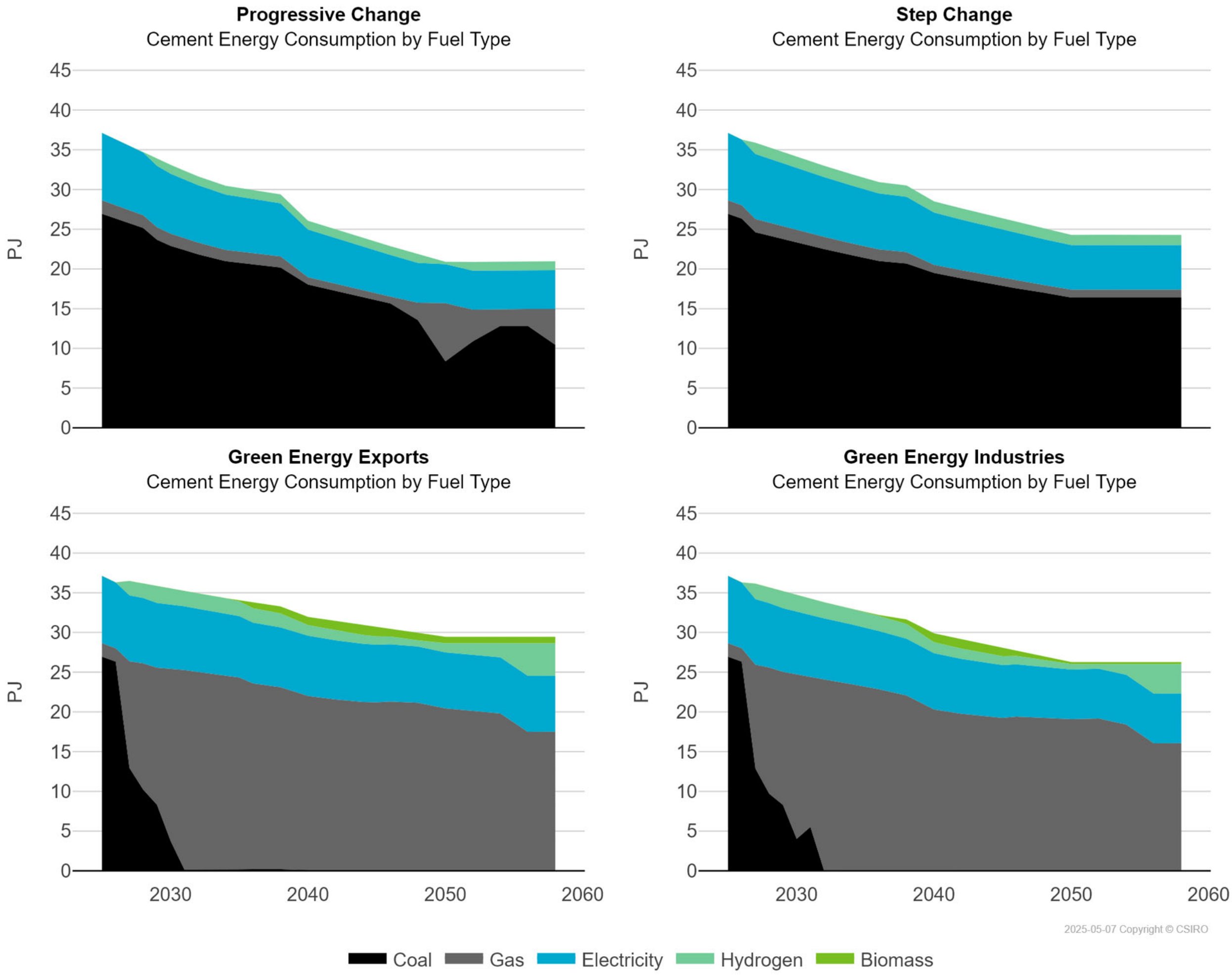


Figure 4-55 Cement energy consumption by fuel type

Iron and Steel

Figure 4-56 shows iron and steel production varying strongly by scenario, with the Green Energy scenarios growing over time to near 120 Mtpa of combined iron (pig and sponge) and steel production in 2060. In the Progressive and Step Change scenarios, the combined output declines slightly over time from the near 10 Mtpa it is today. The sector also produces between 1400 and 1900 Mtpa of crushed iron ore, most of which goes to export.

Two steel production pathways are modelled. Those are the conventional BF-BOF / BF-EAF (Blast Furnace smelting of iron ore to produce pig iron, which is then refined in Basic Oxygen Furnaces or Electric Arc Furnaces to produce steel), and the DRI-EAF pathway (Direct Reduced Iron for reducing iron ore to produce sponge iron – either using hydrogen or natural gas feedstocks – and then refining of the sponge iron in EAFs to produce steel). In the Green Energy scenarios, the switch to the DRI pathway is complete by 2040 and utilises hydrogen as a feedstock. In Step Change the switch to DRI also occurs in 2040, but natural gas is used as the feedstock, and in Progressive Change in 2050 to hydrogen-based DRI.

Figure 4-56 Iron and Steel production by process

Note that the production of crushed iron ore is not shown (although is modelled) to allow the detail of the switch in the steel production pathway to be visible on the scale.

The emissions from the iron and steel sector are shown in Figure 4-57. All scenarios show a sharp drop in emissions when the switch to DRI occurs with Step Change continuing to have significant (albeit far less than those from the BF pathway) emissions from the natural gas based DRI. Pelletization becomes the dominant emissions component of the DRI steel making pathway as is most notable in the Green Energy scenarios where production growth is very high.

In terms of the fuel mix for iron and steel shown in Figure 4-58, the Green Energy scenarios see coal being displaced by natural gas in blast furnaces as early as 2027 and continues through until 2040 when hydrogen-based DRI has displaced the blast furnace pathway. Electricity use increases starting in 2030 due to the DRI process, natural gas increases in pelletization (switching away from coal), and then subsequently to hydrogen in the mid-2050s. For Progressive Change, coal is discontinued as a fuel in 2050, and for Step Change is displaced closer to 2040 by natural gas.

Figure 4-57 Iron and Steel emissions by process

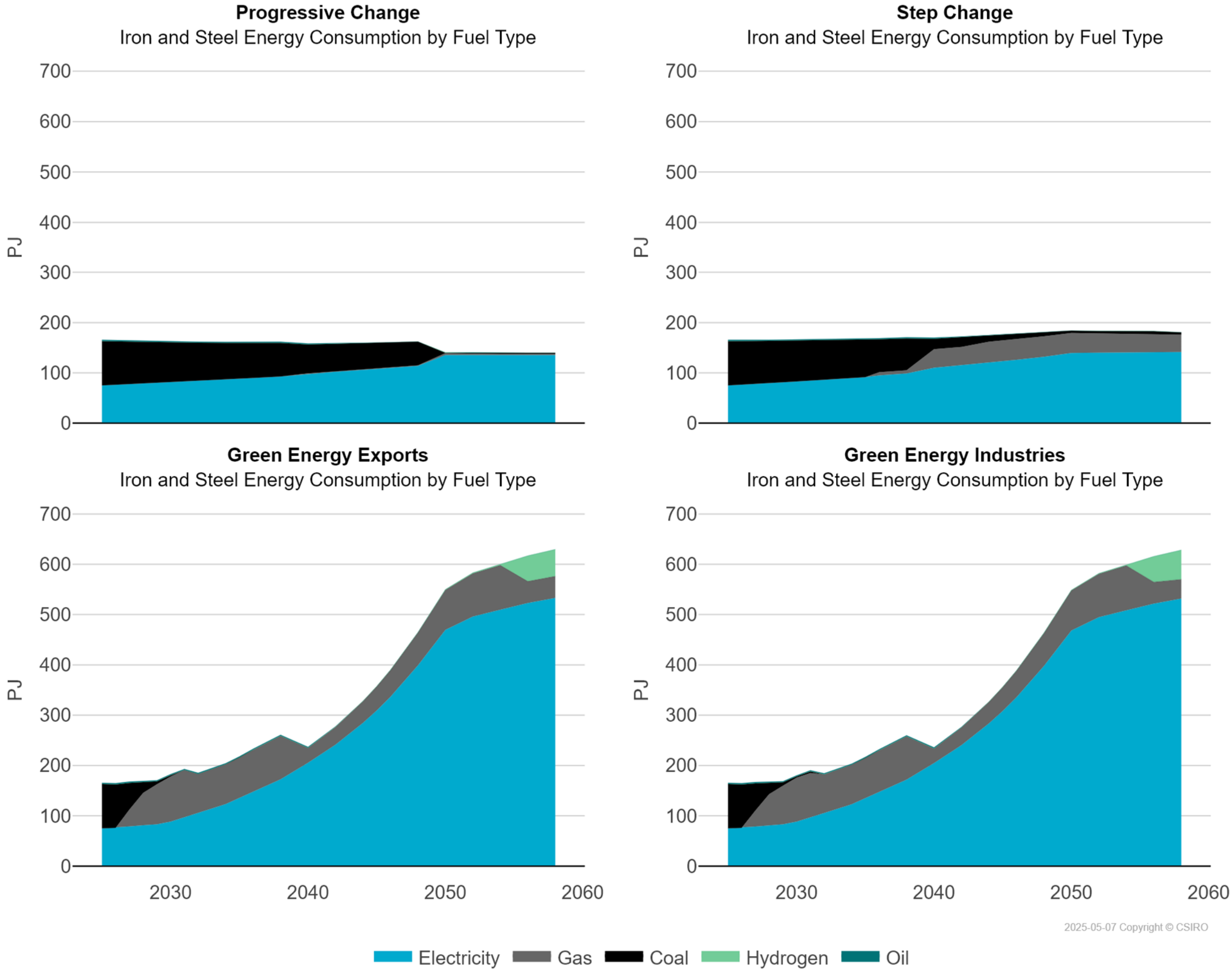


Figure 4-58 Iron and Steel energy consumption by fuel type

4.7.4 Fuel mix in Transport

At the beginning of the projection period, most of the 1400 PJ energy consumption 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 4-59). 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.

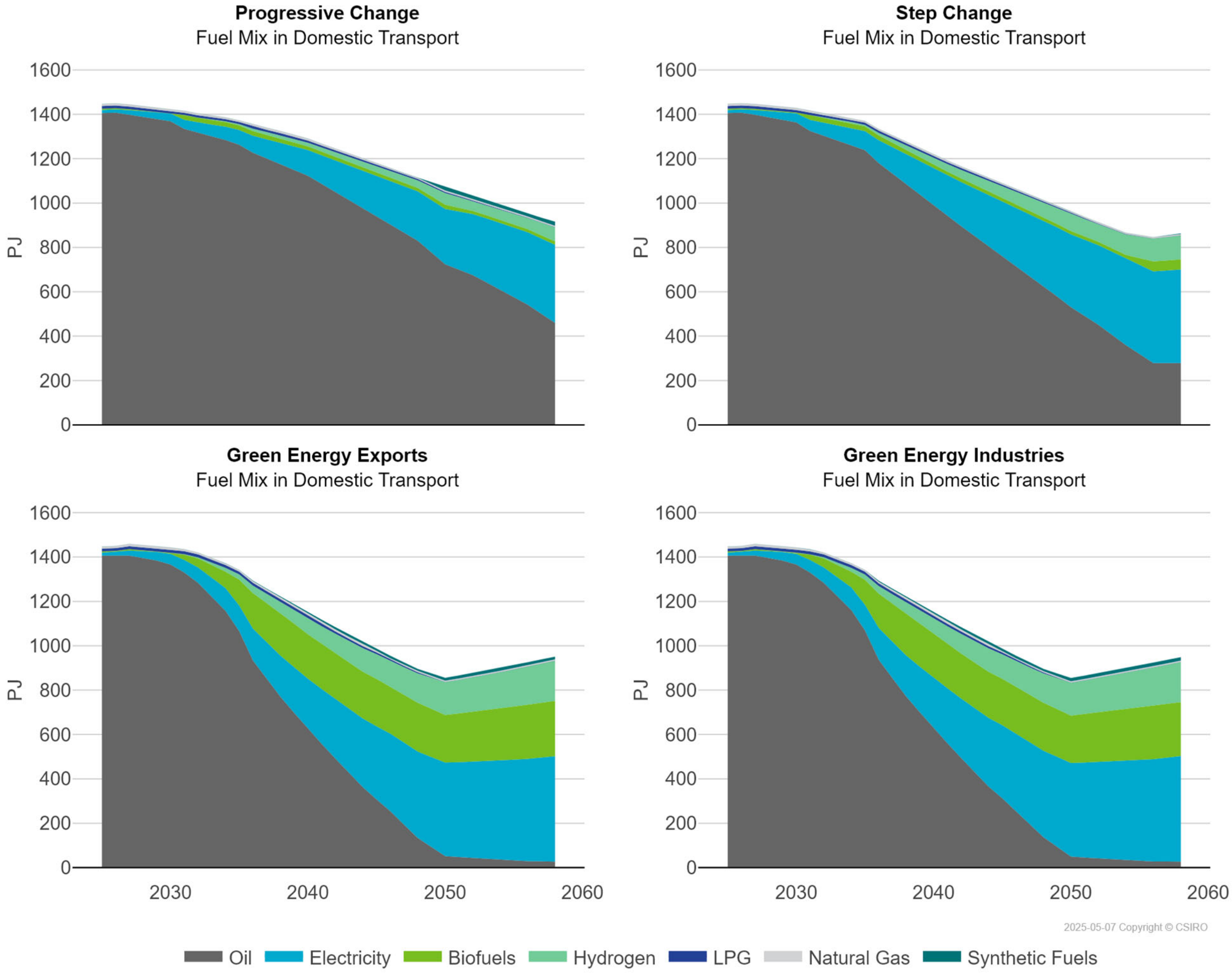


Figure 4-59 Fuel mix in domestic transport nationally

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 Green Energy Exports and Green Energy Industries. Due to more aggressive emissions reduction, there is significant uptake of biodiesel in the mid-2030s, 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. Similar patterns are observed for the NEM (Figure 4-60), Western Australia (Figure 4-61) and the Northern Territory (Figure 4-62).

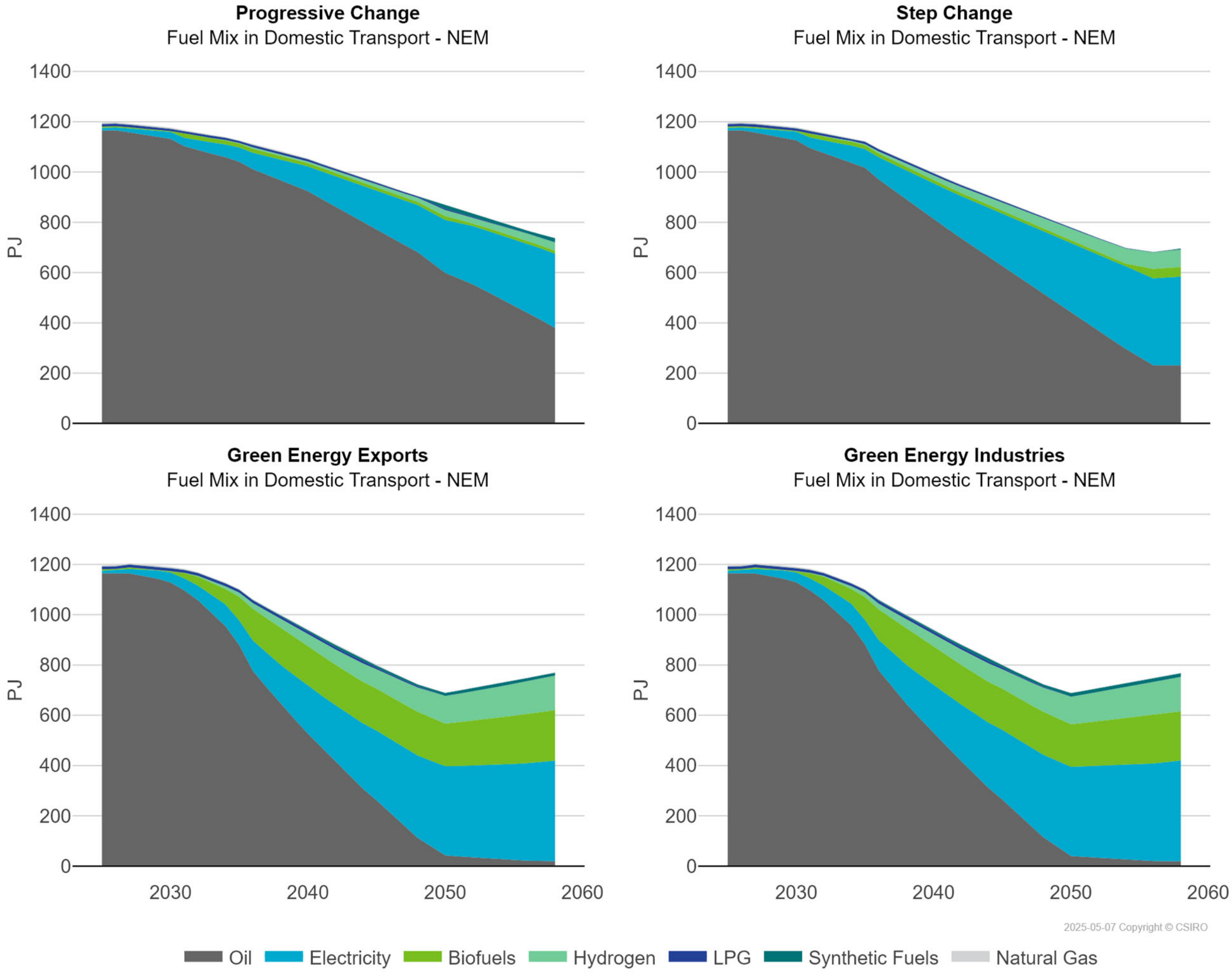


Figure 4-60 Fuel mix in domestic transport in the NEM

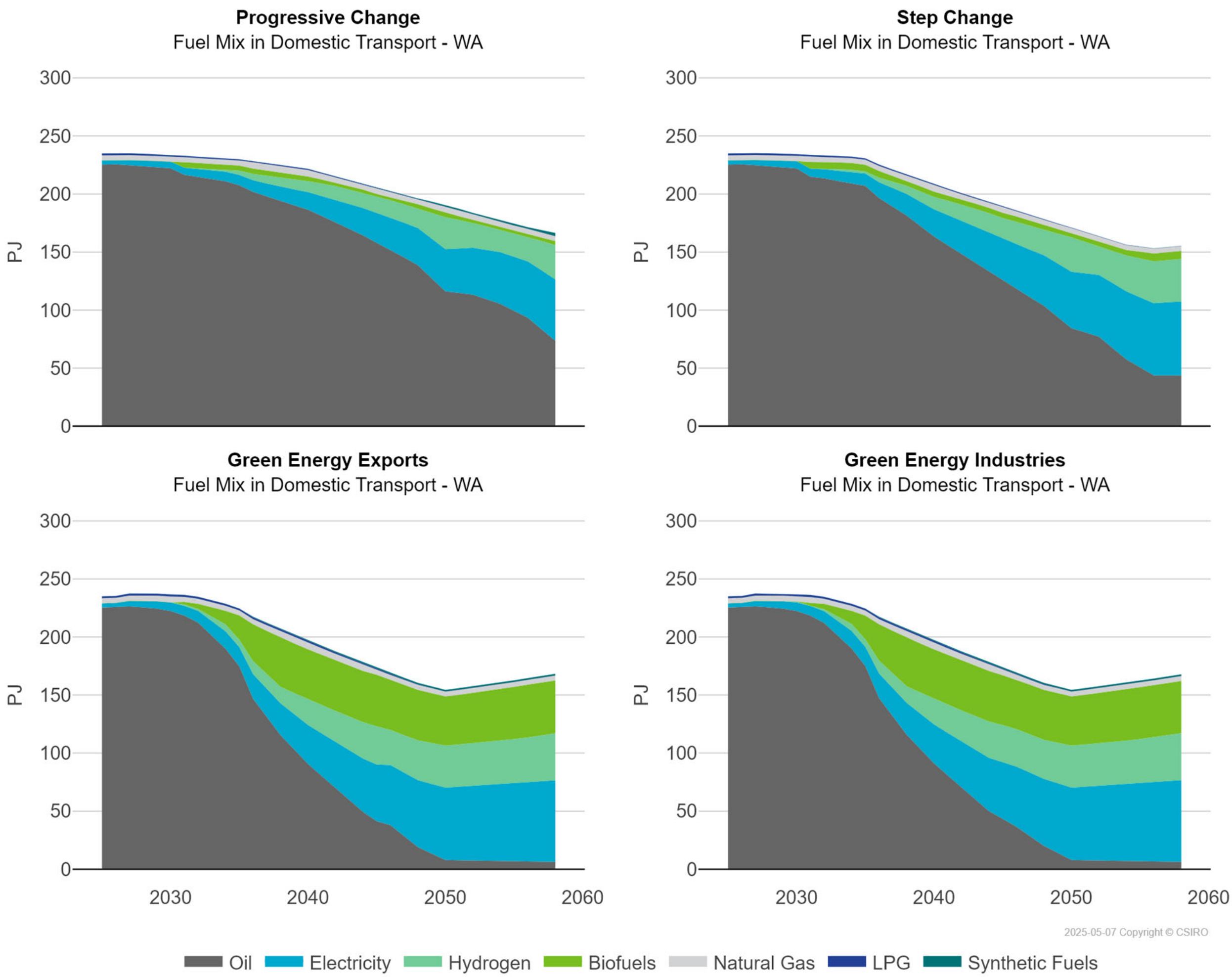


Figure 4-61 Fuel mix in domestic transport in Western Australia

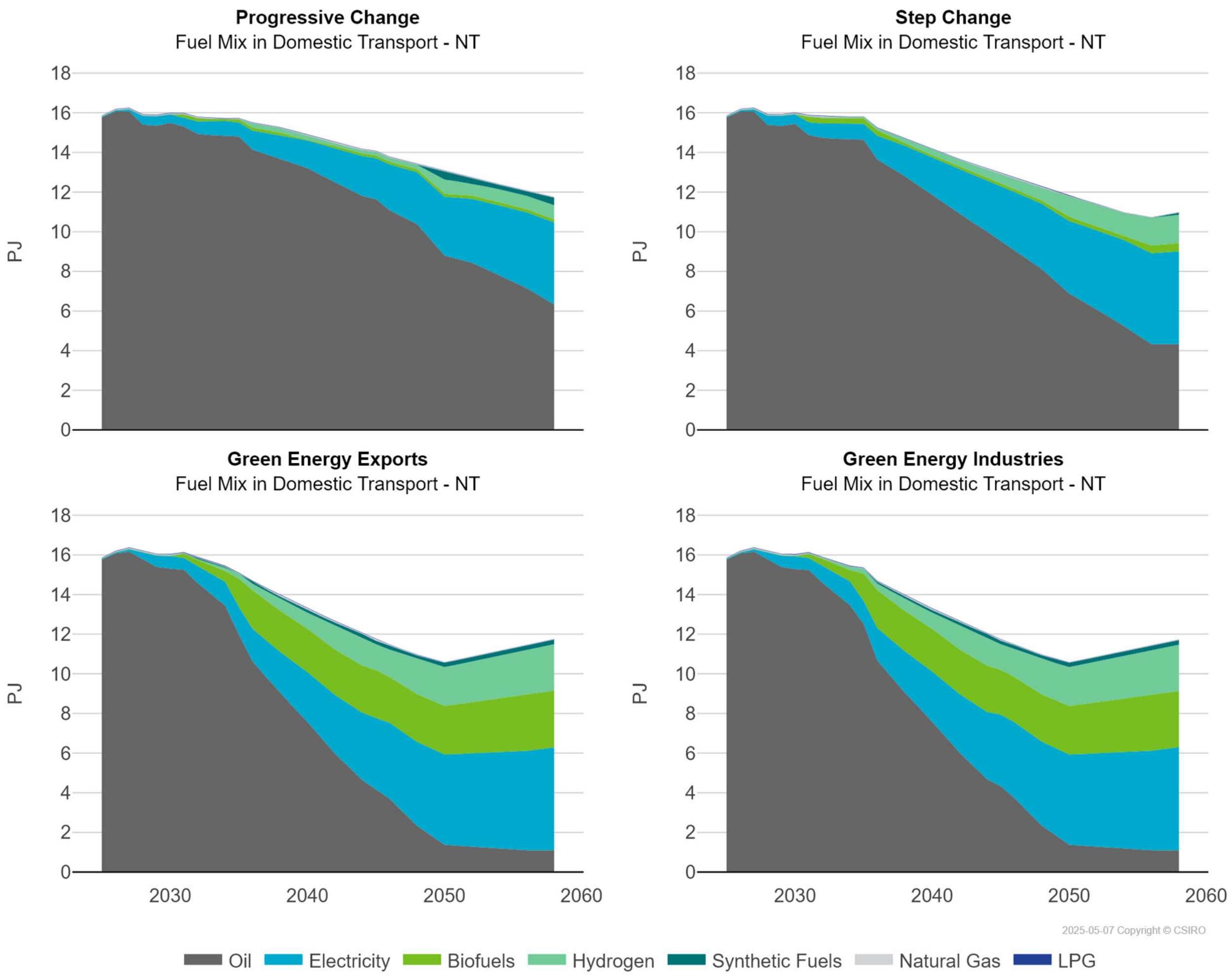


Figure 4-62 Fuel mix in domestic transport in the Northern Territory

Currently, final energy consumption in domestic aviation[15] 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 charts), from late 2030s onwards.

