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Gas Energy in South Australia: A Scenario Exploration

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Glossary of acronyms and initialisms

AGN	Australian Gas Network
ANZSIC	Australian and New Zealand Standard Industrial Classification
CES	Constant Elasticity of Substitution
CGE	Computational General Equilibrium
CCS	Carbon Capture and Storage
CNG	Compressed Natural Gas
CRESH	Constant Relative Elasticity of Substitution, Homothetic
DER	Distributed Energy Resources
DRI	Direct Reduction Iron
EAF	Electric Arc Furnace
EV	Electric Vehicle
EFOM	Energy Flow Optimisation Model
FTE	Full-Time Equivalent
KPMG-SD	KPMG – Statistical Division model
GISERA	Gas Industry Social and Environmental Research Alliance
GDP	Gross Domestic Product
GSP	Gross State Product
GSOO	Gas Statement of Opportunities
GPG	Gas Power Generation
GRP	Gross Regional Product
HyP SA	Hydrogen Park South Australia
IPCC	Intergovernmental Panel on Climate Change
ISP	Integrated System Plan
IO	Input-Output
LNG	Liquified Natural Gas
LPG	Liquified Petroleum Gas
MARKAL	Market Allocation
NEM	National Electricity Market
NTNDP	National Transmission Network Development Plan
PEM	Proton Exchange Membrane
PV	Photo-Voltaic
REZ	Renewable Energy Zone
RTPV	Rooftop PV
RoA	Rest of Australia (region)
SA	South Australia
SMR	Steam Methane Reforming
TIMES	The Integrated MARKAL-EFOM System

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Summary

This report provides an analysis of the outlook for the South Australian energy industry and its economic implications within the context of the national economy and energy industry, with a particular focus on the role of gas, both natural gas and hydrogen. Three alternative future scenarios are considered each with a target of 100% of gas use being hydrogen by 2050. The scenario assumptions also require hydrogen production to be 100% from electrolysis from renewable electricity by 2050, except for a sensitivity scenario that considers that hydrogen production from reforming of methane or coal is permitted as one of the low emissions production pathways, provided it is accompanied by Carbon Capture and Storage (CCS).

The first scenario considered assumes a relatively rapid decline in the costs of hydrogen production from natural gas and low opportunities for electrification. The second scenario includes extensive electrification, higher costs of hydrogen production from natural gas, and lower costs of renewable generation technologies. In order to explore the impact of relaxing the constraint on hydrogen production by 2050 to be only from electrolysis, a sensitivity on this scenario has been considered where Steam Methane Reforming (SMR) with CCS also plays a role as a low emissions hydrogen production pathway. A third “Hydrogen Exports” scenario considers a strong role for hydrogen as part of an Australian export industry, including both the direct export of hydrogen and the export of Direct Reduction Iron (DRI) processed steel for which hydrogen represents a significant energy input.

The metropolitan Adelaide region of South Australia is dominated by the services sector. Because of this, the outlook for economic growth in that region is quite similar across the three scenarios, except that production of hydrogen and steel in the “Hydrogen Exports” scenario is expected to occur in that region, owing to the proximity to the port. The relative costs of energy, the consequences of fuel switching, and increases in electricity generation or natural gas demand required to serve hydrogen production have greater relative implications for regional economies with a higher reliance on manufacturing industries, and where there are favourable energy resources. Across the three scenarios, the differences in GSP and GRP within South Australia are small, making a difference of less than a cumulative 1% over three decades. However, across scenarios, the greatest impacts are under the “Hydrogen Exports” scenario. Across regions, the greatest impacts are for the metropolitan region of Adelaide, followed by the Barossa, York and mid-North region.

In South Australia for each industry, the impacts across the transition scenarios relative to the baseline are broadly similar. The most positively affected industries are the Electricity transmission and distribution sector, Other Chemicals (which includes the hydrogen generation industry) and Other non-ferrous metals (with the largest positive increase in the “Hydrogen Exports” scenario), with a cumulative impact between 1-5% to 2050. There are also minor positive impacts on the output of the Construction sector. The most negatively affected sector is Mining, which includes natural gas production and coal mining, which are both approximately a cumulative 10% smaller relative to a baseline counterfactual scenario where there is no change in the energy mix.

Demand for gas in the electricity generation sector is projected to decline reasonably quickly. The total demand for gas (both natural gas and hydrogen) in industry remains reasonably steady up to 2050 due to energy efficiency and fuel switching measures compensating for increasing production, after which increasing production results in a modest increase once again in gas demand. The demand for natural gas versus hydrogen in industry follows the assumptions in each scenario of the rate of overall average uptake of hydrogen in the gas transmission network. Similarly, the total demand for gas remains reasonably consistent in the commercial sector for all scenarios and the residential sector for most scenarios except the “Hydrogen Exports” scenario. Under this scenario, households across Australia are projected to exit natural gas as electrification occurs in the late 2040’s, but return to hydrogen in the 2050’s. In South Australia in this scenario, continued low electricity costs mean that the return of households to hydrogen gas does not take place. Demand for hydrogen fuel in transport increases steadily but remains a reasonably small component of total demand for gas.

Demand for natural gas as a final fuel declines reasonably rapidly from 2040 in most scenarios, and even earlier in the “Hydrogen Exports” scenario, in line with assumptions about the general move to hydrogen. The extent to which the demand for natural gas as an end-use fuel is replaced by demand for natural gas as a primary fuel, for use as a feedstock in hydrogen production, depends on whether steam methane reforming with carbon capture and storage is permitted as part of the energy mix. In those scenarios where hydrogen production is required to be from electrolysis from renewables by 2050, the demand for natural gas remains low. In the sensitivity case that allows continued production of hydrogen by SMR-CCS instead of electrolysis, and in the “Hydrogen Exports” scenario which permits up to 5% hydrogen production by SMR-CCS, the decline in natural gas demand is slower than the other scenarios, as some proportion of hydrogen production is derived from natural gas. Even so, after 2050 the production of hydrogen from natural gas declines, as a combination of a high shadow carbon price and continuing lower costs of electrolysis favour electricity as the preferred energy input for hydrogen production. In South Australia, however, although the pattern is similar in the “Hydrogen Exports” scenario, the relatively low cost of electricity means that hydrogen continues to be produced by electrolysis even in the sensitivity scenario that permits non-electrolysis hydrogen production in the long run.

In the “Hydrogen Exports” scenario, in which export demand for Australian hydrogen and steel, produced via the direct reduction iron route, increases significantly, the capacity for South Australia to meet this additional demand is limited by existing port capacity (and not by workforce skills). Under this scenario, hydrogen and steel exports in South Australia increase to the limit of the port capacity, exporting about twice as much hydrogen as steel in terms of tonnage, and representing only a modest increase on South Australia’s existing steel production. Less limited by port capacity, Queensland, and to some extent, Western Australia, supply the majority of demand for Australian exports in these high energy intensity commodities.

Limiting hydrogen exports by existing port capacities makes the implicit assumptions that there is no additional investment in capacity expansion throughout the projection period. This is a limitation of the modelling, given that infrastructure upgrades of such a nature may well take place within the next four decades.

The technology mix in the power sector is similar in all scenarios, with a slight difference between the NEM in general and South Australia in particular. There is a consistent shift to renewable solar and wind generation, supported by battery storage. In the broader NEM, the shift is away from existing black coal generation and some gas. In South Australia, the shift is away from existing gas generation. The assumed trajectories of customer side generation (rooftop solar photovoltaics) have a higher uptake in the “Hydrogen Exports” scenario, and more customer side batteries are taken up in the high electrification scenarios.

The greenhouse emissions trajectories are similar across all scenarios, with the modelling showing a reduction of about half nationwide between 2020 and 2050, and by about two-thirds in South Australia. In the agricultural sector, sequestration in forestry plays a significant role in emissions reduction, particularly in the second half of the projection period. Power generation is the sector that reduces emissions the most rapidly and deeply, followed by the transport sector. Based on reasonably conservative technological assumptions, the most challenging sector for emissions reduction remain industry, for both energy use emissions and direct process emissions. However, in all the scenarios, despite industrial output continuing to grow in both real and nominal economic terms, greenhouse emissions remain fairly flat or decline slightly. This represents a decline in emissions intensity, owing to the uptake of energy efficiency measures, and fuel switching to hydrogen and biomass, and electrification. Hydrogen production only ever makes a minor, and reasonably short lived, contribution to total emissions via the reforming of natural gas (SMR), as electrolysis ultimately becomes the dominant production process, even in the sensitivity scenario.

1 Introduction

This report presents final results of an investigation into the future role of gas in South Australia based on techno-economic modelling of the energy industry. It follows on from the scenario scoping report (Brinsmead et al. 2022), and is the second and final of two reports for the “Gas Industry Social and Environmental Research Alliance” (GISERA) project, the “Role of Gas in South Australia” undertaken in 2021-2022 by CSIRO.

The scenario scoping report presented projections from CSIRO techno-economic modelling for two contrasting future scenarios - a counterfactual comparison scenario called “Central”, based on the Central Scenario of the *2020 Integrated System Plan* (AEMO 2020a) and a second, high hydrogen production, scenario called “Australia’s Hydrogen Energy Future” based on DISER (2019).

The scenario scoping report considered key differences across two scenarios in terms of global decarbonisation ambition and the opportunity for exports of green hydrogen and green steel from Australia. It found that the scale of electricity generation required to meet the quantity of hydrogen production for export ultimately significantly exceeds that required for domestic end-use consumption and motivates an extremely high uptake of renewable electricity generation.

Based on these initial findings and up to date information, a final set of three scenarios has been designed to focus more closely on the relationship between hydrogen production and natural gas, as well as the significance of end-use electrification on the Australian energy mix. In addition to a techno-economic analysis of the energy industry, this report also provides further analysis of broader economic impacts of a changing energy mix on the cost of energy and industry growth opportunities, with subsequent impacts on economic development and employment in regional South Australia.

This report is structured as follows. It first presents the key questions to be addressed by the modelling analysis study, as informed by the scoping study. Section 2 defines and describes the scenarios to be investigated. Section 3 describes the overall modelling methodology and key quantitative assumptions underpinning the models. The final sections present results: Section 4, the overall economic results and Section 5, the detailed energy sector results.

2 Scenario Design

The initial scoping study for South Australia's Energy Future Scenarios *South Australia's Energy Future, Scenario scoping study (version 2.0)* (Brinsmead et al. 2022) was based on two comparison scenarios as described in Table 2-1. These scenarios gave rise to preliminary illustrative results that appear in the scoping report (noting that version 2.0 includes further analysis of the demand for natural gas).

Table 2-1: Scoping study scenario narrative overview

The Central Scenario	Consistent with the 2020 Integrated System Plan. Coal power stations in the National Electricity Market (NEM) are progressively replaced with competitively priced renewables and storage, supported by transmission infrastructure augmentation.
Australia's Hydrogen Energy Future	Abundant low-cost renewable energy gives Australia a competitive advantage, enabling it to be a low-carbon energy exporter. There is a surge in energy-intensive industry, including hydrogen and green metals.

For design of the final scenarios, the following steps were performed.

1. Define scenario narrative, including qualitative description.
2. For each scenario, identify relevant drivers and quantitatively specify the driver value.
3. Identify quantitative driver assumptions relevant to all scenarios.

In designing a useful set of scenarios, there is often a choice between a high and low variability range of assumptions. A higher variability range of assumptions will explore more extreme possibilities, preferencing understanding the breadth of range of likely outcomes. A lower variability range will vary only a small number of driving assumptions across the scenario set, preferencing understanding the impact of the individual drivers rather than the potential cumulative effect of several. Feedback from the Technical Reference Group encouraged selection of a scenario portfolio that explored a breadth of technological variations, and expressed a preference to avoid confounding the results with the influence of variations in economic settings.

2.1 Scenario Overview

A key determinant of the outlook for gas in South Australia's energy future is the role of the intermediate fuel, hydrogen. As an end-use fuel, hydrogen can act as a substitute for many existing uses of natural gas that produces no greenhouse gas emissions at the point of combustion. Furthermore, hydrogen can be produced from natural gas via steam methane reforming (SMR). Due to energy losses in the SMR fuel conversion process, the greenhouse emissions from SMR are greater than the direct use of natural gas, however, steam reforming of fossil fuels (natural gas or coal) can be supplemented with carbon capture and utilisation or storage.

Natural gas can alternatively be replaced by other fuels such as electricity. Electricity can substitute for natural gas in many direct end-uses, and also in the production of hydrogen. In response to falling costs of renewable generation and storage technologies, the proportion of electricity generated by renewables continues to rise, in South-Australia as well as the rest of the National Electricity Market. Consequently, the greenhouse emissions intensity of electricity is projected to decrease, improving its attractiveness relative to natural gas.

2.2 Scenario Narratives

Based on the results from the initial scoping study, the scenarios were further adapted. The following portfolio of scenarios for the second phase of the project was eventually decided upon, appearing in Table 2-2 as brief narratives.

Table 2-3 provides qualitative settings for key scenario driving elements, consistent with the narratives of Table 2-2. A small number of elements were varied slightly from their initial determinations, as a consequence of early results from the modelling analysis. An expanded, more comprehensive, tabulation of qualitative settings appears in Appendix A as Table 6-1, where references for the quantitative interpretation of the assumptions can be found. Table 2-3, however, provides an overview at a glance, summarising key contrasts.

The "Blue Hydrogen" scenario explores a transition from natural gas to hydrogen in the gas network as an end-use fuel, with natural gas being used as the feedstock for the production of hydrogen in the early years before an increasing share of production is via electrolysis from renewable electricity generation. This scenario incorporates relatively favourable assumptions for natural gas contribution to electricity generation. The "High Electrification" scenario explores a transition away from gas (whether natural gas or hydrogen) and towards electricity as an end-use, as well as a relatively smaller role for natural gas in power generation itself. The "Hydrogen Exports" scenario explores strong opportunities for hydrogen production. Similarly to the "Blue Hydrogen" scenario, production of hydrogen in the early years is from natural gas feedback, with increasing shares of electrolysis hydrogen in later years. This scenario also incorporates the most rapid transition from natural gas to hydrogen in the gas network.

The demand for natural gas is a modelling result rather than a scenario element. The impact of export demand for natural gas is not explored across these scenarios, and so it is assumed to be identical across them. The scenario element that most directly impacts natural gas demand is the minimum share of hydrogen in the gas network. Hydrogen in the distribution (and transmission) networks is greatest in the “Hydrogen Exports” scenario, providing the greatest opportunity among the three scenarios for natural gas to play a role in contributing to domestic energy supply while reducing carbon emissions (see Figure 2-1). It is the least in “High Electrification”, which is a scenario exploring relatively high electrification fuel switching.

Table 2-2: Scenario narrative overview

Name	Description
“Blue Hydrogen” *Gas supply initially decarbonises with SMR CCS hydrogen (later electrolysis)*	• Domestic gas demand in the residential, commercial, and industrial sectors continues to be relatively flat, with decarbonisation achieved by increasing hydrogen injection into the natural gas pipelines. • Hydrogen production in the near-term is by (low cost) steam methane reforming, with carbon capture and storage for reducing greenhouse gas emissions; electrolysis hydrogen develops in later years. • 10% blend of hydrogen (distribution network) by 2030, 20% by 2040 (and 100% by 2050). • Coal power generation in the NEM is replaced by gas to provide inertia and to balance an increasing generation share of variable renewables. • Comparable to the ‘central’ GSOO scenario (AEMO 2022, GSOO. The ‘Low Gas Price’ sensitivity could also be considered).
“High Electrification” *Natural gas domestic demand declines (renewable hydrogen)*	• The gas share of energy demand comes under increasing threat from a competitive electricity sector, in both buildings and industrial processes. • Hydrogen produced for injection into the natural gas pipelines shifts more quickly from SMR carbon capture and storage (CCS) to electrolysis production due to more rapid improvements in relative capital costs of electrolysis technology and abundant renewable energy resources. (Most comparable to the slow change GSOO scenario: AEMO 2022). • Thermal coal generation of electricity in the NEM declines modestly, and increasing variable renewable generation is supported by investment in energy storage, including pumped hydro. • 10% hydrogen in pipelines by 2030 (and 100% by 2050)
“Hydrogen Exports” *Domestic gas decarbonisation underpins national hydrogen export industry (including SMR CCS)*	• Domestic gas demand in the residential and commercial sectors continues, with hydrogen injection into the natural gas pipelines. • Low-cost hydrogen production by steam methane reforming with CCS underpins growth in energy intensive industries, including green metals and hydrogen. Electrolysis hydrogen is developed later. • Increased hydrogen production capacity and significant international interest enables Australia to become a low-carbon energy exporter. • Coal power generation in the NEM is replaced by natural gas and hydrogen fuels. • 10% hydrogen in pipeline networks by 2030, 100% hydrogen by 2040

The “Blue Hydrogen” scenario exhibits an in-between case. In all scenarios, the greatest demand for natural gas within a decarbonising electrical power system is expected to be for its flexible and dispatchable power generation. To compensate for the variability of low emissions wind and solar resources, requirements for flexible generation are likely to increase, while existing dispatchable generation, thermal coal power, retires. Storage technologies for providing power balancing, such as batteries and pumped hydro, are assumed to be limited in the “Blue Hydrogen” scenario, in order to explore more favourable circumstances for natural gas in electricity generation. In contrast, there will be limited demand for flexible natural gas electricity generation when electricity storage and renewables costs are assumed to be low. More scenario details are provided in the following sections.

Table 2-3: Key Scenario elements

Scenario Element		Natural Gas supply decarbonises with blue hydrogen	High Electrification	Domestic gas decarbonisation supports hydrogen exports
Technological shifts	Electrification	Low	High	Medium
	* Renewables costs * Batteries and EVs costs * Electrolysis costs	High	Low	Medium
	SMR costs	Low	High	Medium
	Hydrogen transmission and distribution	Medium	Low	High
Power Supply	Increased proportion of renewable supply	Low	High	Medium
	Decline in thermal coal generation	High	Medium	Medium
	Increased Electricity storage	Low	High	Medium
Emissions Policy	Emissions stringency (Aust)	Medium	Medium	Medium
	Emissions stringency (SA)	Medium	Medium	Medium
	Renewable subsidies	Low	Medium	Medium
Long-term demand drivers	Hydrogen Demand	Medium	Medium	High
	* Economic growth * Discretionary income * Energy efficiency * Immigration	Medium	Medium	Medium

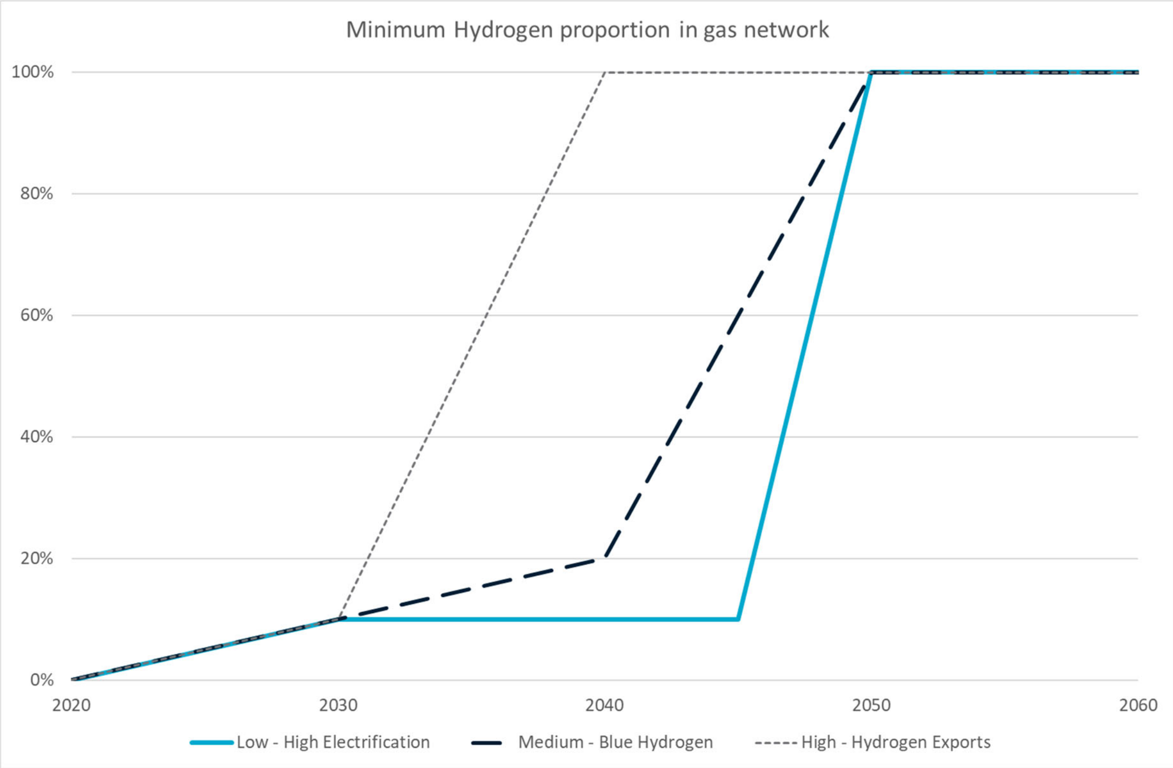

Figure 2-1: Minimum hydrogen proportion in the gas network

2.3 The Future of South Australian Industrial Development Initiatives

A number of initiatives are currently underway in South Australia that may impact on the development of a state hydrogen industry. This includes the Moomba Carbon Capture and Sequestration (CCS) Project[1] and the Hydrogen Park South Australia[2].

The impacts of these initiatives within the scenario projections are included as follows.

- Moomba Carbon Capture and Storage
    - Under both the "Blue Hydrogen" and "High Electrification" scenarios, the project runs for its projected lifespan of 25 years from 2025. It is permitted to expand after five years of operation or have its life extended at the end of the projected lifespan, provided it is economical to do so.
    - Under the "Hydrogen Exports" scenario, it becomes an option to include a SMR plant (without CCS) at the Moomba site after five years, when economic, and to inject the resulting hydrogen product in the transmission pipeline.
- HyP SA
    - Under all three scenarios, HyP SA is assumed to be a part of Australian Gas Networks' target for hydrogen in the gas network (stated as 10% by 2030 and 100% renewable hydrogen by 2050, with a stretch target of 2040[3]). The percentages of hydrogen in the gas network are assumed to be:
        - "Blue Hydrogen" (Medium): a minimum of 10% by 2030, 20% by 2040 and 100% *renewable* (that is, exclusively from renewable electricity) by 2050
        - "High Electrification" (Low): a minimum of 10% by 2030, and 100% renewable by 2050.
            - "High Electrification" Sensitivity (Low): a minimum of 10% by 2030, and 100% *low emissions* (permitting SMR with CCS) by 2050
        - "Hydrogen Exports" (High): a minimum of 10% by 2030 and 100% renewable by 2040.

The requirement for hydrogen in the gas network to be 100% derived from renewable sources by 2050 in effect excludes the possibility of hydrogen production by SMR of natural gas (or coal), whether with or without CCS. To explore the impact of this requirement, we conducted a sensitivity scenario analysis where both SMR with CCS, and electrolysis from renewables, are permitted as a hydrogen production method out to 2050.

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[1] https://www.santos.com/news/santos-announces-fid-on-moomba-carbon-capture-and-storage-project/

[2] http://www.renewablessa.sa.gov.au/topic/hydrogen/hydrogen-projects-south-australia/hydrogen-park-south-australia

[3] https://www.australiangasnetworks.com.au/hyp-sa

2.4 Scenario Common Elements

Scenario common elements (Table 2-4) include sectoral economic growth drivers and immigration. Emissions policy in South Australia is to be the same in all scenarios (consistent with net zero by 2050 as in the *South Australian Climate Change Strategy 2015-2050*, Government of SA 2015).

Table 2-4: Scenario common features

South Australia’s Emissions Performance	Consistent with net zero by 2050
Population growth	Series B from the Australian Bureau of Statistics
Economic growth	Domestic economic demand at 2.1% average growth over the projection period
Domestic Discretionary Income	KPMG-SD default assumptions
Energy Efficiency	Rates of return for investment in energy efficiency measures required to meet medium hurdle rates (4 years payback)
Natural Gas Affordability	Medium
Natural Gas Exports	Consistent with GSOO (2022)

The implications of the *Blue Carbon Strategy for South Australia 2020-2025* (Government of South Australia 2020) are to be the same in each scenario and assumed to be consistent with the carbon forestry assumptions in Government of South Australia (2015)**.** It is assumed that Queensland’s ambitions for liquefied natural gas (LNG) exports from gas extracted from the Cooper Basin has no material implications for SA’s gas supply. In order to focus scenario exploration on sensitivity to non-economic factors, it is assumed that the international price of gas does not vary by scenario. Domestic gas prices are taken from AEMO (2020b), using the ‘Slow’ scenario for fuel prices (Figure 2-2).

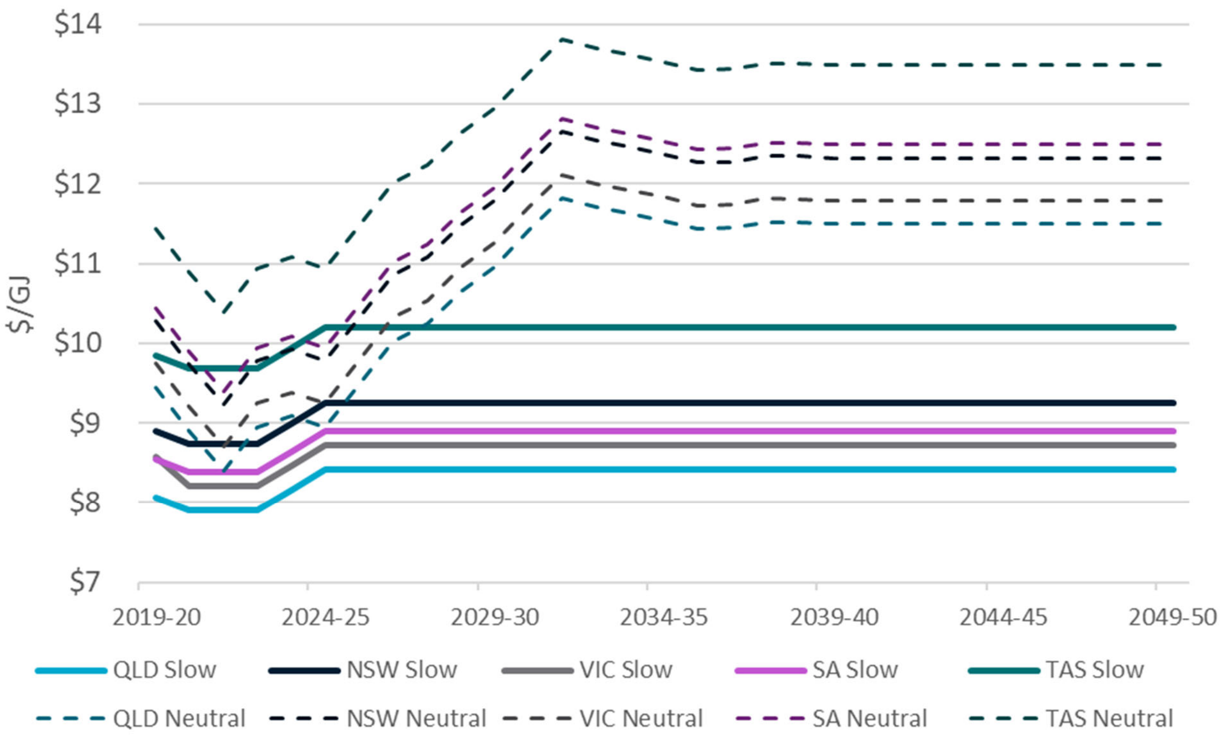

Figure 2-2: Assumed gas prices, all three "Gas Energy in SA" scenarios (Slow Fuel Price Scenario from AEMO 2020b)

2.5 Further Details of Key Scenario Assumptions

Each of the scenario elements in Table 2-3 is parameterised, that is, associated with a particular representation in the quantitative model, if not otherwise decided as being unrepresented. Some elements are parameters that are best interpreted as modelling results, whose values are determined by the modelling assumptions, and others are better interpreted as scenario driving assumptions. Each category of elements is discussed below.

2.5.1 Technological Shifts

In consideration of technological shifts, one of the more significant aspects for the gas industry (natural gas and hydrogen) is the prospective competition between electricity and hydrogen as energy carriers. In general, electricity is a high-quality energy carrier in that it can be transported rapidly (over electrical transmission infrastructure), with few losses, and can be transformed relatively efficiently. However, it is relatively difficult and costly to store. Chemical energy carriers such as hydrogen (or natural gas) are easier to store. However, they are less energy dense than electricity (by both volume and mass) and are more difficult to transport rapidly over long distances.

Across the three scenarios we consider a range of plausible development paths for electricity and hydrogen techno-economic progress. The "Hydrogen Exports" scenario is assumed to be in the mid-range for electrification propensity, costs of electrical generation, storage and fuel switching, and the rate of progress on cost reductions in SMR hydrogen production. The "Blue Hydrogen" scenario is most favourable to domestic hydrogen consumption, with low electrification propensity and higher range costs of electrical generation, storage and fuel switching, and more rapid progress on SMR cost reduction. The "High Electrification" scenario makes the opposite assumptions, with high electrification propensity, lower costs for electricity related technologies and higher costs for SMR.

Assumptions about the uptake of hydrogen in the gas transmission and distribution network complement the electricity assumptions to make for consistent scenarios. That is, the uptake is relatively low in the "High Electrification" scenario, high in the "Hydrogen Exports" scenario (where domestic hydrogen consumption increases earlier, in order to develop a market for production that can later supply an increasing demand for exports), and mid-range in the "Blue Hydrogen" scenario (recall Figure 2-1).

To translate these qualitative assumptions into quantitative modelling parameters, electrification propensity is expressed in terms of the rate of return on capital expenditure that is required for consumers and businesses to invest in either fuel switching to electricity, or in energy efficiency measures. The required rate of return on end user energy technology also affects fuel switching to other low emissions fuels such as biomass or hydrogen. The range of costs of electrical generation and storage were sourced from *Gencost 2021* (Graham et al. 2021c), and costs of energy efficiency and electrification fuel switching capital were sourced from Butler et al. (2020a, 2020b) and ClimateWorks (2016). The low, medium and high assumptions on the uptake of hydrogen in the gas transmission and distribution networks have been described in Section 2.3.

2.5.2 Power Supply

Of the differences in the electrical power sector among scenarios, two of those listed in Table Table 2-3 (increased renewable supply and increased energy storage) are indirect outcomes of other scenario assumptions. The rate of decline in thermal coal generation is the only direct assumption that differs. It is assumed to be mid-range for the "High Electrification" and "Hydrogen Exports" scenario, consistent with a predetermined trajectory of power station closures in line with assumptions in the *2020 Integrated System Plan* (AEMO, 2020a) that are informed primarily by the age of each power station.

2.5.3 Emissions Policy

Emissions policy is assumed to be essentially identical across the three scenarios. Within the modelling, it is represented as a shadow price on the emissions. This is not to suggest that an explicit price on greenhouse gas emissions is an assumed requirement as government policy. Rather, the shadow price in the modelling plays the role as a proxy for the implementation of policies that result in the uptake of least cost solutions from among the modelled options for emissions reduction.

The shadow price of greenhouse gas emissions is assumed to be identical in all three scenarios. Prices are based on those for RCP2.6 reported by the IPCC in Clarke et al. (2014, Chapter 6, p450). In this 'two degrees track' scenario, the global uniform price convergences to $US 20/t-CO2-eq (26.62 AUD) by 2020 with 5% growth thereafter to a little above $US 200/t-CO2-eq (273.80 AUD) by 2060. See the chart in Figure 2-3.

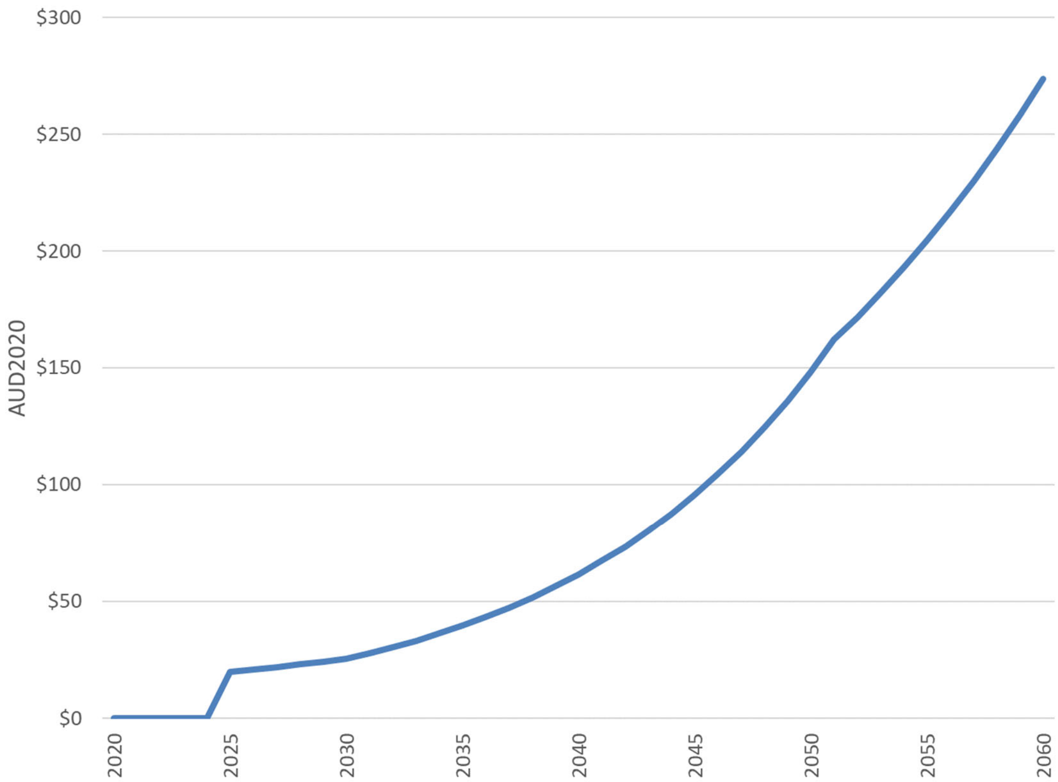

Figure 2-3: Assumed shadow price on CO2 emissions, all three "Future of Gas" scenarios

2.5.4 Long Term Demand Drivers

Long term drivers of economic energy demand, such as economic growth, discretionary income, energy efficiency improvements and population growth, as influenced by immigration, are assumed to be common across all three scenarios, and have been addressed above in Section 2.4. They are assumed to be common in order to focus scenario exploration on the sensitivity of results to technological parameters.

2.6 Other Scenario Element Details

2.6.1 Economic Assumptions

As indicated above in Section 2.5.4, the key assumptions about the state of the global and national economy are essentially the same for each scenario. Differences in technological progress in renewable generation, energy storage, energy efficiency, energy switching and hydrogen production are primarily represented as capital cost differences. Nevertheless, the "Hydrogen Exports" scenario has implied assumptions about additional global market demand for hydrogen and Direct Reduction Iron (DRI) steel exports (see 2.6.3 below).

2.6.2 Demand Growth Assumptions

Under this modelling process, the demand for energy services within each sector is determined by each sector's activity levels. These are themselves determined by calibrated exogenous assumptions on productivity and national growth in Gross Domestic Product (GDP) and somewhat endogenously influenced by relative energy costs in each sector. Further details are given in the description of the economic model in Section 3.2.2.

2.6.3 Hydrogen and Green Steel Demand Assumptions

In all three scenarios, there is an element of domestic hydrogen demand that is induced by the demand for energy services in the buildings, industrial and transport end-use sectors according to competition with other end-use fuels such as electricity, liquid fossil fuels, coal, bioenergy, and natural gas. Hydrogen demand is each state is assumed to be met by production within the state, with no interstate hydrogen trade.

However, in the "Hydrogen Exports" scenario there is an additional assumption of a specified international demand for low emissions hydrogen exported from Australia and an assumed specified demand for "green steel" produced via the DRI (and electric arc furnace) route (see Butler et al. 2021, p30) with hydrogen rather than natural gas or coal. The assumptions regarding the total quantity of hydrogen and green steel are consistent with *Australia's National Hydrogen Strategy* (DISER 2019). In all scenarios, except the sensitivity exploration of "High Electrification", it is required that the percentage of hydrogen produced from electricity (which ultimately decarbonises ove r the projection period) increases to 100% by 2050. The requirement is 33% by 2030 and 66% by 2040. In order to explore the impact of relaxing the requirement on hydrogen production from electricity only, a sensitivity scenario on the "High Electrification" scenario allows the minimum percentage of "low emissions" hydrogen to be produced by either electrolysis or SMR with CCS.

Hydrogen and green steel exports are assumed to be limited in each state according to existing ports, limits that are determined by a combination of local workforce skilled enough to produce hydrogen, and existing port tonnage capacities. The assumptions for each port capacity can be found in Appendix E. For South Australia, the state capacity for hydrogen and steel export is limited to 1120 kt pa, at the port of Adelaide. Five percent (5%) of the existing workforce of some 90 thousand employed in the Mining, Manufacturing, Utilities, and Construction, industries[4] is assumed not to be the limiting factor. This assumption is less constrained than Government of South Australia (2020b), which suggests an export volume of 125-250 kt pa from Port Bonython, 60-250 kt pa from Port Augusta, and 30-80 kt from the Port of Adelaide. As indicated previously, the impact of export demand for natural gas is not explored across these scenarios, and so it is assumed to be identical across them.

2.7 Comparison to the *Future of Gas* Scenarios

The 2021 KPMG Report, *Future of Gas*, for the Australian Gas Infrastructure Group (AGIG) develops four scenarios for gas in Victoria. The *Future of Gas* scenarios can not be mapped directly to those for this report, partly because the focus in KPMG (2021) is on hydrogen, whereas this report also considers natural gas. The "Blue Hydrogen" scenario is closest to the *Future of Gas* scenario 'Duel Fuel', though it also has some elements of 'Muddling Through'. "High

[4] Further hydrogen production economics data available at https://research.csiro.au/hylearning/

Electrification" is closest to 'Electric Dreams' and "Hydrogen Exports" is closest to 'Hydrogen Hero'.

In KPMG (2021), the demand for natural gas is "low" in three out of four scenarios and "medium" in the other, whereas for this GISERA project the "High Electrification" scenario is the only intentionally low gas demand scenario. Economic growth and immigration are not explicitly discussed in KPMG (2021) and are also essentially the same across the three GISERA scenarios. Electrification is not explicitly considered as a driver in KPMG (2021), and renewables costs, and battery and electric vehicle (EV) costs are at best implicit, in contrast to this project where the latter are explicit drivers of electrification.

The transmission of hydrogen in pipeline infrastructure is "high" in the 'Hydrogen Hero' scenario in the *Future of Gas*, as in the corresponding "Hydrogen Exports". It is "medium" in 'Duel Fuel' in the *Future of Gas* which is also consistent with the corresponding "Blue Hydrogen". The demand for hydrogen in the *Future of Gas* is consistent with that assumed for the transmission network in the GISERA analysis and is a modelled result in this report.

In the *Future of Gas* electricity prices are "low" and "gas prices" high in three of the four scenarios corresponding to those presented here, and here international gas prices are consistent across scenarios, and electricity prices are an endogenously modelled result. Emissions ambitions are consistent across the three of four *Future of Gas* scenarios that best map to the GISERA scenarios, which also feature the same emissions ambitions in South Australia. These scenario settings are therefore all quite consistent between the *Future of Gas* and GISERA.

Renewables supply in the *Future of Gas* 'Duel Fuel' scenario is consistent (low) with the capital costs of renewables (high) in the corresponding GISERA scenario, but the medium and high renewables supply of the remaining two *Future of Gas* scenarios reverses these two assumptions for the corresponding GISERA scenarios. It is worth noting that renewables supply will be a modelled result in the GISERA analysis, that renewables costs are the driving factor, and that high demand for renewables may result as an outcome of the "Hydrogen Exports" GISERA scenario as a consequence of required supply for electrolysis hydrogen to meet export demand assumptions.

Discretionary income is consistent across GISERA scenarios, but in the *Future of Gas* it is lower for the scenarios corresponding to "Blue Hydrogen" compared to that corresponding to the other two GISERA scenarios.

3 Combined Economic and Technological Modelling Approach

3.1 Approach Overview

The modelling analysis method underpinning the results in this report is a combination of an economic computational general equilibrium (CGE) model of the Australian economy, configured to focus on South Australia, and a techno-economic partial equilibrium (PE) model of the Australian Energy sector. The economic CGE model is called KPMG-SD and the PE model is called AusTIMES.

The CGE model provides the broader economic context within which the PE energy model operates. Driven by population growth and general assumptions about national economic growth, the economic model develops projections of demand for production on a sector-by-sector basis. This demand is modelled as achieving equilibrium with production function constraints on the supply side. Although the CGE economic model includes a representation of the energy sector, the detailed analysis of the energy sector is provided by AusTIMES. This is because it has more detailed representation of technology types and a more realistic representation of investment and capital generation stock. Consistency with the CGE model is confirmed by imposing relevant results from the PE model on the CGE model: energy production technology mix, fuel demand mix by sector, and checking that the resultant costs do not have a significant impact on demand for production. A schematic representation of the informational interaction between the two models is provided in Figure 3-1. The following two subsections describe each model in detail.

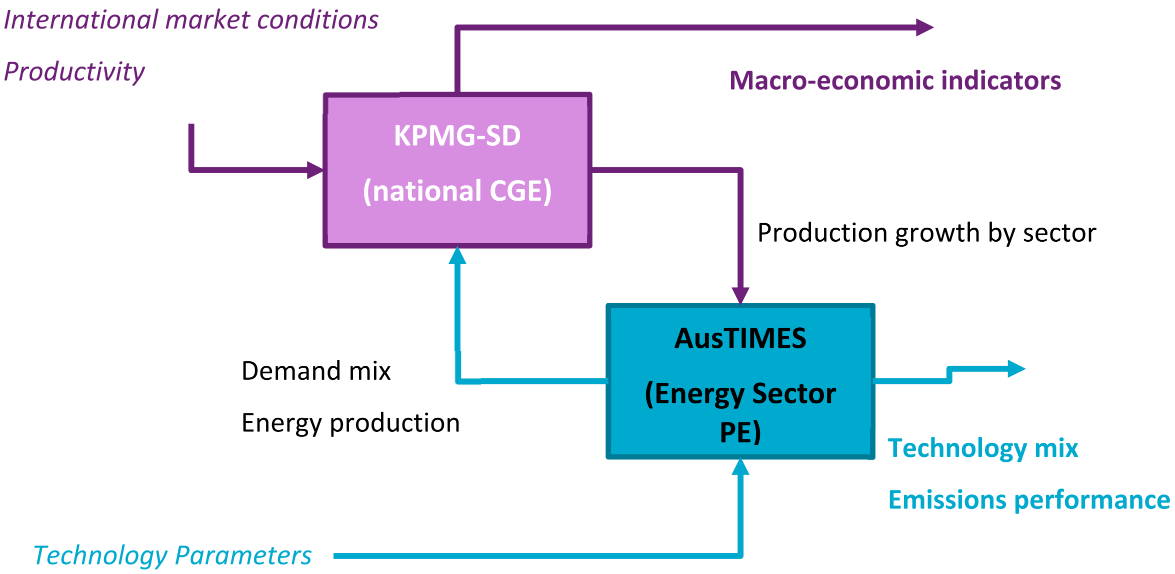

Figure 3-1: Informational transfers between full sector CGE economic model and PE detailed energy sector model

3.2 KPMG-SD

3.2.1 General Structural Overview

The assessment of the economy-wide impacts is conducted with the aid of KPMG-SD, a dynamic multi-region CGE model of the Australian economy. The version of KPMG-SD applied here has been modified with additional focus on the representation of energy sectors. KPMG-SD models the economy as a system of simultaneous equations that represent interdependent economic agents operating in competitive markets. Figure 3.3.1 shows a stylised representation of interlinkages of economic agents, including consumers, investors, producers, and government. By taking into account these economic linkages, KPMG-SD captures not only the direct effects of an investment project but also the indirect (or flow-on) effects on other sectors of the economy.

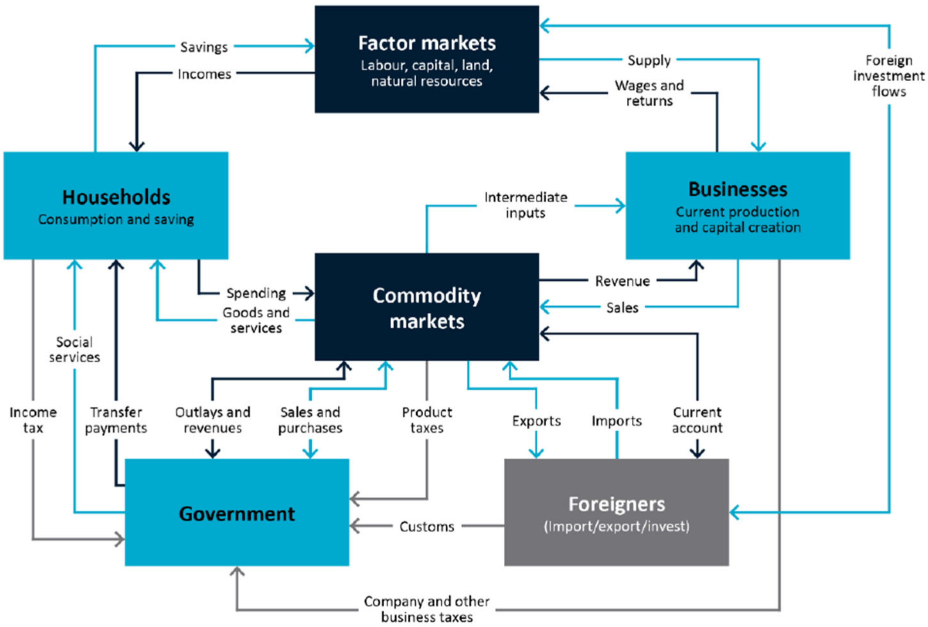

Figure 3-2: System of interdependent economic agents in KPMG-SD

The core data, theory and parameters of KPMG-SD are based on the model formally presented in Verikios et al. (2021). Defining features of the theoretical structure of KPME-SD include:

- optimising behaviour by households and businesses (producers) in the context of competitive markets with explicit resource constraints and budget constraints;
- the price mechanism operates to clear markets for goods, and factors such as labour and capital, that is, prices adjust so that supply and demand are equal; and
- marginal costs are equal to marginal revenues in all economic activities.

Household behaviour. There is an infinitely-lived, single representative, household agent that owns the major share of factors of production with foreigners owning the remainder; the representative household can either spend or save its income. Household consumption decisions by commodity are determined by a Stone-Geary utility function that distinguishes between subsistence (necessity) and discretionary (luxury) consumption (Stone, 1954). Households can also change their mix of imported and domestically produced commodities given constant elasticity of substitution (CES) preferences.

Producer (business) behaviour. Each sector is modelled as a single representative firm that produces only one commodity. Commodities are distinguished between those destined for export markets and those destined for domestic sales, so that the ratio of export prices to domestic prices may vary. Production technology is represented by nested CRESH (constant ratios of elasticities of substitution, homothetic) functions (Hanoch, 1971) allowing a high degree of flexibility in the parameterisation of substitution and technology parameters. Energy goods such as electricity, and hydrogen, are each explicitly represented as intermediate goods, distinct from other intermediate goods and services in production, and are complementary to primary factors, including primary fuels such as coal, oil, and natural gas.

Labour market. The supply of labour is determined by a trade-off between labour and leisure that allows workers in each occupation to respond to changes in after-tax wage rates, thus determining the hours of work they offer to the labour market. The overall supply of labour is normalised on the projected working-age population.

Investment behaviour. Investment behaviour is industry specific and is positively related to the (past modelled) rate of return on capital (it is not forward looking). This rate considers company taxation and a variety of capital allowances, including the structure of the Australian dividend imputation system, which affects how tax liability is shared between Households and Businesses.

Multiregional modelling. KPMG-SD takes a 'bottom-up' approach to multiregional modelling. In each region, economic agents decide the allocation of labour, capital, and land among different productive activities. The cost structure of firms in each sector, the composition of investment goods, the endowments and preferences of households, and the level and composition of public expenditures - are each specific to each region. Regions are economically interdependent via bilateral flows of goods and services, between regions and with the rest of the world. Bilateral trade is represented via a detailed specification of transport margins for goods.

Regional and sectoral detail. For the study presented in this report, KPMG-SD is configured so that regional economies in SA are explicitly represented and there is a detailed representation of energy sectors including explicit representation of a hydrogen sector. Table 3-1 provides the regional aggregation for this study. We use a regional aggregation in KPMG-SD that separately identifies six interrelated regional economies in South Australia and a composite Rest of Australia (RoA) region. This regional disaggregation is consistent with Australian Bureau of Statistics standard geographical classification at the Statistical Area 3 and 4 levels (see Appendix B). Each region is represented as a separate economy linked by interregional flows of goods and services, investment and labour.

Table 3-1: KPMG-SD regional disaggregation

	Regional name	Definition
1	GtrAdl	1. Greater Adelaide
2	BrsaYrkMdNth	2. Barossa - Yorke - Mid North
3	SAOutback	3. South Australia – Outback
4	FleuriKangIs	4. Fleurieu - Kangaroo Island
5	LimestoneCst	5. Limestone Coast
6	MurrayMallee	6. Murray and Mallee
7	RoAus	7. Rest of Australia

We assume that Australia is a price taker in the international market where imported prices are exogenously given in KPMG-SD. This implies that movements in the terms of trade are mainly driven by changes in export prices.

The industrial structure of each of the seven regional economies is based on the Australian and New Zealand Standard Industrial Classification (ANZSIC) Divisions, see Table 3-2. In this work, we explicitly represent four electricity technologies and three hydrogen sectors. Each of the electricity technologies represent individual industries but produce the same commodity (electricity). This represents a joint production approach to representing multiple electricity technologies. Hydrogen production by coal gasification and steam methane reforming is not included in the technology mix, either with or without CCS, as previous AusTIMES investigations have shown it to be generally not taken up by the model.

3.2.1.1 Modelling Scenario Alternatives

KPMG-SD is a dynamic model; thus, it generates results depicting the time path of the economic impacts. To generate the results for each project case scenario, the model is run twice over a specified time horizon (for this project, 2020-2060). First, we run a baseline simulation that captures the assumptions of the baseline scenario, which results in the calibration of some model parameters. Second, we run a project case simulation that captures the elements of a counterfactual project case scenario in addition to the baseline assumptions. The economic effects of the project case scenarios are measured by the difference in the values of economic variables between the baseline and project scenario simulation results. Results are reported in the form of changes to Gross Regional Product (GRP), GDP, employment and sectoral value-added. More than one project case scenario may be modelled, to investigate the effects of alternative counterfactual assumptions.

We assess the economic impacts of the three *Gas Energy in SA* scenarios (that is, project cases – specifically "Blue Hydrogen", "High Electrification" and "Hydrogen Exports" scenarios) against the same baseline scenario. The baseline and project case scenarios can be summarised as follows:

- ***Baseline scenario***. This is a projection in the absence of the assumptions specific to the different *Gas Energy in SA* scenarios, providing an estimate of how the size and structure of the economy will evolve over the projection period. That is, the baseline scenario excludes the impacts of changes in the energy sector, and assumes that exogenous influences on the economy are constant or zero.
- ***Project case scenario(s)***. The counterfactual scenario(s) where we shock the baseline scenario by incorporating the direct impacts of gas and hydrogen sector development and modelling the indirect (or flow-on) impacts that are projected by AusTIMES. Economic activity may be impacted by energy industry changes such as fuel mix, electricity sector generation technology mix, investment in energy efficiency and fuel switching, and growth of the hydrogen sector.

Investment projects typically have two distinct phases - an investment phase and an operational phase. The investment phase is an initial phase where there is significant but temporary construction expenditure related to establishment of physical capital (land acquisition, buildings, machinery, equipment). After the investment phase begins the operational phase; here the project generates new output and revenue that has a permanent impact on the economy. These phases usually have very different economic effects, e.g., the terms of trade usually rises above baseline levels during the investment phase and returns to baseline during the operational phase.