Road transport fuel mix

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 4-63), reflecting the greater efficiency of the electric drivetrain to deliver more kilometres per unit of energy. Informed by adoption modelling (Graham et al., 2025), this acceleration occurs in the mid-2030s as EVs dominate new vehicle sales, especially in

[15] 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.

the Green Energy scenarios. In these scenarios, only zero emission fuels are consumed by the late 2040s, compared to the mid-2050s for Step Change and late 2050s for Progressive Change. Similar patterns are observed for the NEM (Figure 4-64), Western Australia (Figure 4-65) and the Northern Territory (Figure 4-66).

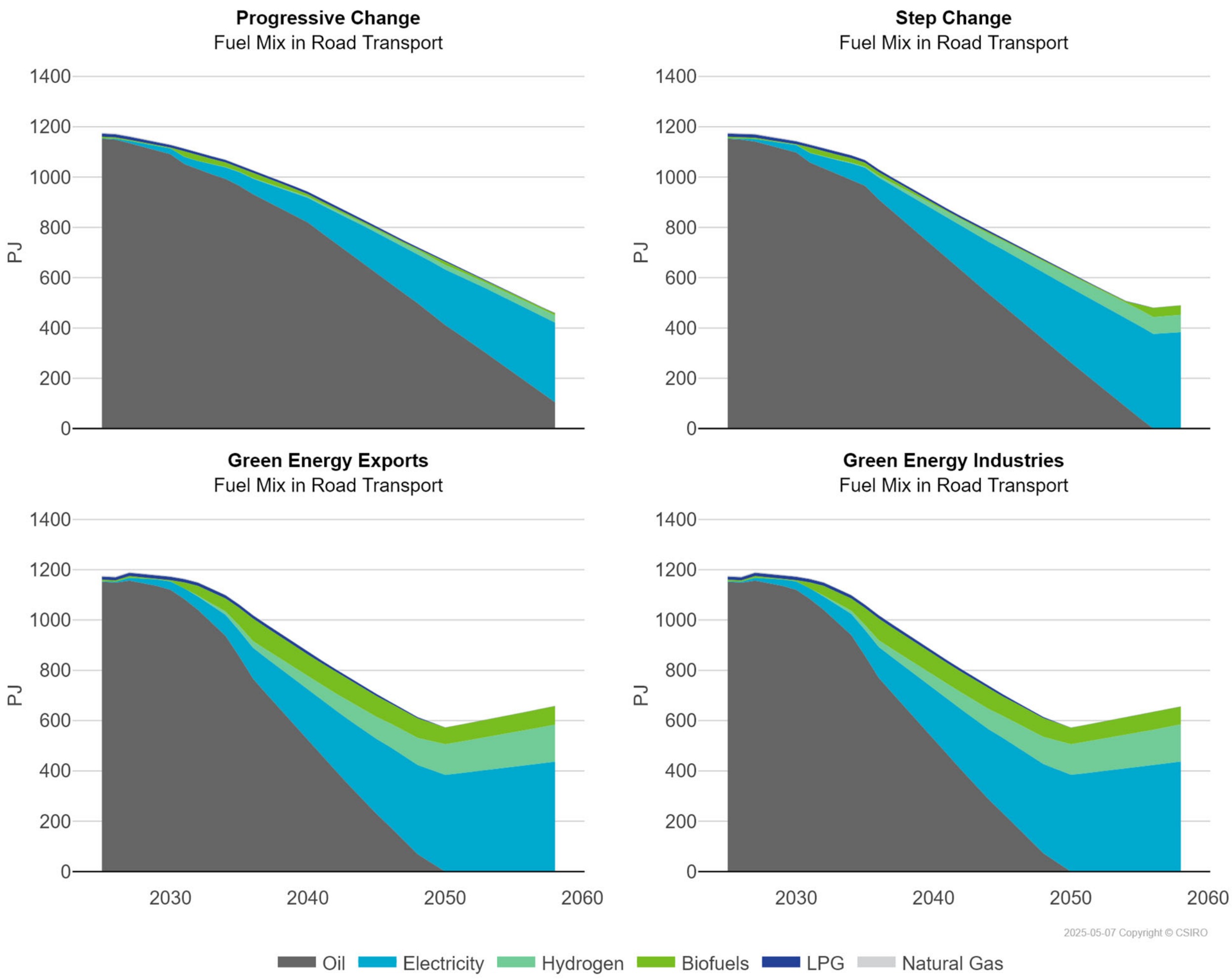


Figure 4-63 Fuel mix in domestic road transport nationally

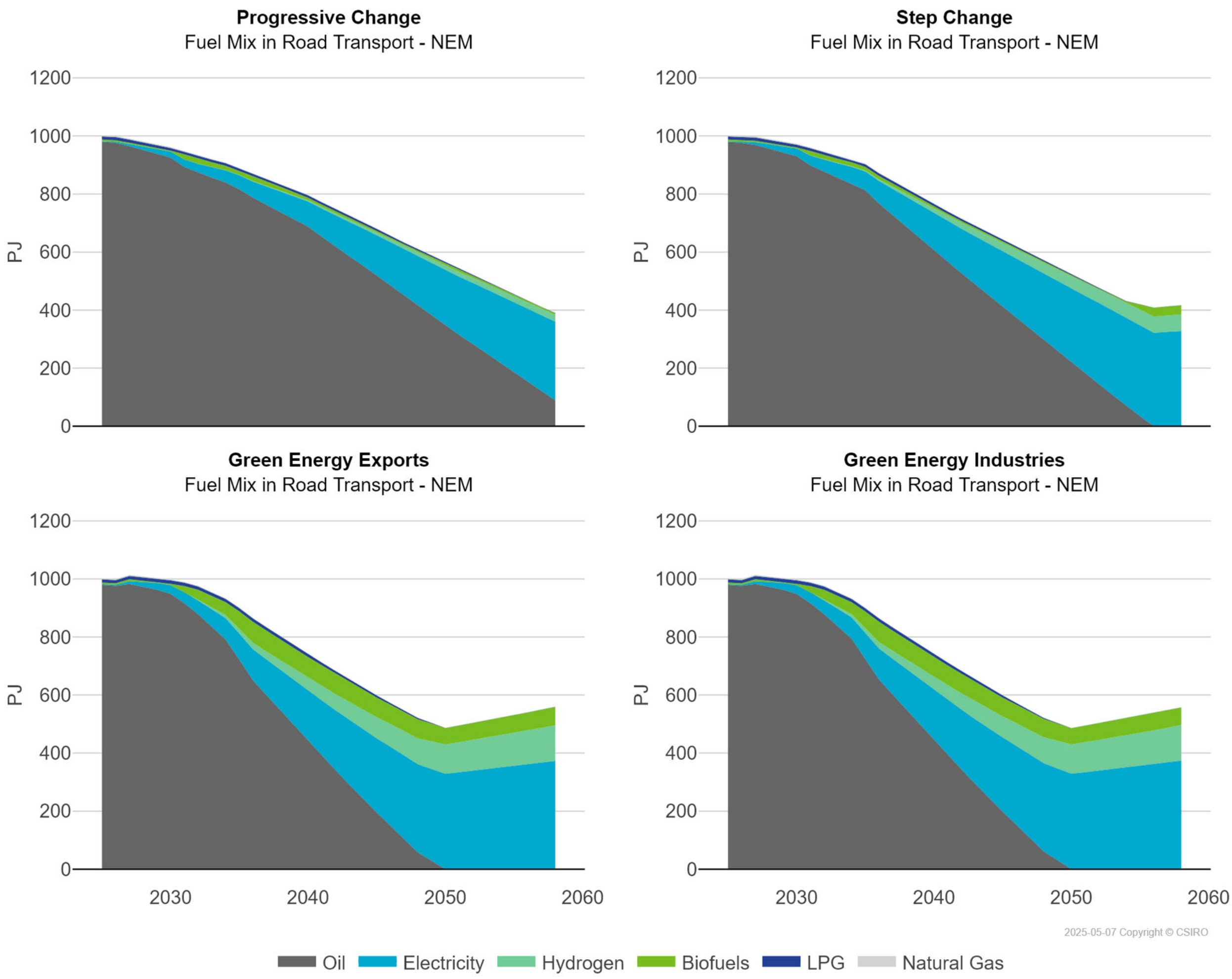


Figure 4-64 Fuel mix in domestic road transport in the NEM

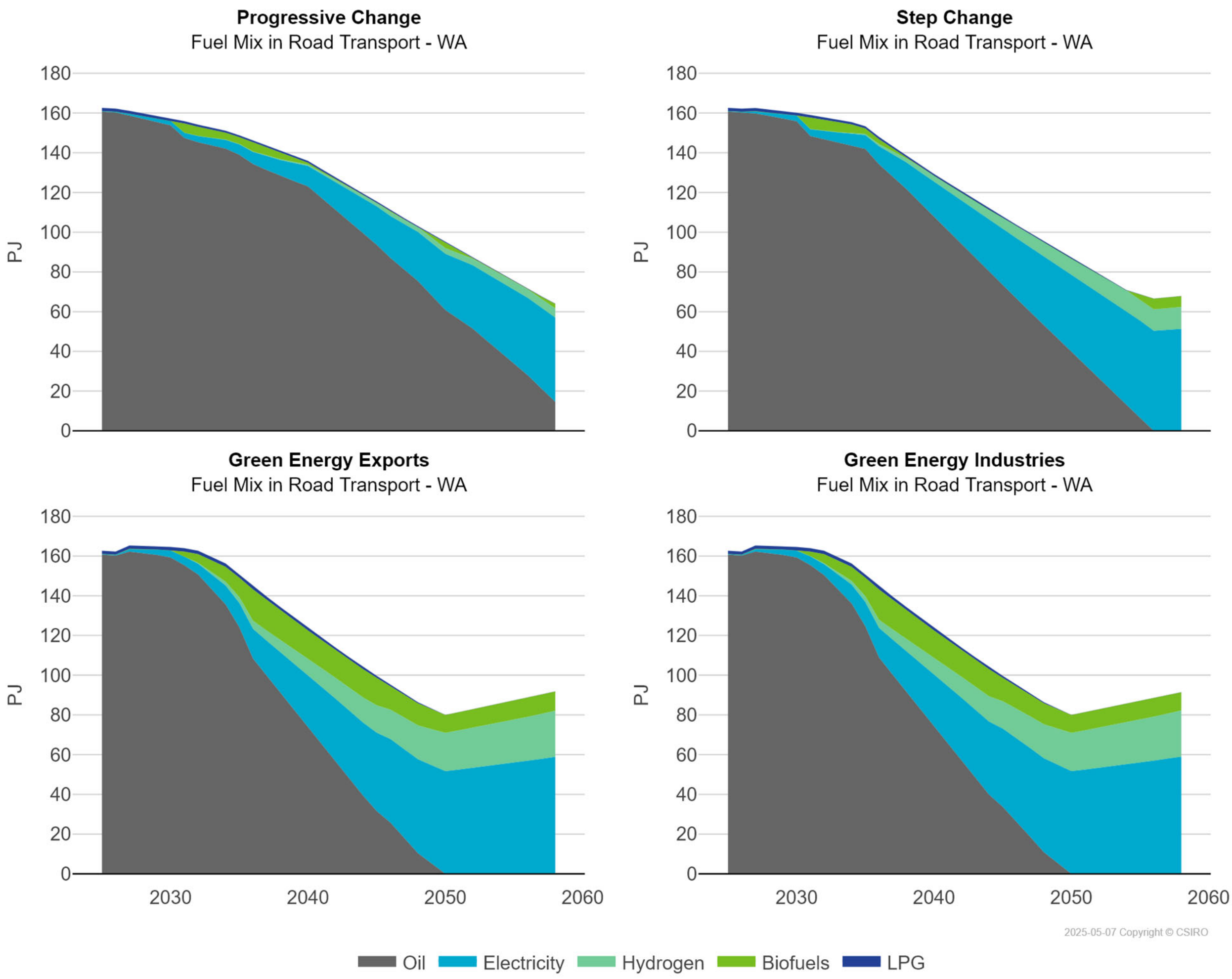


Figure 4-65 Fuel mix in domestic road transport in Western Australia

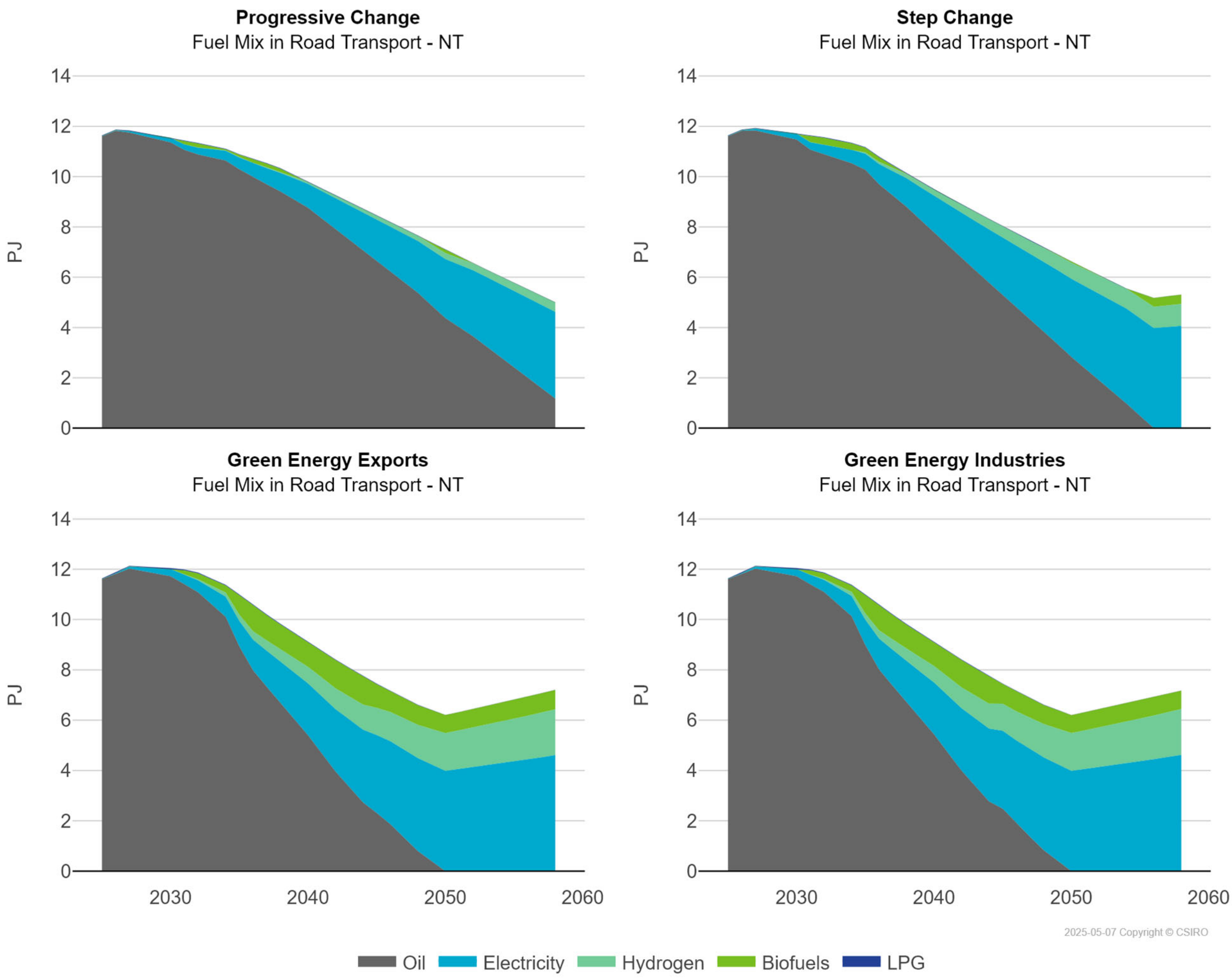


Figure 4-66 Fuel mix in domestic road transport in the Northern Territory

4.7.5 Fuel mix in Residential Buildings

The mix of fuels in the total energy consumption for residential buildings is shown in Figure 4-67 for all regions in Australia under four different scenarios: Progressive Change, Step Change, Green Energy Exports, and Green Energy Industries. These scenarios highlight the evolving role of electricity, wood (biomass), natural gas, biomethane, liquefied petroleum gas (LPG), and hydrogen in meeting residential energy demand from now until 2058. The final energy consumption represents the net energy consumed after considering energy efficiency, electrification, hydrogen and biomethane uptake. The underlying baseline demand is driven by population growth, with the residential fuel mix in 2023 comprising 54% of electricity, 32% of natural gas, 11% of biomass and 3% of LPG.

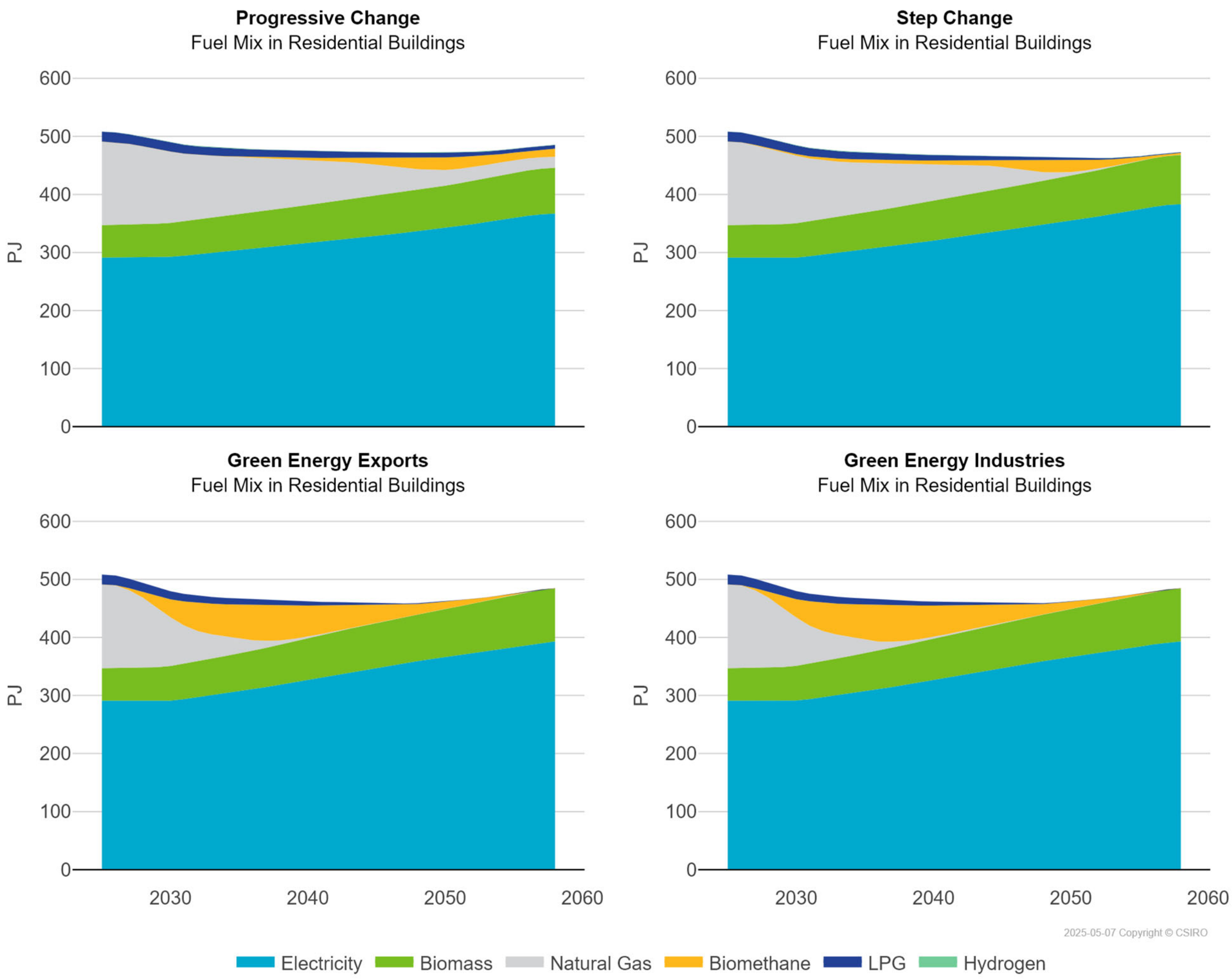


Figure 4-67 Fuel mix in residential buildings nationally

Electricity remains the dominant energy source across all scenarios, steadily increasing from around 54 per cent in 2023 to around 76 per cent of final energy consumption in the Progressive Change scenario, and around 81 per cent in the other three scenarios. This shift is largely driven by the electrification of heating, cooling, and cooking. Biomethane, which is blended into natural gas pipelines, plays a role in all scenarios except Progressive Change, featuring significant uptake in the Green Energy scenarios to assist in decarbonisation, and delayed uptake in Step Change.