Table 3-2: KPMG-SD sectoral disaggregation

	Sector name	Definition	Reporting
1	ShpGrnBefDry	Sheep, Grains, Beef and Dairy Cattle	**Agriculture, Forestry and Fisheries**
2	PoulOthLive	Poultry and Other Livestock	
3	OthAg	Other Agriculture	
4	AgForFishSrv	Agriculture, Forestry and Fishing Support Services	
5	Coal	Coal mining	**Energy Extraction**
6	Oil	Oil Extraction	
7	NatGas	Natural Gas Extraction	
8	OthGas	Other Gas Extraction	
9	CSG	Coal Seam Gas	
10	IrnOre	Iron Ore Mining	**Other Mining**
11	NonMetOre	Non-Ferrous and Metal Ore Mining	
12	OthMining	Exploration and Mining Support Services	
13	Meat	Meat and Meat product Manufacturing	**Manufacturing**
14	OthFodPro	Other Food Product Manufacturing	
15	BevTob	Beverage and Tobacco Product Manufacturing	
16	TexCloFot	Textile, Clothing and Footwear Manufacturing	
17	WoodProd	Wood Product Manufacturing	
18	PaprPrint	Pulp, Paper and Paperboard Manufacturing, Printing	
19	PetCoal	Petroleum and Coal Product Manufacturing	
20	OthChem	Other Chemical Manufacturing	
21	H2PEMGreen	Hydrogen proton exchange membrane (PEM) "Green" Product Manufacturing	
22	H2SMRGas	Hydrogen steam methane reforming (SMR) Gas Product Manufacturing	
23	H2SMRGasBlue	Hydrogen SMR with carbon capture & storage (SMR-CCS) "Blue" Product	
24	OthNonMetMin	Other Non-Metallic Mineral Product Manufacturing	
25	CemLimeConc	Cement, Lime and Ready-Mixed Concrete Manufacturing	
26	IrnSteel	Iron and Steel Manufacturing	
27	OthNonFerMet	Other Non-Ferrous Metal Manufacturing	
28	OthMetPro	Other Non-Metallic Mineral Product Manufacturing	
29	MotVeh	Motor Vehicles and Parts	
30	TransEqp	Other Transport Equipment Manufacturing (e.g. Ships, Boats, Aircraft, Railway)	
31	MachEqp	Machinery and Equipment Manufacturing	
32	OthManPro	Other Manufacturing	
33	ElecCoal	Electricity generation – Coal	**Electricity generation and distribution**
34	ElecGas	Electricity generation – Gas	
35	ElecOil	Electricity generation – Oil	
36	ElecRenw	Electricity generation – Renewables	
37	ElecTranDist	Electricity Transmission, Distribution, On Selling and Market Operation	
38	GasSupply	Gas Supply	**Gas Supply**
39	WatSup	Water Supply	**Water Supply**
40	ConSer	Construction	**Construction**
46	FinInsServ	Financial & Insurance Services	**FinInsServ**
47	Dwellings	Ownership of Dwellings	**Dwellings**
49	ProfSciTech	Professional, Scientific & Technical Services	**ProfSciTech**
53	HealthCare	Healthcare & Social Assistance	**HealthCare**
41	WholeTrade	Wholesale trade	**Other Services**
42	RetailTrade	Retail trade	
43	AccFoodSrv	Accommodation & Food Services	
44	TranPostWare	Transport, Postal & Warehousing	
45	InfMedTel	Information Media & Telecommunications	
48	RentHireReal	Rental, Hiring & Real Estate Services	
50	AdmSupSrv	Administrative & Support Services	
51	PubAdmSafe	Public Administration & Safety	
52	EducTrain	Education & Training	
54	ArtsRecSrv	Arts & Recreation Services	
55	OthServ	Other Services	

For the *Gas Energy in SA scenarios*, the investment and operational phases occur simultaneously. This is because growth in hydrogen production and electricity generation occurs throughout the entire projection period. Hence, investment in electricity generation capacity, transmission & distribution, hydrogen production, fuel switching, and energy efficiency measures happen continually, and the operational phases of previous investments occur simultaneously with new investment in subsequent phases.

For the ***project scenarios***, we imposed the following changes from AusTIMES:

- Investment in hydrogen production – this parameter is modelled as an investment shock on the hydrogen sector in Greater Adelaide, the Rest of South Australia in aggregate, and Rest of Australia (RoA) regions.
- Investment costs of (1) electrification and (2) energy efficiency. The former is modelled as a change in sectoral demand for electrification while the latter is modelled as a technology change for intermediate input usage of energy. The shocks are imposed for commercial, industrial and residential sectors in South Australia and Rest of Australia regions.
- Hydrogen demand – this modelling input is imposed as a shock on the intermediate use of hydrogen in SA and RoA. The shock is imposed at the aggregate level and the model endogenously distributes the total demand cross sector using the initial shares in the CGE database. As output is tied to demand, we don't have to impose a separate shock for hydrogen output. We have spread the shock so that it has this smoother distribution over the projection period.
- Electricity generation mix – this shock is imposed as a technology change that increases the shares of renewable energy and less of non-renewable sources.

3.2.2 Key Quantitative Assumptions

The key data input used by KPMG-SD are the 2017-18 input–output (IO) tables produced by the Australian Bureau of Statistics (2020). In standard form, KPMG-SD distinguishes 117 sectors and commodities. Primary factors are distinguished by 117 types of capital (one type per industry), nine occupations, two types of land (primary and non-primary production land), natural resource endowments (one per industry), and owner-operator labour.

KPMG-SD is calibrated by input-output data that quantifies the flows of goods and services from producers to various uses: intermediate inputs to production, inputs to capital creation, household consumption, government consumption, and exports. The input-output data also quantifies (in financial units) the flows associated with primary factor inputs: labour, capital, land, and natural resources. Regional data is created from the national input-output tables and other supplementary data using a combination of industry shares in employment (persons or labour hours) and commodity-specific consumption shares to split production, consumption, and investment across regions. The data inputs are combined with the model's theoretical structure to quantify behavioural responses including:

- Price and wage adjustments, which are driven by resource constraints;
- Tax and government spending adjustments, which are driven by budget constraints;
- Input substitution possibilities in production; and

- Responses by consumers, investors, foreigners, and other agents to changes in prices, taxes, technology changes, and taste changes (non-price related changes in preferences).

3.2.2.1 Initial Year Model Settings

In 2020, South Australia produced some $206 billion worth of goods and services (in nominal terms), representing 5.6% of Australian GDP of $3,707 billion. For the purposes of report results, South Australia is divided into five regions, namely

a) Greater Adelaide, which dominates the contribution to economic activity at 78.5% of South Australian GRP in 2020;

b) the Barossa, Yorke, Mid-North Region (5.8%) just to the north of Adelaide;

c) Outback South Australia (5.6%) in the north of the state;

d) the Murray Mallee region (5.7%) including Kangaroo Island and the Fleurieu Peninsula just south of Adelaide (this is composed from regions 4 and 6 of Table 3-1 combined), and

e) the Limestone Coast (4.4%) further south near the Victorian border (see Figure 3-3).

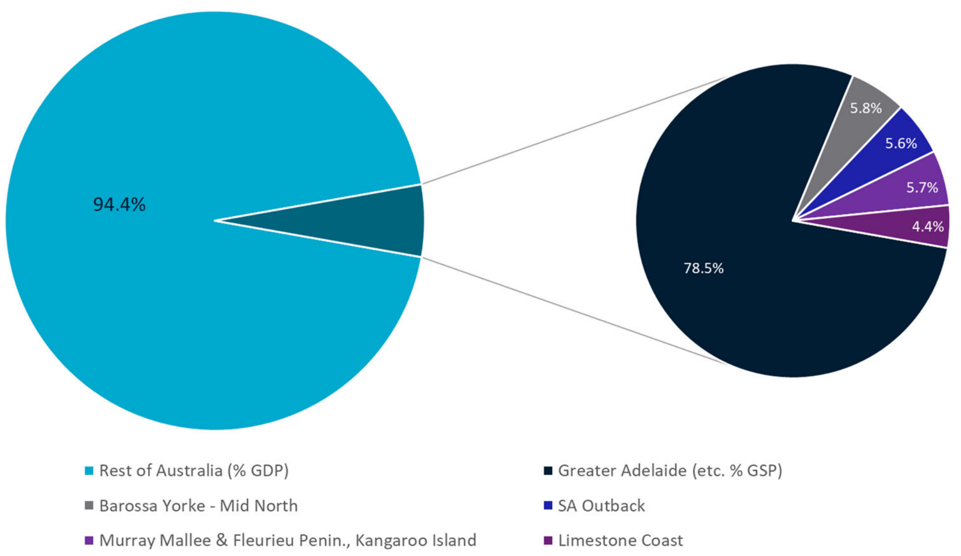

Figure 3-3: Relative size of GRP: National, South Australia, SA Regions

As a modern, services-based economy like the rest of Australia, the South Australian economy is dominated by services production (see Figure 3-4, services include utilities, construction, professional & technical, financial services, health care, dwellings and other services). Excluding construction, services represented 63% of the 2020 South Australian economy, with this proportion being the greatest in the Greater Adelaide region (68%) and least in the Outback SA region (40%). Construction services contribute 7-10% across each of the five regions. The significance of the manufacturing sector to the South Australian economy (13%) is similar to Australia as a whole, and more significant in the Barossa/Yorke Peninsula region and Limestone Coast (22-25%). Energy extraction is significant in the SA Outback region (5.4% of the economy), as is other mining (almost 20%), although these sectors are much less significant in the rest of South Australia.

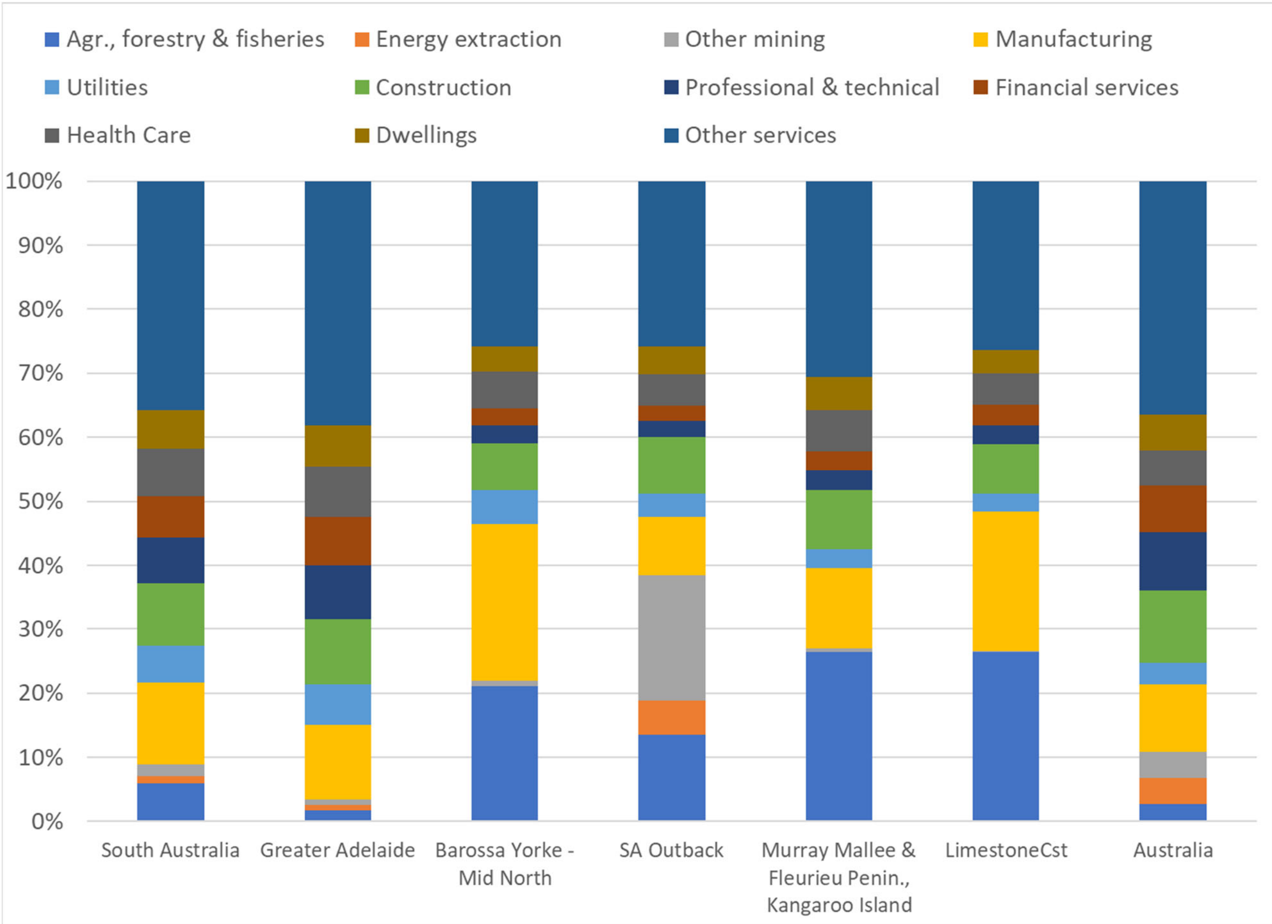

Figure 3-4: Relative shares of economic sectoral activity in 2020 by region

Agriculture, forestry, fishing, and related services are important in regional South Australia (excluding Greater Adelaide) contributing to 21-27% of production in Barossa/Yorke Peninsula, the Murray Mallee region and Limestone Coast, and 13% in the SA Outback region. Approximately half of this agricultural activity comprises sheep, grain, beef, dairy, poultry and other livestock.

3.2.2.2 Calibration of Economic Growth

In the baseline, the economy is projected to follow a balanced growth path over the projection period. We implement this by targeting a 2.2% annual growth in GDP (see Table 2-4) that is achieved by imposing a 1.2% annual growth in population, 1% annual growth in labour productivity, and 2.2% annual growth in the effective supply of land and natural resources. We also impose 2% annual growth in the consumer price index over the baseline projection. The economy reaches a new-steady state in the long-run when the capital-labour ratio stops changing.

For calibration of the baseline scenario, we adjust sector-specific technology changes to achieve a target average growth rate for each sector over the projection period. The target growth rates are drawn from projections based on historical growth rates and various assumptions about future global demand for export-oriented sectors that sell most of their output on international markets and are consistent with Reedman et al. (2021a). For these export-oriented sectors we further calibrated the path of their baseline output growth by adjusting assumed export demand schedules. This adjustment ensures a smoother growth path for export-oriented sectors. See Table 3-3 for the target and achieved calibrated baseline growth rates. Although the baseline sectoral growth rates do not necessarily closely match the target rates, the purpose is to establish a common baseline for comparison of the three *Gas Energy in SA* scenarios rather than match a specific target economic growth scenario – approximate calibration to a plausible trajectory is sufficient.

Table 3-3: Calibrated and target sectoral growth rates

Baseline (average growth rate per year)		South Australia (SA)			Rest of Australia (RoA)			Australia (Aus)	
Sectors		Relative Initial Activity $	Calibrated Growth Rate %	Target Growth Rate %	Relative Initial Activity $	Calibrated Growth Rate %	Target Growth Rate %	Calibrated Growth Rate %	Target Growth Rate %
Agriculture	AgrForFish	7.1	1.396	2.85	94.2	1.465	1.66	1.464	1.76
Coal mining	CoalMin	0	-0.308	NA	141.5	-3.445	-2.52	-3.440	-2.52
Oil and gas extraction	OilGasMin	27.8	0.312	0.60	380.3	-0.863	0.80	-0.806	0.78
Other mining	OthMin	13.0	1.597	2.28	176.5	4.546	4.30	4.492	4.20
Food, beverages and tobacco	FoodBevTob	4.1	0.961	2.66	142.3	1.494	2.07	1.458	2.08
Textile, clothing, footwear and leather	TexCloFot	1.0	-2.658	-2.54	6.1	-3.199	-3.18	-3.154	-3.08
Wood and wood products	WoodProd	2.9	0.979	0.87	13.9	0.449	0.36	0.520	0.46
Pulp, paper and printing	PaperPrint	1.0	0.339	-0.67	36.3	-0.559	-1.30	-0.550	-1.28
Petroleum refining	PetCoal	*0*	*NA*	*NA*	102.9	0.257	0.05	0.307	0.05
Basic Chemical and Chemical, Polymer and Rubber Product Manufacturing	ChemPolyRubr	10.5	0.277	2.55	175.1	0.778	2.00	0.743	2.04
Non-metallic mineral products	NonMetMinMnf	12.6	1.294	0.26	76.2	0.552	-0.17	0.668	-0.10
Iron and steel	IrnSteel	36.9	0.460	-0.49	93.4	0.271	-0.91	0.280	-0.78
Basic non-ferrous metals	NonFerMet	6.3	1.722	3.21	326.8	0.990	1.13	1.009	1.19
Fabricated metal products	OthMetPro	0.6	0.550	1.54	5.9	0.881	1.20	0.858	1.24
Machinery and equipment	MachEqp	0.9	-2.266	-2.16	5.3	-2.646	-2.70	-2.603	-2.61
Furniture and other manufacturing	FurnOthManuf	*0*	*NA*	*NA*	1.0	0.106	0.03	0.172	0.03
Gas supply	GasSupply	0.1	-2.239	-2.11	6.6	-1.419	-0.87	-1.467	-0.87
Water supply, sewerage and drainage services	WatSup	2.3	-0.026	-0.10	14.1	1.299	1.10	1.157	0.96
Construction	ConSer	1.4	0.626	0.66	22.3	1.708	2.19	1.643	2.12
Electricity generation, transmission and distribution	ElcGenTrnDst		0.951			1.722		1.606	
Other Services	OthSrv		1.191			1.860		1.815	
Disaggregated sectors									
Hydrogen production and distribution	Hydrogen		-1.167			0.316		0.143	
Electricity generation from coal	ElecCoal		0.000			1.563		1.563	
Electricity generation from gas	ElecGas		0.329			1.724		1.439	
Electricity generation from oil	ElecOil		1.112			1.754		1.730	
Electricity generation from renewables	ElecRenw		1.259			1.881		1.806	
	RealGDP		1.016			1.679		1.631	
	Employment		0.570			1.260		1.220	

3.3 AusTIMES

3.3.1 General Structural Overview

AusTIMES is a partial equilibrium model of the Australian energy sector, including the electricity (power) and hydrogen energy generation sectors explicitly, as well as end-use energy demand sectors including the residential, commercial, industrial and transport sectors. Rather than a (nonlinear) computational general equilibrium economic simulation model, AusTIMES is a technologically explicit, linear optimisation model, selecting the least total economic cost options to meet energy end-use demand requirements, and subject to technological energy transformation and energy-balance constraints (Reedman et al. 2018).

Time is represented in five yearly or annual increments, and each year is subdivided into sixteen sub-annual periods, covering four seasons and four time-of-day divisions (peak, off-peak, evening, night). Electricity storage is required to balance supply and demand in each sub-annual time period, with technologies such as pumped hydro, and utility scale and customer scale batteries.

The electricity generation sector allows for the various alternative technologies such as fossil-fuelled generation (coal, gas, and some liquid fossils), renewables including hydroelectricity, solar PV and wind. The electricity generation sector is spatially resolved to the National Transmission Network Development Plan (NTNDP) zone with each AEMO Renewable Energy Zones (REZ) represented as associated directly with a specific NTNDP zone. The power sector representation includes transmission interconnections between NTNDP zones.

The hydrogen sector allows for a small number of alternative generation technologies. Steam methane reforming (SMR) of both coal with carbon capture and storage, or natural gas, with or without carbon capture and storage, is permitted. Two alternative electrolysis technologies, namely Proton Exchange Membrane (PEM) and Alkaline Electrolysers (AE) are permitted. Hydrogen is assumed to be produced only in NTNDP zones that are associated with marine ports, to permit convenient export.

3.3.2 Key Quantitative Assumptions

The base year of AusTIMES is calibrated to the *Australian Energy Statistics* (for example, Office of the Chief Economist, 2020) for energy demand in each sector of the Australian economy. Projected costs of energy generation and storage technology (both electricity and hydrogen) are derived from Graham, Hayward, Foster and Havas (2021c). Assumptions about the growth in residential dwellings are derived from the Australian Bureau of Statistics population forecasts, and commercial buildings growth is based on *Commercial Buildings Baseline Study* (Commonwealth of Australia 2012), *Australian Energy Statistics*. Buildings energy technology specifications are from the *Low Carbon High Performance* report (CWA, 2016). Further details about the structure of AusTIMES, including details of the representation of end-use sectors, are available in Appendix C. Projections of end consumer uptake of rooftop solar PV, battery storage and electric vehicles are based on Graham (2021c) and Graham and Havas (2021b, see Appendix D).

4 Economy-wide Modelling Results

This chapter provides the economic simulation results from KPMG-SD. For each of the project scenarios being modelled, the broader economic impacts are measured relative to a baseline scenario that does not include the development of the natural gas and hydrogen sectors. The simulation results presented comprise macroeconomic impacts, including changes to real Gross Domestic, State and Regional Products (GDP, GSP and GRP), employment, and sectoral effects.

In general, it can be observed that the economic impacts of each scenario follow the same dynamics, that is, the time trend of most variables follows a similar pattern for each of the project scenarios. Hence, we discuss in detail only the results of Scenario 1 to explain the causality of economic effects arising from the impacts of changes in the energy sector. Then, for the other scenarios we focus on comparing the magnitude of results relative to Scenario 1 and similarly for any significant differences in the dynamics.

4.1 Economic Sectoral Projections: baseline

The baseline economic modelling results show a growth in each sector consistent with the calibrated target growth rates described in Table 3-3. South Australia shows a more rapid rate of growth in the first 20 years of the projection period, which slows down in the following two decades as long-term economic growth returns to equilibrium and the agricultural sector, which comprises a relatively larger share of economic activity, declines slowly (Figure 4-2). The economy of Australia as a whole however, is more consistent over the projection period (Figure 4-1), supported by growth in demand for mining exports.

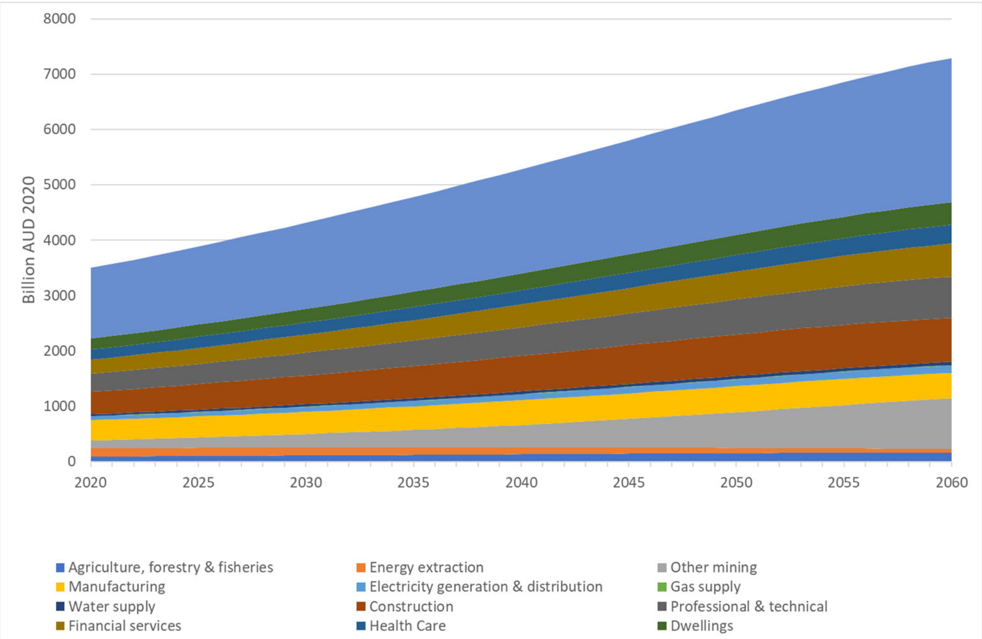

Figure 4-1: Nominal (sector output prices adjusted) sectoral growth in Rest of Australia

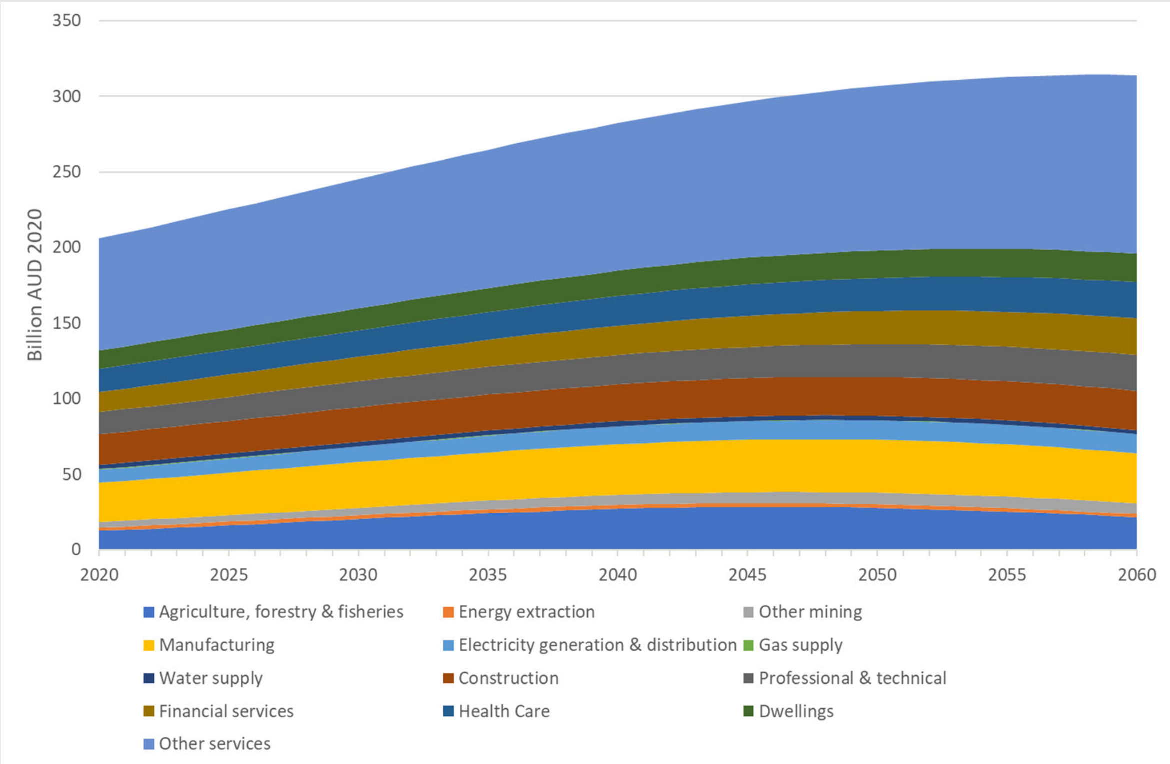

Figure 4-2: Nominal (sector output prices adjusted) sectoral growth in South Australia

More regionally detailed Gross Regional Product (GRP) projections can be found in Appendix F (see Figure 6-2). Further subsectoral detail on the Mining and Manufacturing sectors, showing the projections corresponding to Figure 3-4 can be found as Figure 6-3.

The following sections describe the economic results for the project case scenarios. It will be seen that the differences among the three project case scenarios are generally smaller than the difference between the baseline scenario and the three project cases. Section 4.2 describes the differences between the baseline and the "Blue Hydrogen" scenario and Section 4.3 describes the differences among the "Blue Hydrogen", "High Electrification" and "Hydrogen Exports" scenarios.

4.2 Blue Hydrogen versus Baseline Scenario Results

4.2.1 Macroeconomic Results: comparison to baseline

An overall measure of the economic impact at various levels of the economy is the Gross Domestic Product (GDP) or Gross State Product (GSP). This is the total market value of goods and services produced in an economy. Figure 4-3 provides the cumulative changes in real GSP and GDP. Under the "Blue Hydrogen" Scenario, the CGE modelling indicates that GSP in South Australia would be higher than the baseline by 0.70% over the projection period. The GSP gain is slightly higher for the rest of Australia (0.96% at the end of the simulation period). This is consistent with the higher magnitude of shocks (that is, investment and hydrogen production) applied to the rest of the country as compared to the SA region. Furthermore, Figure 4-4 decomposes the GSP result for SA across its regions. Results show that Greater Adelaide is the biggest contributor to the GSP gain followed by Barossa - Yorke Peninsula – Mid-North Region.

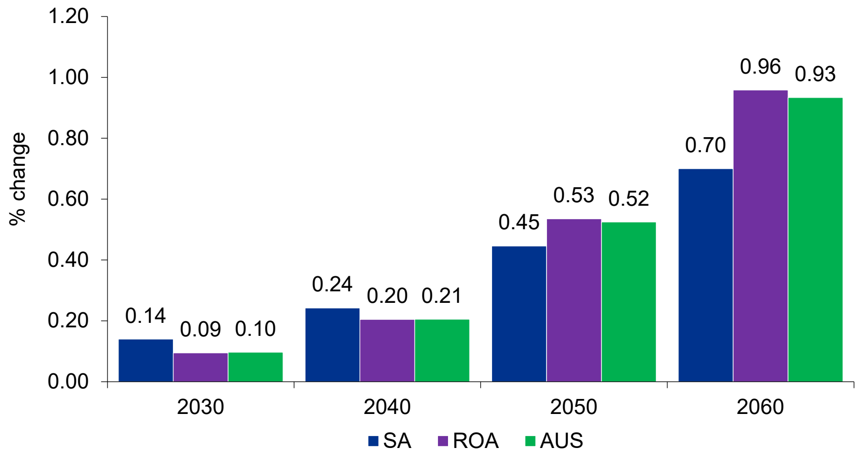

Figure 4-3: Real GSP and GDP, % deviation from baseline over projection period under the "Blue Hydrogen" scenario

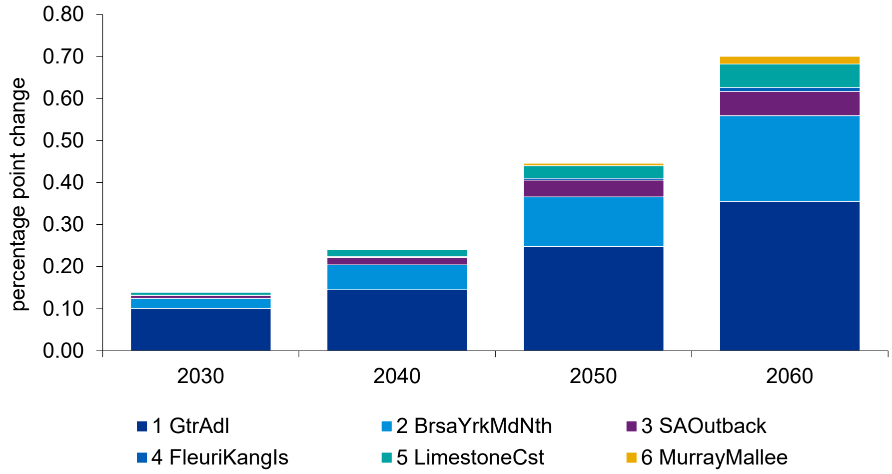

Figure 4-4: Decomposition of SA GSP across SA regions, %-point change relative to baseline SA GSP under the "Blue Hydrogen" scenario

Figure 4-5 shows the employment effects of the "Blue Hydrogen" Scenario. The increase in economic activity arising from investment projected by AusTIMES for this scenario will support a 0.33% increase in full time equivalent (FTE) jobs for SA and 0.08% increase for the Rest of Australia (RoA) relative to the baseline over the projection period. The national percentage increase in FTE is close to that of the RoA, reflecting RoA's much bigger proportion of total employment.

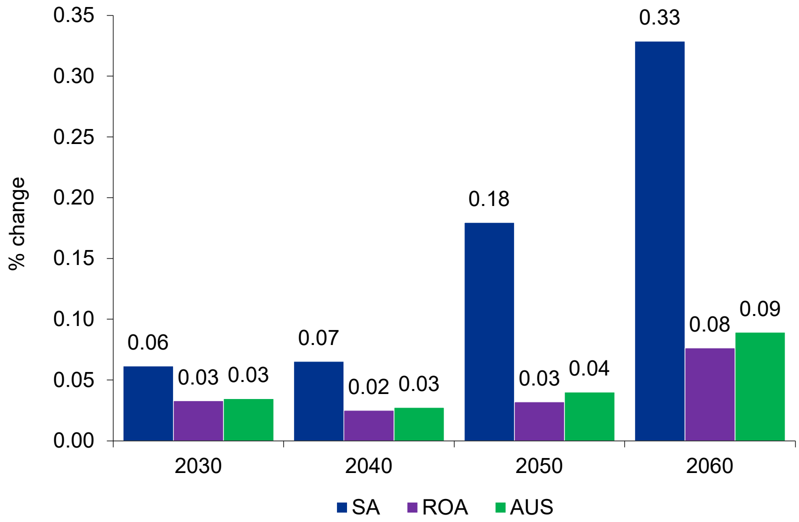

Figure 4-5: Employment effects, % deviation from baseline over projection period under the "Blue Hydrogen" scenario

4.2.2 Sectoral Results: comparison to baseline

Figure 4-6 shows the projected hydrogen production based on AusTIMES fuel mix modelling results (recall that although KPMG-SD model provides AusTIMES with growth paths for end-use sectoral demand, as an energy sector partial equilibrium model, AusTIMES projects fuel mix including hydrogen demand and hence growth in the hydrogen sector). These are exogenously specified as shocks to KPMG-SD. By the end of the projection period, about $2.6 billion of hydrogen is produced in SA (or a 7% contribution to national output) while $36.5 billion is produced in RoA.

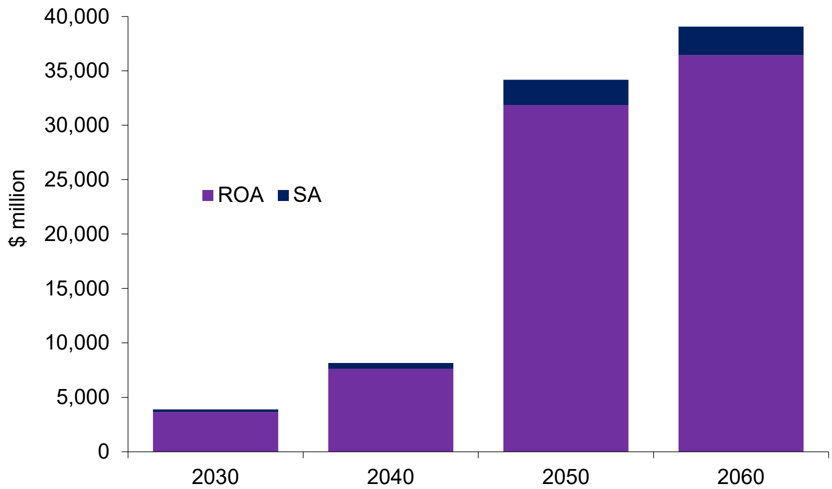

Figure 4-6: Hydrogen output over projection period ($million) under the "Blue Hydrogen" scenario

Figure 4-7 presents the production output results relative to the baseline for other sectors. The pattern of sectoral results is generally similar across regions. There is an overall contraction in the activity of Mining sectors. This is driven by fuel switching to more renewable sources of energy and electrification. Related to this is the contraction in Petroleum and coal manufactured products and Gas supply services. In contrast, the Electricity generation, transmission and distribution sector expands as this is a major input supplier to green hydrogen production. There is also an expansion in the activity of hydrogen-using industries such as the Chemical sector, Other non-ferrous metals (e.g., aluminium) and Other metal products. Construction services also expand as they are the main inputs to investment.

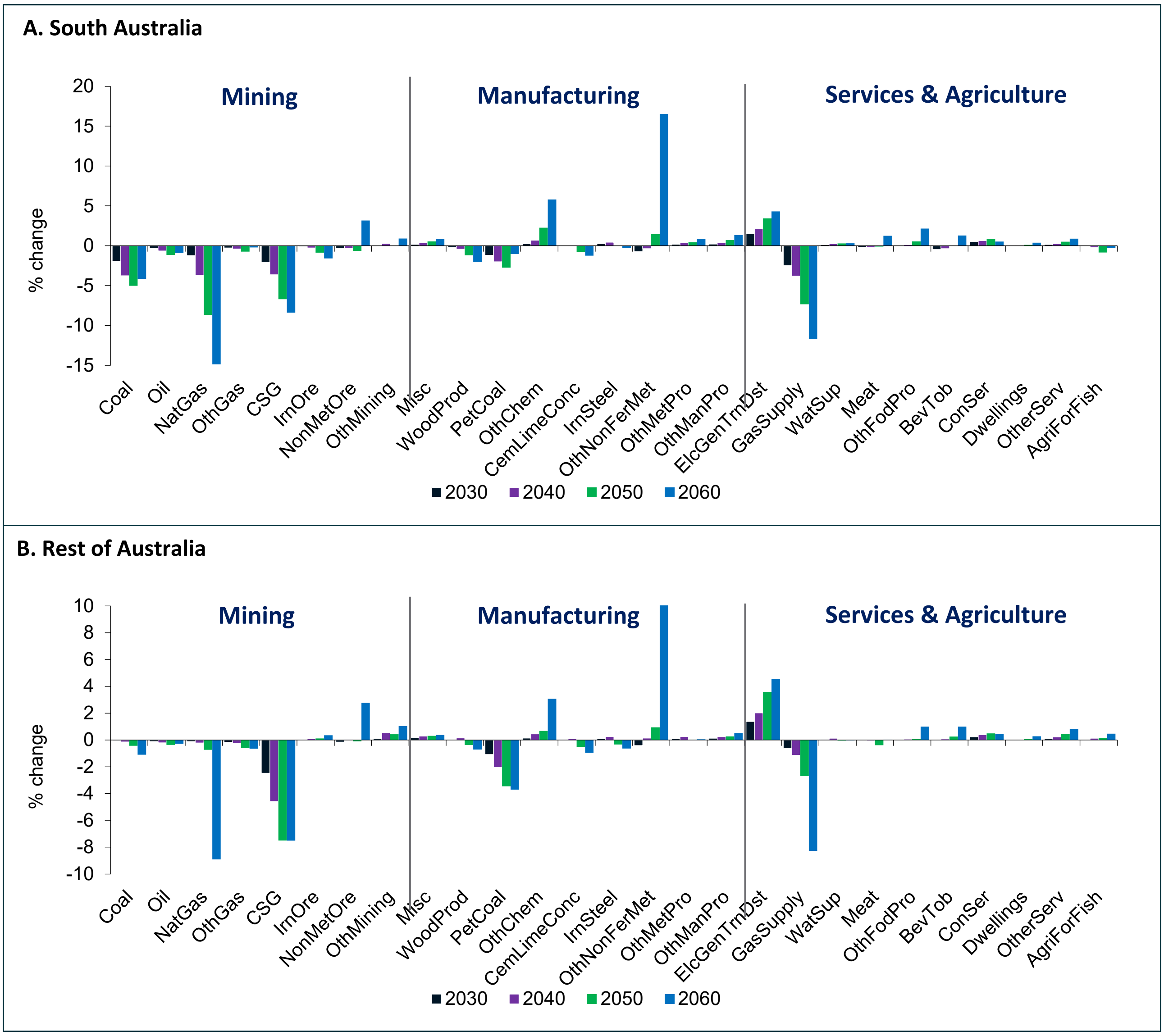

Figure 4-7: Sectoral output, cumulative % deviation from baseline sectoral output over projection period under the "Blue Hydrogen" scenario

Figure 4-8 presents the changes in sectoral shares of SA's total output. Initially, the mining sectors contribute about 3% to total production (see Panel A) while the manufacturing sectors has a slightly higher contribution at 9% (Panel B). The Services sector is still the largest sector in SA contributing 75% of total production; 10% of this is from Construction services and 5% from the

Dwellings sector (Panel C, Services includes only Construction services, Dwellings, Other services, and Agriculture, forestry and fishing services).[5]

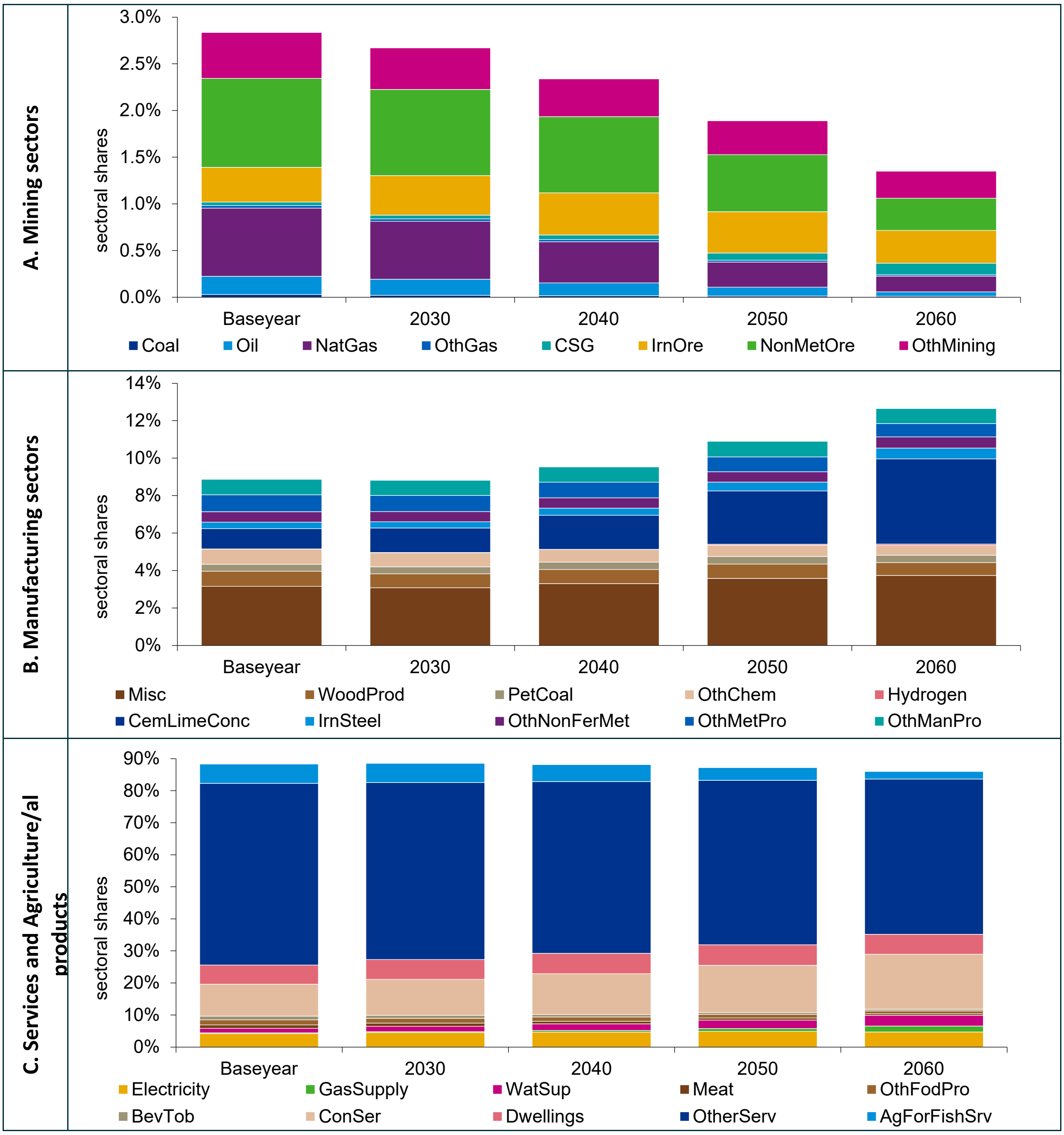

Figure 4-8: Sectoral shares to total production, South Australia ("Blue Hydrogen" scenario)

Primary agriculture and Food, beverages and tobacco products contribute about 10% of total output. The "Blue Hydrogen" scenario leads to structural change as represented by these sectoral contributions. For example, the SA economy becomes less dependent on mining activities (Panel A). This is compensated by the expansion in Manufacturing activities particularly by the Cement, lime and ready-mixed concrete industry (Panel B), which is a key input supplier to Construction services (Panel C).

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[5] In the industrial classification used by the Australian Bureau of Statistics (that is, ANZSIC), the Dwellings sector represents actual and imputed housing services flowing to households.

4.3 Scenario results comparisons

4.3.1 Macroeconomic results: scenario comparisons

Figure 4-9 summarises the GSP, GDP and employment results for all scenarios over the projection period. For South Australia, the GSP and employment effects within the “Blue Hydrogen” and “High Electrification” scenarios are very similar, whereas the impacts of investment in the “Hydrogen Exports” Scenario are larger, particularly towards the end of the projection period.

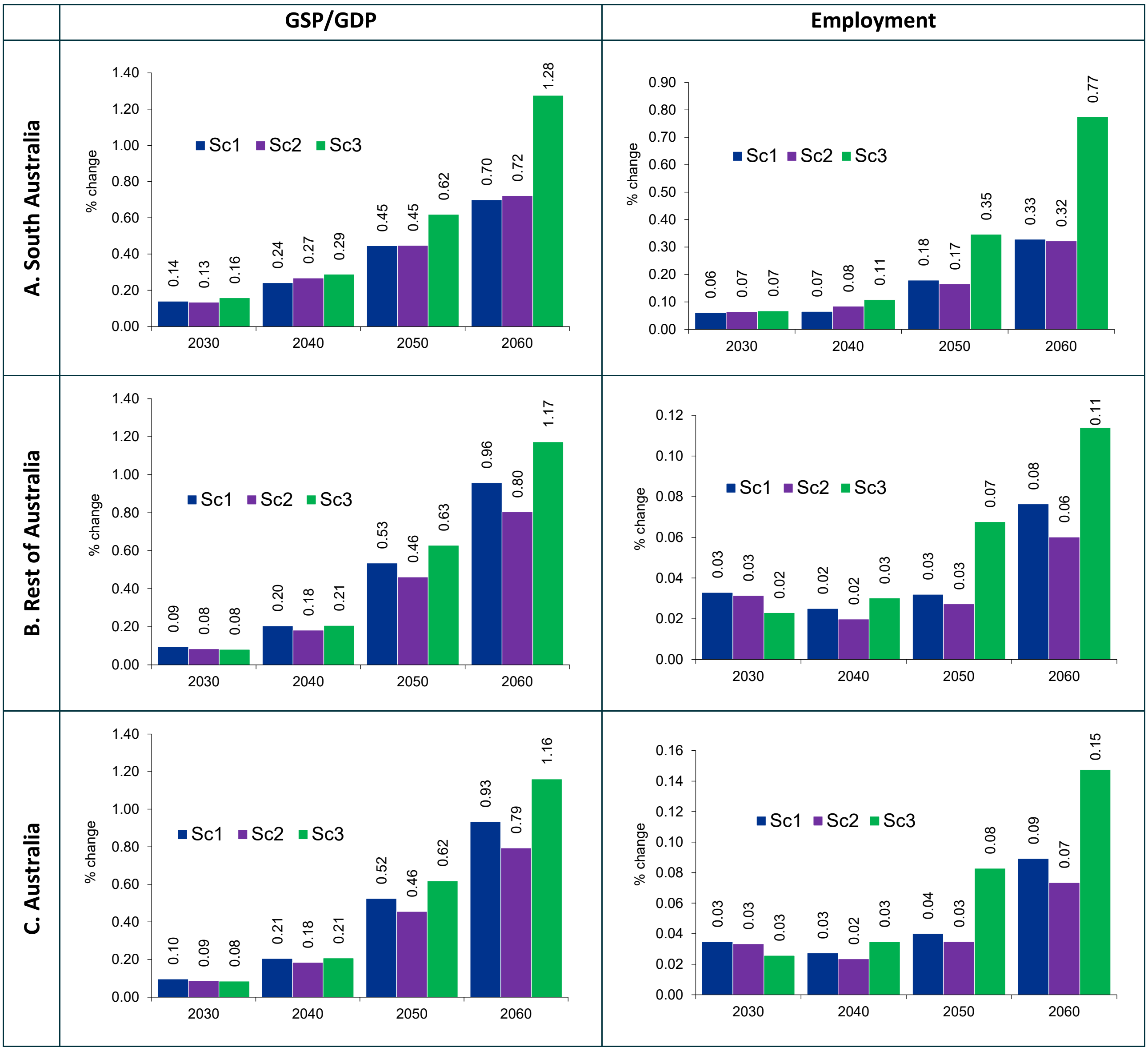

Figure 4-9: Real GSP/GRP/GDP and Employment across project scenarios, % cumulative deviation from baseline, Sc1: “Blue Hydrogen”, Sc2: “High Electrification”, Sc3: “Hydrogen Exports”

For the RoA, as for SA, the economic impacts relative to the baseline are largest in the "Hydrogen Exports" Scenario. For the RoA the economic impacts of the "Blue Hydrogen" Scenario are slightly greater than those for the "High Electrification" Scenario. This pattern of results is driven by the larger magnitude shocks for hydrogen production and investment in the "Hydrogen Exports" Scenario compared to the other scenarios.

Figure 4-10 provides the decomposition of South Australian GSP across regions. Results show that, for all three scenarios, the Greater Adelaide region provides the largest share of the GSP gain in South Australia followed by the Barossa – Yorke Peninsula – Mid-North Region.

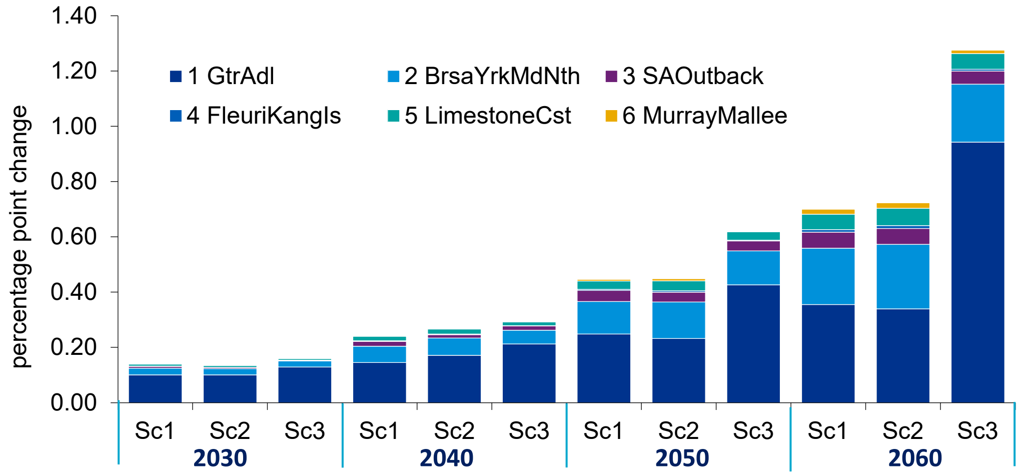

Figure 4-10: Decomposition of GSP across SA regions, %-point change relative to baseline SA GSP, Sc1: "Blue Hydrogen", Sc2: "High Electrification", Sc3: "Hydrogen Exports"

4.3.2 Sectoral results: scenarios comparison

Figure 4-11 compares the changes in hydrogen output across scenarios. The production of hydrogen increases over time, and it is projected to be highest for the "Hydrogen Exports" scenario with additional output intended for exports (Figure 4-12). This pattern is consistent across regions with the RoA being the largest producer of hydrogen.

Figure 4-13 shows the sectoral results for other sectors. The pattern of sectoral effects is similar across scenarios, but the magnitude is greatest under the "Hydrogen Exports" scenario followed by the "High Electrification" scenario. Figure 4-14 shows the changes in sectoral shares. Although these shares change over time, the results are not significantly different across scenarios.