Natural gas and LPG consumption decline steadily across all scenarios, except in Progressive Change, where a small amount of natural gas use persists into the 2050s. In 2025, residential natural gas consumption is 145 PJ, but in Step Change, Green Energy Exports, and Green Energy Industries, it reaches zero by the 2050s, reflecting the substitution of biomethane as a decarbonisation alternative. In contrast, the Progressive Change scenario features 19 PJ of natural gas use in 2058. Biomethane blending into natural gas pipelines begins in 2027, with rapid uptake in the Green Energy scenarios until the 2040s. However, its use declines beyond this point as electricity consumption increases and energy efficiency measures take effect. In contrast, biomethane use remains minimal in the Progressive Change and Step Change scenarios due to a stronger shift towards electrification and energy efficiency.

In contrast to biomethane, hydrogen blending into pipelines is limited to 10 per cent by volume as part of the scenario settings (see Appendix B.10.4). However, its uptake in residential energy use remains negligible, particularly in the Progressive Change and Step Change scenarios, while in the Green Energy scenarios, biomethane is preferred.

As noted in the 2022 Multi-Sector Modelling, residential biomass consumption follows projected residential activity levels, as conversion pathways for biomass are not implemented in AusTIMES (Reedman et al., 2022). While wood remains a significant energy source, its efficiency is much lower than electricity, making large-scale fuel switching unlikely to cause a substantial increase in electricity consumption. Furthermore, wood-burning has externalities, such as emissions and air quality impacts, that may influence its continued use. Since biomass is treated as a net-zero emission energy source in the model, further research is required to assess the economic, health, and cultural factors influencing fuel switching from wood and its implications for residential electricity demand.

In residential buildings, electricity remains the primary energy source across all scenarios, driven by national level energy efficiency improvements and increased electrification, in part due to prohibition on new natural gas connections in VIC and ACT. Biomethane plays a minor role, with uptake varying by scenario. Hydrogen has minimal impact on residential energy consumption in Australia. Similar patterns are observed for the NEM (Figure 4-68) and Western Australia (Figure 4-69). However, in the Northern Territory (Figure 4-70), there is no uptake of biomethane and hydrogen throughout the modelling period.

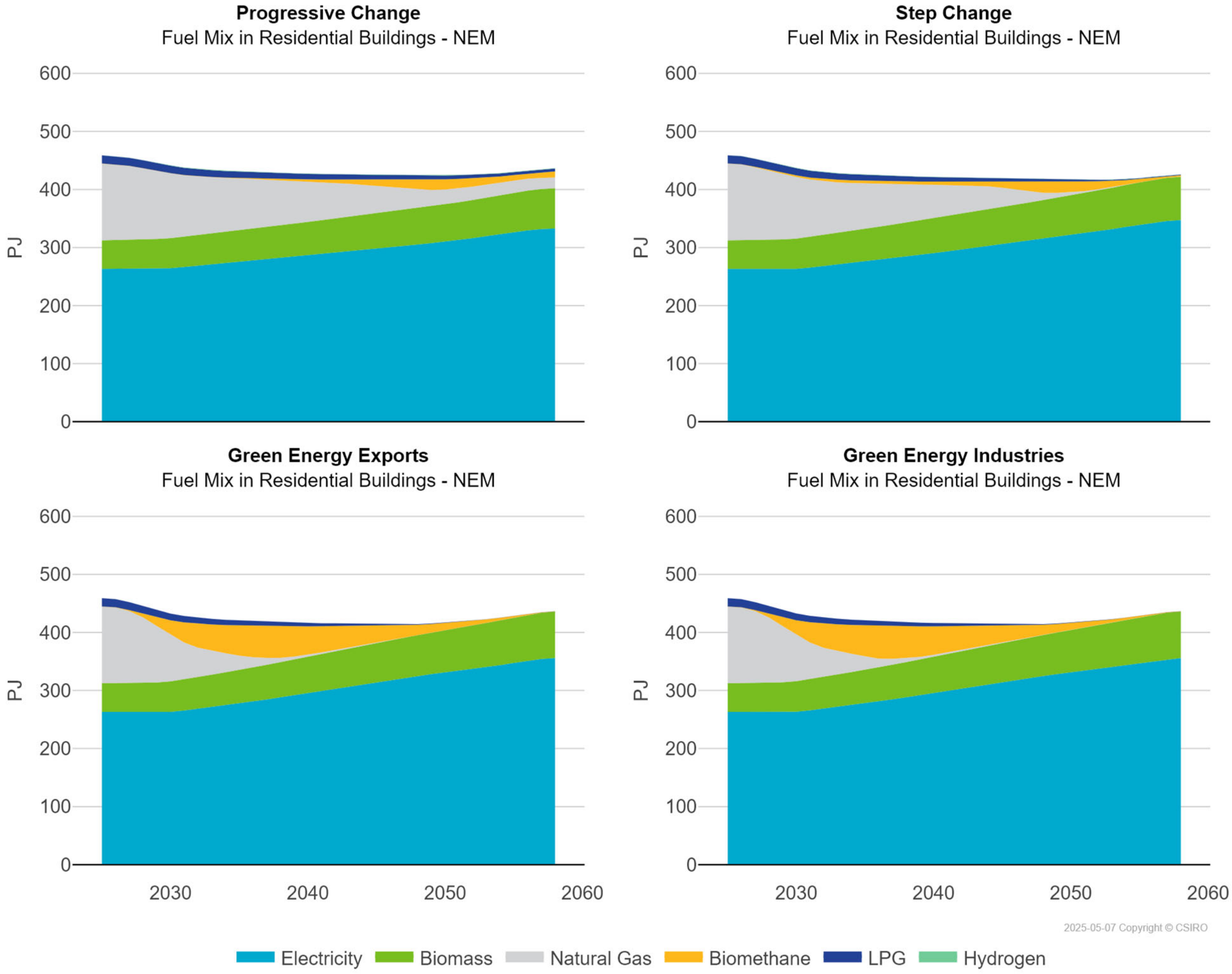


Figure 4-68 Fuel mix in residential buildings in the NEM regions

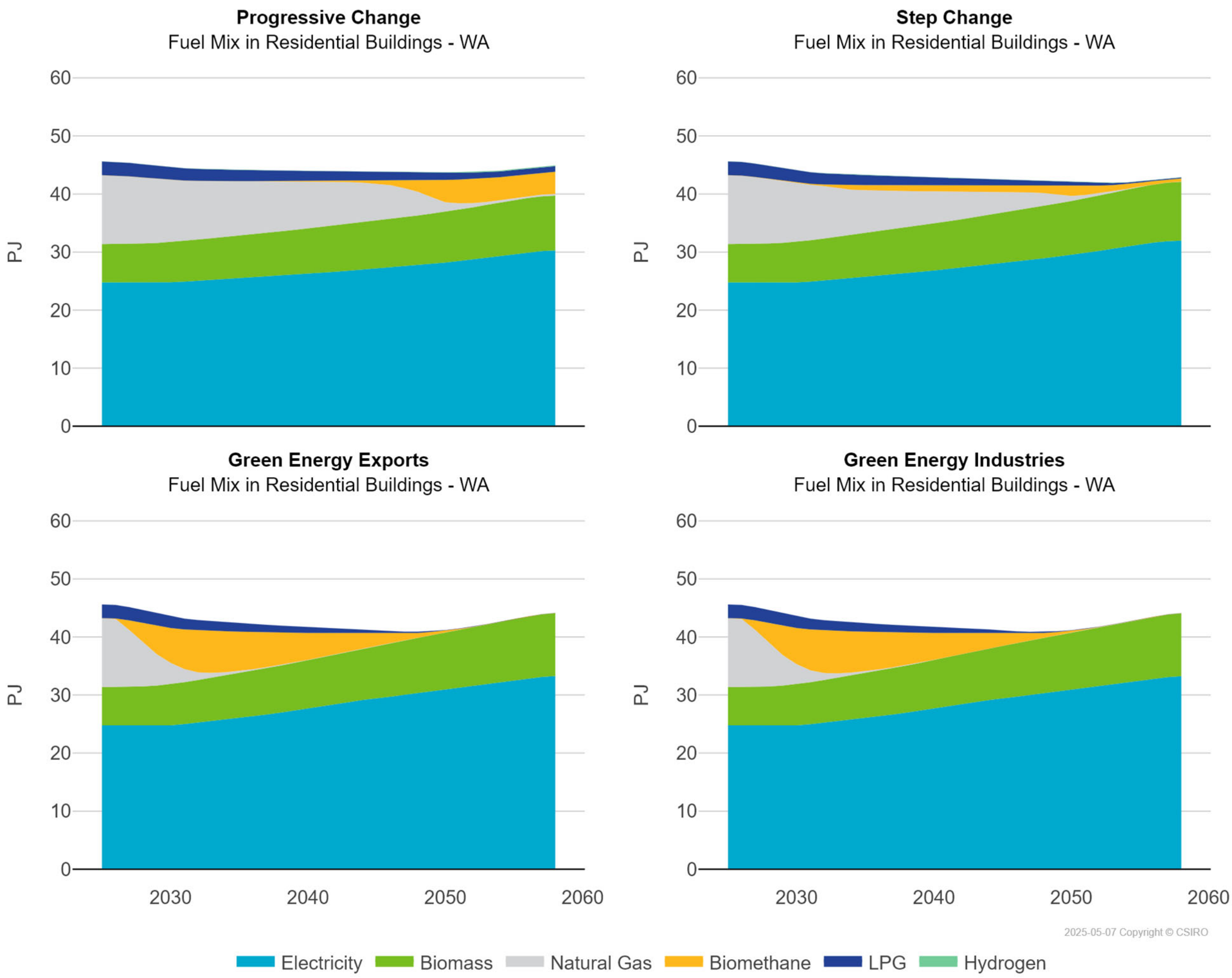


Figure 4-69 Fuel mix in residential buildings in Western Australia

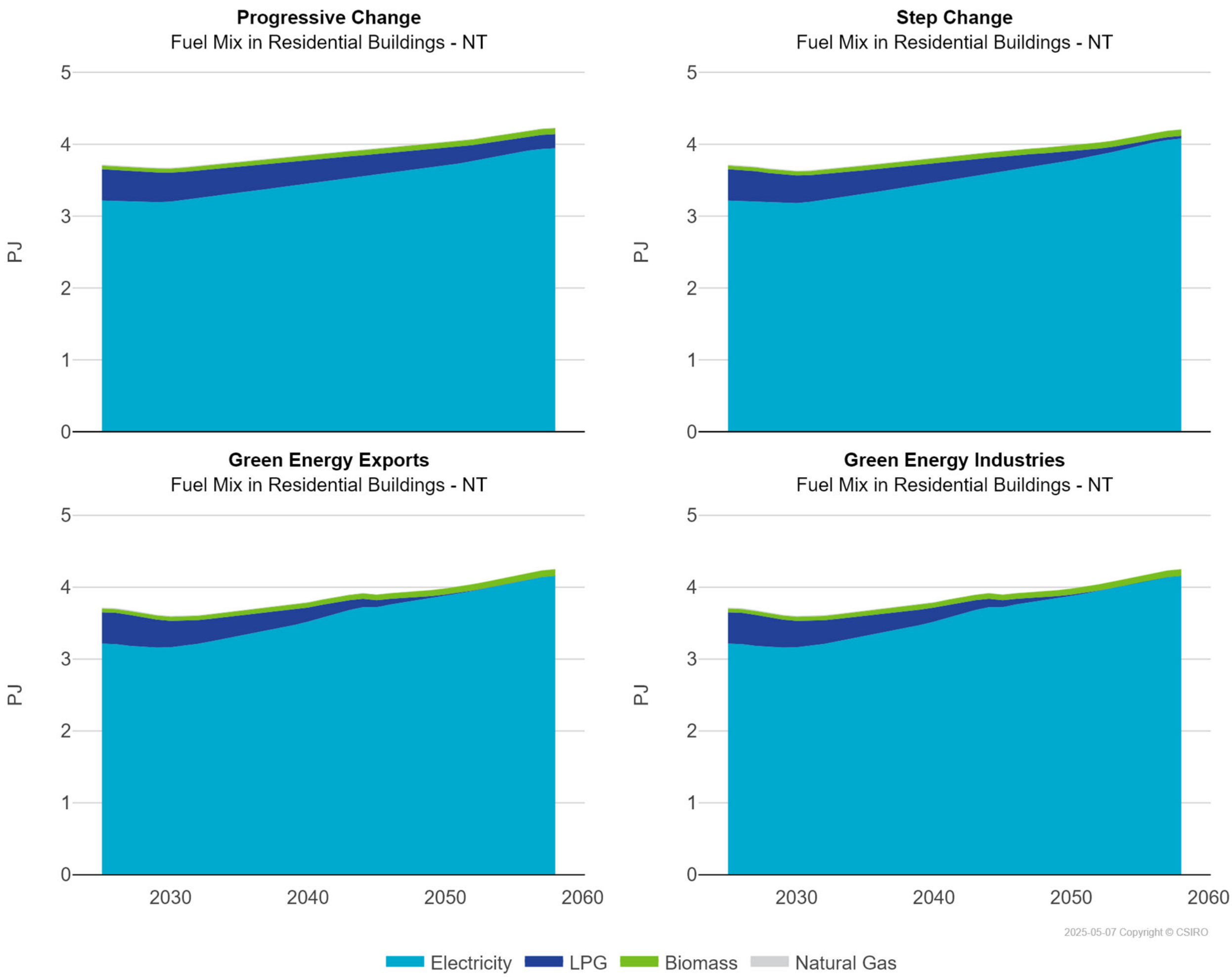


Figure 4-70 Fuel mix in residential buildings in the Northern Territory

4.7.6 Fuel mix in Commercial buildings

The fuel mix in total energy consumption for commercial buildings across all regions in Australia is depicted in Figure 4-71. This total consumption represents the net energy used, accounting for energy efficiency, electrification, and other fuel switching. The charts show the projected fuel mix in commercial buildings under four scenarios: Progressive Change, Step Change, Green Energy Exports, and Green Energy Industries. Each scenario illustrates the evolving contribution of various energy sources, including electricity, oil, natural gas, hydrogen, and biomethane.

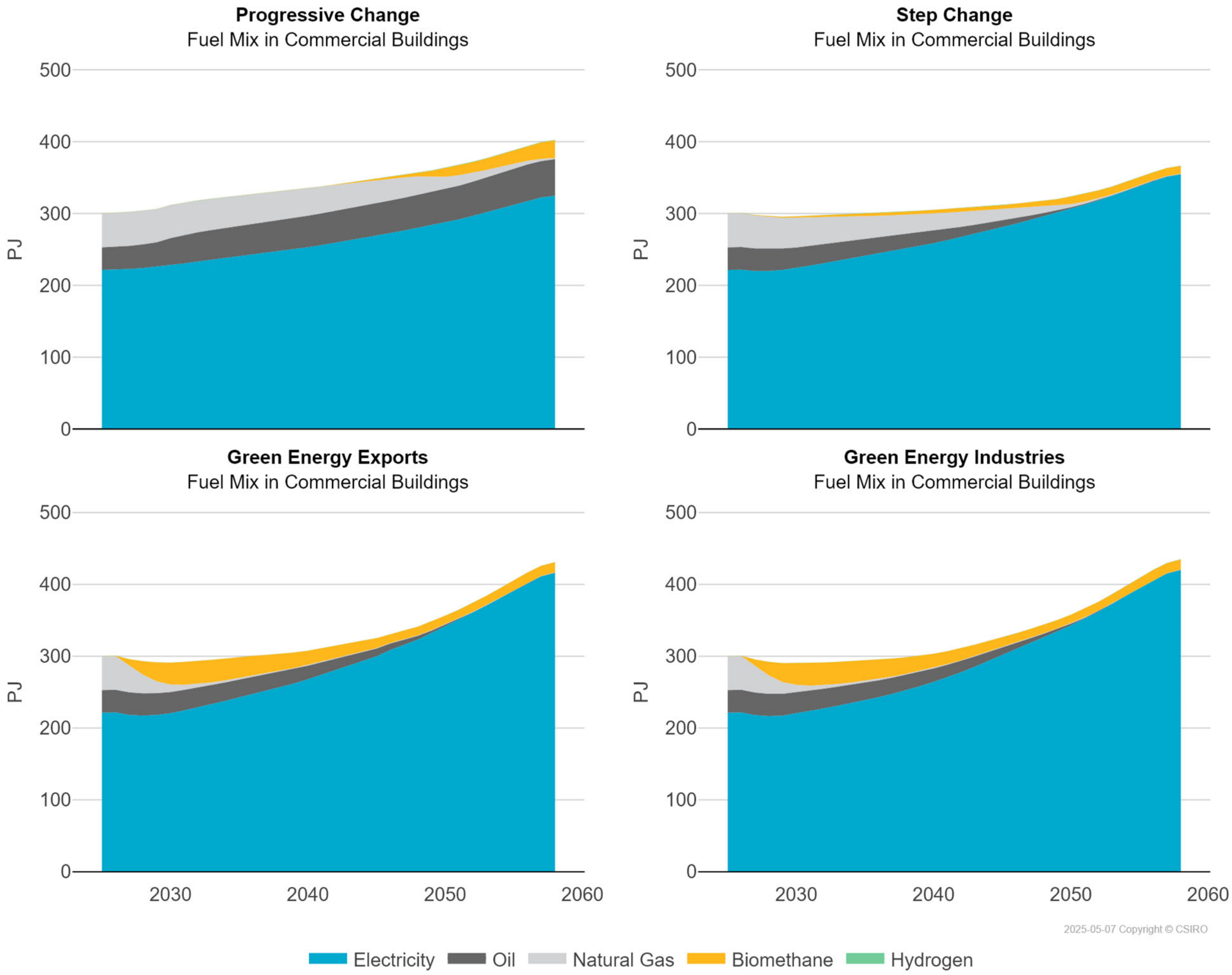


Figure 4-71 Fuel mix in commercial buildings nationally

Electricity remains the dominant energy source, steadily increasing over time in all scenarios. Given that commercial buildings are already largely electrified, the scope for further electrification is limited, with variations in energy efficiency uptake being the primary driver of differences in total energy consumption across the scenarios. By 2058, electricity consumption exceeds 400 PJ in the Progressive Change scenario, 375 PJ in the Step Change scenario and approximately 430 PJ in the Green Energy Exports and Green Energy Industries scenarios, indicating a shift towards further electrification.

Commercial buildings electricity consumption increases across all scenarios, most notably in the Green Energy scenarios, where electricity accounts for around 77 per cent and 97 per cent of energy demand by 2030 and 2058, respectively, with natural gas use reaching 4 percent in 2030 and zero by 2058. In the Step Change scenario, natural gas consumption is around 16 per cent, declining to zero by 2058. In the Progressive Change scenario, natural gas consumption decreases the most, from around 16 per cent in 2025 to around zero in 2058, primarily due to electrification and energy efficiency.

Similar to the 2022 multi-sector modelling, all four scenarios include exogenous assumptions for the electrification of commercial oil use (Reedman et al., 2022). However, oil uptake remains between 10-13 per cent in the Progressive Change scenario, while in the other scenarios, it declines from 10 per cent in 2025 to zero by 2058.

Similar to residential buildings, biomethane is blended into natural gas pipelines starting in the late 2020s, but its uptake is minimal across all the scenarios, where biomethane is not adopted as a cost-effective fuel in the commercial sector. Biomethane uptake is negligible in the Progressive Change scenario until the 2040s when some adoption begins. In the Green Energy scenarios, uptake begins in 2027 but gradually declines from 2030s as electrification accelerates and energy efficiency measures take effect. In the Step Change scenario, biomethane uptake starts in the late 2020s, followed by moderate increases from the 2040s onward.

Hydrogen blending into pipelines is limited to 10 per cent by volume as part of the scenario settings (see Appendix B.10.5). However, hydrogen uptake in commercial buildings remains zero across all scenarios, primarily due to its high-cost relative to electrification and biomethane.

In commercial buildings, the projected fuel mix demonstrates a clear trend toward electrification, in part due to prohibition on natural gas connections in ACT and the adoption of energy efficient technologies, with fossil fuel use diminishing across all scenarios at the national level. Despite its cost, biomethane uptake remains limited, and no hydrogen consumption is observed in any of the scenarios. Similar patterns are observed for the NEM (Figure 4-72) and Western Australia (Figure 4-73). However, in the Northern Territory (Figure 4-74), there is no uptake of biomethane across all scenarios, and natural gas consumption remains negligible, except in the Progressive Change scenario, throughout the modelling period.

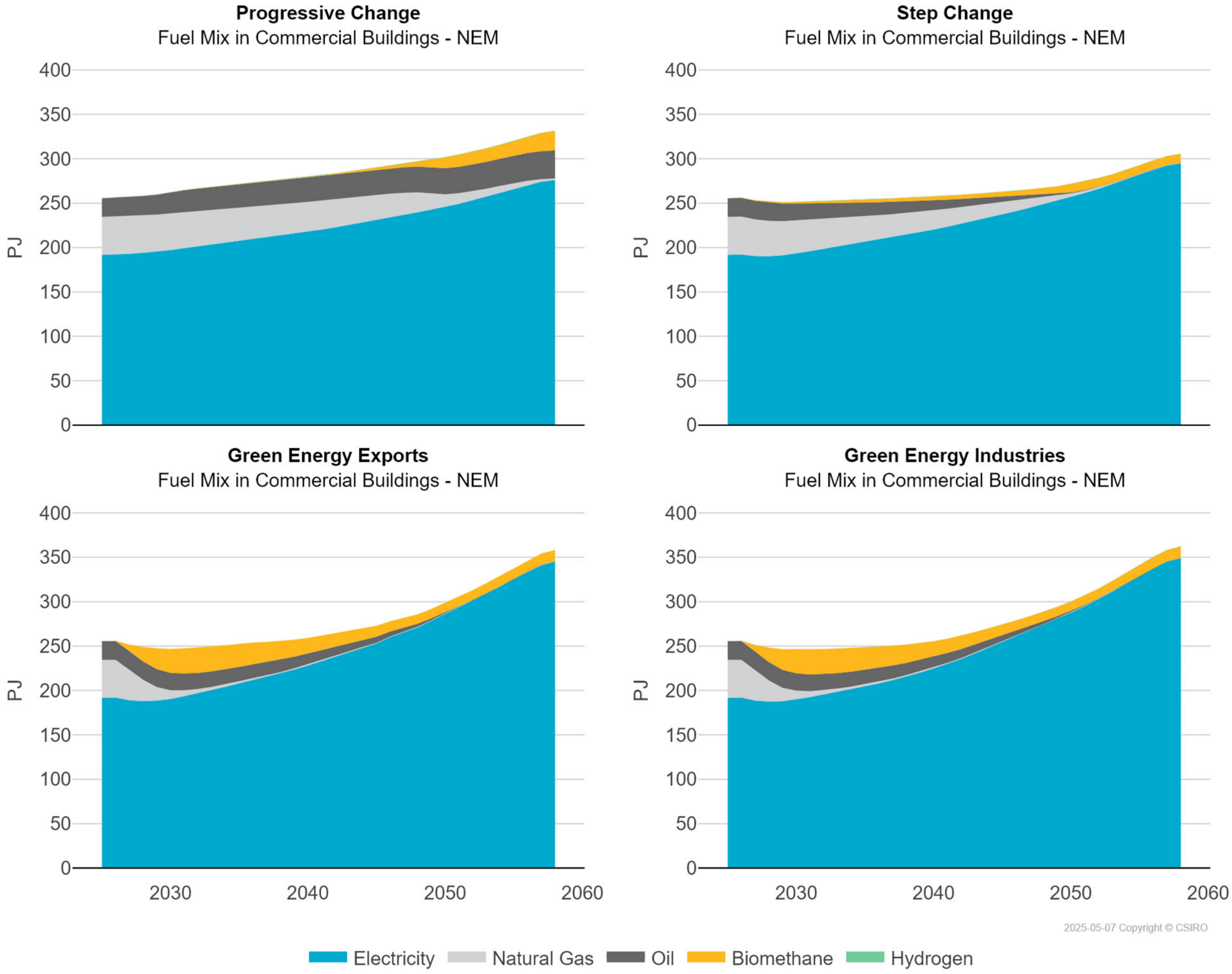


Figure 4-72 Fuel mix in commercial buildings in the NEM regions

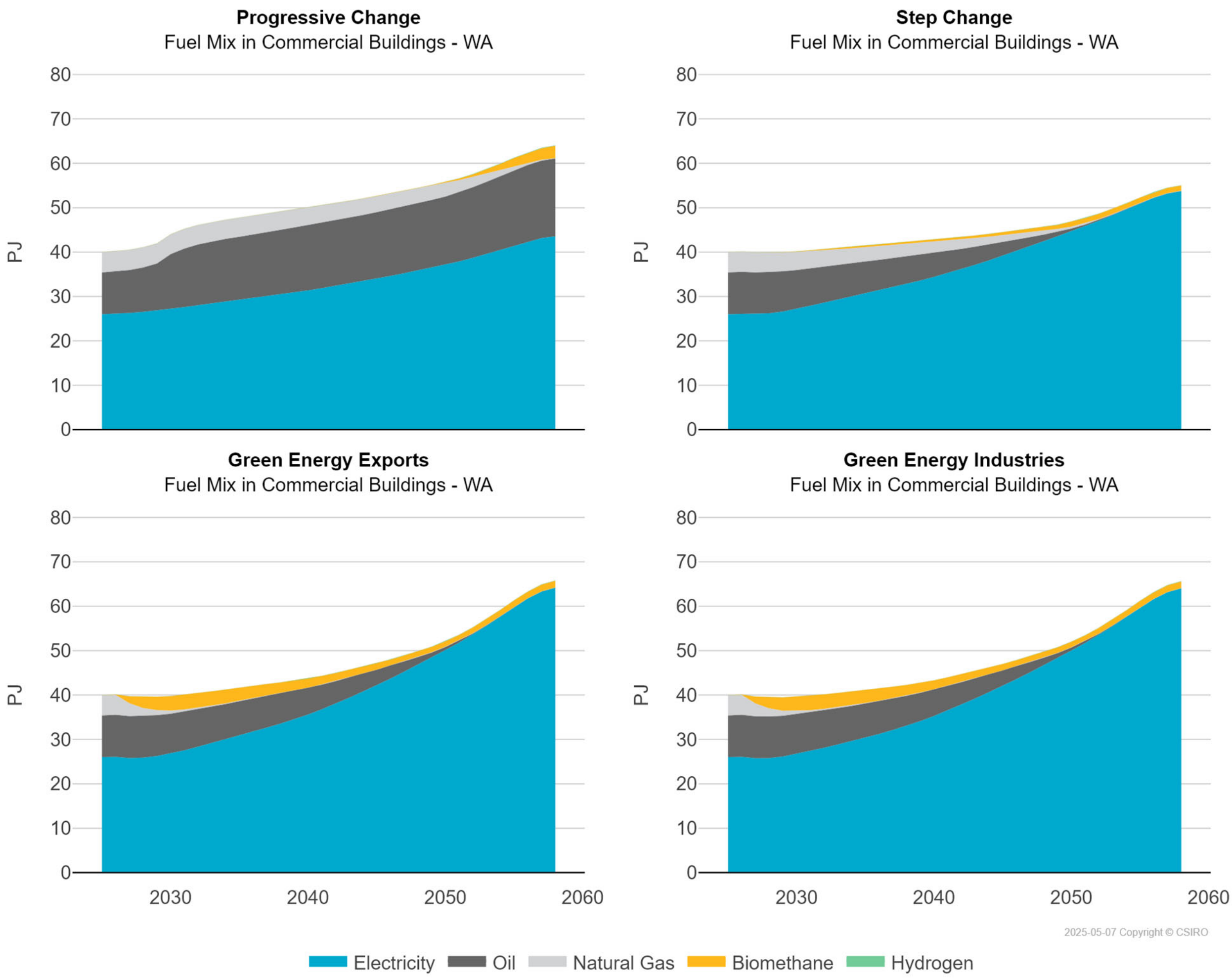


Figure 4-73 Fuel mix in commercial buildings in Western Australia

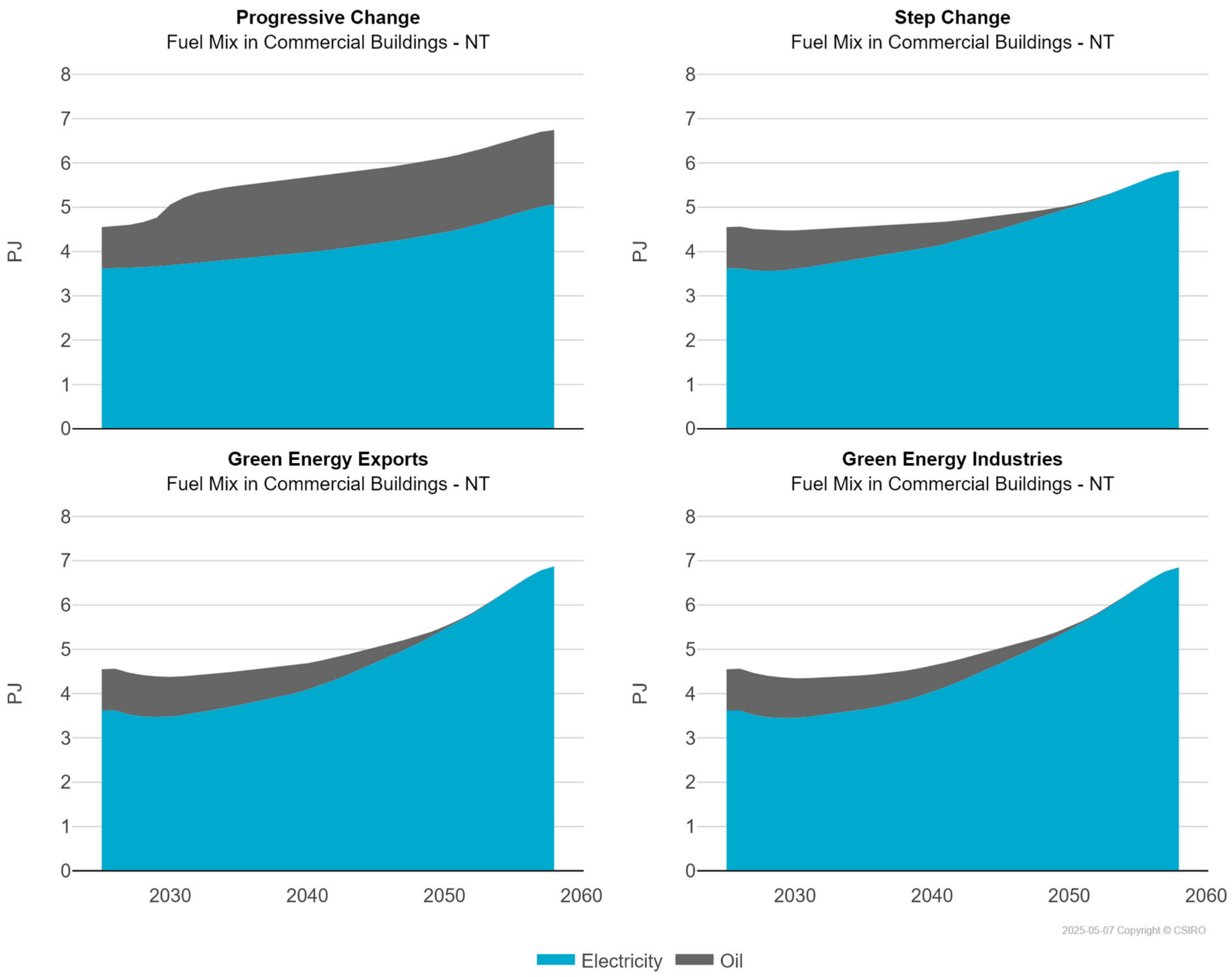


Figure 4-74 Fuel mix in commercial buildings in the Northern Territory

4.8 Hydrogen and biomethane production

There are numerous hydrogen production pathways that are considered in AusTIMES: steam methane reforming (SMR); SMR with carbon capture and storage (CCS); brown coal gasification with CCS; alkaline electrolysis, and; proton exchange membrane (PEM) electrolysis; by-product hydrogen produced in the chemicals industry. The modelling framework optimises the production process and location of the hydrogen production as part of the least cost optimisation for each of the scenarios. However, there is a requirement that in the Green Energy scenarios, any hydrogen that is produced is from electrolysis using renewable electricity (beyond existing hydrogen production capacity).

Figure 4-75 Hydrogen production by technology nationally

There are existing plants that produce hydrogen (mainly for feedstock) utilising SMR (Figure 4-75). It is assumed that these plants continue operation with any growth in capacity from the deployment of new technologies. Based on scenario narratives, there is an option to deploy new SMR plants provided they are coupled with carbon capture and storage (CCS) in the Progressive Change and Step Change scenarios. SMR with CCS is not a technology option in either the Green Energy Exports or Green Energy Industries scenarios.

There is modest production of hydrogen in the near-term in both Progressive Change and Step Change with some growth in the 2030s. In the Green Energy scenarios, where the hydrogen demand for feedstock is significant (more so in Green Energy Exports) for green iron and ammonia production, hydrogen production accelerates in the 2030s, predominantly supplied by alkaline electrolysis. Similar patterns are observed, at different scales, for the NEM (Figure 4-76), Western Australia (Figure 4-77) and the Northern Territory (Figure 4-78).

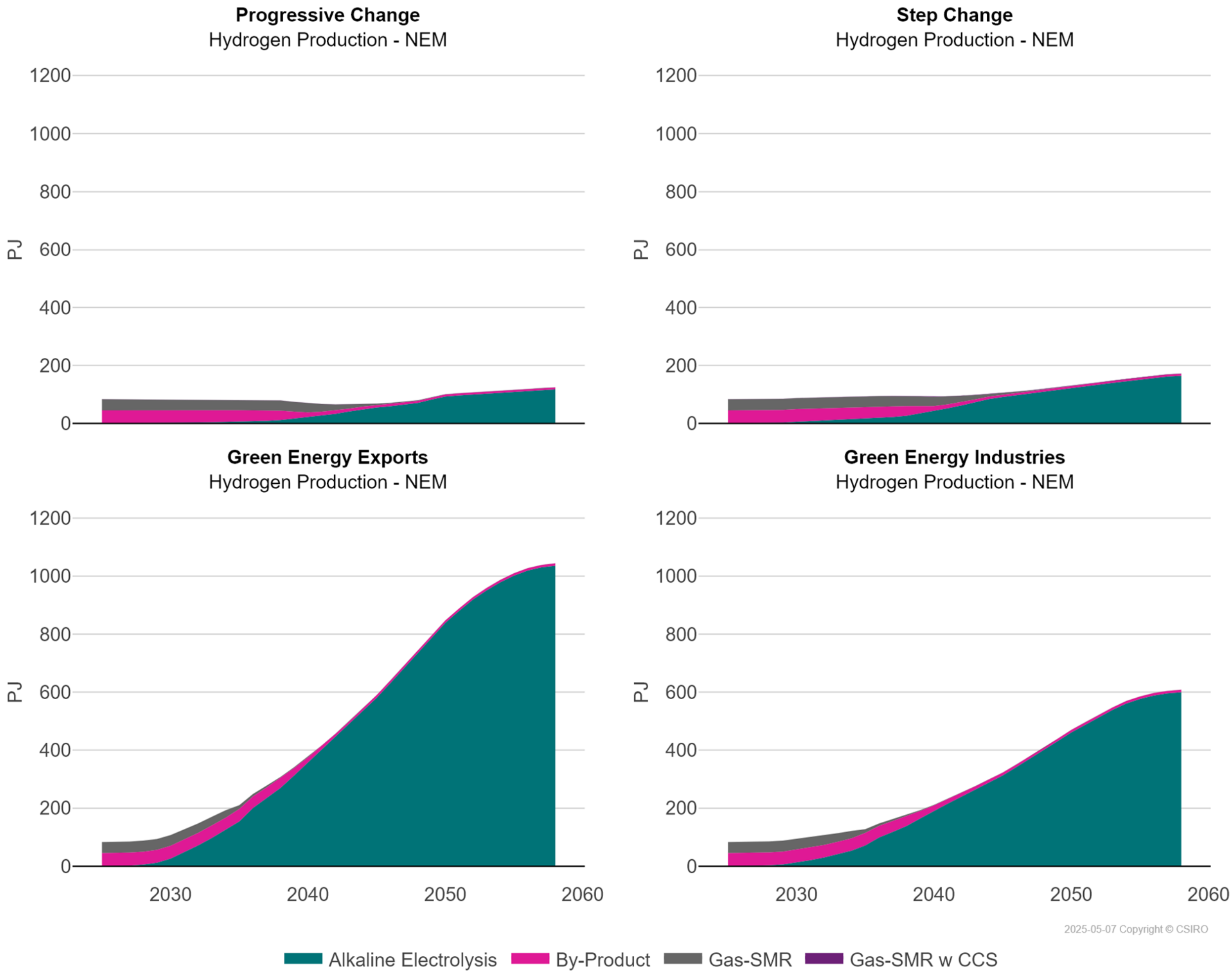


Figure 4-76 Hydrogen production by technology in the NEM

Figure 4-77 Hydrogen production by technology in Western Australia

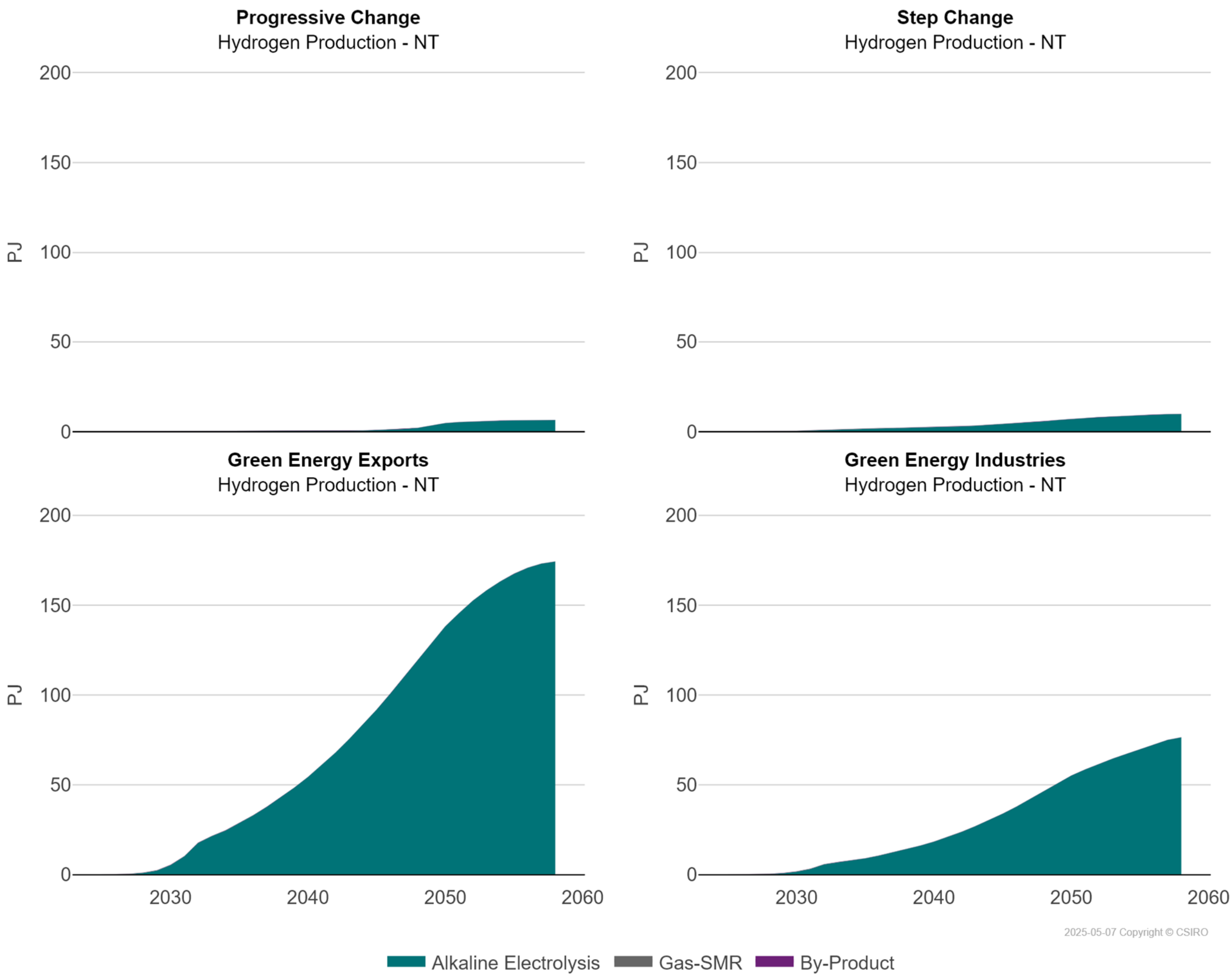


Figure 4-78 Hydrogen production by technology in the Northern Territory

The dominance of alkaline electrolysis differs from the 2022 multi-sectoral modelling. In that work, it was observed that early in the projection period, alkaline electrolysis was the least-cost production process due to its lower cost than proton exchange membrane (PEM) electrolysis. Over time, PEM electrolysis became the preferred production process as capital costs declined and the electricity system transitioned to high variable renewables. There are two main reasons for the change to alkaline electrolysis. First, in this work, minimum annual utilisation factors were applied based on feedback from industry stakeholders. The model assumes a linear decline from 2025 at 70%, to 35% at 2058. Second, the outlook for capital cost projections for electrolysers has changed. Based on GenCost 2025 Consultation Draft, both electrolyser technologies have similar capital costs in the near-term. However, over the projection period, the capital costs for alkaline decline much faster than PEM (see Appendix B.6). This is a significant change since the 2022 GenCost (used in the 2022 multi-sectoral modelling). Based on those assumptions, Alkaline electrolyser costs fell rapidly to below that for PEM, explaining the switch in least-cost electrolyser technology in this round of multi-sectoral modelling. For Progressive and Step Change, hydrogen production via Steam Methane Reforming (SMR) with Cabon Capture and Storage (CCS) was allowed. While the pre-carbon-price cost of supply for SMR+CSS based hydrogen was lower than that of electrolysis, the presence of an internally-consistent carbon price in the modelling resulted in electrolysis being the least cost.

Based on the data provided by ACIL Allen (2024), there are three different production pathways for biomethane specified in AusTIMES:

- Landfill gas
- Anaerobic digesters using municipal solid waste as feedstock
- Gasification and methanation of lignocellulosic sources (crop waste).

The results show that in the Progressive Change and Step Change scenarios the production of biomethane is limited to the landfill gas and waste streams. In the Green Energy scenarios, the more stringent decarbonisation imperative drives greater uptake in the near-term, utilising all the available waste feedstocks and using higher cost crop residues. As electrification increases, the demand for natural gas (and therefore biomethane) starts to abate.

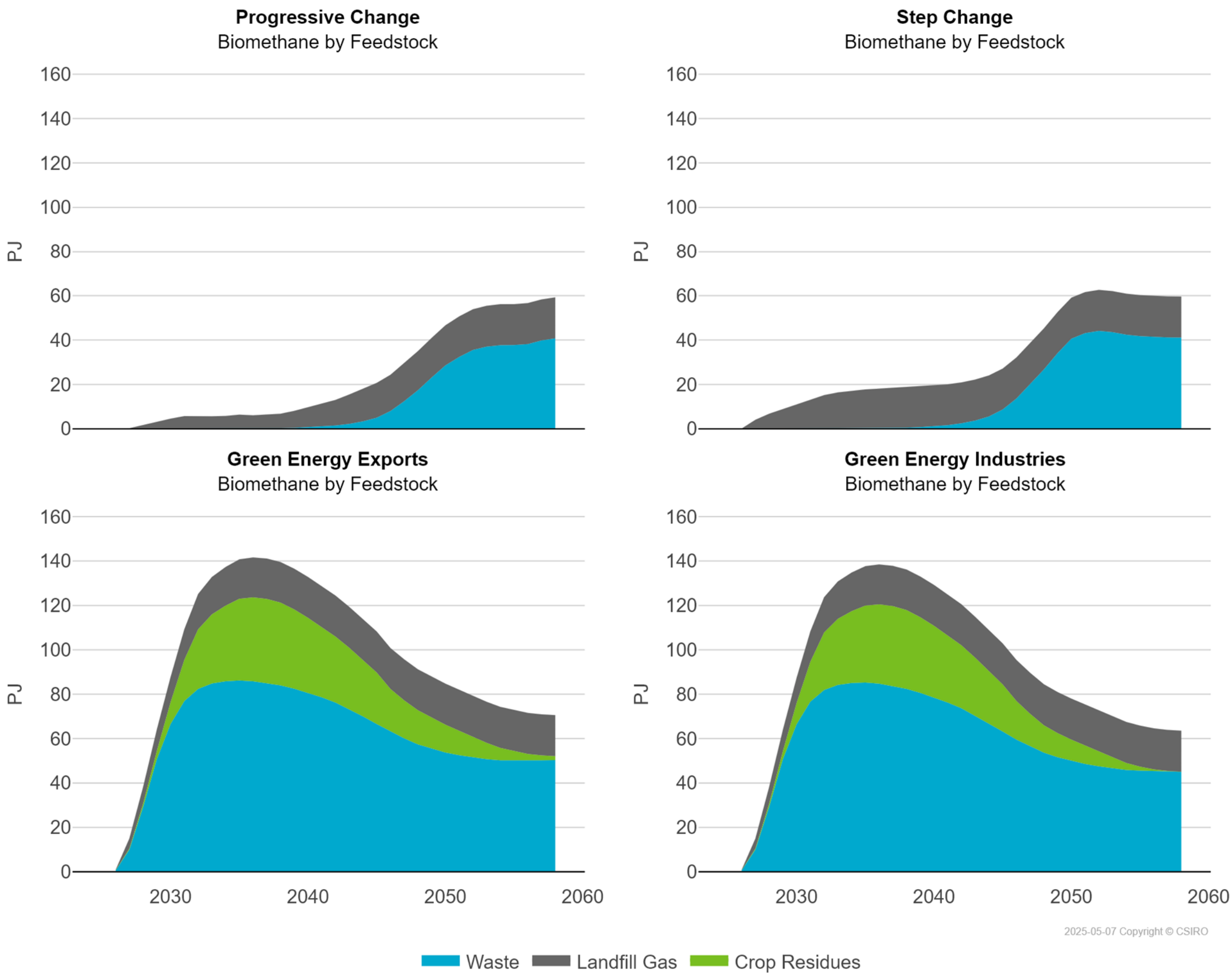


Figure 4-79 Production of biomethane nationally

Appendix A Structural Detail of AusTIMES model

A.1 End-use sectors

Numbering is included in the style (A.1, A.2).