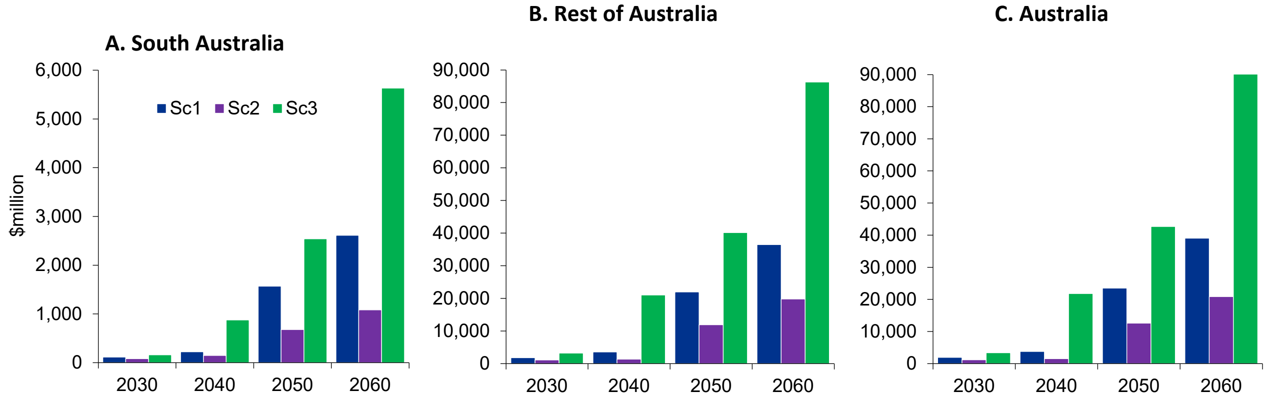

Figure 4-11: Hydrogen output ($million) over projection period, Sc1: "Blue Hydrogen", Sc2: "High Electrification", Sc3: "Hydrogen Exports"

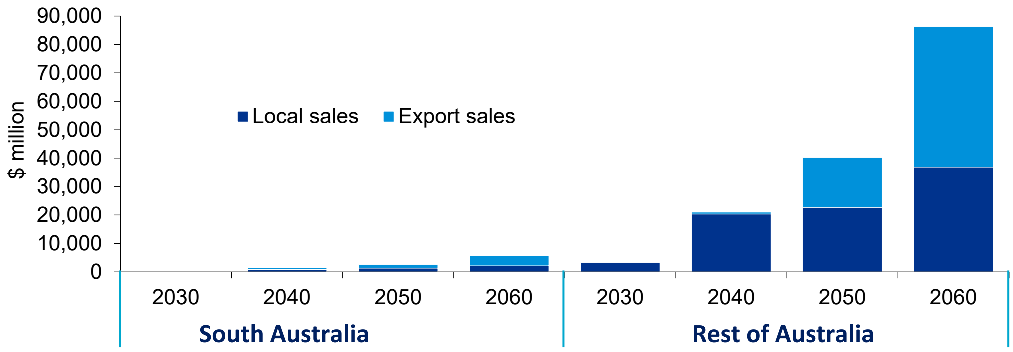

Figure 4-12: Hydrogen production output in "Hydrogen Exports" Scenario ($million)

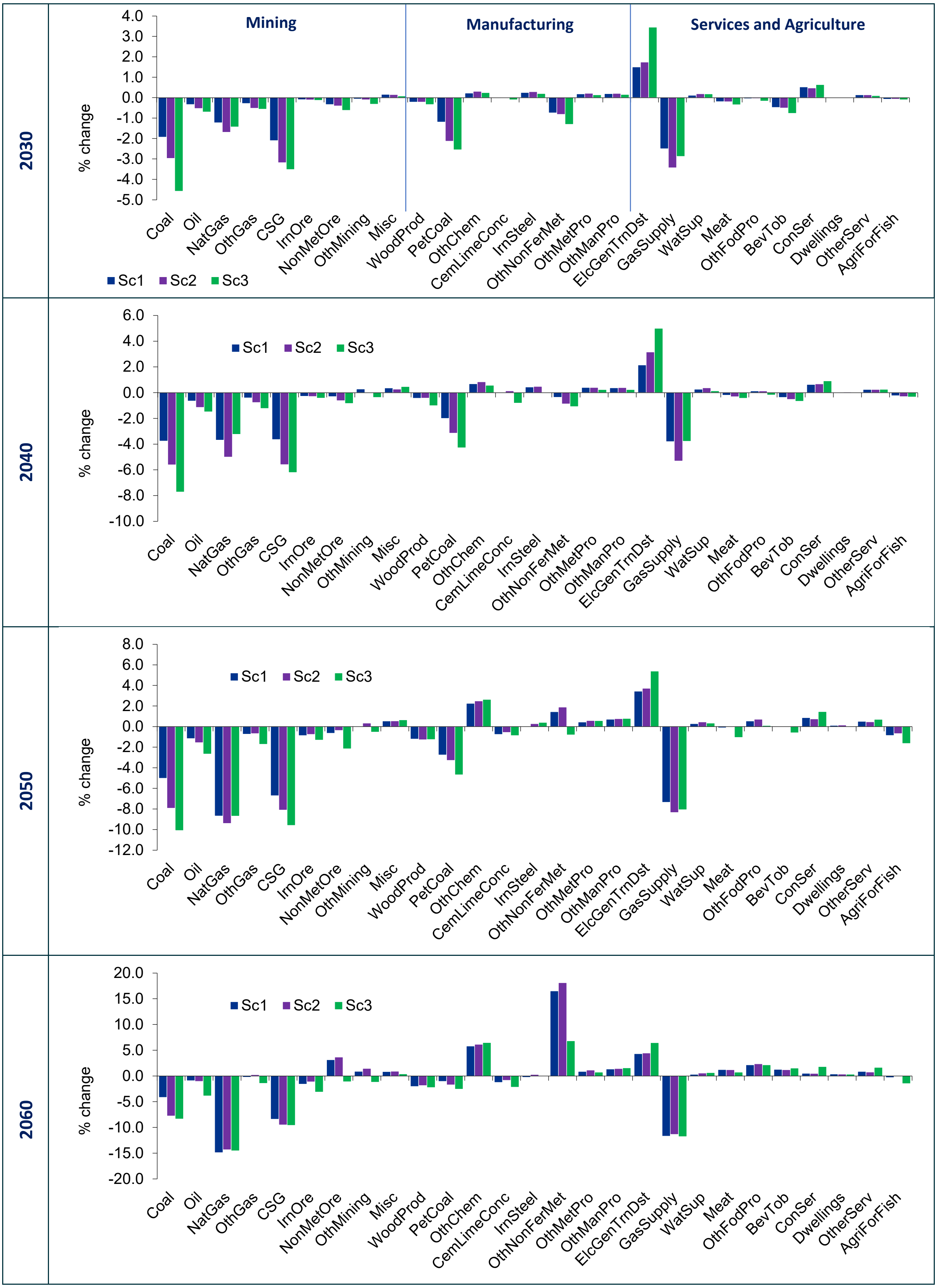

Figure 4-13: Sectoral output change in South Australia, cumulative % change relative to baseline sectoral production, Sc1: "Blue Hydrogen", Sc2: "High Electrification", Sc3: "Hydrogen Exports"

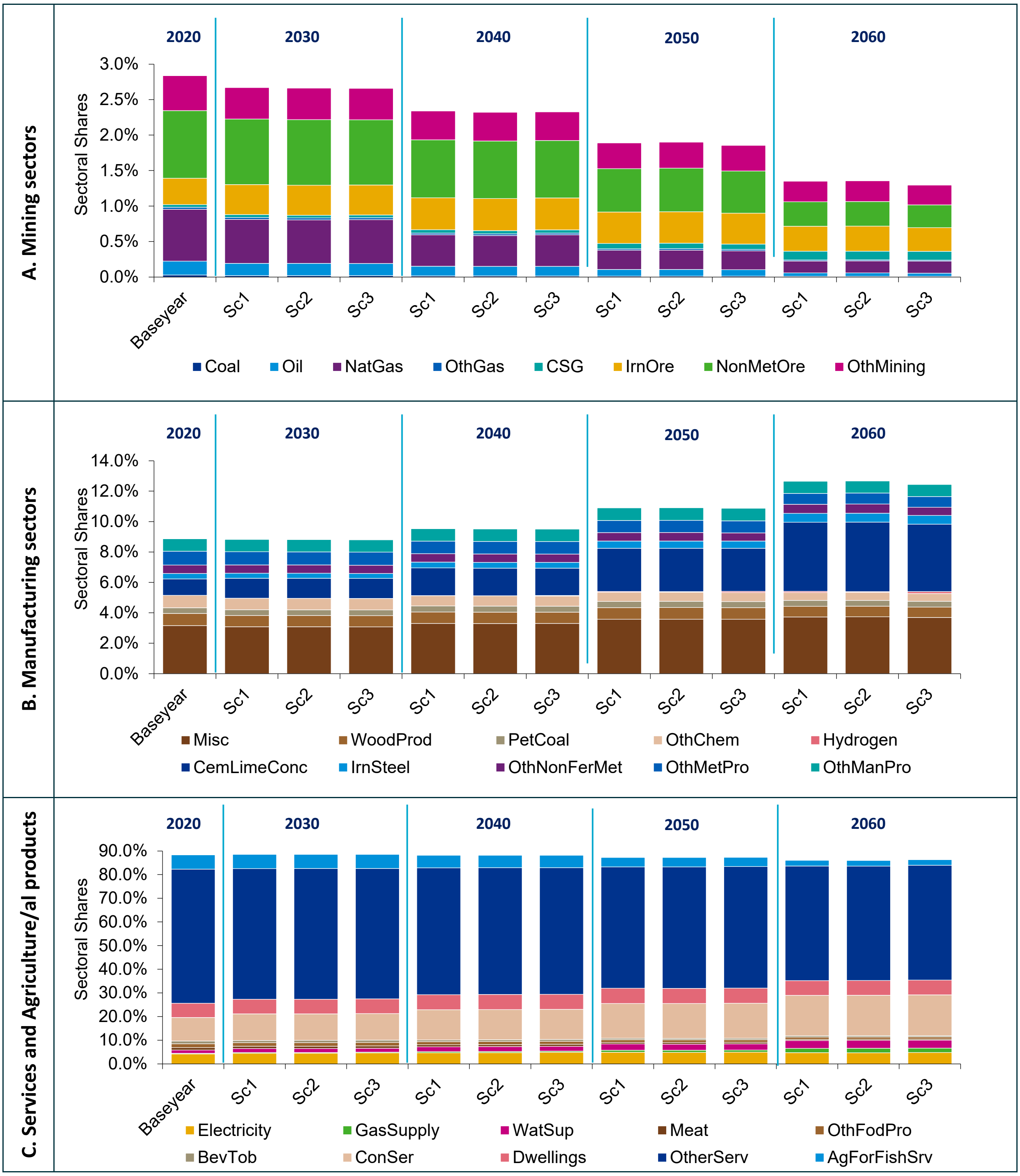

Figure 4-14: Sectoral shares to total production across scenarios, South Australia, Sc1: "Blue Hydrogen", Sc2: "High Electrification", Sc3: "Hydrogen Exports"

5 Energy Demand and Fuel Supply

Having understood the general pattern of economic growth, which is quite similar across the three scenarios from the perspective of the overall economy, we now inspect the details of energy consumption and hence supply.

5.1 Buildings Demand

The projected fuel mix across the three scenarios is fairly similar in the buildings sector, which represents about a quarter of final energy demand. In the residential sector, across all three scenarios, the demand for electricity remains fairly constant to about 2040, as the combined impact of electrification and growth in housing stock, against energy efficiency measures, balance each other out (see also Figure 5-25 and Figure 5-26 on page 72). As the opportunities for existing, modelled, energy efficiency measures become exhausted over this time period, but demand for electricity for household electric vehicles starts to become significant, the residential housing sector demand for electricity (including household electric vehicles) starts to increase post 2050. The growth in overall energy use is slower for the "High Electrification" scenario.

The demand for gas (natural gas and hydrogen combined) in the residential sector declines across the projection period for all three scenarios, nationally and in South Australia (Figure 5-1 and Figure 5-2). However, the decline is slow for all three scenarios at the national scale, while in South Australia it is much more rapid in the "Hydrogen Exports" scenarios, where it is all but eliminated by 2045. The relatively rapid decline in total residential gas use in this scenario in South Australia corresponds to a slight increase in the residential consumption of electricity over time.

Both nationally and in South Australia the share of gas demand between natural gas and hydrogen shifts from primarily natural gas now to essentially 100% hydrogen by 2050, with the rate of change of share slightly different across scenarios reflecting differences in the assumptions about the share of hydrogen and natural gas (recall Figure 2-1). Nationally in the "Hydrogen Exports" scenario there is first a decline in the demand for gas, which is predominantly natural gas, in the residential sector. This is replaced by electricity demand, a situation which lasts for a decade or more before gas demand recovers, this time in the form of hydrogen. In South Australia however, this scenario sees a decline in overall residential demand for gas to zero which never recovers, and the total demand for hydrogen in residential buildings does not ever reach a significant share of the overall residential energy market.

The modelling projections also show an increase in the total demand for residential biomass (firewood for heating). This is a direct result of assumptions of the use of wood per household remaining constant at its present rate, with projected increases reflecting solely the growth in building stock. In fact, for buildings with wood heating, we would expect to see the heating requirements for residential biomass decrease, as building thermal envelope efficiency improves over time. This represents an aspect of the model that could be improved in future developments.

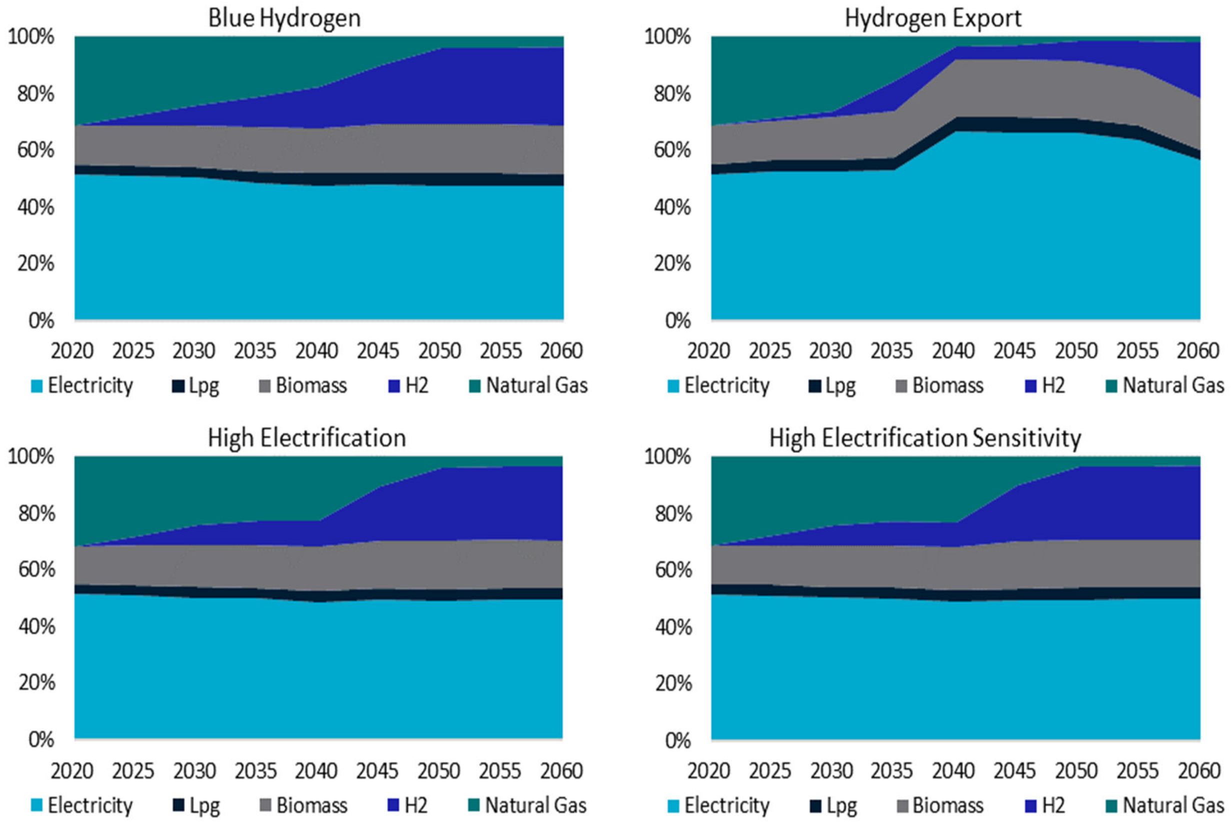

Figure 5-1: Fuel use as a percentage of total energy demand for residential buildings across NEM states

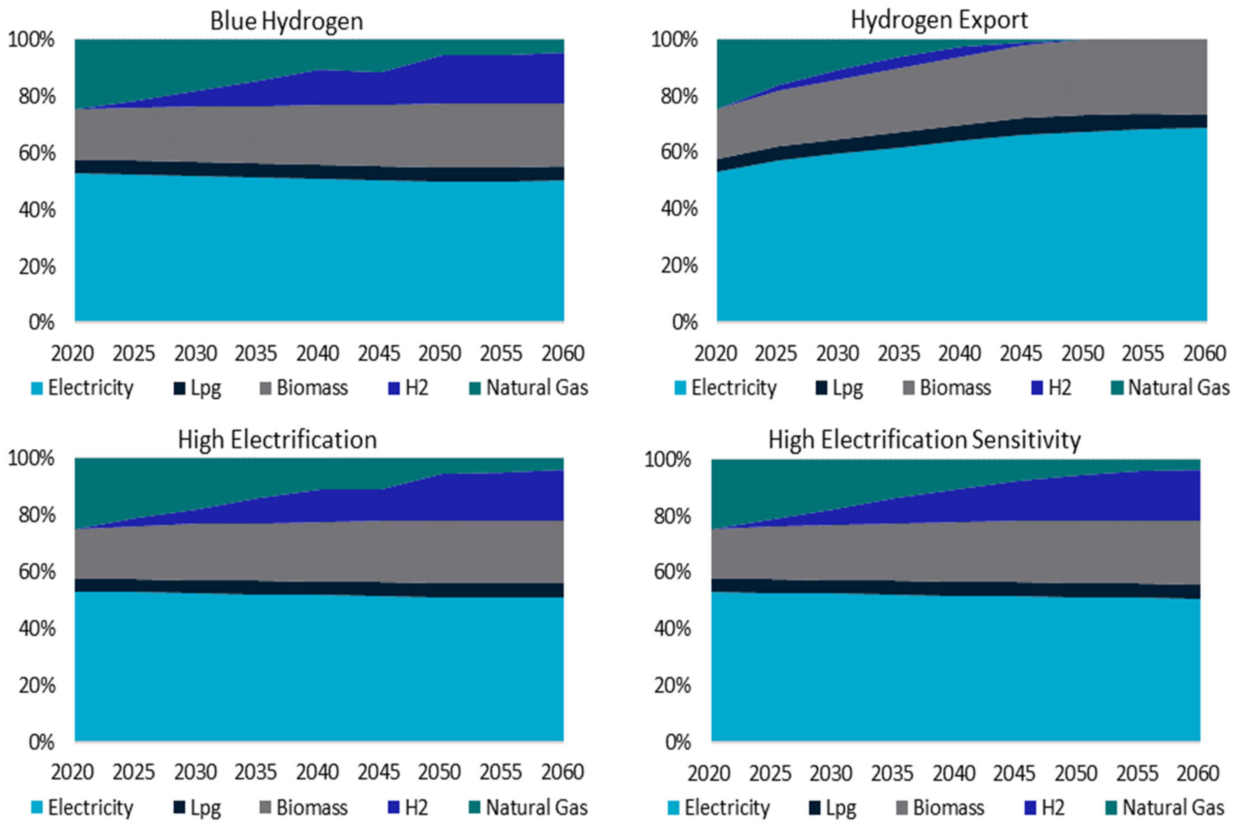

Figure 5-2: Fuel use as a percentage of total energy demand for residential buildings in SA

Commercial buildings (Figure 5-3 and Figure 5-4) are similar overall to the residential sector, although they start with a greater share of electricity demand, and hydrogen eventually makes a modest contribution to energy supply even in the “Hydrogen Exports” scenario. Oil demand in commercial buildings is assumed constant, as is residential biomass demand.

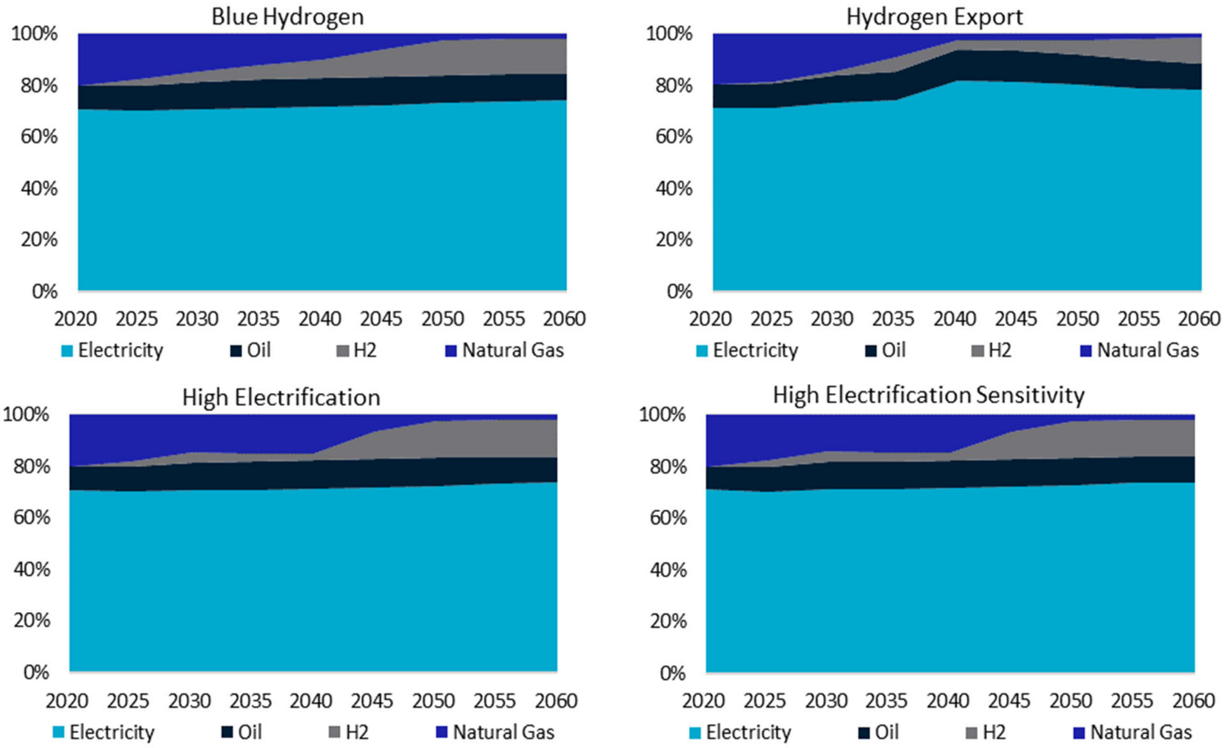

Figure 5-3: Summary of fuel use as a percentage of total energy demand for commercial buildings across NEM

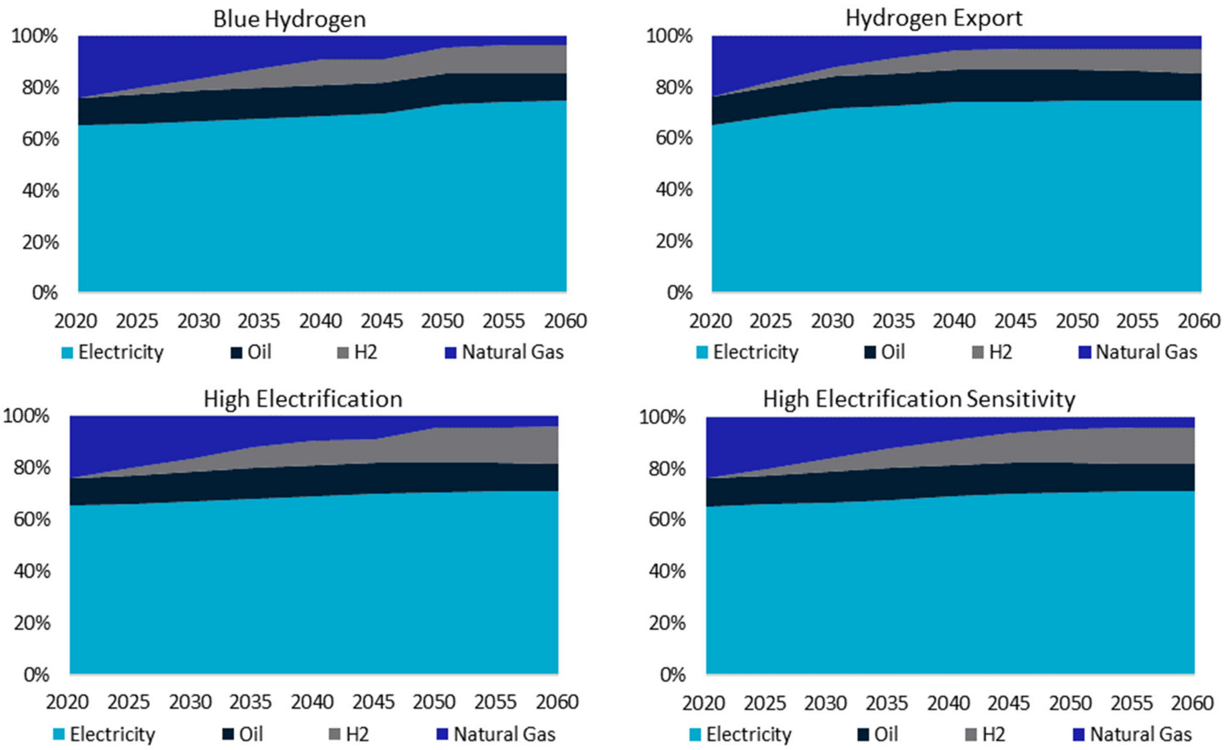

Figure 5-4: Summary of fuel use as a percentage of total energy demand for commercial buildings in SA

5.2 Transport Demand

The outlook for energy demand by the road transport sector is similar across all three scenarios, with slight difference in timing (Figure 5-5). The outlook for South Australia is similar, in proportion, to the national transport energy totals and fuel mix (Figure 5-6). The use of compressed natural gas (CNG) is projected to decline from its existing small contribution to the share of transport fuel and hydrogen grows to make a small contribution to transport fuel supply.

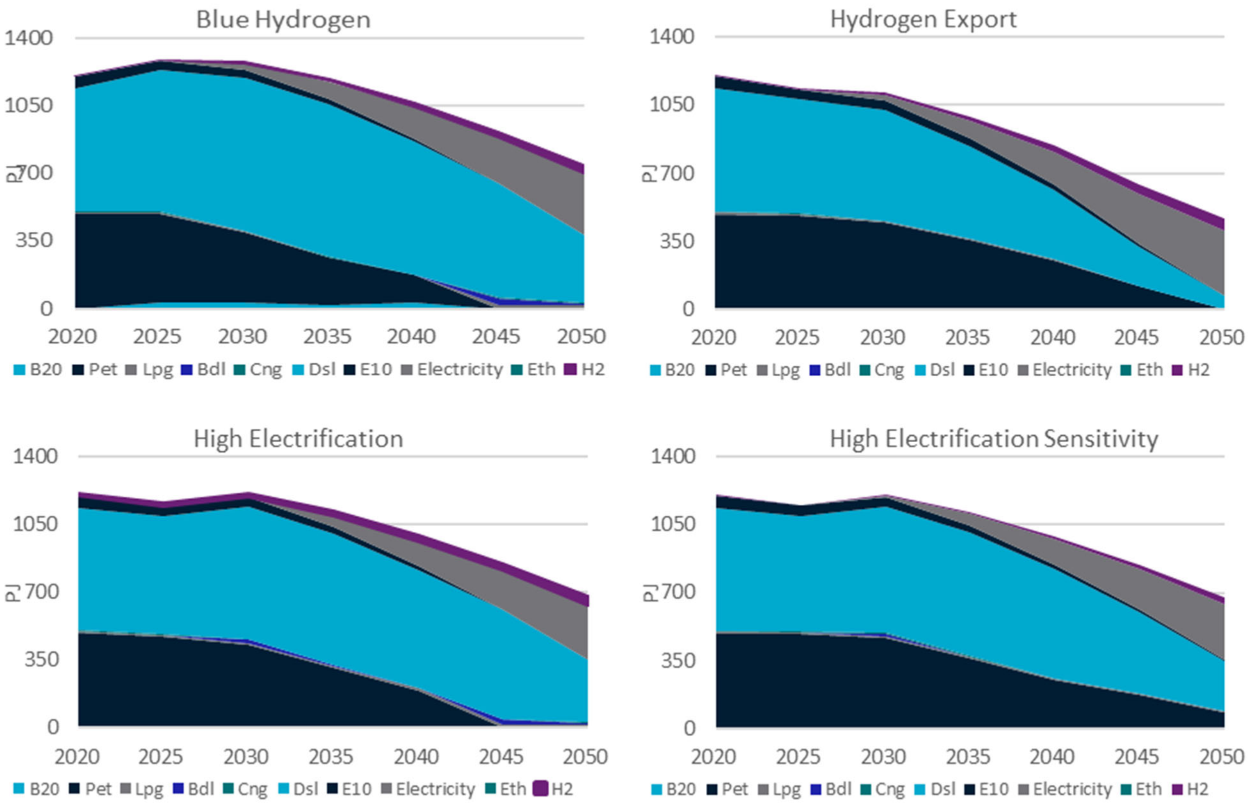

Figure 5-5: Projected national road transport vehicle fuel consumption for Australia

In all three scenarios, both nationally and in South Australia, electricity replaces diesel and petrol as the dominant transport fuel by 2050. Owing to the relative energy requirements per unit distance for electric motors compared to internal combustion engines, the total demand for direct (final) transport fuel declines in terms of energy units. Road transport electrification begins slightly later in the high electrification scenario, and road transport electrification is slightly more extensive in “Hydrogen Exports” than in “Blue Hydrogen” (with some remaining diesel) and “High Electrification” (with some remaining both petrol and diesel). Hydrogen is slightly less popular as a road transport fuel in the “High Electrification” sensitivity scenario than the other comparisons.