A.1.1 Industry

Energy use in industry is disaggregated into several sub-sectors. The mapping of AusTIMES to ANZSIC industry subsectors is displayed below (Apx Table A-1).

Apx Table A-1 Mapping of AusTIMES subsectors to ANZSIC industry subsectors and divisions

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

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

Hydrogen and biomethane uptake in industry is implemented endogenously to service end-uses through pipeline blending with natural gas. In this case, 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 based on costs of fuels involved and the shadow carbon price (determined internally in the model based on scenario emissions objectives and the cost of available decarbonisation options). The fuel cost of hydrogen and biomethane is determined by fuel production capacity and operation to deliver fuels to end-uses at least cost. Assuming hydrogen replaces natural gas with existing pipeline infrastructure, the capital cost of switching from natural gas to hydrogen technologies is not considered.

In addition to hydrogen blended via the gas distribution 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.

A.1.2 Residential buildings

The stock of buildings is sourced from the Residential Buildings Baseline Study (DISER, 2022c), 2023 ABS populations and dwellings projection, ABS household and family projections (ABS, 2024), Australian Energy Statistics (DCCEEW, 2024a). The ABS dwelling types (separate house, semi-detached, row or terrace house, townhouse etc. with one/two storey, flat or apartment attached to a house or flat or apartment in a one/two/three storey block) and household types from ABS population and dwellings projections (family, group, lone person households) are mapped to separate house, townhouse and apartment in AusTIMES respectively. The growth rate in number of households is calculated for each state based on the ABS Series II household projections. The energy intensity by building type is derived from the Residential Buildings Baseline Study (DISER, 2022c).

The residential building types, end-use service demands and fuel types are listed below (=Apx Table A-2.

Apx Table A-2 Residential building types, end-use service demands and fuel types

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

All residential buildings experience an autonomous efficiency improvement at no cost, where existing technologies are assumed to become more efficient over time, in line with historic rates. This is analogous to equipment being replaced at end-of-life with something of equivalent cost - but where the equipment available in the market is now more efficient than the equipment being replaced. 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. Assumptions for costs and savings for electrification are derived from sources including Climate Choices ACT (2021) and *Renovation Pathways* (Climateworks Centre, 2023), and costs and savings for energy efficiency are derived from the *Low Carbon High Performance Report* (ClimateWorks Australia, 2016).

Gas policies for Victoria (VICTORIA State Government, 2025) and ACT (ACT Government, 2022) have been incorporated into the model and ban on new gas connections for residential buildings begins in 2024, with all new residential buildings assumed to be fully electrified from that year onward. For the ACT, the model also reflects a complete transition to renewable electricity for all residential (both new and existing) by 2045.

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 if it is economically attractive based on relative costs of fuels involved and the decarbonisation imperative. 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 and appliances is not considered.

A.1.3 Commercial buildings

The stock of buildings is sourced from the *Commercial Buildings Baseline Study (DCCEEW 2022b)*, and *Australian Energy Statistics (DCCEEW 2024a)*, and the *Low Carbon High Performance* report *(ClimateWorks Australia, 2016)* have been used to inform energy intensity for the range of building types modelled.

The commercial building types, end-use service demands and fuel types are listed below (Apx Table A-3).

Apx Table A-3 Commercial building types, end-use service demands and fuel types

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

Similar to residential buildings, all commercial buildings undergo an autonomous efficiency improvement at no cost. Additional endogenous energy efficiency and electrification options are available, at an additional incremental cost. Should these be economically attractive, they will be taken up in the model. All assumptions on costs and savings are derived from the *Low Carbon High Performance Report* (ClimateWorks Australia, 2016).

The ACT gas policy (ACT Government, 2022) has been incorporated into the model, with assumptions reflecting a full transition to electricity in all commercial buildings by 2045.

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.

A.1.4 Agriculture

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

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

Aus-TIMES subsector (agriculture)	ANZSIC (2006) codes	ANZSIC Division
Agriculture - Sheep and cattle	0141, 0142, 0143, 0144, 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

Similar to the structure for industry described above, hydrogen and biomethane uptake in agriculture sector is implemented endogenously to service end-uses through pipeline blending with natural gas, where available.

Note that for modelling purposes, non-energy emissions for mixed-use farms are categorised on the basis of agricultural activities. For example, livestock emissions in mixed grain-sheep farming are exclusively modelled under Agriculture – Sheep and cattle.

A.1.5 Transport

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

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

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

Key inputs are BITRE data on vehicle stock (BITRE, 2024), average kilometres travelled (BITRE, 2023) and *Australian Energy Statistics* data (DCCEEW, 2024a) on fuel use, NGA emission factors for fuel (DCCEEW, 2024f), transport activity projections (Graham et al., 2025), assumptions around future vehicle costs and efficiency improvements (Graham et al., 2025), oil price projections (IEA, 2024) and production costs on biofuels (Butler et al., 2021). The delivery price of electricity and hydrogen for road transport is endogenously determined within AusTIMES.

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

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

Market segments	Fuels
Rail	Diesel Electricity Biodiesel Hydrogen
Aviation – domestic Aviation- international	Avgas Kerosene Bio-kerosene Electricity Synthetic kerosene Hydrogen
Shipping – domestic Shipping – international	Diesel Fuel oil Biodiesel Hydrogen

Key inputs are BITRE (2023) and *Australian Energy Statistics* data (DCCEEW, 2024a) on fuel use, NGA emission factors for fuel (DCCEEW, 2024f), transport activity projections (Graham et al., 2025), assumptions around activity and fuel efficiency improvements (Graham et al., 2025), oil price projections (IEA, 2024) and production costs on biofuels (Butler et al., 2021). The delivery price of hydrogen for aviation and shipping is endogenously determined within AusTIMES.

A.2 Electricity sector

In the TIMES framework, the power (electricity) sector is a transformation sector that converts forms of primary energy (i.e., coal, natural gas, renewable resources) into electricity that is a derived demand of the end-use sectors (see Appendix A.1). An advantage of the TIMES model is that different spatial and temporal scales can be implemented in different sectors. The electricity sector in AusTIMES has the following features:

- Electricity demand aggregated to 16 load blocks reflecting seasonal and time of day variation across the year
- 19 transmission zones: 16 zones in the National Electricity Market (NEM)[16]; 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

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

- 36 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); 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; nuclear large-scale, 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; grid battery with 12 hours of storage; grid battery with 24 hours of storage; residential battery; commercial battery.
- Current policies: national large-scale 82% renewable energy target in main grids; Northern Territory, Queensland, Tasmania and Victoria Renewable Energy Targets; Victorian energy storage target; Victorian offshore wind target; Small-scale renewable energy scheme; NSW Energy Security Target, NSW *Electricity Infrastructure Investment Act 2020*; the Snowy 2.0 energy storage project.

Appendix B Key assumptions

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

B.1 Emissions point targets and cumulative constraints

All scenarios have both point emissions targets in 2030 and 2050 in alignment with Australia's current commitments under the Paris Agreement, and cumulative emissions constraints which are mapped to temperature targets via the methodology in Appendix A . These are summarized in Apx Table B-1.The point targets are (at least) net zero emissions by 2050 (and beyond), and a Nationally Determined Contribution (NDC) to reduce emissions by (at least) 43% on 2005 levels by 2030 (and beyond). The emissions budget target in Australia's NDC (4.381 Gt CO_{2-e} from 2021-2030) was not explicitly incorporated in the scenarios (DISER 2022b) although is implicitly met by all scenarios[17]. For the Green Energy scenarios, an additional point target was applied as (at least) net zero emissions by 2042 (and beyond) while allowing overshoot in the carbon budget by up to 35%. The 2042 year was model-determined as the earliest net-zero year (consistent with the particular assumptions for those scenarios) by solving the model at progressively earlier years until a solution could not be found.

Apx Table B-1 National cumulative and point emissions targets and mapping to temperature increases[18]

Scenario	2023-2060 Cumulative Emissions [$GtCO_2$-e]		2030 % Reduction over 2005		2050 % Reduction over 2005		Mapped Temperature Target [Temp. @ likelihood]	
	Target	Achieved	Target	Achieved	Target	Achieved	Goal	Achieved
Progressive Change	<= 14.9	7.7	>= 43%	44%	>= 100%	100%	2.6 deg @ 83%	2 deg @ 80%
Step Change	<= 6.8	6.8	>= 43%	46%	>= 100%	100%	1.8 deg @ 66%	1.8 deg @ 66%
Green Energy Exports	<= 3.8	3.8 (4.6)	>= 43%	55%	>= 100%	106%	1.5 deg @ 43%	1.5 deg @ 43% (30%)
Green Energy Industries	<= 3.8	3.8 (4.6)	>= 43%	54%	>= 100%	106%	1.5 deg @ 43%	1.5 deg @ 43% (30%)

[17] The cumulative emissions over the 2021-2030 period for all scenarios are under those specified in the NDC (4.381 $GtCO_2$-e) as follows: Progressive Change 4.21, Step Change 4.17, Green Energy Exports and Green Energy Industries 3.98 $GtCO_2$-e.

[18] Note that the model solution was approximately every two years over the model horizon (sometimes yearly) and for years where there is no explicit model solution, linear interpolation is used for the cumulative emissions calculations in Apx Table B-1

Percentage values are the typical "likelihood" notation as used in climate scenario science. Note that all scenarios are fixed to the model solution for Progressive Change through to 2026, after which the scenario dependent settings are applied. Figures in parentheses indicate limited overshoot of the carbon budget, i.e., the carbon budget is exceeded, and net-negative emissions return the cumulative emissions to the constrained budget over the period between the net-zero year and 2060. The values in parentheses are those if using the maximum value of the cumulative emissions curve for the calculations (as opposed to the final value at 2060). For this work, only the Green Energy scenarios exhibit overshoot (of 0.8 GtCO_2-e) which maps to a 1.5 degree at 43% likelihood overshooting to 30% likelihood - similar to the A40/G1.5 scenario published by CSIRO and the Climate Change Authority[19] (Verikios et al., 2024; Climate Change Authority, 2024).

In all the scenarios the maximum cumulative emissions are an upper bound; however, the model may reach net zero emissions earlier as it tries to solve for the least cost optimal pathway within a carbon budget constraint in each of the scenarios.

While some state policies are incorporated in the electricity sector, state-based emission reduction targets are not included in these modelled scenarios. AusTIMES does not currently have a representation of the full scale of emissions sequestration from different methods at a state level. It also does not have the capability to model the trading of emissions credits across state borders, where such activities may be allowed under the relevant state legislation. As any net zero emissions target at a state level requires a robust understanding of the contribution of negative emissions within or outside of that state's boundaries, such targets were not possible to model under the current setup of AusTIMES.

Apx Table B-2 Cumulative emissions constraints and emission target assumptions by scenario

Model Input Assumptions	Progressive Change	Step Change	Green Energy Exports and Green Energy Industries
Global emissions outcome	83% chance of limiting global warming to 2.6 C, with no temperature overshoot.	66% chance of limiting global warming to below 1.8C, with no temperature overshoot.	43% chance of limiting global warming to 1.5°C above pre-industrial levels, with limited overshoot.
Cumulative emissions constraint for Australia (from 2023-2060)	14.9 Gt CO2-e (Chosen such that the cumulative emissions constraint is not binding, and only the point targets at 2030 and 2050 drive emissions pressure)	6.8 Gt CO_2-e (Chosen as a midway point between the two other cumulative emissions constraints, and mapping to a 1.8 degree @ 66% likelihood temperature goal).	3.8 Gt CO_2-e (Chosen as being the most ambitious temperature goal the model could achieve – and with carbon budget overshoot allowed for consistency with recent work by CSIRO and the CCA)
Decarbonisation target/s	Emissions fall **below** Australia's 2030 commitments under the *Paris Agreement* (43% reduction on 2005 levels by 2030)	Emissions fall **below** Australia's 2030 commitments under the *Paris Agreement* (43% reduction on 2005 levels by 2030)	Emissions fall **below** Australia's 2030 commitments under the *Paris Agreement* (43% reduction on 2005 levels by 2030)

[19] For the A40/G1.5 scenario published by CSIRO and the Climate Change Authority, the mapping to temperature was 1.5 degrees @ 51% (31%), i.e., 51 % likelihood with overshoot which maps to 31% likelihood with some of the main differences being that in this work there is a revised approach for land-based sequestration availability and rate of sequestration and high growth of green commodities.

	Economy-wide net zero emissions **by** 2050	Economy-wide net zero emissions **by** 2050	Economy-wide net zero emissions **by or before** 2042

B.2 Domestic carbon budget to temperature mapping methodology

While the minimum and maximum carbon budgets were determined by examination of model results over a range of budgets to find the points of no budget pressure and maximum budget pressure, the mapping from those budgets to global temperature outcomes (assuming the rest of the world matches the Australian climate ambition in each case) is based on the following methodology.

Global temperature rise is closely linked to the cumulative concentration of greenhouse gases in the atmosphere. The IPCC (Arias et al., 2021) has published global carbon budgets consistent with global temperature outcomes, which represent the cumulative amount of carbon dioxide that can be emitted above a particular baseline before a given temperature outcome is reached (Apx Table B-3). These targets involve inherent uncertainties, including:

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

Apx Table B-3 Global carbon dioxide budgets from the IPCC Working group I contribution to the Sixth Assessment Report (from Arias et al. 2021)

Global surface temperature change since 2010-2019	**Global surface temperature change since 1850 – 1900**	**Estimated remaining carbon budgets from 1 January 2020 and subject to variations and uncertainties quantified in the columns on the right**					**Scenario variation**	**Geophysical uncertainties**			
°C	°C	Percentiles of TCRE $GtCO_2$					Non-CO_2 scenario variation	Non-CO_2 forcing and response uncertainty	Historical temperature uncertainty	Zero emission commitment uncertainty	Recent emissions uncertainty
		17th	33rd	50th	67th	83rd	$GtCO_2$	$GtCO_2$	$GtCO_2$	$GtCO_2$	$GtCO_2$
0.43	1.5	900	650	500	400	300	Values can vary by at least ±220 due to choices related to non-CO_2 emissions mitigation	Values can vary by at least ±220 due to uncertainty in the warming response to future non-CO_2 emissions mitigation	±550	±420	±20
0.53	1.6	1200	850	650	550	400					
0.63	1.7	1450	1050	850	700	550					
0.73	1.8	1750	1250	1000	850	650					
0.83	1.9	2000	1450	1200	1000	800					
0.93	2	2300	1700	1350	1150	900					

1.5-degree and 2-degree climate scenarios typically show temperatures peaking between 2040-2060. All the scenarios were mapped to temperature outcomes using a mapping function which maps a cumulative Australian emissions number to a line in the space of global temperature rise and likelihood. That map is shown in Apx Table B-4 and was calculated using a sequence of steps starting at the globally accepted values in Apx Table B-5.

Apx Table B-4 Mapping from cumulative national emissions (from 2023 onwards) to global temperature

Temperature outcome	Likelihood	Budget (GtCO2-e)
1.5 degrees	83%	1.2
1.5 degrees	67%	2.2
1.5 degrees	50%	3.3
1.6 degrees	83%	2.2
1.6 degrees	67%	3.8
1.6 degrees	50%	4.8
1.7 degrees	83%	3.8
1.7 degrees	67%	5.3
1.7 degrees	50%	6.9
1.8 degrees	83%	4.8
1.8 degrees	67%	6.9
1.8 degrees	50%	8.4
2 degrees	83%	7.4
2 degrees	67%	9.9
2 degrees	50%	12.0
2 degrees	33%	15.6

Note that to map the carbon budgets to a point on one of the temperature-likelihood lines in this space a linear fit with extrapolation is employed allowing for mappings outside of the range explicitly represented in this table. Since the data is well represented by a linear function (in both temperature and likelihood directions), this enables the 43% and 30% mappings to the 1.5 degree line for the Green Energy scenarios, and to the 2.6 degree at 83% (non-binding) budget for Progressive Change.

Apx Table B-5 A range of global carbon dioxide budgets from 2020

Temperature outcome and probability	Global budget (CO_2 only; from 2020)	Details
2°C (67%)	1,150 Gt CO_2	67th percentile of ‘2’ warming row from Apx Table B-4
1.8°C (67%)	850 Gt CO_2	67th percentile of ‘1.8’ warming row from Apx Table B-4
1.5°C (50%)	500 Gt CO_2	50th percentile of ‘1.8’ warming row from Apx Table B-4

To align all assumptions with the approach used in Meinshausen (2019), it is necessary to adjust the start year from 2020 to 2013. This is achieved by adding 277 Gt to each of the budgets (approximate global emissions between 2013-2019), resulting in the updated budgets in Apx Table B-6 (Meinshausen, 2019; Nicholls & Meinshausen, 2022).

Apx Table B-6 A range of global carbon dioxide budgets from 2013

Temperature outcome and probability	Global budget (CO_2 only; from 2013)	Details
2°C (67%)	1,427 Gt CO_2	Add 277 Gt to budgets from Apx Table B-5 representing global emissions from 2013-2019
1.8°C (67%)	1127 Gt CO_2	
1.5°C (50%)	777 Gt CO_2	

The carbon budgets provided in Apx Table B-3 refer to temperature rise relative to an 1850-1900 baseline. However, it is useful to construct scenarios relevant to the Paris Agreement (UNFCCC 2015), which refers to a pre-industrial baseline and to handle this difference, we subtract an additional 150 GtCO_2 from all carbon budgets, which is based on an assumed additional warming of 0.1°C and the relative differences in budgets at that warming interval from the IPCC budgets, and is consistent with Nicholls & Meinshausen (2022). This results in the budgets in Apx Table B-7.

Apx Table B-7 A range of global carbon dioxide budgets from 2013 adjusted to a pre-industrial baseline

Temperature outcome and probability	Global budget (CO_2 only; from 2013)	Details
2°C (67%)	1,277 Gt CO_2	Subtract 150 Gt from budgets in Apx Table B-6 representing warming that already occurred from pre-industrial times until 1850-1900.
1.8°C (67%)	977 Gt CO_2	
1.5°C (50%)	627 Gt CO_2	

Up to this point, carbon budgets apply to carbon dioxide only. For accurate comparison with our modelling outcomes, greenhouse gases other than carbon dioxide (for example nitrous oxide and methane) must be considered. We take an approach by Meinshausen (2019) and updated by Nicholls and Meinshausen (2022) that adjusts the carbon budget based on the relationship between cumulative carbon dioxide and cumulative (total) GHG emissions across scenarios from the IPCC Assessment Report 6 database. The final relationship used is:

$$Cumulative\ total\ GHG\ emissions\ =\ 1.21 \times CO_2\ budget + 235.37$$

This equation aligns to the approach in Nicholls & Meinshausen (2022) (Nicholls, Z, Pers. Comm., 15 July 2022), and updated based on The Superpower Transformation (Garnaut, 2022). This equation is applied to reach the global carbon budgets (i.e. total GHG budgets) in Apx Table B-8.

Apx Table B-8 A range of global carbon budgets (applicable to all GHG emissions) from 2013 adjusted from relevant global CO2-only budgets, before accounting for LULUCF accounting differences

Temperature outcome and probability	Global budget (All GHGs; from 2013)	Details
2°C (67%)	1,781 Gt CO_2	Adjust budgets in Apx Table B-7 using the linear fit 1.21×CO_2 budget + 235.37 (Garnaut, 2022)
1.8°C (67%)	1,418 Gt CO_2	
1.5°C (50%)	994 Gt CO_2	

Differences in land use, land use change and forestry (LULUCF) accounting approaches used in national greenhouse gas reporting figures necessitate an adjustment to the global budget to ensure these emissions are not undercounted. We take the approach used in Nicholls & Meinshausen (2022) to adjust these, which is based on Grassi et al. (2021). Under this approach, 15% of the CO2-only portion of each budget is subtracted (Nicholls, Z, Pers. Comm., 15 July 2022). This is applied to reach the final global carbon budgets (i.e. total GHG budgets) in Apx Table B-9.

Apx Table B-9 A range of global carbon budgets (applicable to all GHG emissions) from 2013 accounting for global LULUCF accounting differences

Temperature outcome and probability	Global budget (CO_2 only; from 2013)	Details
2°C (67%)	1,589 Gt CO_2	Subtract 15% of the budgets in Apx Table B-8 from budgets in Apx Table 0-12. (Nicholls, Z, Pers. Comm., 15 July 2022; Nicholls & Meinshausen 2022)
1.8°C (67%)	1,271 Gt CO_2	
1.5°C (50%)	903 Gt CO_2	

The next step is to exclude the effect of emissions from international shipping and aviation by subtracting 50 GtCO2 (Garnaut, 2022) to avoid double counting in the calculation of Australia's fair share of international emissions budget in the next step (Apx Table B-10).

Apx Table B-10 A range of Australian carbon budgets (applicable to all GHG emissions) from 2013

Temperature outcome and probability	Australian budget (All GHGs; from 2013)	Details
2°C (67%)	1,539 Gt CO_2	Subtract 50 GtCO2 from the values in Apx Table B-9 (Garnaut, 2022)
1.8°C (67%)	1,221 Gt CO_2	
1.5°C (50%)	953 Gt CO_2	

There are several methods that can be used to determine Australia's 'fair share' of the global carbon budget based on different 'burden-sharing' approaches. Our chosen approach aligns to that used by the Garnaut Review (2008), adopted by the Climate Change Authority (2014) and validated by Meinshausen et al. (2018) that takes Australia's fair share to be 0.97% of the global carbon budget, based on the modified contraction and convergence approach. Applying this percentage results in carbon budgets for Australia (from 2013) shown in Apx Table B-11.

Apx Table B-11 A range of Australian carbon budgets (applicable to all GHG emissions) from 2013

Temperature outcome and probability	Australian budget (All GHGs; from 2013)	Details
2°C (67%)	14.928 Gt CO_2	Take 0.97% of the budgets in Apx Table B-10, representing Australia's 'fair share' under a modified contraction and convergence approach.
1.8°C (67%)	11.844 Gt CO_2	
1.5°C (50%)	8.274 Gt CO_2	

Finally, to produce carbon budgets relevant to modelling outcomes, it is necessary to adjust the budget to begin from 2023. This is achieved by subtracting Australia's emissions from 2013-2022 (4.987 Gt CO_2-e) to reach final national budgets from 2023, in Apx Table B-12 (DCCEEW 2022). Sub-national carbon budgets (including for NEM-connected states) are not specifically considered. However, the cumulative emissions outcome for NEM-connected states can be considered an indication of the portion of this budget that those states could feasibly be constrained to in a given scenario.

Apx Table B-12 A range of Australian carbon budgets (applicable to all GHG emissions) from 2023

Temperature outcome and probability	Australian budget (All GHGs; from 2023)	Details
2°C (67%)	9.94 Gt CO_2	Subtract 4.987 from the budgets in Apx Table B-11 representing actual emissions from 2013-2022.
1.8°C (67%)	6.856 Gt CO_2	
1.5°C (50%)	3.287 Gt CO_2	

B.3 Electrification and energy efficiency

Energy efficiency and electrification improvements are implemented in the model using two main approaches:

- **Autonomous:** This only applies to energy efficiency. The industry, commercial and residential buildings end-use sectors experience a business-as-usual energy efficiency improvement at no cost which is known as autonomous energy efficiency. The rates of efficiency gain do not vary across scenarios, and range from 0.45%-1.41% p.a. in residential buildings, 0.11-0.95% p.a. in commercial buildings, and -0.09% (efficiency reduction; particularly in some mining subsectors where operations become more energy intensive as mines expand) to 0.7% p.a. by 2050 in industry. The rates for all sectors are informed by long-term energy efficiency trends (for example, improvements in HVAC energy efficiency over time), and other external sources including ASSET (2018).

- **Endogenous**: This applies to both energy efficiency and electrification. These are costed options which are implemented if they are economically attractive based on a combination of capital costs, equipment lifetime and fuel costs, subject to uptake constraints as detailed below. The final uptake of endogenous efficiency and electrification is determined by the model to achieve a whole-of-system least cost solution and is not an input. This category largely represents technologies that are commercially available today. Examples for the buildings sector include technologies such as LED lighting and heat pump hot water systems. In industry, this captures a broad range of technologies under the broad categories of process improvements, small equipment upgrades and large equipment upgrades.

Constraints on the uptake of endogenous energy efficiency and electrification are varied by scenario. Depending on the sector, these are applied on the basis of either annual uptake constraints on deployment of energy efficiency or electrification technologies, or an upper limit on the overall share of energy that can be avoided or displaced over time, or a combination of these two approaches. These assumptions are detailed in the remainder of this section.

AusTIMES incorporates base constraints that are broadly representative of the **maximum feasible** penetration of electrification or energy efficiency technologies under the least restricted case. Specifically:

- In **industry**, **resources and agriculture,** the maximum feasible electrification rate is based on a literature review to understand the technological potential for electrification, and a maximum annual technology build rate is implemented for the different subsectors to limit the speed of uptake. For example, the maximum electricity share for the agriculture subsectors was calculated based on Brown and Elliot (2005). For mining, the energy use that cannot be electrified in mining was calculated based on research from ETI (2023) and DCCEEW (2022c) to inform the maximum rate of electrification. This rate can be varied by scenario. For energy efficiency, the maximum uptake rate is based on previous work to understand efficiency opportunities across industrial sectors based on type, e.g. light manufacturing, heavy manufacturing, mining etc., and split across three categories – process improvements, small equipment upgrades and major equipment upgrades.
- In **residential buildings**, upper limits on electrification uptake are based on the assumption that relevant end uses are able to fully electrify by 2050. Energy efficiency uptake limits are based on savings potentials for relevant end uses. Assumptions on costs and savings are derived from a variety of sources including the Low Carbon High Performance report (ClimateWorks Australia, 2016) and updated over time.
- In **commercial buildings**, upper limits on electrification vary by end-use by 2050, based on research derived from various reports and literature on commercial buildings energy use and electrification potential. Some sources of electrification are from QUT (2022), UTS (2023), Li and Rismanchi (2023). Energy efficiency uptake limits are based on savings potentials for relevant end uses derived from ClimateWorks Australia (2016).

The maximum uptake rates determined through the research above is used for Green Energy Exports and Green Energy Industries scenarios. Limits and uptake rates for the Progressive Change and Step Change scenarios are then determined based on the relative uptake of energy efficiency or electrification in their associated scenarios from the IEA's World Energy Outlook (2024). Electrification and energy efficiency settings are outlined below in Apx Table B-13. Before 2027, most scenarios are subject to more constrained limits to represent less divergence expected in the immediate term.

Apx Table B-13 Energy efficiency and electrification input assumptions that vary by scenario (based on maximum feasible rates that vary by technology and subsector, derived from a range of sources as noted above)

Model Input Assumptions	Progressive Change	Step Change	Green Energy Exports	Green Energy Industries
Mapped IEA WEO2024 scenario	Stated Policies (STEPS)	Announced Policies (APS)	Net Zero 2050 (NZE2050)	Net Zero 2050 (NZE2050)
Annual uptake rates of energy efficiency	54% of maximum feasible rate	79% of maximum feasible rate	Maximum feasible rate	Maximum feasible rate
Annual uptake of electrification in industry, resources and agriculture	Pre 2027: 13% of maximum feasible rate Post 2027: 26% of maximum feasible rate	Pre 2027: 26% of maximum feasible rate Post 2027: 74% of maximum feasible rate	Pre 2027: 26% of maximum feasible rate Post 2027: Maximum feasible rate	Pre 2027: 26% of maximum feasible rate Post 2027: Maximum feasible rate
Annual uptake of electrification in residential and commercial buildings	Pre 2027: 27% of maximum feasible rate Post 2027: 54% of maximum feasible rate	Pre 2027: 54% of maximum feasible rate Post 2027: 75% of maximum feasible rate	Pre 2027: 54% of maximum feasible rate Post 2027: Maximum feasible rate	Pre 2027: 54% of maximum feasible rate Post 2027: Maximum feasible rate

B.4 Activity growth

Deloitte Access Economics was engaged by AEMO to develop long-term macro-economic forecast for Australia. These forecasts were developed at the national, state and territory levels using a Deloitte Access Economics Macroeconomic model (DAEM). DAEM uses key Australian Bureau of Statistics data to develop these economic forecasts.

Industry, resources and agriculture activity projections have been developed by using the historical energy demand from Australian Energy Statistics (Table F) and calculating the growth rates in energy demand for each Australian and New Zealand Standard Industrial Classification (ANZSIC) division based on the Gross Value Added (GVA) projections provided by DAEM.

For commercial buildings, the growth rates in floorspace are informed by the Commercial Buildings Baseline Study (DCCEEW, 2022b) and the gross value added (GVA) forecasts that relate to the commercial building sector from DAEM. These projections are varied by scenario based on mapping the respective AusTIMES commercial buildings types to the ANZSIC divisions to match the GVA data provided by DAEM and then indexing the GVA data provided for each scenario to a base year (2022) and a base scenario (Progressive change). The mapping of the building types is shown below in Apx Table B-14.

Apx Table B-14 Commercial building mapping from ANZSIC division

Current AusTIMES sector	Mapped ANZSIC division	Details
Hospital	Q	Q Health Care and Social Assistance > 84 Hospitals
Hotel	E	30 Building Construction> 302 Non-Residential Building Construction > 3020 Non-Residential Building Construction
Law Court	O	O Public Administration and Safety >754 Justice > 7540 Justice
Office	E	E Construction > 302 Non-Residential Building Construction > 3020 Non-Residential Building Construction
Public Building	E	E Construction > 302 Non-Residential Building Construction > 3020 Non-Residential Building Construction
Retail	G	G Retail Trade
Supermarket	G	G Retail Trade > 41 Food Retailing > 411 Supermarket and Grocery Stores > 4110 Supermarket and Grocery Stores
School	P	P Education and Training > 80 Preschool and School Education
Tertiary	P	P Education and Training > 81 Tertiary Education
Data Centre	J	J Information Media and Telecommunications> 59 Internet Service Providers, Web Search Portals and Data Processing Services > 592 Data Processing, Web Hosting and Electronic Information Storage Services
Aged Care	Q	Q Health Care and Social Assistance > 86 Residential Care Services > 860 Residential Care Services > 8601 Aged Care Residential Services

For residential buildings, the growth rate in number of households is calculated for each state based on the Australian Bureau of Statistics (ABS) Series II household projections and the scenario-specific residential energy demand projections are scaled based on the ratio of scenario-specific population projections provided by DAEM to the ABS Series II household projections.

Activity growth in transport demand for road vehicle kilometres travelled and energy consumption in non-road transport are sourced from Graham et al. (2025).

B.5 Electricity sector

The input assumptions that vary by scenario are shown in Apx Table B-15.

Apx Table B-15 Electricity sector input assumptions that vary by scenario

Model Input Assumptions	Progressive Change	Step Change	Green Energy Exports	Green Energy Industries
Generator and storage build costs	CSIRO GenCost 2024-25 Consultation Draft Current Policies	CSIRO GenCost 2024-25 Consultation Draft	CSIRO GenCost 2024-25 Consultation Draft Global NZE by 2050	CSIRO GenCost 2024-25 Consultation Draft Global NZE by 2050

		Global NZE post 2050		
Generator retirements	In line with expected closure years, or earlier if economic or driven by decarbonisation objectives beyond 2030.	In line with expected closure year, or earlier if economic or driven by decarbonisation objectives	In line with expected closure year, or earlier if economic or driven by decarbonisation objectives	In line with expected closure year, or earlier if economic or driven by decarbonisation objectives
Fuel price settings (natural gas)	NEM and NT: ACIL Allen (2024), Progressive Change WA: ACIL Allen (2024), Low case: Progressive Change	NEM and NT: ACIL Allen (2024), Step Change WA: ACIL Allen (2024), Expected case: Step Change	NEM and NT: ACIL Allen (2024), Green Energy Exports Scenario WA: ACIL Allen (2024), High case: Hydrogen Export	NEM and NT: ACIL Allen (2024), Green Energy Exports Scenario WA: ACIL Allen (2024), High case: Hydrogen Export
Fuel price settings (coal)	ACIL Allen (2024) Progressive Change	ACIL Allen (2024) Step Change	ACIL Allen (2024) Green Energy Exports	ACIL Allen (2024) Green Energy Exports
Installed capacity of distributed generation and customer owned storage	CER adoption modelling, Progressive Change (Graham and Mediwaththe, 2024)	CER adoption modelling, Step Change (Graham and Mediwaththe, 2024)	CER adoption modelling, Green Energy Exports (Graham and Mediwaththe, 2024)	CER adoption modelling, Green Energy Exports (Graham and Mediwaththe, 2024)

There are several data assumptions for the electricity sector that do not vary by scenario. These assumptions mainly relate to existing generators, some elements for new generation technologies, and state or national policies. These assumptions apply to all scenarios. The assumptions that are not varied by scenario are outlined in the ISP assumptions workbook and are listed below for the NEM (Apx Table B-16) and the AEC (2024) and advice from the AEMO Future System Design Team for the South West Interconnected System (SWIS) (Apx Table B-17), and includes the recent WA Government announcement on closure of state-owned coal-fired generators.

Apx Table B-16 ISP assumptions workbook used across the scenarios for the NEM

Assumption	Source
Nameplate capacity of existing generators	"Maximum capacity" tab https://aemo.com.au/-/media/files/major-publications/isp/2023/2023-iasr-assumptions-workbook.xlsx?la=en
Cost and performance data on existing power stations	"Existing Gen Data Summary" tab https://aemo.com.au/-/media/files/major-publications/isp/2023/2023-iasr-assumptions-workbook.xlsx?la=en
Expected closure year	Generating unit expected closure year – July 2024 https://aemo.com.au/en/energy-systems/electricity/national-electricity-market-nem/nem-forecasting-and-planning/forecasting-and-planning-data/generation-information

Regional reserves	"Reserves" tab https://aemo.com.au/-/media/files/major-publications/isp/2023/2023-iasr-assumptions-workbook.xlsx?la=en
Regional cost factors	"Locational Cost Factors" and "Renewable Energy Zones" tabs https://aemo.com.au/-/media/files/major-publications/isp/2023/2023-iasr-assumptions-workbook.xlsx?la=en
GHG emission factors	"Emissions intensity" tab https://aemo.com.au/-/media/files/major-publications/isp/2023/2023-iasr-assumptions-workbook.xlsx?la=en

Apx Table B-17 Assumptions used across the scenarios for the SWIS

Assumption	Source
Nameplate capacity of existing generators	Appendix 1 (AEC, 2024)
Cost and performance data on existing power stations	GHD, 2018 AEMO cost and technical parameter review https://aemo.com.au/-/media/files/electricity/nem/planning_and_forecasting/inputs-assumptions-methodologies/2019/ghd-aemo-revised---2018-19-costs_and_technical_parameter.xlsb?la=en&hash=B4BE15FE1B665E5B63F691E22A6916FB
Expected closure year	WA Government announcement 14 June 2022: https://www.mediastatements.wa.gov.au/Pages/McGowan/2022/06/State-owned-coal-power-stations-to-be-retired-by-2030.aspx Advice from AEMO System Design Team
Regional reserves	335 MW (AEMO)
GHG emission factors	DCCEEW (2024f)

National and state/territory renewable policies included in all scenarios are listed in Apx Table B-18.

Apx Table B-18 National and State/Territory Renewable Policies

Policy	Description
Renewable policies (national)	Renewable Energy Target (RET) consisting of: large-scale RET (LRET): 33,000 GWh of large-scale renewables, so that 23.5% of Australia's electricity in 2020 will be generated from renewables (33,000 GWh maintained until 2030). Small-scale renewable energy scheme (SRES): incentives for home-owners and small businesses to install eligible small-scale renewable energy systems and solar water-heating systems. The Federal Government has aims to reach 82% share of renewable generation by 2030 by unlocking investment to enable upgrades to the electricity grids through the Rewiring the Nation policy.

Renewable policies (state)	Northern Territory Renewable Energy Target: 50% of electricity consumed in 2030 from grid connected installations, including all Aboriginal communities supplied by Indigenous Essential Services to be sourced from renewable energy by 2030. Queensland Renewable Energy Target (QRET): 50% renewable electricity generation by 2028, 70% renewable generation by 2032, 80% renewable generation by 2035. Victoria Renewable Energy Target (VRET): 40% renewable electricity generation by 2025; 65% renewable electricity generation by 2030; and 95% renewable electricity generation by 2035. Victoria Offshore Wind Energy Target: at least 2gigawatts (GW) of offshore generation capacity by 2032; 4 GW by 2035; and 9 GW by 2040. Victoria Energy Storage Target: at least 2.6 GW of energy storage capacity by 2030; and at least 6.3 GW by 2035. Tasmanian Renewable Energy Target (TRET): 15,750 GWh by 2030; 21,000 GWh by 2040. NSW *Electricity Infrastructure Investment Act 2020*: The Act sets out minimum objectives that by the end of 2029, construction of renewable generation infrastructure that produces at least the same amount of electricity in a year as 8 GW in New England, 3 GW in Central-West Orana and 1 GW of additional capacity. The Act also includes a minimum target of the construction of 2 GW of long-duration (8 hours or more) storage infrastructure by the end of 2029 in addition to Snowy 2.0. The annual construction trajectory of energy generating capability that is specified in the Consumer Trustee's Infrastructure Investment Opportunities Report over the period until the minimum objective is met will be applied as a modelling input (providing a development floor that the model can exceed if appropriate). That trajectory outlines 33,600 GWh of equivalent generating capacity by the end of 2029. Current CER policies (Graham and Mediwaththe, 2024)

B.6 Hydrogen production

There are numerous hydrogen production pathways specified in AusTIMES:

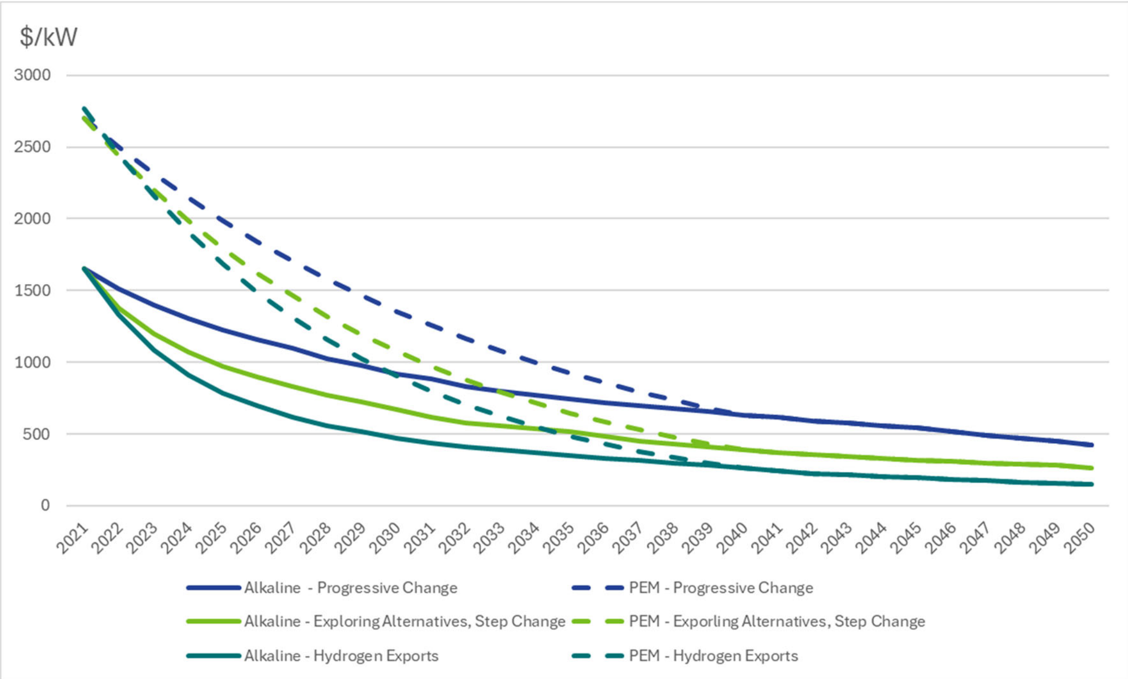
- Proton exchange membrane (PEM) electrolysis;
- Alkaline electrolysis (AE)
- Steam methane reforming (SMR)
- SMR with carbon and storage (CCS)
- Brown coal gasification with CCS
- By-product hydrogen produced in the chemicals industry.

Based on the demand for hydrogen which is a combination of exogenous inputs (e.g. export demand for hydrogen and commodities, uptake of fuel cell vehicles in road transport) and endogenous outcomes (e.g. hydrogen reciprocating engines in the electricity sector; hydrogen co-firing in existing or new gas turbines; least cost fuel switching in buildings, uptake across industry and non-road transport), AusTIMES optimised investment in production capacity to satisfy demand. Costs of transport and storage of hydrogen to deliver hydrogen to end-users is based on ACIL Allen (2024).

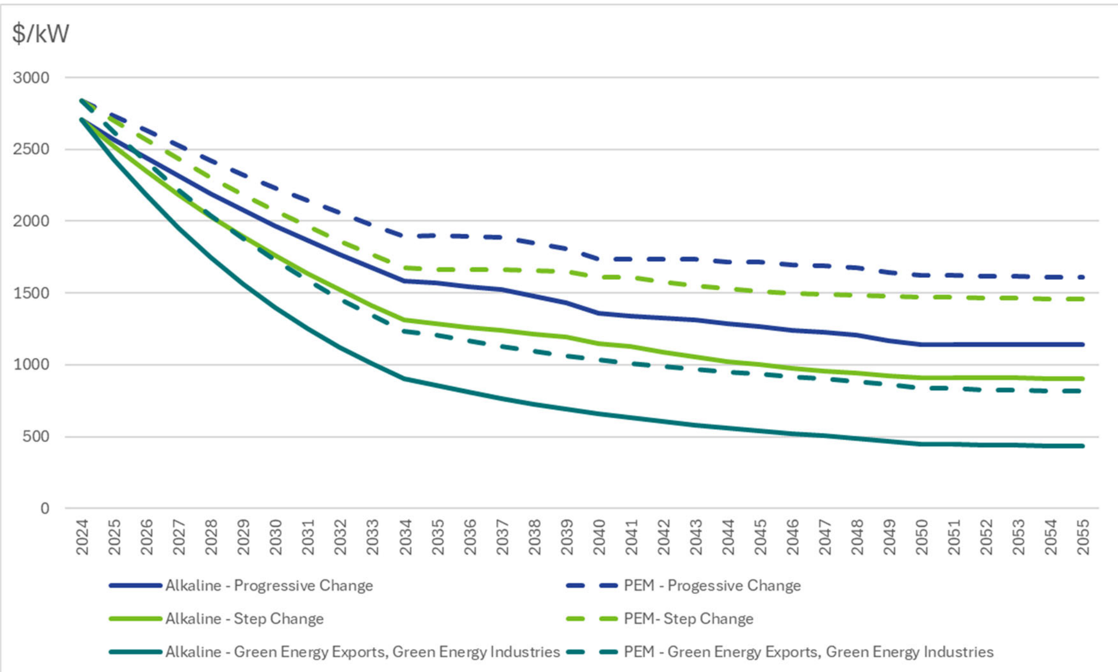
Cost and performance data for non-electrolyser production pathways were initially developed in the *National Hydrogen Strategy*, then subsequently updated in the *Technology Investment Roadmap* process led by DISER and are now available as part of GenCost (Graham et al., 2024). Cost and performance data for electrolyser production pathways are mapped to the relevant global scenario (see Apx Figure B-1 and Apx Figure B-2 for the electrolyser cost projections, respectively, and Apx Table B-20 for SMR and SMR+CCS cost projections), although the differences between the scenarios was expanded to better account for uncertainty and to differentiate across the scenarios.

Apx Table B-19 Mapping of global scenario to hydrogen production costs

Model Input Assumptions	Progressive Change	Step Change	Green Energy Exports	Green Energy Industries
Hydrogen production process capital costs	CSIRO GenCost 2024-25 Consultation Draft Current Policies	CSIRO GenCost 2024-25 Consultation Draft Global NZE post 2050	CSIRO GenCost 2024-25 Consultation Draft Global NZE by 2050	CSIRO GenCost 2024-25 Consultation Draft Global NZE by 2050



Apx Figure B-1 Electrolyser capital costs by scenario for MSM 2022 (previous work) iteration



Apx Figure B-2 Electrolyser capital costs by scenario and MSM 2024 (this work) iteration

Apx Table B-20 SMR technology capital costs by scenario ($/kW)

	Progressive Change		Step Change		Green Energy Exports, Green Energy Industries	
	SMR	SMR + CCS	SMR	SMR + CCS	SMR	SMR + CCS
2022	1380	2208	1386	2222	1386	2222
2023	1390	2235	1390	2235	1390	2235
2024	1400	2262	1394	2248	1394	2248
2025	1411	2288	1398	2261	1398	2261
2026	1421	2316	1401	2275	1401	2275
2027	1432	2343	1405	2288	1405	2288
2028	1427	2338	1409	2301	1409	2301
2029	1422	2333	1413	2315	1413	2315
2030	1417	2329	1417	2329	1417	2329
2031	1412	2324	1412	2324	1412	2324
2032	1407	2319	1407	2319	1407	2319
2033	1402	2314	1402	2314	1402	2314
2034	1397	2309	1397	2309	1397	2309
2035	1392	2304	1392	2304	1392	2304
2036	1387	2300	1387	2300	1387	2300
2037	1382	2295	1382	2295	1382	2295
2038	1377	2290	1377	2290	1377	2290
2039	1373	2285	1373	2285	1373	2285
2040	1368	2281	1368	2281	1368	2150
2041	1363	2276	1363	2276	1363	2145
2042	1358	2271	1358	2271	1358	2140
2043	1354	2267	1354	2267	1354	2136
2044	1349	2262	1349	2262	1349	1843
2045	1344	2257	1344	2257	1344	1828
2046	1339	2253	1339	2253	1339	1824
2047	1335	2248	1335	2248	1335	1819
2048	1330	2244	1330	2244	1330	1806
2049	1325	2239	1325	1906	1325	1799
2050	1321	2235	1321	1810	1321	1794
2051	1321	2235	1321	1810	1321	1794
2052	1311	2226	1311	1810	1311	1794

2053	1311	2226	1311	1810	1311	1784
2054	1302	2217	1302	1792	1302	1775
2055	1302	2217	1302	1792	1302	1775
2056	1302	2217	1302	1792	1302	1775
2057	1302	2217	1302	1792	1302	1775
2058	1302	2217	1302	1792	1302	1775

B.7 Green commodities and hydrogen export

Green commodity production and hydrogen export volumes were an input into the 2024 multi-sectoral modelling. Methodology and assumptions embedded in the green commodity and hydrogen export trajectories can be found in ACIL Allen (2024).