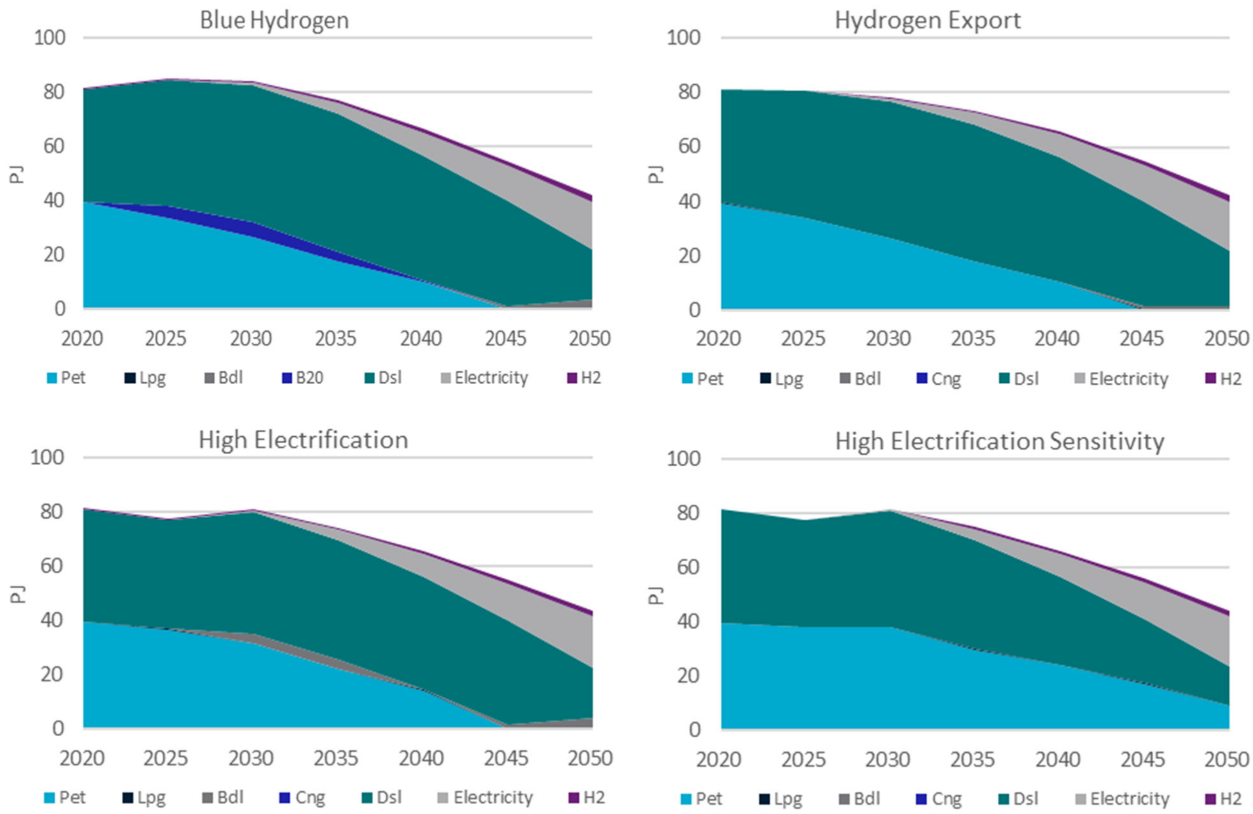

Figure 5-6: Projected state road transport vehicle fuel consumption for SA

For the non-road transport sector, a significant difference across scenarios is that the "Blue Hydrogen" scenario shows diesel being largely replaced by biodiesel (Figure 5-7), as the model does not represent hydrogen as a fuel option for non-road transport. In the other scenarios biodiesel plays a much smaller role. As for road transport, the development pattern for non-road transport energy demand in South Australia is a representative microcosm (Figure 5-8).

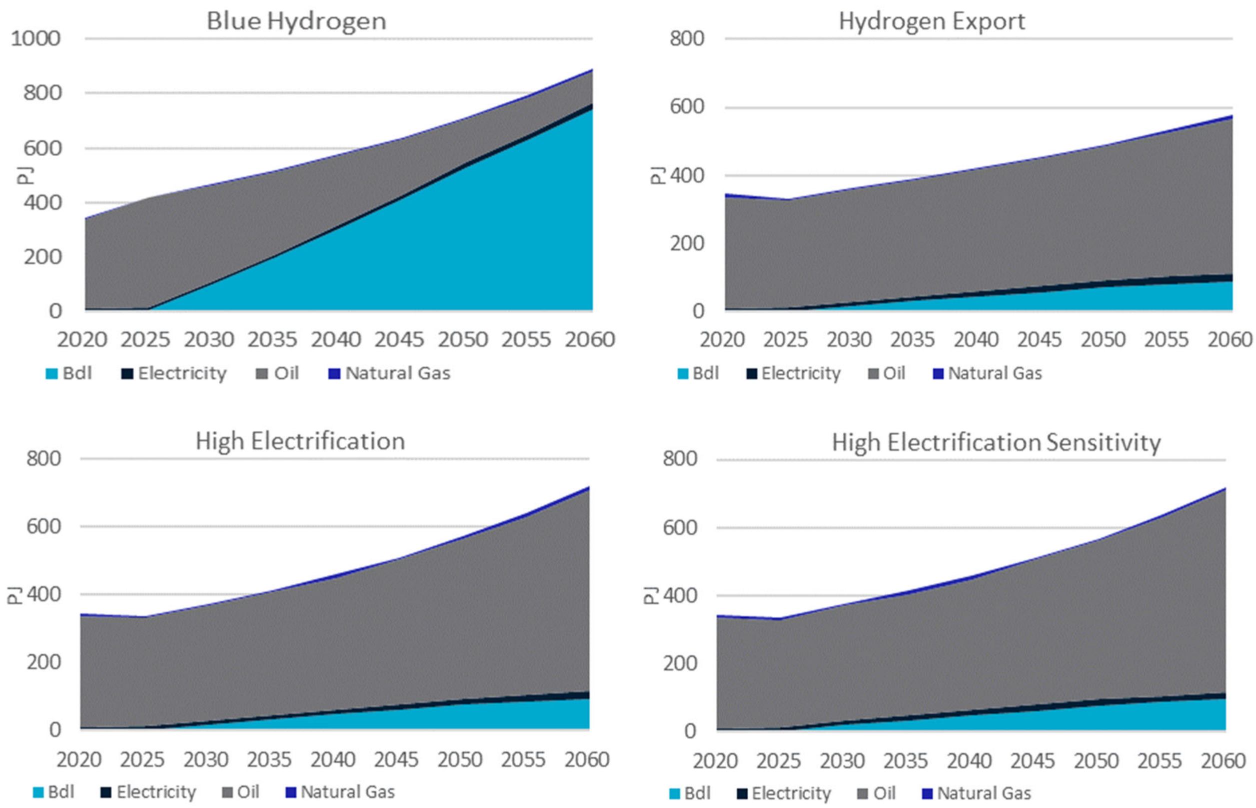

Figure 5-7: Projected national non-road transport vehicle fuel consumption for Australia (Bdl is biodiesel).

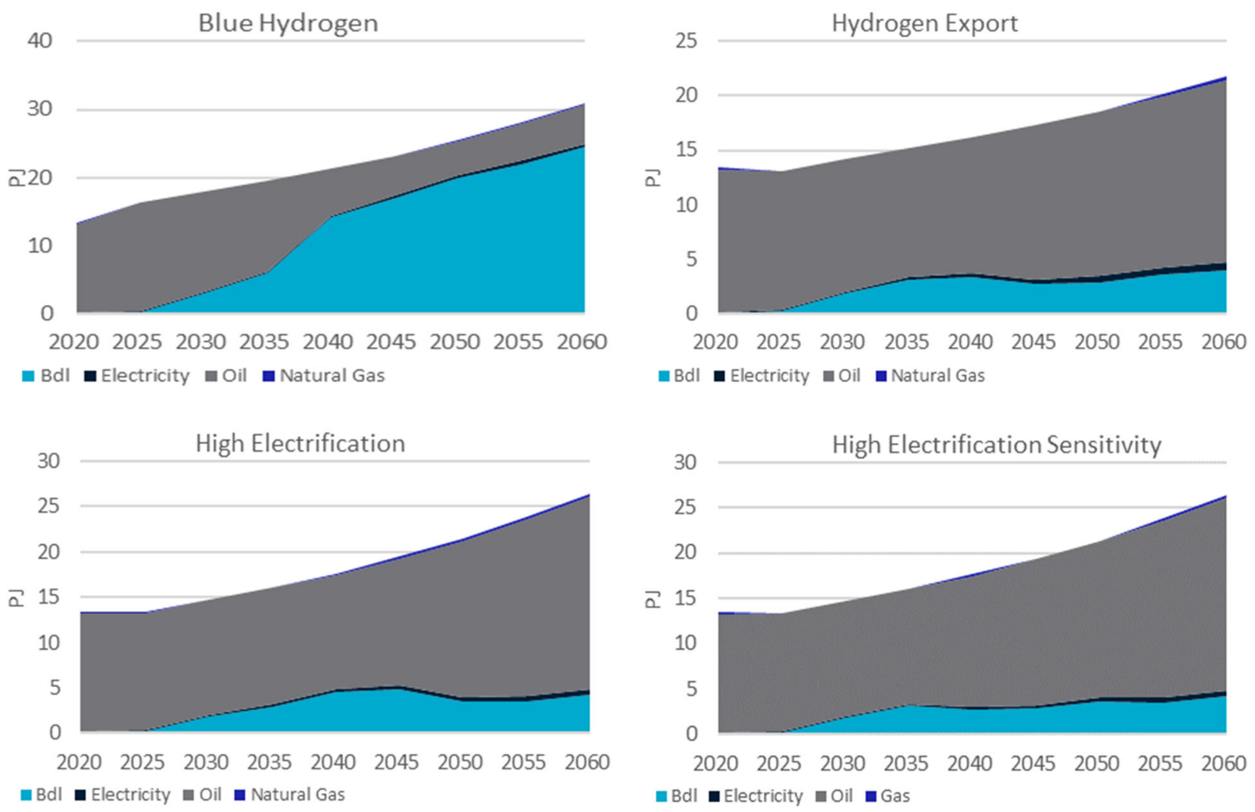

Figure 5-8: Projected state non-road transport vehicle fuel consumption for SA (Bdl is biodiesel)

5.3 Industry Demand

Industry currently represents about half of final energy demand, with the remainder consumed by buildings and transport. In all three scenarios, projections show total SA industrial energy demand declining slightly by 2060 (Figure 5-9) as a consequence of improvements in energy efficiency even as total production increases. The fuel mix, however, differs across scenarios, both nationally (Figure 5-10) and in South Australia (Figure 5-11).

For each scenario, the patterns of industrial fuel consumption are similar for South Australia to those in Australia as a whole. In “Blue Hydrogen”, industrial consumption of liquid fossil fuel grows modestly (Figure 5-9), as does electricity consumption. The consumption of gas also increases significantly, with hydrogen increasingly substituting for natural gas over the projection period.

In the “High Electrification” scenario, however, the use of electricity in industry increases its contribution to energy demand, displacing some demand for diesel in the middle of the projection period relative to the “Blue Hydrogen” scenario. Again, we see the substitution of hydrogen for natural gas to 2050 in line with the minimum uptake assumptions imposed in the scenario. In the “Hydrogen Exports” scenario, in line with assumptions of the gas fuel mix for this scenario, hydrogen displaces natural gas more rapidly.

Within industry, the manufacturing sector tends to switch from gas to hydrogen in line with the assumed contribution of hydrogen to the gas supply (Figure 5-9). Energy use in the manufacturing sector declines as energy efficiency and fuel switching options are taken up. The modelling suggests that fuel switching from coal use is primarily to biomass substitute options, though there is slightly more electrification in “Hydrogen Exports”, likely owing to lower electricity costs under this scenario.

Modest growth in demand is seen in the expanding export-oriented mining sector, with a small amount of fuel switching to hydrogen in the “Blue Hydrogen” and “Hydrogen Exports” scenario, and to electricity in the “High Electrification” scenarios. The agriculture sector shifts away from diesel as it electrifies its relatively small contribution to demand in all scenarios except “Blue Hydrogen”, while the even smaller services demand for energy (primarily the construction sector) remains mostly reliant on diesel. The modelled assumptions about the technological potential for emissions reduction in manufacturing and mining are conservative relative to some more recent studies. A more detailed subsector by subsector analysis of options for decarbonisation in Australian industry, including fuel switching, electrification, energy efficiency, process change, and material efficiency options can be found in Climateworks Centre and Climate-KIC Australia (2022) and related publications.

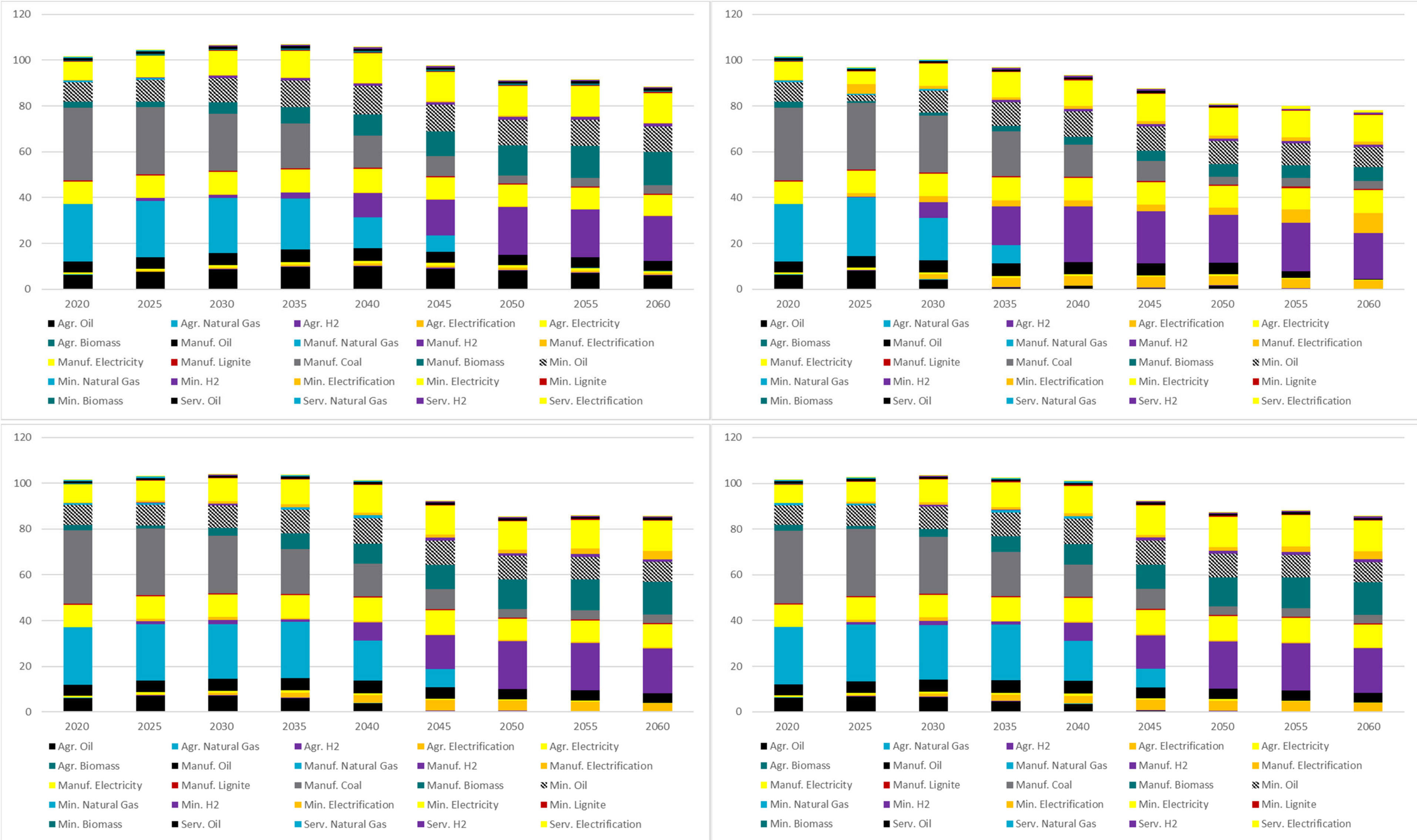

Figure 5-9: Fuel mix in SA industry (PJ), by division: Agriculture, Manufacturing, Mining excluding gas extraction, Services (Construction). (Top Left: Blue Hydrogen, Top Right: Hydrogen Exports, Bottom Left and right: High Electrification and Sensitivity)

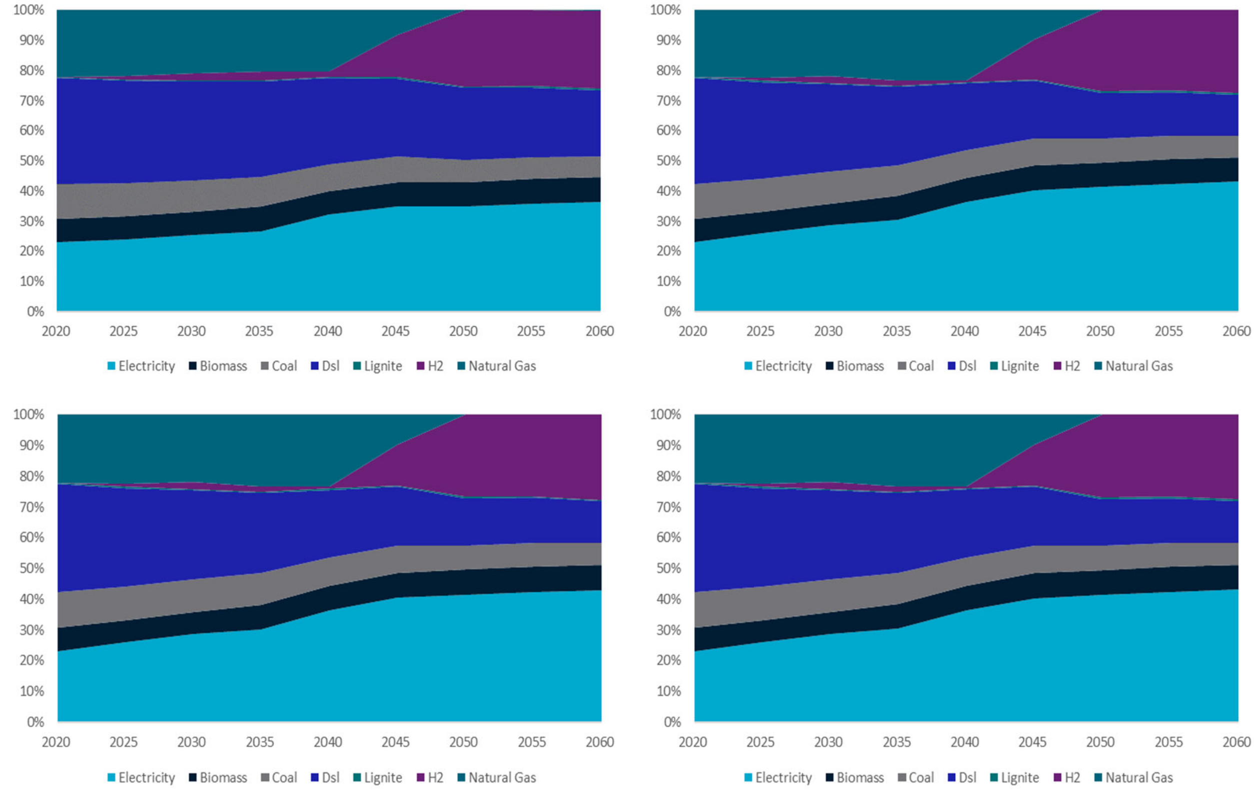

Figure 5-10: Fuel use as a percentage of total energy demand for industry across NEM states (Top Left: Blue Hydrogen, Top Right: Hydrogen Exports, Bottom Left and right: High Electrification and Sensitivity)

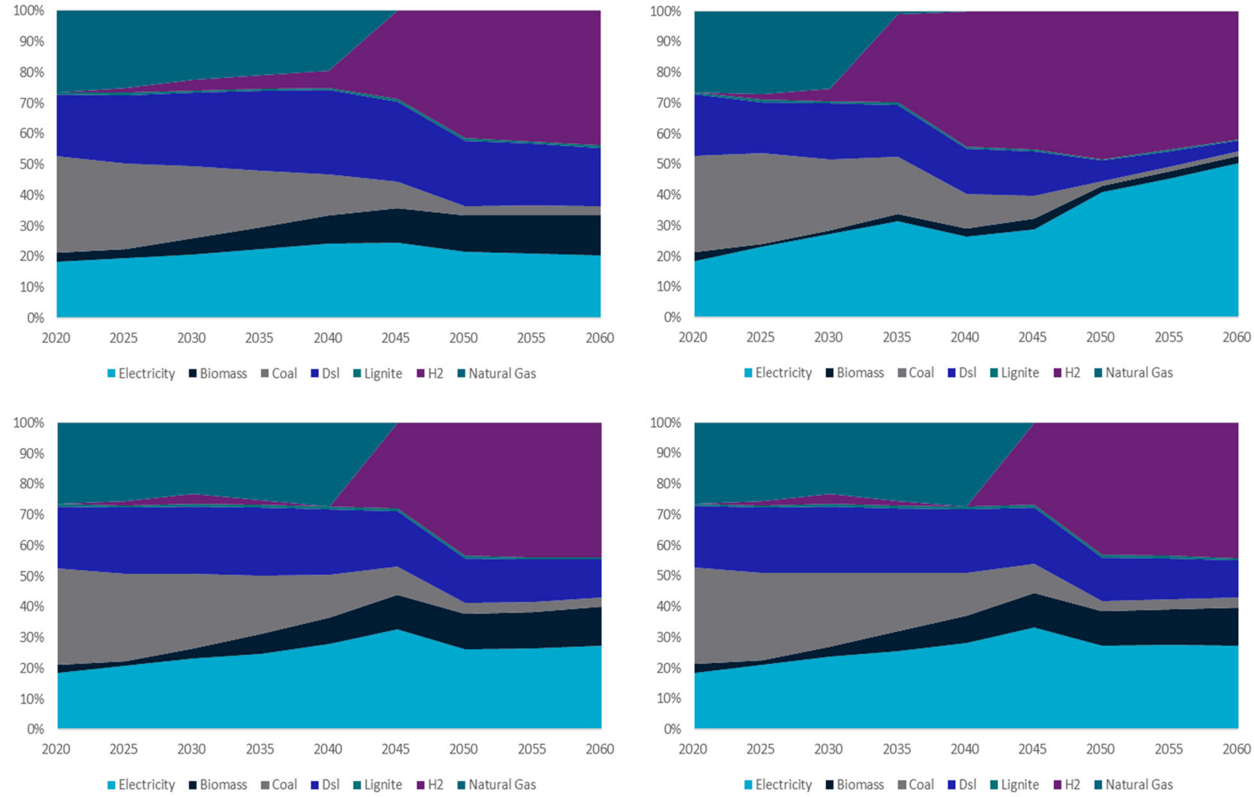

Figure 5-11: Fuel use as a percentage of total energy demand for industry across SA (Top Left: Blue Hydrogen, Top Right: Hydrogen Exports, Bottom Left and right: High Electrification and Sensitivity)

5.4 Gas Demand Projections

The three scenarios and sensitivity scenario show similar outcomes in terms of total demand for gas (natural gas plus hydrogen), but differences in the relative mix. Both nationally (Figure 5-12) and in South Australia (Figure 5-13), the total demand for gas is somewhat flat until 2040 before rising slightly as the economy continues to grow. The mix, however, between natural gas and hydrogen, reflects the changing gas supply, with an earlier switch to hydrogen in the “Hydrogen Exports” scenario. South Australia once again follows the pattern at the national scale, though with lower gas demand in the “Hydrogen Exports” scenario as households switch to electricity rather than gas (which is mostly hydrogen) in the 2040’s and do not switch back to gas in the 2050’s (by then completely hydrogen).