B.8 Biomethane production

Production volumes and cost estimates of biomethane were an input into the 2024 multi-sectoral modelling. Methodology and assumptions that produced the cost-quantity functions can be found in ACIL Allen (2024).

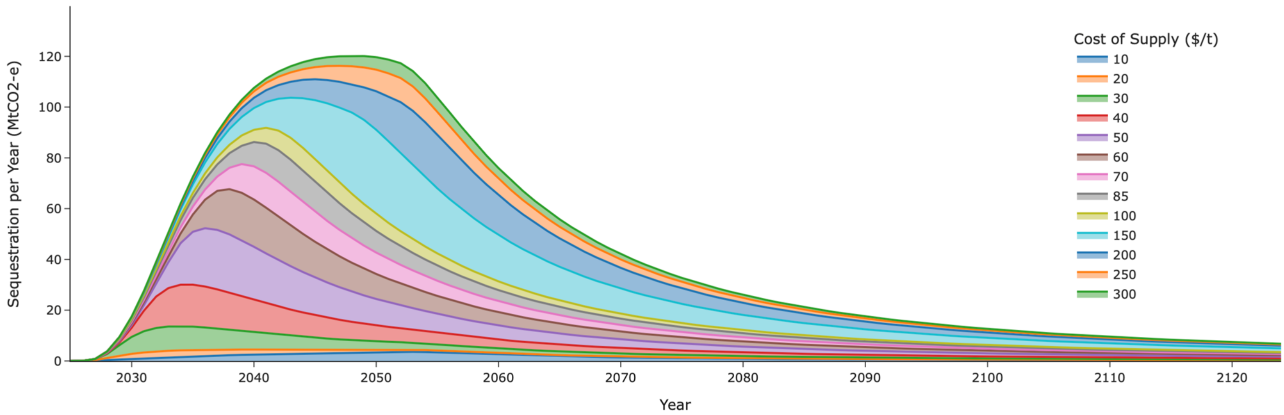
B.9 Emissions sequestration

Emissions sequestration (or negative emissions) is required for the economy to meet net zero emissions while residual emissions are still occurring. Land-based emissions sequestration, direct air capture (DAC) and carbon capture & storage (CCS) are the primary methods considered in AusTIMES. All sequestration in AusTIMES is assumed to occur domestically within Australia – the use of international offsets is not considered.

B.9.1 Land-based sequestration

Land-based emissions sequestration is represented in AusTIMES as a discrete category of emissions for communication purposes but could be considered under the same ANZSIC codes (03, 051) as “Forestry and logging”. Land-based emissions sequestration is modelled using a cost-curve approach. This curve was derived using results from the Land-Use Trade-offs (LUTO) model (see Verikios et al. (2024) for a description of the LUTO model). In short, LUTO calculates the volume of sequestration that would be profitable to supply, up to maximum thresholds, where delivery of carbon credits would provide higher economic return than competing agricultural land uses. It is based on a scenario that does not consider the use of international offsets towards Australia’s climate targets. To construct the cost curve, LUTO was run multiple times, each with an input carbon price matching the listed costs of supply. A hurdle rate of 5 was used for those LUTO calculations (the factor by which switching from other land uses to sequestration is more profitable), and LUTO’s limits on uptake rate were enabled. All other settings were consistent with the work detailed in Verikios et al. (2024).

In addition to the cost curve, LUTO provides the sequestration rate over time for each bundle of plantings for that cost, i.e., all new plantings exhibit a profile of sequestration which starts at zero, reaches a maximum some number of years later which varies strongly with the quality of the available land / types of plantings available for that land. This is an improvement to the way land-based sequestration is modelled from the 2022 version of this work. Apx Figure B-3 illustrates this variation and the maximum possible sequestration but differs from the actual model solution since Apx Figure B-3 assumes all plantings are taken up immediately and at their full potential whereas for the model results the model determines those endogenously.



Apx Figure B-3 Maximum availability of land-based sequestration if all volume was planted in 2025

Note that this plot is for illustrative purposes only since it assumes all new plantings occur in 2025. For the model results above, the model determines when each component of the cost curve is taken up. The decrease starting in the late 2050s indicate indicates that if all the land-based sequestration at the model's disposal were taken up in 2025, then the rate of sequestration would reach a maximum near 2050 and decline after that as the plantings rate of carbon absorption naturally slows. In previous work the rate of sequestration for each cost block was assumed flat with time.

B.9.2 Technical sequestration

The technical emissions sequestration options in AusTIMES include direct air capture (DAC) and select applications of carbon capture and storage (CCS).

While generally considered a higher cost option compared to other abatement and sequestration technologies, cost and technical parameters for DAC were introduced to AusTIMES for the 2022 multi-sector modelling. DAC is currently a non-mature technology that is yet to be demonstrated at scale, and as such there is a wide range of uncertainty around the costs and technical effectiveness. Best-estimate costs and technical parameters were drawn from the literature. Most parameters including initial capital cost assumptions, O&M costs, electricity and heat requirements and efficiency are derived from Fasihi et al. (2019), with the assumption that efficiencies and costs improve over time in line with cost analysis from IEA (2022) (see Apx Table B-21), and that DAC plants cannot be built until the year 2030.

Apx Table B-21 Technical and cost parameters for direct air capture (DAC) in AusTIMES, drawn from Fasihi et al. (2019) and IEA (2022)

Parameter	Unit	2020	2030	2040	2050
Capital cost	A$/tCO2	$1,132	$487	$399	$311

Fixed operational cost	% Capital cost p.a.	4%	4%	4%	4%
Lifetime	Years	20	20	20	20
Electricity demand	kWh electricity/tCO2	250	225	203	182
Low-temperature heat demand	kWh thermal heat/tCO2	1,750	1,500	1,286	1,102

Carbon capture and storage is available as an option for select applications including hydrogen production, electricity generation (where it is generally not taken up), and heavy industry. Specifically, for process and energy emissions in chemical manufacturing, gas extraction, LNG liquefaction, alumina, metal ore mining and steelmaking. Cost and technical assumptions for industrial CCS are drawn from background research under the Australian Energy Transitions Initiative. These technologies are fully-costed in AusTIMES and the model may choose to implement them as part of its cost optimisation. Typically, CCS is one of the most expensive solutions to decarbonise industry, and is not taken up at a large scale when compared with other sequestration methods.

B.10 Other end-use sector assumptions

Apx Table B-22 below details the key input assumptions for the industrial sector.

Apx Table B-22 Industry sector inputs that vary by scenario

Model input Assumptions	Progressive Change	Step Change	Green Energy Exports	Green Energy Industries
Industrial activity projection	Activity growth rates of most industrial subsectors are based on the Gross Value Added (GVA) projections of ANZSIC Divisions B to E provided by AEMO, except coal and natural gas mining (which are informed by IEA World Energy Outlook 2024), and green commodity production (ACIL Allen, 2024).			
Activity compound annual growth rates	Overall, 0.20% p.a. from 2024 to 2058	Overall, 0.63% p.a. from 2024 to 2058	Overall, 3.79% p.a. from 2024 to 2058	Overall, 1.10 % p.a. from 2024 to 2058
Coal export projections compound annual growth rates	Consistent with IEA STEPS at -1.49 % p.a. from 2023 to 2050	Consistent with IEA APS at -4.12 % p.a. from 2023 to 2050	Consistent with IEA NZE2050 at –9.47% p.a. from 2023 to 2050	
LNG export projections compound annual growth rates	Data provided by AEMO -1.97% p.a from 2024 to 2058	Data provided by AEMO -3.08% p.a from 2024 to 2058	Data provided by AEMO -3.97% p.a from 2024 to 2058	
Autonomous energy efficiency	Varies by subsector, between -0.09% efficiency decline and 2.01 % improvement per year			
Annual uptake limits for energy efficiency	54% of maximum feasible rate	79% of maximum feasible rate	Maximum feasible rate (as outlined in Section B3)	

Annual uptake limits for electrification	Pre 2027: 13% of maximum feasible rate Post 2027: 26% of maximum feasible rate	Pre 2027: 26% of maximum feasible rate Post 2027: 74% of maximum feasible rate	Pre 2027: 26% of maximum feasible rate Post 2027: Maximum feasible rate (as outlined in Section B3)

B.10.1 Transport

Adoption modelling of alternative vehicles (plug-in hybrid electric vehicles, battery electric vehicles, and fuel cell electric vehicles using hydrogen) has been conducted by CSIRO, under a separate consultancy, in parallel to the multi-sector energy modelling. The varying inputs be scenario are outlined below (Apx Table B-23). For more detail, please refer to Graham et al., 2025).

Apx Table B-23 Transport sector inputs that vary by scenario

Model input Assumptions	Progressive Change	Step Change	Green Energy Exports and Green Energy Industries
Activity growth	Lower	Moderate	Higher
ICE vehicle availability	New vehicles unavailable beyond 2050	New vehicles unavailable beyond 2045	New vehicles unavailable beyond 2040
Cost of fuel cell vehicles	High	Medium	Low
ICE commercial services collapse / no longer viable to operate[1]	2060	2055	2050

1. Special purpose vehicles exempted. Commercial services include fuel supply, parts supply, and mechanical repairs. ICE refers to an Internal Combustion Engine.

Economic and population growth impacts both passenger and freight transport demand across road and non-road transport. Demand projections by transport segment are consistent with Graham et al. (2025). The uptake of alternative vehicle technologies by scenario is an input into AusTIMES for the multi-sectoral modelling. The assumptions impacting this potential uptake are documented in Graham et al. (2025).

B.10.2 Non-road transport

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

Until recently, the main option considered for decarbonising aviation is sustainable jet fuel which is a drop-in fuel for existing turbine aircraft currently using kerosene. This fuel can be blended with kerosene up to 100% based on numerous successful trials over the last two decades. Previously, aviation was not considered a candidate for electrification due to range limitations and weight considerations. However, with further improvements in battery technology, the success of electric-based drone technology in non-passenger applications and the continued proliferation of transport-on-demand business models in cities, electrification of aviation is considered to be more plausible and is gaining traction in some segments like regional flights (<1000km range). Currently, delivery models being considered are diverse and include: hybrids (single electric engine added to aircraft with other conventional propulsion), pure electric with modified air frame, vertical aero propeller / helicopter designs, hydrogen fuel aircraft designs and electric on-ground taxiing power. However, it is unclear if any of these designs could replace some long-haul aviation. It is more likely to be adopted for shorter route aviation.

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

The electricity consumption projections for passenger rail are similar to the projected rail passenger demand in Graham et al. (2025). This is estimated by multiplying the extrapolated trend in rail energy requirements per passenger kilometre. For rail freight and aviation electrification, CSIRO estimates the total overall energy demand for each non-road transport sector before estimating the electricity demand for each non-road sector in accordance with the assumptions outlined in Apx Table B-24. The adopted assumptions are a subjective assessment of potential technology readiness for the non-road sector based on the scenario narratives.

Apx Table B-24 Rail freight and aviation electrification assumptions

Scenario	Electrification commencement date		Maximum share by 2050 (%)
	Rail freight	Aviation	
Progressive Change	2048	2047	3
Step Change	2035	2030	10
Green Energy Exports	2030	2027	20
Green Energy Industries	2030	2027	20

There are several transport sector assumptions that do not vary by scenario. These are listed in Apx Table B-25.

Apx Table B-25 Transport sector inputs that do not vary by scenario

Model Input Assumptions	Data sources

Energy balance	*Australian Energy Statistics (DCCEEW, 2024a)*
Vehicle stock, scrapping rate	*Road Vehicles, Australia, January 2024* (BITRE, 2024)
Average vehicle kilometres travelled	*Australian Infrastructure Statistics Yearbook 2023* (BITRE, 2023)
GHG emission factors	*Australian National Greenhouse Accounts Factors 2024* (DCCEEW, 2024f)
Maintenance costs	ATAP (2016); RACQ (2018)
Registration, insurance costs	State/territory government websites
ICE vehicle fuel efficiency improvements	Graham et al. (2025)
Retail fuel price components	Australian Institute of Petroleum
Fuel excise rates	Australian Taxation Office
Subsidies	Current policies on stamp duty, registration exemptions or direct financing retained until 2030
Biofuel mandates	NSW - *Biofuel (Ethanol Content) Act 2007*, historical take-up of ethanol and biodiesel is from the *Office of Fair Trading*. QLD - The *Liquid Fuel Supply (Ethanol and Other Biofuels Mandate) Amendment Act 2015*
New Vehicle Efficiency Standard	Apply the carbon dioxide (g/km) emission limits to Type 1 (passenger) and Type 2 (light commercial) vehicles for the period 2025-2029 as set out in Section 22 of the *New Vehicle Efficiency Standard Act 2024*

B.10.3 Residential buildings

Apx Table B-26 below details the key input assumptions for the Residential sector.

Apx Table B-26 Residential buildings input assumptions

Model input Assumptions	Progressive Change	Step Change	Green Energy Exports and Green Energy Industries
Household activity projection (millions of dwellings)	Based on the Australian Bureau of Statistics (ABS) Series II 2024 household projections, the residential energy demand is scaled to the scenario-specific population projections provided by AEMO.		
Compound annual growth rates (net increase in dwellings)	1.19% p.a. from 2024 to 2058	1.41% p.a. from 2024 to 2058	1.6% p.a. from 2024 to 2058
Autonomous energy efficiency	Ranging from 0.45 % p.a. to 1.41% p.a. depending on end use (does not vary by scenario)		
Annual uptake limits for energy efficiency	54% of maximum feasible rate	79% of maximum feasible rate	Maximum feasible rate (as outlined in Section B3)
Annual uptake limits for electrification	Pre-2027: 27% of maximum feasible rate Post-2027: 54% of maximum feasible rate	Pre-2027: 54% of maximum feasible rate Post-2027: 75% of maximum feasible rate	Pre-2027: 54% of maximum feasible rate Post-2027: Maximum feasible rate (as outlined in Section B3)
Hydrogen uptake potential	Endogenously determined based on production cost of hydrogen compared to that of other gaseous fuel options. See Appendix B.6 for more details. All scenarios allow a maximum of 10% by volume to be blended in pipelines.		

Biomethane uptake potential	Endogenously determined based on production cost of biomethane compared to that of other gaseous fuel options. See Appendix B.8 for more details. No explicit upper or lower bound at an end-user level for all scenarios.

B.10.4 Commercial buildings

Apx Table B-27 below details the key input assumptions for the Commercial sector.

Apx Table B-27 Commercial buildings input assumptions

Model input Assumptions	Progressive Change	Step Change	Green Energy Exports	Green Energy Industries
Commercial activity projection (millions m2 of floorspace)	Based on the Commercial Buildings Baseline Study (2022) commercial floorspace, the floorspace change is scaled to the scenario-specific GVA projections provided by AEMO (see A.1.3 for details).			
Compound annual growth rates (mapped commercial buildings GVA)	1.61% p.a. from 2024 to 2058	2.06% p.a. from 2024 to 2058	2.86% p.a. from 2024 to 2058	2.81% p.a. from 2024 to 2058
Autonomous energy efficiency	Ranging from 0.11 % p.a. to 0.9% p.a. depending on end use (does not vary by scenario)			
Annual uptake limits for energy efficiency	54% of maximum feasible rate	79% of maximum feasible rate	Maximum feasible rate (as outlined in Section B3)	
Maximum annual uptake limits for electrification	Pre-2027: 27% of maximum feasible rate Post-2027: 54% of maximum feasible rate	Pre-2027: 54% of maximum feasible rate Post-2027: 75% of maximum feasible rate	Pre-2027: 54% of maximum feasible rate Post-2027: Maximum feasible rate (as outlined in Section B3)	
Hydrogen uptake potential	Endogenously determined based on production cost of hydrogen compared to that of other gaseous fuels. See Appendix B.6 for more details. All scenarios allow a maximum of 10% by volume to be blended in pipelines.			
Biomethane uptake potential	Endogenously determined based on production cost of biomethane compared to that of other gaseous fuels. See Appendix B.8 for more details. No explicit upper or lower bound at an end-user level for all scenarios.			

B.10.5 Agriculture

Apx Table B-28 below details the key input assumptions for the agriculture sector.

Apx Table B-28 Agriculture input assumptions

Model input Assumptions	Progressive Change	Step Change	Green Energy Exports	Green Energy Industries
Agricultural activity projection	Activity growth rates are based on the Gross Value Added (GVA) projections of ANZSIC Division A provided by DAEM.			

Compound annual growth rates (industrial GVA)	0.51% p.a. from 2024 to 2058	0.83 % p.a. from 2024 to 2058	1.38% p.a. from 2024 to 2058	1.44% p.a. from 2024 to 2058
Autonomous energy efficiency	0.4% p.a. is assumed across all subsectors (consistent with analysis of long-term energy efficiency trends that have occurred)[20]			
Annual uptake limits for energy efficiency	54% of maximum feasible rate	79% of maximum feasible rate	Maximum feasible rate (as outlined in Section B3)	
Annual uptake limits for electrification	Pre 2027: 13% of maximum feasible rate Post 2027: 26% of maximum feasible rate	Pre 2027: 26% of maximum feasible rate Post 2027: 74% of maximum feasible rate	Pre 2027: 26% of maximum feasible rate Post 2027: Maximum feasible rate (as outlined in Section B3)	
Average share of baseline non-energy emissions that can be avoided via endogenous non-energy abatement options	2030: 0% 2050: 22%	2030: 20% 2050: 33%	2030: 20% 2050: 33%	

B.11 Changes from the 2022 Multi-Sector Modelling

In 2022, CSIRO and Climateworks Centre were commissioned by AEMO to provide similar Multi-Sector Modelling outputs to this piece of work, ahead of the 2024 Integrated System Plan. The outcomes of this work were documented in the Multi-Sector Modelling report prepared by CSIRO and Climateworks Centre for AEMO (Reedman et al., 2022).

Between the 2022 and 2024 Multi-Sector Modelling projects, a number of changes were made. These are summarised below.

B.11.1 Modelled scenarios

Four scenarios were modelled for AEMO in the 2022 Multi-sector Modelling project: Progressive Change, Step Change, Exploring Alternatives and Hydrogen Export (subsequently renamed Green Energy Exports). An updated set of scenarios has been modelled in the 2024 Multi-Sector Modelling, as outlined in Section 2.1, and several of these relate directly to the scenarios in the 2022 modelling.

Progressive Change, Step Change and Green Energy Exports remain, although with minor differences. Exploring Alternatives has not been retained. The fourth scenario constitutes a variation on the Green Energy Exports scenario and is called Green Energy Industries.

[20] Based on ClimateWorks Decarbonisation Futures work https://www.climateworkscentre.org/resource/decarbonisation-futures-solutions-actions-and-benchmarks-for-a-net-zero-emissions-australia/

B.11.2 Regional scope of work

AusTIMES is a national whole-of-economy model and was run including full coverage of all states and territories in the 2022 Multi-Sector Modelling. However, in 2022, results were reported only for the NEM-connected states and territories (New South Wales, Victoria, Queensland, South Australia, Tasmania and Australian Capital Territory) and Western Australia. The development of inputs and assumptions was also focused primarily on these states and territories.

For this modelling, AusTIMES was once again run including full coverage of Australia. However, the regional scope of outputs reported, and of input development, was expanded to consider Northern Territory. This means that the regional coverage of this study includes all Australian states and mainland territories.

B.11.3 Carbon budget approach

Both the method for determining the most ambitious carbon budget, and the accounting within the method for mapping cumulative emissions to temperature rise have been updated.

The carbon budget to temperature mapping approach documented in Appendix B.2 has been updated to incorporate the latest science on carbon budgets from the IPCC's Sixth Assessment Report (Arias et al., 2021) and the most current approach for translating this to an Australian level, based on consultation with Australian-based IPCC experts (Nicholls, Z, Pers. Comm., 15 July 2022). This has included an update to the 'true pre-industrial' baseline adjustment, to ensure the value includes non-CO2 emissions effects, to align with the basis for the budgets from IPCC AR6 (+72GtCO_2-e to global budgets), as well as an update to the adjustment for non-CO2 emissions to the total budget, based on an updated relationship between CO2 and GHG emissions from AR6 (+~40GtCO_2-e to global budgets). Consideration of emissions from international shipping and aviation (-50GtCO_2-e from global budgets) has also been included, as well as an adjustment to final Australian budgets, based on historical national inventory updates up to 2022 (-0.7GtCO_2-e from Australian budgets).

The method for determining which carbon budget to use was changed away from using the temperature target as the starting point (and deriving a carbon budget) to instead using a series of model solutions to determine what the most ambitious budget was that the set of assumptions, technologies, etc would support; and then mapping that model determined budget to temperature target using the above. This allows a more effective setting of the range of scenario budgets, i.e., fastest decarbonisation (in the Green Energy scenarios), and decarbonisation driven only by the legislated 2030 and 2050 targets (in Progressive Change). The allowed overshoot in the carbon budget was more constrained in this work (previously it extended to more than 50% of the imposed budget in the hydrogen focused scenario whereas here it is limited to 35% and is only taken up in the Green Energy scenarios – previously there was also overshoot in Step Change). This level of overshoot is broadly consistent with the recent emissions pathways work by CSIRO and the Climate Change Authority [Verikios et al., 2024; Climate Change Authority, 2024].

B.11.4 Emissions sequestration in AusTIMES

The approach to emissions sequestration in AusTIMES, documented in Appendix B.9 has been updated between the 2022 and 2024 Multi-Sector Modelling work. Previously this relied on an exogenous trajectory based on a cost-curve approach used by DISER (2021a). This effectively delays the uptake of LULUCF compared to previous work as it more accurately models the variable carbon absorption over time of new plantings. Assumptions related to Direct Air Capture (DAC) have also been updated (see Appendix B.9).

B.11.5 Biomethane

Biomethane was modelled as an endogenous fuel option in the 2022 Multi-Sector Modelling work. In 2024, cost-quantity functions for the production cost of biomethane from three different production processes estimated by ACIL has been imposed in AusTIMES (see ACIL Allen, 2024).

B.11.6 Electrification and Energy Efficiency

Similar to the 2022 Multi-Sector Modelling work, the same approach was used to control energy efficiency and electrification uptake via a combination of annual uptake rates or penetration rates, that could vary by scenario based on relativities observed in the IEA WEO 2024 scenarios, to which the 2024 multi-sectoral modelling scenarios are mapped. The rates and mapping to the latest WEO have been updated (Apx Table B-29 and Apx Table B-30).