Figure 5-12: Demand for natural gas and hydrogen (PJ) for Australia, by domestic end-use sector, ie, excluding export steel and hydrogen. (Top Left: Blue Hydrogen, Top Right: Hydrogen Exports, Bottom Left: High Electrification, Bottom Right: High Electrification Sensitivity)

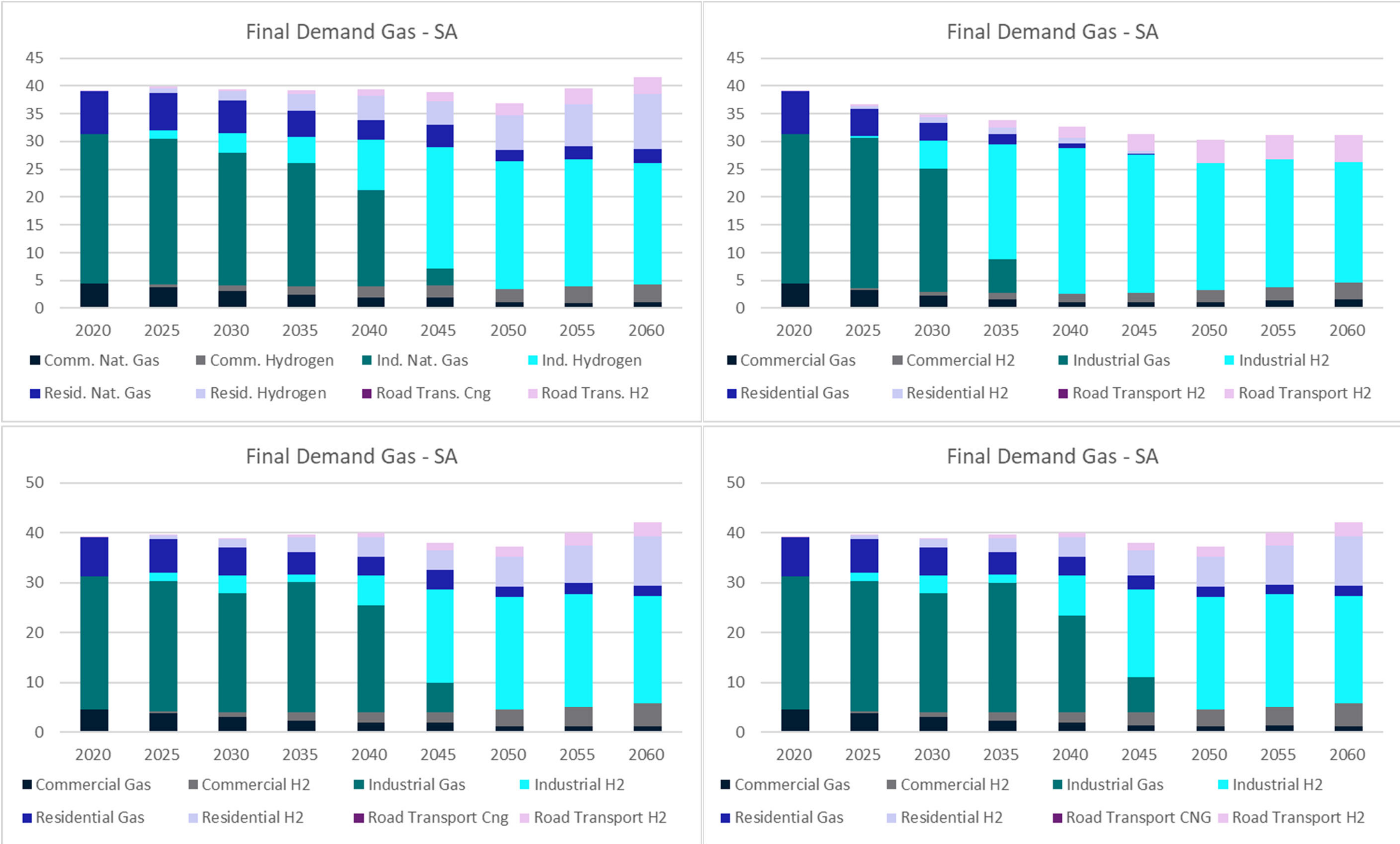

Figure 5-13: Demand for natural gas and hydrogen (PJ) for SA, by domestic end-use sector, ie, excluding export steel and hydrogen. (Top Left: Blue Hydrogen, Top Right: Hydrogen Exports, Bottom Left: High Electrification, Bottom Right: High Electrification Sensitivity)

5.4.1 Natural Gas and Hydrogen Demand Projection Details

Both nationally (Figure 5-14) and in South Australia (Figure 5-15), the net impact of the scenario assumptions in the “Hydrogen Exports” scenario and the “Blue Hydrogen” Scenario for the demand for natural gas is quite similar. This is true especially up to 2035, whereupon the rate of decline for natural gas demand is slightly slower in the “Hydrogen Exports” scenario owing to natural gas being used for hydrogen production as direct use within the gas market declines. In the “High Electrification” scenarios, the demand for natural gas is similar up to about 2040 for both the default and sensitivity case. However, in the default “High Electrification” scenario the demand for natural gas declines quickly to 2050, as the low emissions hydrogen injected into the gas distribution network is required to be 95% supplied by (renewable) electricity. In the sensitivity scenario, however, the demand for natural gas persists for much longer, as it continues to be used in the production of hydrogen – in this case via SMR CCS.

The general pattern of demand for natural gas and hydrogen is similar nationally and in South Australia. A notable difference, however, is that in the “High Electrification” sensitivity case, although the demand for natural gas is greater later in the projection period from 2050 compared to all the other scenarios, between 2040 and 2050 it does fall by a greater percentage in South Australia (by about two-thirds) than nationally (where it falls by about one-third).

Although the gas demand and mix between hydrogen and natural gas are somewhat different among scenarios in the Residential and Commercial sectors, Industrial demand dominates the market and largely explains the outlook for domestic natural gas and hydrogen demand.

Both nationally and in South Australia, industrial demand for gas is greatest in Other Chemicals and Non-metal construction materials excluding Cement. The Iron and Steel production sector and Cement sectors are also large consumers of natural gas.

In South Australia, the AusTIMES model projects that each of these sectors switches to hydrogen over the course of the projection period, with lower demand for industrial gas in the “High Electrification” scenario (due to a greater share of fuel switching to electricity) and perhaps a slightly greater share for hydrogen in the “Hydrogen Exports” scenario compared to the “Blue Hydrogen” scenario. Remaining users of gas in South Australia include the following sectors: Food processing; Rubber production; Textiles clothing and footwear; Non-metal ore mining; and Construction services. The food processing, rubber production and non-metal ore mining sectors are unusual in that hydrogen demand increases in these industries in the “High Electrification” scenario. This is likely due to the greater options for hydrogen use and less for electrification in those sectors, combined with the assumption in that scenario of a lower required ROI to justify investments in demand side energy measures including fuel switching.

The national demand for industrial gas displays a similar pattern to South Australia, with some differences in the relative importance of each sector. For example, nationally, the Alumina production industry is of similar significance to Other Chemicals production, whereas in South-Australia there is no Alumina industry.

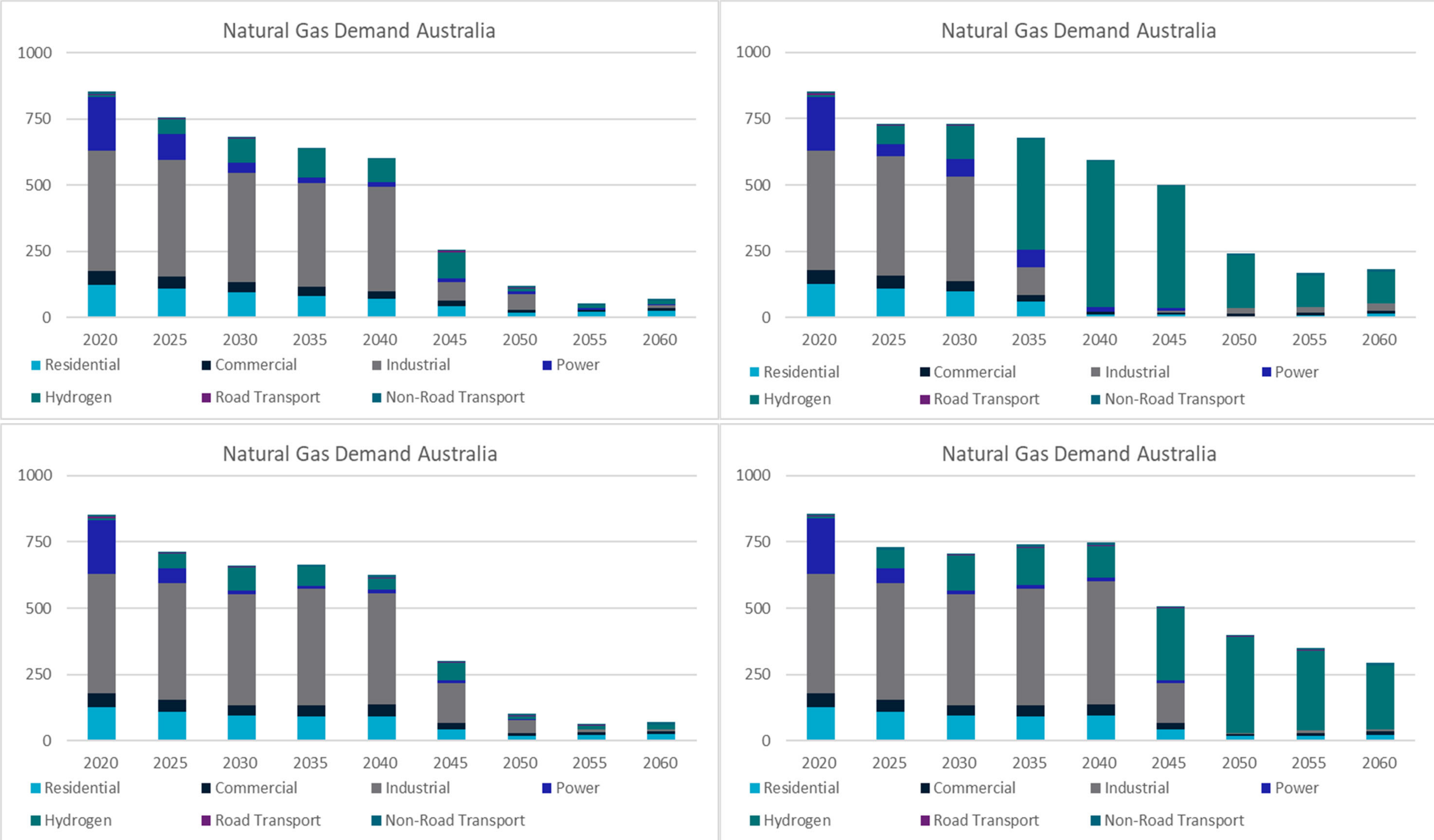

Figure 5-14: Natural gas demand (PJ) for Australia, by sector including power and hydrogen production. (Top Left: Blue Hydrogen, Top Right: Hydrogen Exports, Bottom Left and Right: High Electrification and Sensitivity)

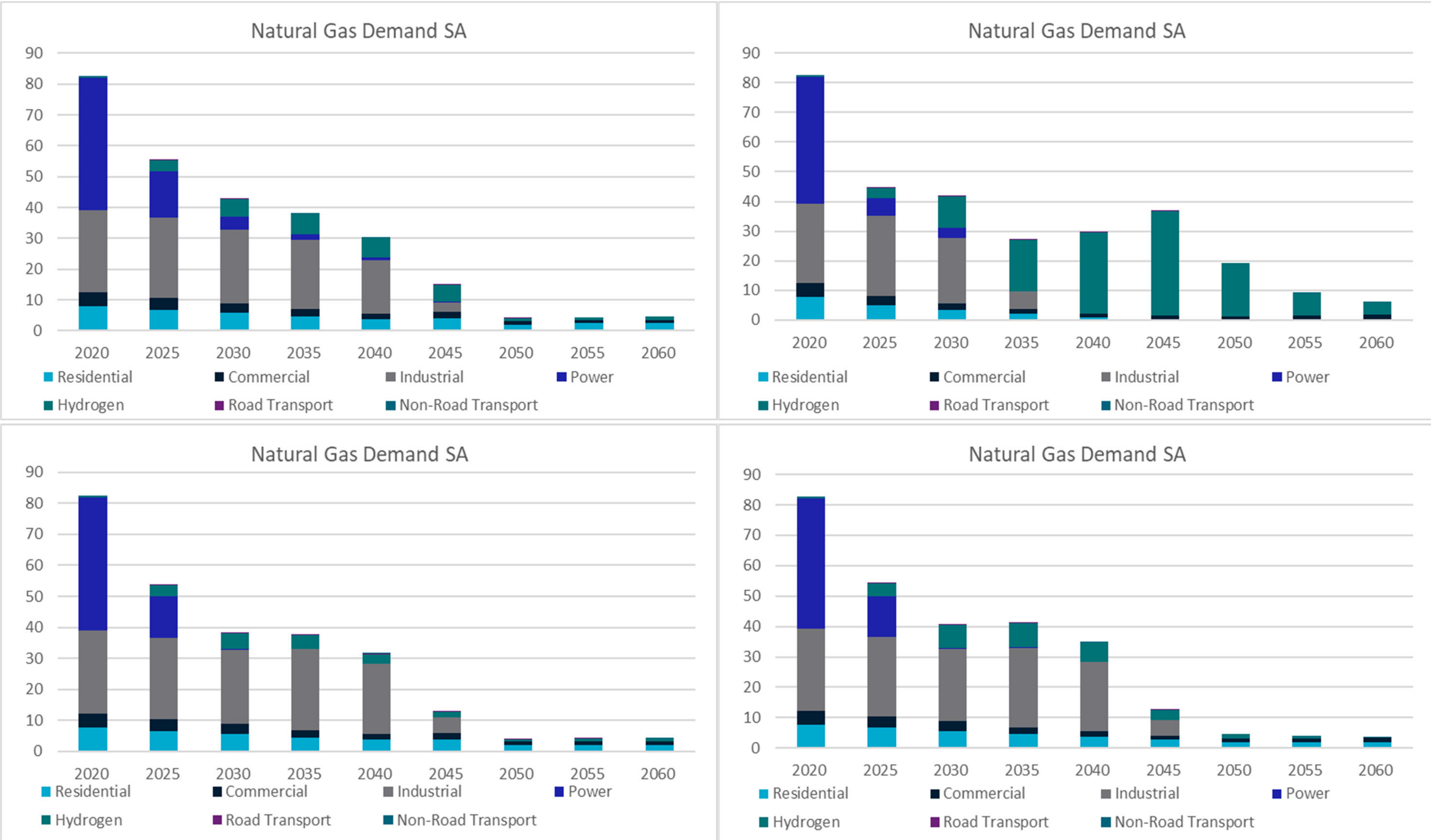

Figure 5-15: Natural gas demand (PJ) for SA, by sector including power and hydrogen production. (Top Left: Blue Hydrogen, Top Right: Hydrogen Exports, Bottom Left and Right: High Electrification and Sensitivity)

Closer inspection of the high energy demand subsectors of the manufacturing industry reveals the following observations. Food processing, Rubber production, and Petroleum refining, are each relatively less significant in South Australia than nationally. Relatively more important industries in South Australia include Non-metal construction materials excluding cement, Iron and steel production, and Cement. The Food processing, Rubber production and Non-metal ore mining industries show similar patterns to each other of increasing hydrogen demand in the “High Electrification” scenario at the national scale, in addition to in South Australia in particular.

The modelling projections show the timing of the switch from natural gas to hydrogen in most industries is approximately in line with the timing of hydrogen uptake assumed in the scenario definitions as constraints. This suggests that it is primarily these assumptions that are driving the fuel switch. A smaller subset of industries each demonstrate an earlier switching to hydrogen, suggesting that they may enjoy a relative cost advantage for the use of hydrogen fuel. Industries that tend to show earlier uptake include Alumina, Steel production, and Cement production. Note that, owing to the relatively high greenhouse emissions produced by these industries, the model has provided additional explicit options for fuel switching in these industries in particular – including options for fuel switching from gas to hydrogen boilers. These additional options may explain why these industries are switching to hydrogen earlier than others, although it is also to be noted that their relatively high greenhouse emissions provides a modelled financial incentive to do so as well. Other industries that switch to hydrogen more quickly relative to the typical average include those sectors whose hydrogen consumption increases in the “High Electrification” scenario, that is, food processing, rubber production and non-metal ore mining. These two consequences are likely due to the same influence - a relative economic advantage apparently available to hydrogen in these industries.

Both nationally and in South Australia, in buildings (both Residential and Commercial), demand for gas increases in the “Blue Hydrogen” scenario and in both the “High Electrification” scenarios, but declines in the “Hydrogen Exports” scenario. There is a particularly substantial decline in households as the share of hydrogen in the gas pipelines reaches their high target levels at 95%. Despite the shift in hydrogen share of gas in all scenarios, the decline in overall demand for gas in South Australian households in the “Hydrogen Exports” scenario implies that very little hydrogen is ever taken up by buildings in these scenarios. In the other scenarios, where there is a relatively low propensity for electrification and the assumed costs of hydrogen versus electricity are in the favour of hydrogen, the demand for hydrogen in buildings maintain the magnitude across the projection period comparable to those for natural gas today.

The overall result is that hydrogen uptake is high in both the buildings sectors and in industry in the “Blue Hydrogen” and “High Electrification” scenario. In the “Hydrogen Exports” scenario, there is low uptake of hydrogen in the building sector (and so decline in demand for gas), but a quite high uptake in industry (and in production for direct export and production of green steel). Although the demand for hydrogen in the transport sector is noticeably greater in the “Hydrogen Exports” scenario, at the scale of total demand for gas, it remains a relatively small market share across the projection period.

A comparison of the "Blue Hydrogen" scenario projections for natural gas demand with the *2022 Gas Statement of Opportunities* (AEMO 2022) 'Step Change' scenario is shown in the figures below. For both national (Figure 5-16) and South Australian (Figure 5-17) demand, the "Blue Hydrogen" scenario shows a more rapid decline in gas power generation (GPG) than AEMO (2022), but a slower decline in the demand in the combined residential and commercial sectors, and also the industrial sector. The decline in natural gas demand for power generation in South Australia is projected to be even more rapid in the other scenarios than in the "Blue Hydrogen" Scenario.

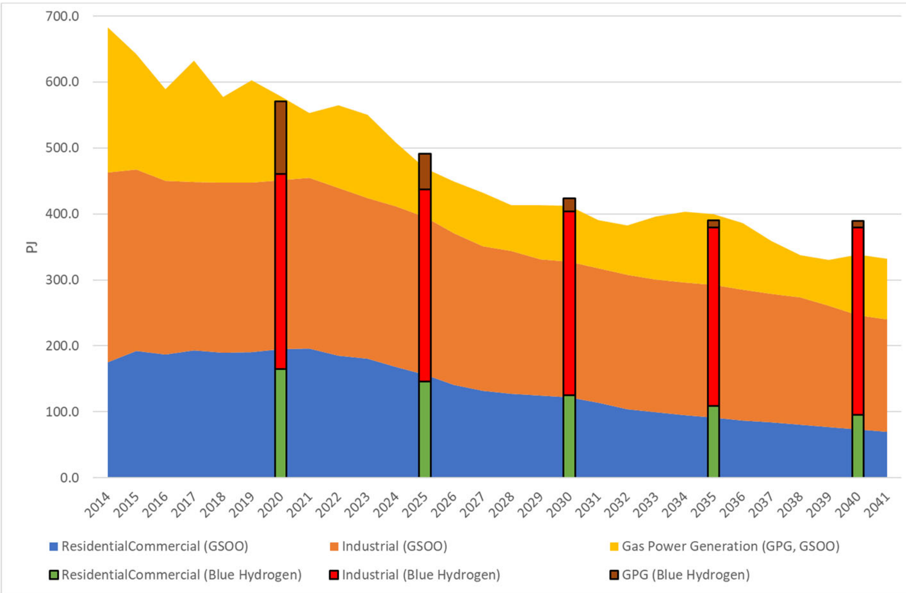

Figure 5-16: Natural gas demand (PJ) "Blue Hydrogen" Scenario comparison with GSOO (Australia)

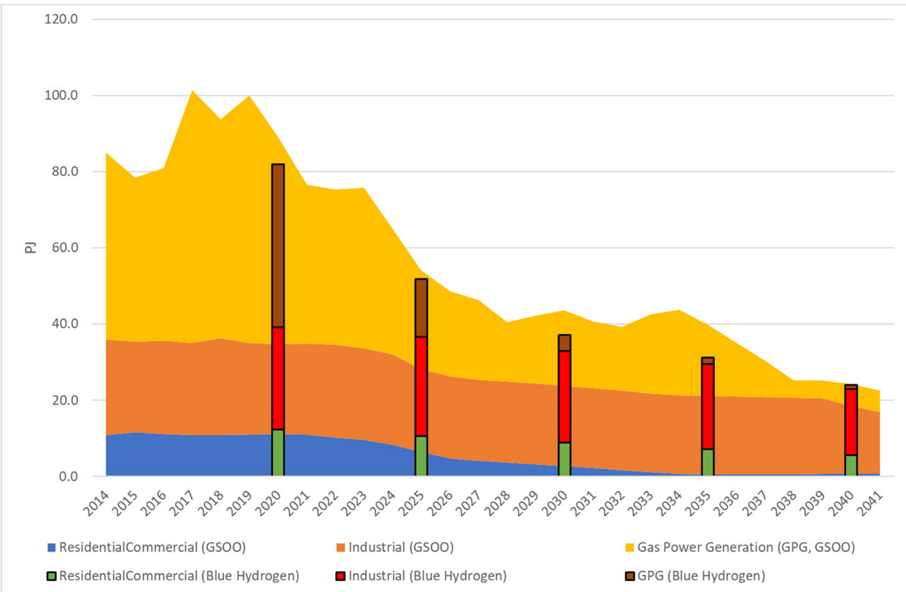

Figure 5-17: Natural gas demand (PJ) "Blue Hydrogen" Scenario comparison with GSOO (South Australia)

5.5 Hydrogen and Steel Projections

The share of hydrogen production across Australia is similar in both the relatively high production "Hydrogen Exports" scenario and the other scenarios (Figure 5-18), although at higher volumes market share in Victoria is limited by constraints on the capacity of the Port of Melbourne (Appendix E), so that Queensland provides an increasing share. In all cases, however, South Australia contributes to less than 5% of the market share by 2050. The "Hydrogen Exports" scenario has, as expected, the greatest production of hydrogen. Of 1.4Mt of hydrogen produced in South Australia in 2060, 0.6Mt is used domestically with the remaining 0.8Mt exported, limited by port capacity of a total of 1.1Mt.

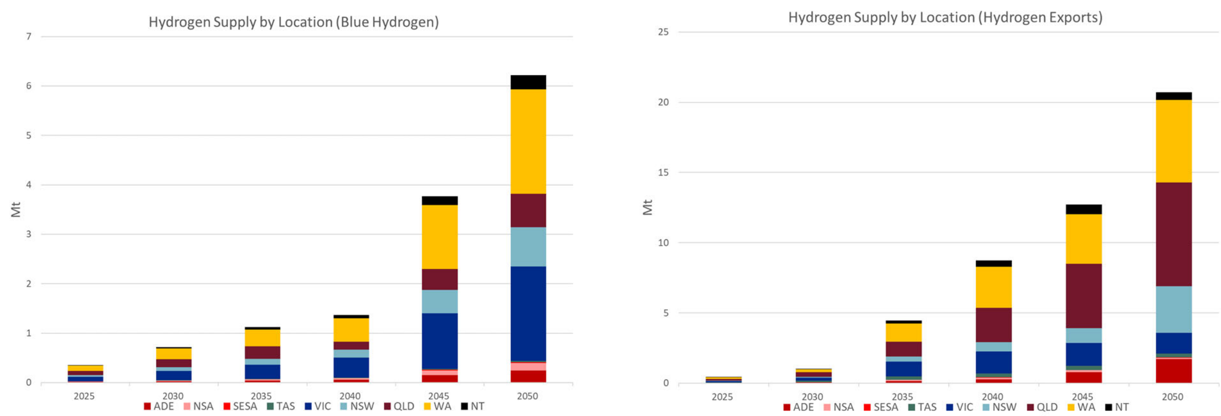

Figure 5-18: Projected hydrogen production for Australia, by state (and SA transmission zone)

Steel for export is produced via the direct reduction of iron (and electric arc furnace smelting) only in the "Hydrogen Exports" scenario, with the Adelaide region production of 1.6Mt representing about a fifth of national steel production at the beginning of the projection period (Figure 5-19). It is assumed that South Australian steel exports are limited by port capacity, so that given the 0.8Mt hydrogen exports, only an additional 0.3Mt of steel can be exported, representing a growth of only 20%. Ultimately production in Queensland, and to a lesser extent, WA, significantly outstrips South Australian production capacity leaving it with a little less than 2% of national share of steel production by 2050.

In all scenarios except the "High Electrification" sensitivity scenario, the constraints on hydrogen production to be primarily by electrolysis significantly limit the quantity of hydrogen production by SMR (even with CCS, see Figure 5-20 and Figure 5-21). Nevertheless, SMR provides a majority of the relatively lower production volumes up to about 2040, after which electrolysis hydrogen starts to dominate the market share of hydrogen production, as the demand for hydrogen itself significantly increases.

In the "High Electrification" sensitivity scenario, which permits SMR with CCS to be part of a low emissions hydrogen production mix, much more hydrogen is produced by SMR with CCS than by electrolysis in the Rest of Australia, reaching more than half the share of production across Australia as demand grows significantly in the 2040's but beyond 2040 the share of production by SMR with CCS declines as electrolysis continues to grow. In South Australia however, even when the constraint on SMR is relaxed under this scenario the cost of electricity is sufficiently low to favour production via electrolysis. In the Rest of Australia, the production of hydrogen by SMR-CCS declines after 2050, as the combination of a shadow price on carbon emissions and reducing costs of electrolysis production shifts the preferred method of hydrogen production towards renewable electricity.