The electrification limits themselves have been reviewed and updated since the 2022 MSM, with a major focus on the industry and agriculture subsectors. Previously, uptake rates had been more generic rates (i.e. industry averages) applied across the sectors, whereas the review focused on developing a greater understanding of the subsector detail. Available information across all 40+ subsectors was reviewed to understand key processes and energy uses. This was used to make assumptions about what share of overall energy could be electrified in the short term (i.e. by 2030), long term (2050), and some small amounts that likely cannot be electrified. This has largely led to a reduction in electrification potential by 2030, with similar rates retained for 2050, reflecting an assumption that new technology may be developed by that time to support current hard-to-electrify sectors.

Apx Table B-29 Assumptions for the maximum theoretical share of electricity in industry and agriculture subsectors used in current MSM24

Subsectors	Maximum theoretical share of electricity in final energy	
	2030	2050
Sheep and cattle	42%	100%
Dairy	28%	100%
Other animals	18%	100%
Agricultural services and fishing	29%	100%
Grains	43%	100%
Other agriculture	36%	100%
Forestry and logging	54%	100%
Coal mining	28%	99%

Gas mining	0%	100%
Oil mining	0%	100%
Iron ore mining	24%	99%
Non-ferrous metal ores	56%	98%
Bauxite mining	66%	99%
Lithium mining	62%	99%
Copper mining	74%	97%
Nickel mining	84%	98%
Zinc mining	87%	97%
Other mining	43%	99%
Meat products	60%	100%
Other food and drink products	62%	100%
Textiles, clothing and footwear	76%	100%
Wood products	18%	100%
Paper products	90%	100%
Printing and publishing	42%	100%
Petroleum refinery	42%	65%
Other chemicals	25%	65%
Ammonia	30%	30%
Fertilisers	6%	6%
Explosives	63%	63%
Rubber and plastic products	42%	100%
Cement	10%	30%
Non-metallic construction	27%	71%
Alumina	67%	100%
Other non-ferrous metals	24%	36%
Other metal products	26%	32%
Motor vehicle and parts	35%	71%
Other manufacturing products	53%	71%
Gas supply	42%	71%
Gas export (LNG)	0%	100%
Water supply	42%	71%
Construction services	42%	71%

Apx Table B-30 Assumptions for the maximum theoretical share of electricity in industry and agriculture subsectors used in the previous Multisector modelling 2022 (MSM22)

Subsectors	Maximum theoretical share of electricity in final energy	
	2030	2050
Sheep and cattle	100%	100%
Dairy	100%	100%
Other animals	100%	100%
Agricultural services and fishing	100%	100%
Grains	100%	100%
Other agriculture	100%	100%
Forestry and logging	100%	100%
Coal mining	100%	100%
Gas mining	100%	100%
Oil mining	100%	100%

Iron ore mining	100%	100%
Non-ferrous metal ores	100%	100%
Bauxite mining	100%	100%
Lithium mining	100%	100%
Copper mining	100%	100%
Nickel mining	100%	100%
Zinc mining	100%	100%
Other mining	100%	100%
Meat products	100%	100%
Other food and drink products	100%	100%
Textiles, clothing and footwear	100%	100%
Wood products	100%	100%
Paper products	96%	100%
Printing and publishing	100%	100%
Petroleum refinery	65%	65%
Other chemicals	65%	65%
Ammonia	65%	65%
Fertilisers	65%	65%
Explosives	65%	65%
Rubber and plastic products	96%	100%
Cement	4%	30%
Non-metallic construction	80%	97%
Alumina	67%	67%
Other non-ferrous metals	46%	92%
Other metal products	46%	92%
Motor vehicle and parts	53%	100%
Other manufacturing products	53%	100%
Gas supply	100%	100%
Gas export (LNG)	100%	100%
Water supply	100%	100%
Construction services	100%	100%

Shortened forms

Abbreviation	Meaning
ABS	Australian Bureau of Statistics
ACCU	Australian Carbon Credit Unit
AE	Alkaline Electrolysis
AEEI	Autonomous Energy Efficiency Improvement
AEMO	Australian Energy Market Operator
ANZSIC	Australian and New Zealand Standard Industrial Classification
APS	Announced Pledges Scenario
AR5	IPCC Assessment Report 5
AR6	IPCC Assessment Report 6
AusTIMES	Australian TIMES
BEV	Battery Electric Vehicle
BITRE	Bureau of Infrastructure and Transport Research Economics
BTL	Biomass to Liquids
CCA	Climate Change Authority
CCGT	Combined Cycle Gas Turbine
CCS	Carbon Capture and Storage
CER	Consumer Energy Resources
CGE	Computational General Equilibrium
CO_2-e	Carbon-dioxide equivalent (based on AR5 GWP)
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CWC	Climateworks Centre
DAC	Direct Air Capture
DCCEEW	Department of Climate Change, Energy, Environment and Water
DISER	Department of Industry, Science, Energy and Resources
DKIS	Darwin Katherine Interconnected System
DoEE	Department of the Environment and Energy
DRI	Direct Reduced Iron
DSP	Demand Side Participation
EAF	Electric Arc Furnace
EE	Energy Efficiency
EFOM	Energy Flow Optimization Model
ERF	Emissions Reduction Fund
ETSAP	Energy Technology Systems Analysis Project
EV	Electric Vehicle
FRG	Forecasting Reference Group

GBCA	Green Building Council Australia
GDP	Gross Domestic Product
GHG	Greenhouse gas
GJ	Gigajoule
GSP	Gross State Product
Gt	Gigatonne
GVA	Gross Value Added
GW	Gigawatt
GWh	Gigawatt hour
GWP	Global Warming Potential
HVAC	Heating, Ventilation, and Air Conditioning
ICE	Internal Combustion Engine
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
ISP	Integrated System Plan
kW	Kilowatt
kWh	Kilowatt hour
LED	Light Emitting Diode
LGC	Large-scale Generation Certificates
LNG	Liquefied Natural Gas
LRET	Large-scale Renewable Energy Target
LULUCF	Land Use, Land-Use Change and Forestry
LUTO	Land Use Trade-Offs
MARKAL	MARKet ALlocation
Mha	Million hectares
MJ	Megajoule
MSM	Multi-Sector Modelling
Mt	Million tonnes
Mtpa	Million tonnes per annum
MW	Megawatt
MWh	Megawatt hour
NDC	Nationally Determined Contribution
NEM	National Electricity Market
NGA	National Greenhouse Accounts
NZE	Net Zero Emissions
NWIS	North West Interconnected System
NZE	Net Zero Emissions
OCE	Office of the Chief Economist
OCGT	Open-cycle gas turbine
PEM	Proton exchange membrane

PJ	Petajoules
PV	Photovoltaic
QRET	Queensland Renewable Energy Target
RCP	Representative Concentration Pathway
RET	Renewable Energy Target
REZ	Renewable Energy Zone
SGSC	Smart Grid Smart Cities
SMR	Steam Methane Reforming
SSP	Shared Socioeconomic Pathway
STC	Small-scale Technology Certificates
STEPS	Stated Policies Scenario
SWIS	South West Interconnected System
TIMES	The Integrated MARKAL-EFOM System
TRET	Tasmania Renewable Energy Target
TWh	Terawatt hour
UNFCCC	United Nations Framework Convention on Climate Change
VEEC	Victorian Energy Efficiency Certificate
VPP	Virtual Power Plant
VRE	Variable Renewable Energy
VRET	Victorian Renewable Energy Target
WA	Western Australia

References

Albanese, A, (2022), *Australia Legislates Emissions Reduction Targets*, Media release, https://www.pm.gov.au/media/australia-legislates-emissions-reduction-targets [accessed 17 November 2022].

ACIL Allen 2024, Gas, liquid fuel, coal and renewable gas projections: Final report, December, https://aemo.com.au/-/media/files/major-publications/isp/2025/acil-allen-2024-fuel-price-forecast-report.pdf?la=en [accessed 6 February 2025]

ACT Government 2022, *Powering Canberra: Our Pathway to Electrification*, https://www.cmtedd.act.gov.au/open_government/inform/act_government_media_releases/barr/2022/powering-canberra-our-pathway-to-electrification#:~:text=We%20have%20also%20released%20Powering%20Canberra%3A%20Our%20Pathway,to%20the%20transition%20over%20the%20coming%20two%20decades. [accessed 14 April 2025].

ACT Government, 2023. *Singing in the shower: a guide to hot water heat pumps*. ACT Government – Climate Choices. Available at: https://www.climatechoices.act.gov.au/policy-programs/sustainable-household-scheme/buyers-guides/singing-in-the-shower-a-guide-to-hot-water-heat-pumps [accessed 15 November 2024]

Arias, P.A., N. Bellouin, E. Coppola, R.G. Jones, G. Krinner, J. Marotzke, V. Naik, M.D. Palmer, G.-K. Plattner, J. Rogelj, M. Rojas, J. Sillmann, T. Storelvmo, P.W. Thorne, B. Trewin, K. Achuta Rao, B. Adhikary, R.P. Allan, K. Armour, G. Bala, R. Barimalala, S. Berger, J.G. Canadell, C. Cassou, A. Cherchi, W. Collins, W.D. Collins, S.L. Connors, S. Corti, F. Cruz, F.J. Dentener, C. Dereczynski, A. Di Luca, A. Diongue Niang, F.J. Doblas-Reyes, A. Dosio, H. Douville, F. Engelbrecht, V. Eyring, E. Fischer, P. Forster, B. Fox-Kemper, J.S. Fuglestvedt, J.C. Fyfe, N.P. Gillett, L. Goldfarb, I. Gorodetskaya, J.M. Gutierrez, R. Hamdi, E. Hawkins, H.T. Hewitt, P. Hope, A.S. Islam, C. Jones, D.S. Kaufman, R.E. Kopp, Y. Kosaka, J. Kossin, S. Krakovska, J.-Y. Lee, J. Li, T. Mauritsen, T.K. Maycock, M. Meinshausen, S.-K. Min, P.M.S. Monteiro, T. Ngo-Duc, F. Otto, I. Pinto, A. Pirani, K. Raghavan, R. Ranasinghe, A.C. Ruane, L. Ruiz, J.-B. Sallée, B.H. Samset, S. Sathyendranath, S.I. Seneviratne, A.A. Sörensson, S. Szopa, I. Takayabu, A.-M. Tréguier, B. van den Hurk, R. Vautard, K. von Schuckmann, S. Zaehle, X. Zhang, and K. Zickfeld 2021, *Technical Summary*. In *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_TS.pdf. [accessed 19 July 2022]

ASSET 2018, *Technology pathways in decarbonisation scenarios*, https://op.europa.eu/en/publication-detail/-/publication/599a1d8e-509a-11eb-b59f-01aa75ed71a1 [accessed 19 July 2022]

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

Australian Bureau of Statistics 2021a. *Motor Vehicle Census, Australia, 31 Jan 2021, Catalogue No. 9309.0*. Australian Bureau of Statistics, Canberra.

Australian Bureau of statistics 2024, Household and Family Projections, Australia, https://www.abs.gov.au/statistics/people/population/household-and-family-projections-australia/latest-release#data-downloads [accessed 14 February 2025]

Australian Energy Commission 2024. Electricity Gas Australia 2022-23 (Australian Energy Commission: Melbourne).

Australian Energy Market Operator 2021b, *2022 Forecasting Update Assumptions Workbook*, https://aemo.com.au/-/media/files/electricity/nem/planning_and_forecasting/inputs-assumptions-methodologies/2020/2020-inputs-and-assumptions-workbook-dec20.xlsx?la=en [accessed 17 June 2022]

Australian Energy Market Operator 2021a, *2021 Inputs and Assumptions Workbook*, https://aemo.com.au/-/media/files/electricity/nem/planning_and_forecasting/inputs-assumptions-methodologies/2020/2020-inputs-and-assumptions-workbook-dec20.xlsx?la=en [accessed 17 June 2022]

Bryan, B, Nolan, M, McKellar, L, Connor, JD, Newth, D, Harwood, T, King, D, Navarro, J, Cai, Y, Gao, L, Grundy, M, Graham, P, Ernst, A, Dunstall, S, Stock, F, Brinsmead, T, Harman, I, Grigg, NJ, Battaglia, M, Keating, B, Wonhas, A and Hatfield-Dodds, S 2016. *Land-use and sustainability under intersecting global change and domestic policy scenarios: Trajectories for Australia to 2050*. Global Environmental Change, 38, pp.130-152.

Bureau of Infrastructure, Transport and Regional Economics 2023. Australian Infrastructure Statistics Yearbook 2023. Bureau of Infrastructure, Transport and Regional Economics, https://www.bitre.gov.au/publications/2023/australian-infrastructure-and-transport-statistics-yearbook-2023 [accessed 12 February 2025]

Bureau of Infrastructure, Transport and Regional Economics 2024. Road Vehicles, Australia, January 2024. Bureau of Infrastructure, Transport and Regional Economics, https://www.bitre.gov.au/publications/2024/road-vehicles-australia-january-2024 [accessed 12 February 2025]

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

Butler, C, Maxwell, R, Graham, P, Hayward, J 2021. Australian Industry Energy Transitions Initiative Phase 1 Technical Report. ClimateWorks Australia: Melbourne, Phase-1-Technical-Report-June-2021.pdf (energytransitionsinitiative.org) [accessed 1 November 2022]

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

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

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

Climate Change Authority 2024. Sector Pathways Review, https://www.climatechangeauthority.gov.au/sites/default/files/documents/2024-09/2024SectorPathwaysReview.pdf [accessed 15 April 2025]

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

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

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

CSIRO 2019, *Australian National Outlook 2019*, https://www.csiro.au/en/work-with-us/services/consultancy-strategic-advice-services/csiro-futures/innovation-business-growth/australian-national-outlook [accessed 19 July 2022]

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

Department of Agriculture, Fisheries and Forestries (DAFF) 2022, *Snapshot of Australian Agriculture 2022*, https://www.agriculture.gov.au/abares/products/insights/snapshot-of-australian-agriculture-2022 [accessed 1 December 2022]

Department of Climate Change, Energy, Environment & Water (DCCEEW) 2022a, Stationary energy (excluding electricity) - mining and energy technology and efficiency opportunities 2022, https://www.dcceew.gov.au/sites/default/files/documents/stationary-energy-excluding-electricity-mining-energy-technology-efficiency-opportunities-advisian.pdf [accessed 17 October 2024]

Department of Climate Change, Energy, the Environment and Water (DCCEEW) 2022b, Commercial Buildings Baseline Study 2022, https://www.dcceew.gov.au/energy/publications/commercial-building-baseline-study-2022 [accessed 14 February 2025]

Department of Climate Change, Energy, the Environment and Water (DCCEEW) 2024a. Australian Energy Statistics 2024, https://www.energy.gov.au/publications/australian-energy-update-2024 [accessed 30 November 2024]

Department of Climate Change, Energy, the Environment and Water (DCCEEW) 2024b. Australian Energy Statistics Table O Electricity generation by fuel type 2022-23 and 2023, https://www.energy.gov.au/sites/default/files/2024-04/table-o-australian-energy-statistics-2024.xlsx [accessed 6 February 2025]

Department of Climate Change, Energy, the Environment and Water (DCCEEW) 2024c. National Hydrogen Strategy 2024, https://www.dcceew.gov.au/sites/default/files/documents/national-hydrogen-strategy-2024.pdf [accessed 4 February 2025]

Department of Climate Change, Energy, the Environment and Water (DCCEEW) 2024d. Emissions inventories – Paris Agreement Inventory, https://greenhouseaccounts.climatechange.gov.au/ [accessed 14 February 2025]

Department of Climate Change, Energy, Environment & Water (DCCEEW) 2024e, Australia's emissions projections 2024, https://www.dcceew.gov.au/climate-change/publications/australias-emissions-projections-2024 [accessed 14 February 2025]

Department of Climate Change, Energy, the Environment and Water (DCCEEW) 2024f. Australian National Greenhouse Accounts Factors: 2024, https://www.dcceew.gov.au/climate-change/publications/national-greenhouse-accounts-factors-2023 [accessed 11 January 2025]

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

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

Department of Industry, Science, Energy & Resources (DISER) 2021-LTER. Australia's long-term emissions reduction plan: Modelling and analysis. https://www.industry.gov.au/sites/default/files/November%202021/document/australias-long-term-emissions-reduction-plan-modelling.pdf [accessed 19 July 2022]

Department of Industry, Science, Energy & Resources (DISER) 2022a. *Australia submits new emissions target to UNFCCC*. https://www.industry.gov.au/news/australia-submits-new-emissions-target-to-unfccc [accessed 19 July 2022]

Department of Industry, Science, Energy & Resources (DISER) 2022b. *Australia's Nationally Determined Contribution Communication*. https://unfccc.int/sites/default/files/NDC/2022-06/Australias%20NDC%20June%202022%20Update%20%283%29.pdf [accessed 1 December 2022]

Department of Industry, Science, Energy and Resources (DISER) 2022c, *2021 Residential Baseline Study for Australia and New Zealand for 2000 to 2040*, 2021 Residential Baseline Study for Australia and New Zealand for 2000 to 2040 | Energy Rating [accessed 14 February 2025]

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

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

ENEA Consulting and Deloitte 2021. Australia's Bioenergy Roadmap. Prepared for the Australian Renewable Energy Agency (ARENA), australia-bioenergy-roadmap-report.pdf (arena.gov.au) [accessed 1 November 2022]

Energy Transformation Taskforce (ETT) 2020. *Whole of System Plan Appendix B – Assumptions Workbook* Government of Western Australia, Perth, August, https://www.wa.gov.au/system/files/2020-11/Whole-of-System-Plan-Appendix-B%20%283%29.xlsx [accessed 17 June 2022]

Australian Industry Energy Transition Initiative (ETI) 2023. Pathways to industrial decarbonisation

https://arena.gov.au/assets/2023/02/pathways-to-industrial-decarbonisation-australian-industry-eti-phase-3-report.pdf [accessed 11 Nov 2024]

Fasihi, M, Efimova, O & Breyer, C, 2019. 'Techno-economic assessment of CO2 direct air capture plants', *Journal of Cleaner Production*, vol. 224, pp.957-980.

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

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

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

Graham, P, Hayward, J, and Foster, J 2024. *GenCost 2024-25: Consultation Draft,* CSIRO, Australia, file:///C:/Users/ree125/Downloads/GenCost2024-25ConsultDraft_20241205.pdf [accessed 11 December 2024]

Graham, P and Mediwaththe, C 2024. *Small-scale Solar PV and Battery Projections 2024: Commissioned for AEMO's Draft 2025 Inputs, Assumptions and Scenarios Report*, CSIRO, Australia.

Graham, P, Mediwaththe, C, Green, D 2025. *Electric Vehicle Projections 2024: Commissioned for AEMO's Draft 2025 Inputs, Assumptions and Scenarios Report*, CSIRO, Australia.

Grassi, G, Stehfest, E, Rogelj, J, van Vuuren, D, Cescatti, A, House, J, Nabuurs, G, Rossi, S, Alkama, R, Vinas, RA, Calvin, K, Ceccherini, G, Federici, S, Fujimori, S, Gusti, M, Hasegawa, T, Havlik, P, Humpenoder, F, Korosuo, A, Perugini, L, Tubiello, FN and Popp, A 2021. *Critical adjustment of land mitigation pathways for assessing countries' climate progress*, Nature Climate Change, 11, pp.425-434.

Green Building Council of Australia (GBCA) (2022) *A practical guide to electrification: For new buildings*, https://gbca-web.s3.amazonaws.com/media/documents/a-practical-guide-to-electrification.pdf [accessed 17 November 2022]

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

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

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

International Energy Agency (IEA) 2022. Direct Air Capture: A key technology for net zero. International Energy Agency: Paris.

International Energy Agency (IEA) 2024. World Energy Outlook 2024. International Energy Agency: Paris.

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

Lewis Grey Advisory 2021. Gas Price Projections for Eastern Australia Gas Market 2022, Prepared for the Australian Energy Market Operator, https://aemo.com.au/-/media/files/major-publications/isp/2022/iasr/lewis-grey-advisory-gas-price-projections-report.pdf?la=en [accessed 12 July 2022]

Lombard, D., Price, K., Reddaway, A., & Moyse, D., 2018. *Household fuel choice in the National Energy Market: implications for emissions, energy use and bills*. Revised July 2018. Alternative Technology Association, https://renew.org.au/wp-content/uploads/2018/08/Household_fuel_choice_in_the_NEM_Revised_June_2018.pdf [Accessed 15 November 2024]

Madeddu et al. (2020), *The CO2 reduction potential for the European industry via direct electrification of heat supply (power-to-heat)*, Environmental Research Letters, 15, 124004.

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

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

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

Nicholls, Z & Meinshausen, M 2022, *Comparison between Australia's 2030 and 2050 emission reduction targets and 1.5C pathways*, https://www.climate-resource.com/reports/wwf/WWF_March2022_a.pdf. [accessed 19 July 2022]

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

On farm energy use characterisations (Brown and Elliot, 2005),

https://www.aceee.org/sites/default/files/publications/researchreports/ie052.pdf [accessed 11 Nov 2024].

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

Queensland University of Technology (QUT, 2022). Technical Report - Analysis of Hospital Future Energy Use. Australian Institute of Refrigeration, Air Conditioning and Heating, Australia https://eprints.qut.edu.au/235965/1/LLHC4_Technical_Report_Analysis_of_Future_Energy_Use_V5.pdf [accessed 11 Nov 2024]

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

Reedman, L.J., Gordon, J., Murugesan, M., Croser, L., Li, M., Hayward, J.A., Khandoker, T., Brinsmead, T.S. and Havas, L. 2022. *Multi-sector energy modelling 2022: Methodology and results: Final report*, CSIRO, Australia, https://aemo.com.au/-/media/files/stakeholder_consultation/consultations/nem-consultations/2022/2023-inputs-assumptions-and-scenarios-consultation/supporting-materials-for-2023/csiro-climateworks-centre-2022-multisector-modelling-report.pdf?la=en [accessed 14 February 2025]

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

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

University Technology Sydney – Institute of Sustainable Futures (UTS, 2023). Domestic Hot Water and Flexibility, https://arena.gov.au/assets/2023/06/uts-domestic-hot-water-and-flexibility-report.pdf [accessed 11 Nov 2023]

Verikios, G., Reedman, L., Green, D., Nolan, M., Lu, Y., Rodriguez, S., Murugesan, M., and Havas, L., 2024, Modelling Sectoral Pathways to Net Zero Emissions, EP2024-4366, CSIRO, Australia.

VICTORIA State Government 2025, *Victoria's Gas Substitution Roadmap*, https://www.energy.vic.gov.au/renewable-energy/victorias-gas-substitution-roadmap [accessed 17 April 2025]

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

As Australia's national science agency and innovation catalyst, CSIRO is solving the greatest challenges through innovative science and technology.

CSIRO. Unlocking a better future for everyone.

Contact us

1300 363 400
+61 3 9545 2176
csiro.au/contact
csiro.au

For further information

CSIRO Energy
Luke Reedman
luke.reedman@csiro.au