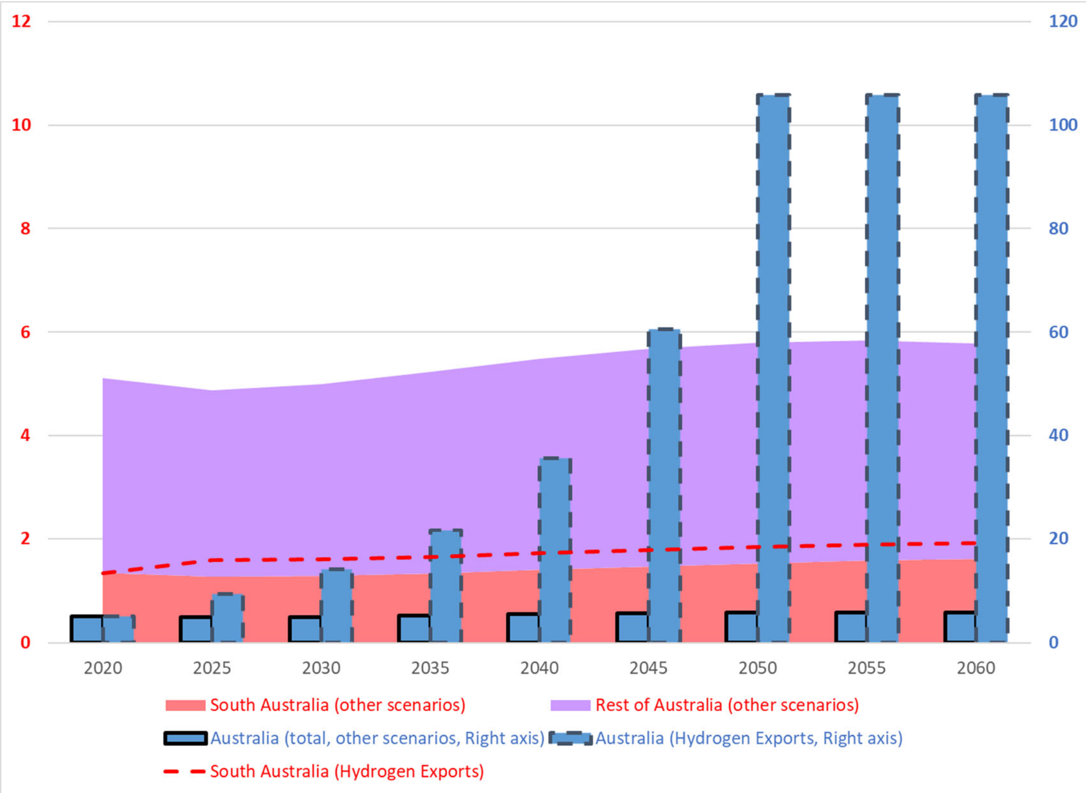

Figure 5-19: Assumed steel production (Mt), by region and scenario

In the "Hydrogen Exports" scenario across Australia generally, SMR with CCS replaces hydrogen generation by SMR without CCS from the mid 2040's; this becomes a relatively small share of hydrogen generation by this decade. In this scenario in South Australia, the modelling projects replacement of SMR without CCS by electrolysis production.

Hydrogen production costs are at about $3-5/kg ($25-40/GJ) and tend to decline over the projection period in all scenarios, and in all states except WA (Figure 5-22) as capital costs decline. Production costs are lowest in Queensland and highest in Victoria and NSW. Costs in South Australia tend to be in the middle or at the lower end of the range. In all scenarios except the "High Electrification" sensitivity, relative hydrogen generation costs among the various regions are roughly correlated with those for electricity generation (see Figure 5-33).

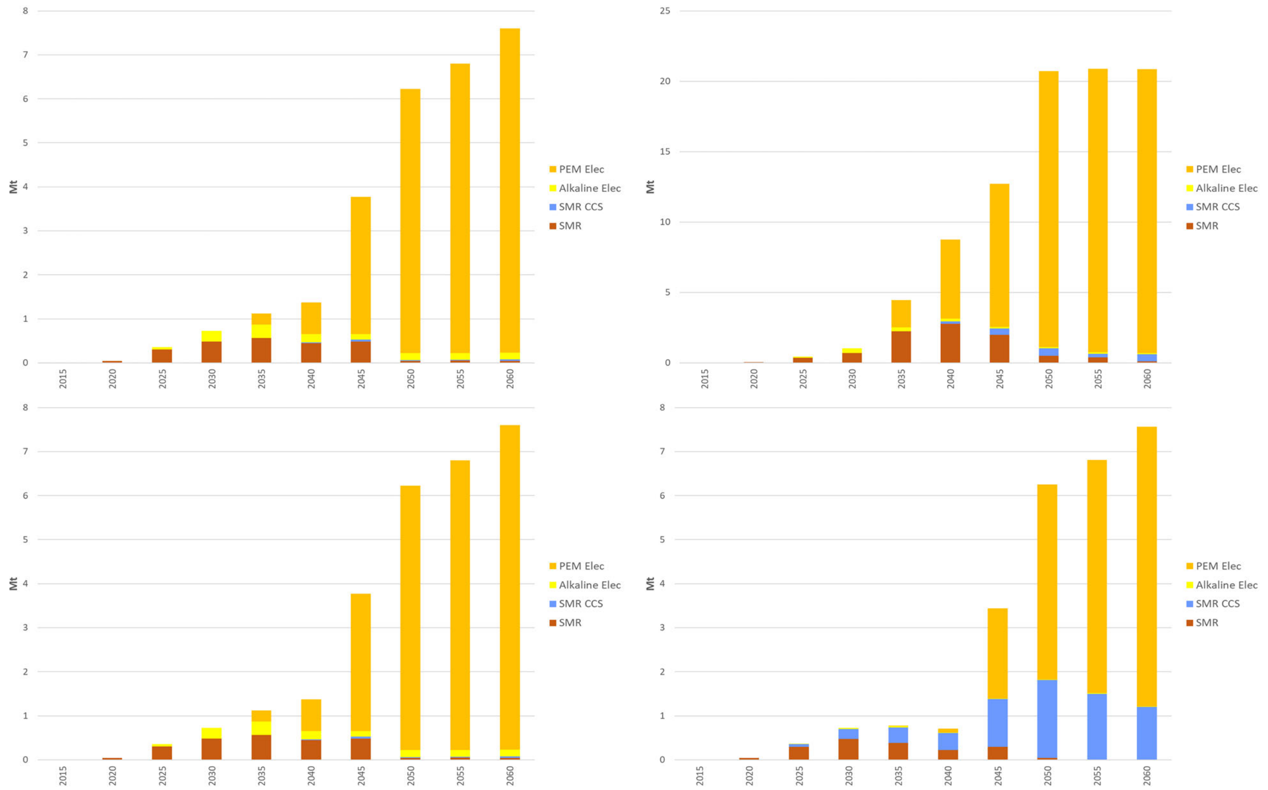

Figure 5-20: Projected hydrogen production for Australia, by technology (Top Left: Blue Hydrogen, Top Right: Hydrogen Exports, note scale, Bottom Left: High Electrification, Bottom Right: High Electrification Sensitivity)

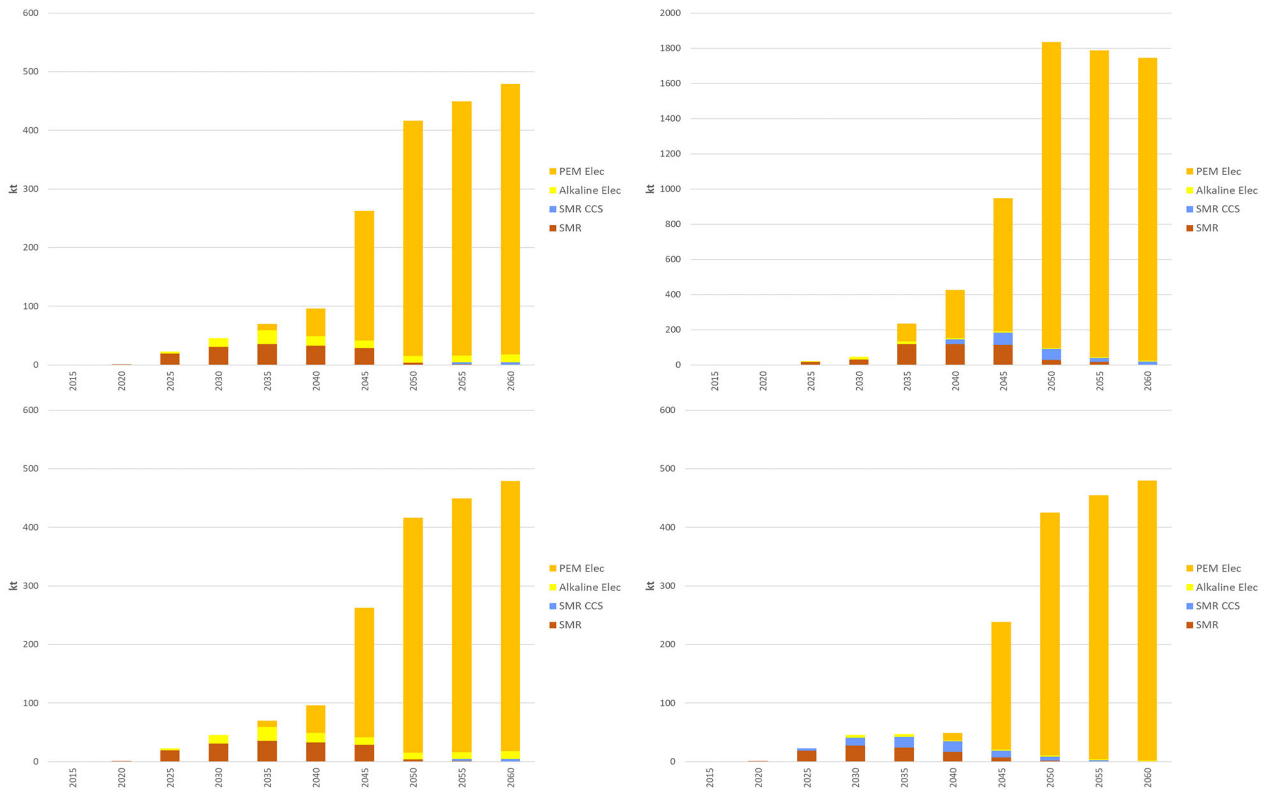

Figure 5-21: Projected hydrogen production for South Australia, by technology (Top Left: Blue Hydrogen, Top Right: Hydrogen Exports, note scale, Bottom Left: High Electrification, Bottom Right: High Electrification Sensitivity)

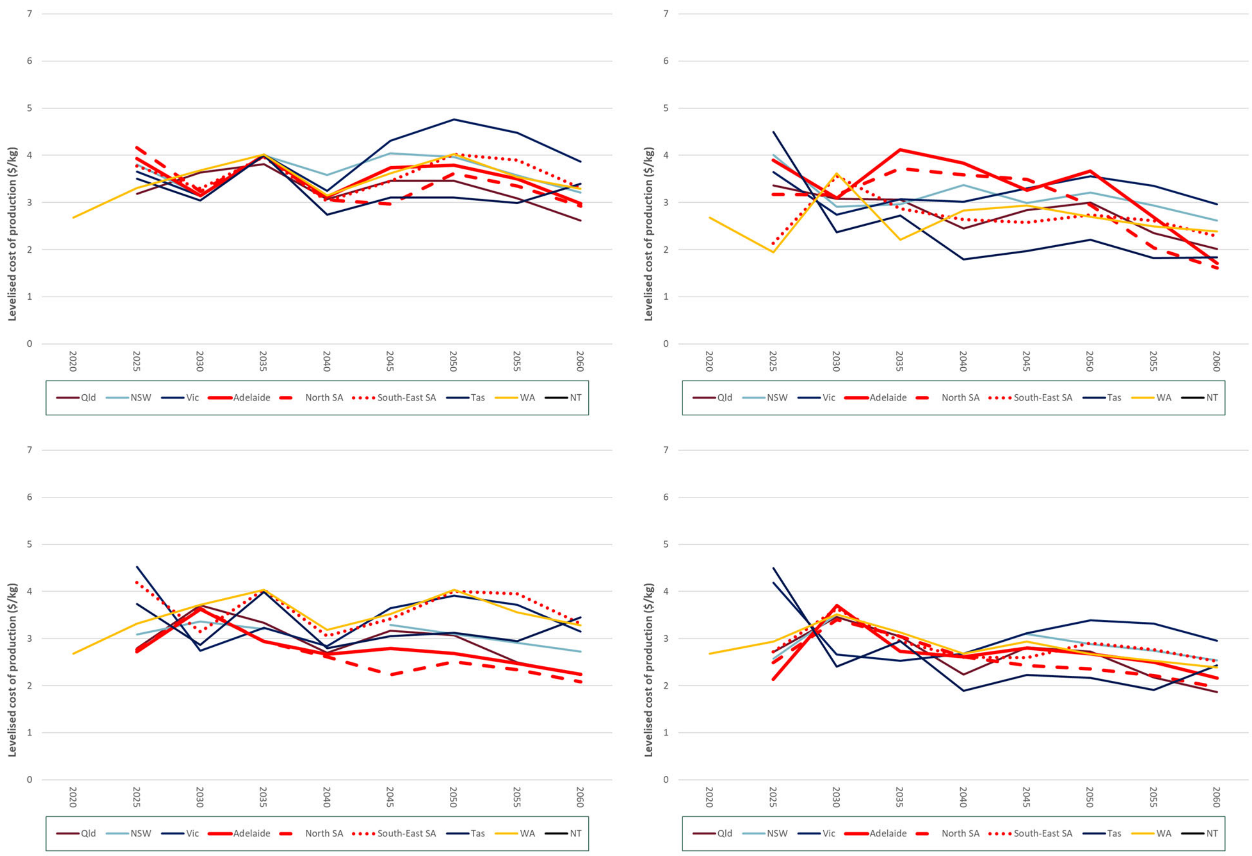

Figure 5-22: Projected hydrogen production costs, by state and SA region (Top Left: Blue Hydrogen, Top Right: Hydrogen Exports, Bottom Left: High Electrification, Bottom Right: High Electrification Sensitivity)

5.6 Power Sector

The end-use demand for power in the NEM and in South Australia appears in Figure 5-23 and Figure 5-24. This does not include the additional demand from the hydrogen sector for the production of hydrogen by electrolysis, as this would otherwise dominate the results in the "Hydrogen Exports" scenario. However, it does include the electricity required for the electric arc furnace component of green steel production, as this is classified within industrial demand. It can be seen that demand is lowest in the "Blue Hydrogen" scenario, greatest in "Hydrogen Exports" and in between in the "High Electrification" scenarios. Even though the electrification of existing production is greatest in the "High Electrification" scenarios, the additional demand for electricity for green steel production in the "Hydrogen Exports" scenario is more significant.

The breakdown of electricity consumption by end-user, in the NEM and in South Australia, this time including the hydrogen sector, is shown in Figure 5-25 and Figure 5-26. We see a very similar pattern of electricity consumption in the residential and commercial sectors in all scenarios – fairly flat until 2050 as growth in demand for energy services is balanced by investment in energy efficiency measures, after which demand starts to grow again. There is a similar pattern in demand for electricity for transport across scenarios – steady growth from about 2030 through the projection period, until it reaches a similar quantum to that for each of the residential and commercial sectors.

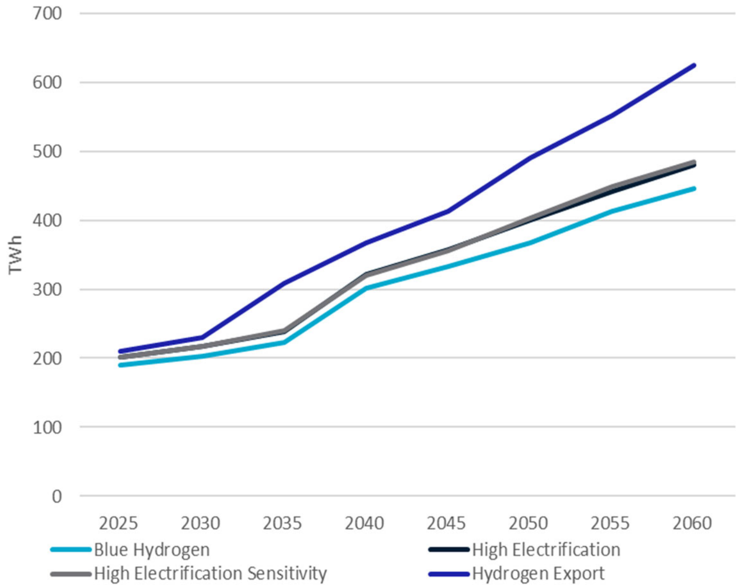

Figure 5-23: Total NEM electricity demand by scenario

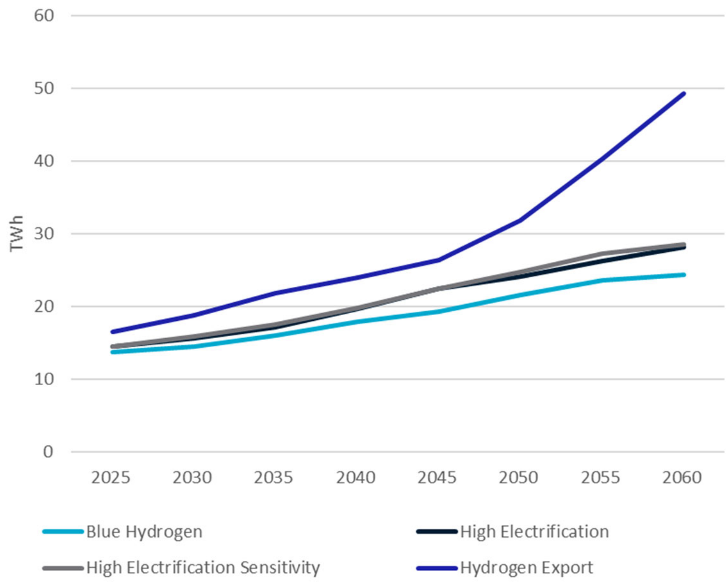

Figure 5-24: South Australian electricity demand

The industrial demand for electricity is similar in the “Blue Hydrogen” and “High Electrification” scenarios. However, in the “Hydrogen Exports” scenario, industry electrifies strongly in about 2045 in the NEM and especially strongly in South Australia under the influence of relatively low electricity costs (Figure 5-33). As is to be expected, the demand for electricity for hydrogen production is highest in the “Hydrogen Exports” scenario, both in the NEM and in South Australia. In the “High Electrification” sensitivity case, the demand for electricity for hydrogen production is lower than in the standard “High Electrification” scenario, as more hydrogen is permitted to be produced via SMR-CCS. However, somewhat unexpectedly, even in the sensitivity case the production SMR-CCS hydrogen remains limited in South Australia, so the use of electricity for hydrogen production is similar in both the standard and sensitivity scenarios.

5.6.1 Projected Electricity Generation and Storage Mix

The national projected electricity generation mix is similar across the three scenarios (Figure 5-27). In particular, the mix of fossil fuel generation across the three scenarios is quite similar, with the differences in total electricity demand, which especially occurs later in the projection period, made up by differences in the scale of renewables generation. Renewable electricity is at essentially 100% of consumption by 2050, and more than 80% (in physical units) by 2040.

Although wind generation is projected to be greater than solar generation to 2045, solar generation becomes dominant after 2050. Because there is greater variability in electricity generation requirements across scenarios in the later years, solar generation accounts for more of the variability between scenarios than wind, suggesting that solar is playing the role of a backstop electricity generation technology.

The generation mix in South Australia across the four scenarios are similar to those at the national scale (Figure 5-28), although renewable generation is essentially at 100% by as early as 2040. This is explained by the high-quality renewable energy resource in South Australia, and the absence of coal power. This conclusion is supported by an assumption that utility scale or virtual power plant batteries will assist in smoothing the intermittency of renewable generation on shorter time scales and that pumped hydro from Snowy Hydro 2.0 will provide storage over longer periods.

The projections show natural gas playing only a relatively small role in South Australia by 2025, essentially providing only support for variable renewables. The use of gas in the power sector is projected to decline very quickly in South Australia, essentially eliminated by 2045 in the “Hydrogen Exports” Scenario, and by 2040 in the other two scenarios.

More large-scale battery storage is required nationally in the “Hydrogen Exports” scenario (~120GW by 2060) than in the other two scenarios (~70-100GW in respectively “Blue Hydrogen” and “High Electrification”). This is required in order to balance the larger scale of variable renewable generation. The difference in large scale battery storage among scenarios is slightly more pronounced in South Australia than nationally, with ~10-11GW installed for “Blue Hydrogen” and “High Electrification”, but ~17GW installed in the “Hydrogen Exports” scenario.

5.6.1.1 Coal Generation Retirement and Extension

Noting that South Australia no longer operates any coal generation, from the national perspective across the four scenarios the generation of electricity from coal is strongly influenced by the assumptions regarding projected retirements for fossil plant. The scale of fossil fuel generation is somewhat higher over 2030-2040 in the “Hydrogen Exports” scenario, because of the greater demand for electricity in general, and brown coal generation persists at a greater scale during that time frame in the “High Electrification” scenario, continuing to supply Victorian electricity.

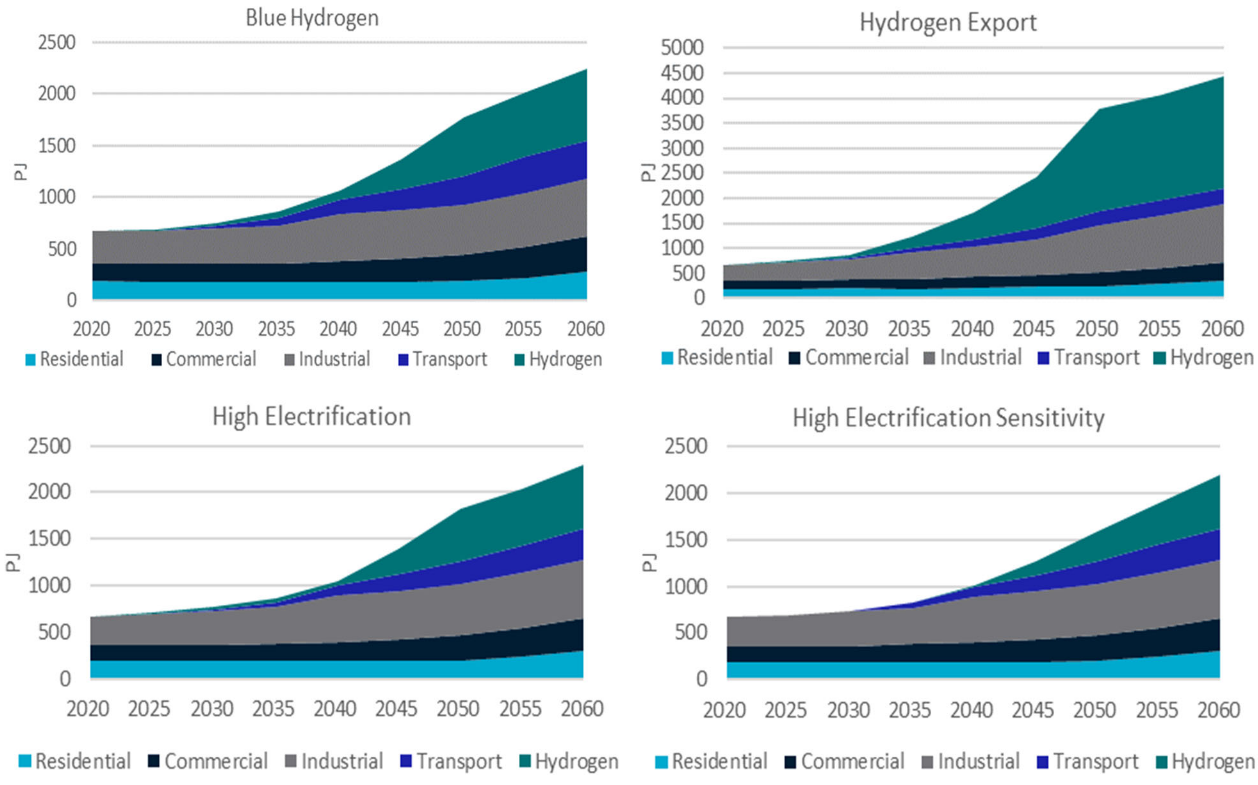

Figure 5-25: Summary of underlying NEM demand across each scenario split by end-use sector

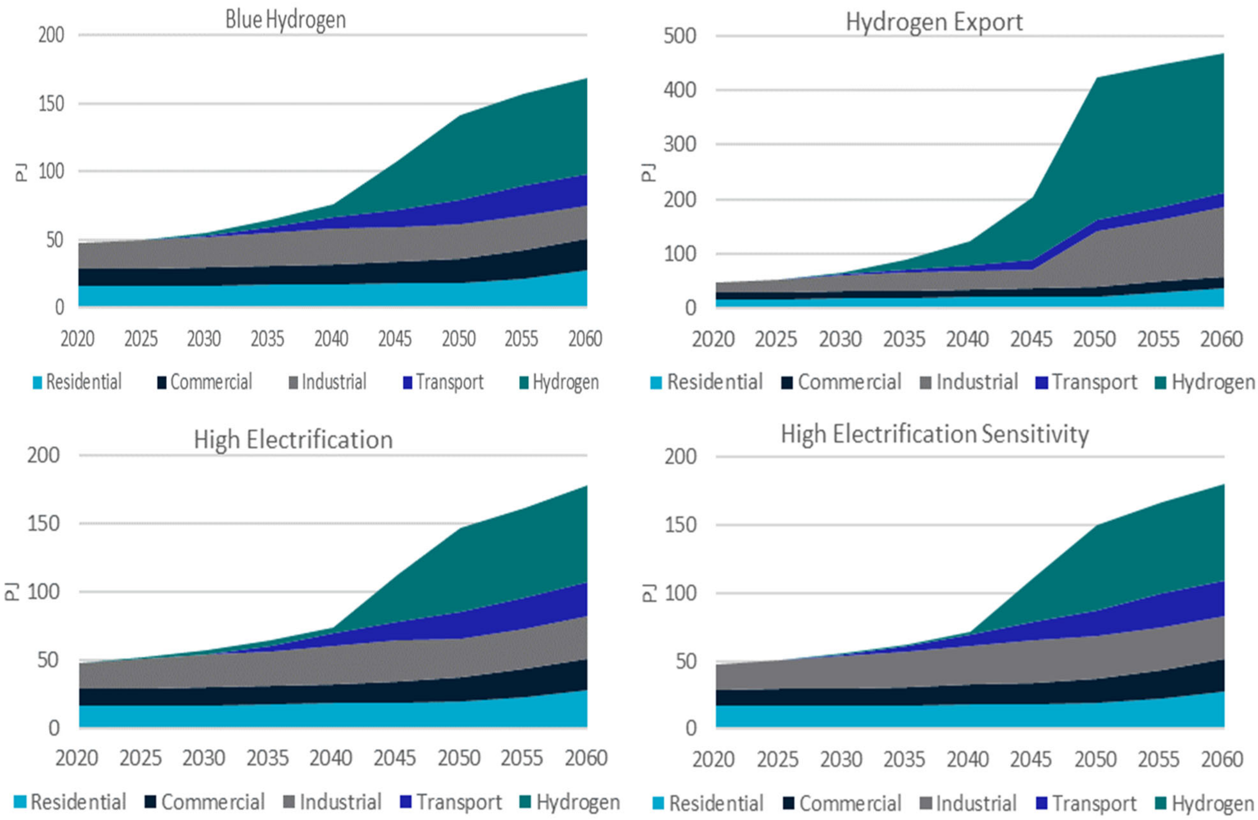

Figure 5-26: Summary of underlying SA demand across each scenario split by end-use sector

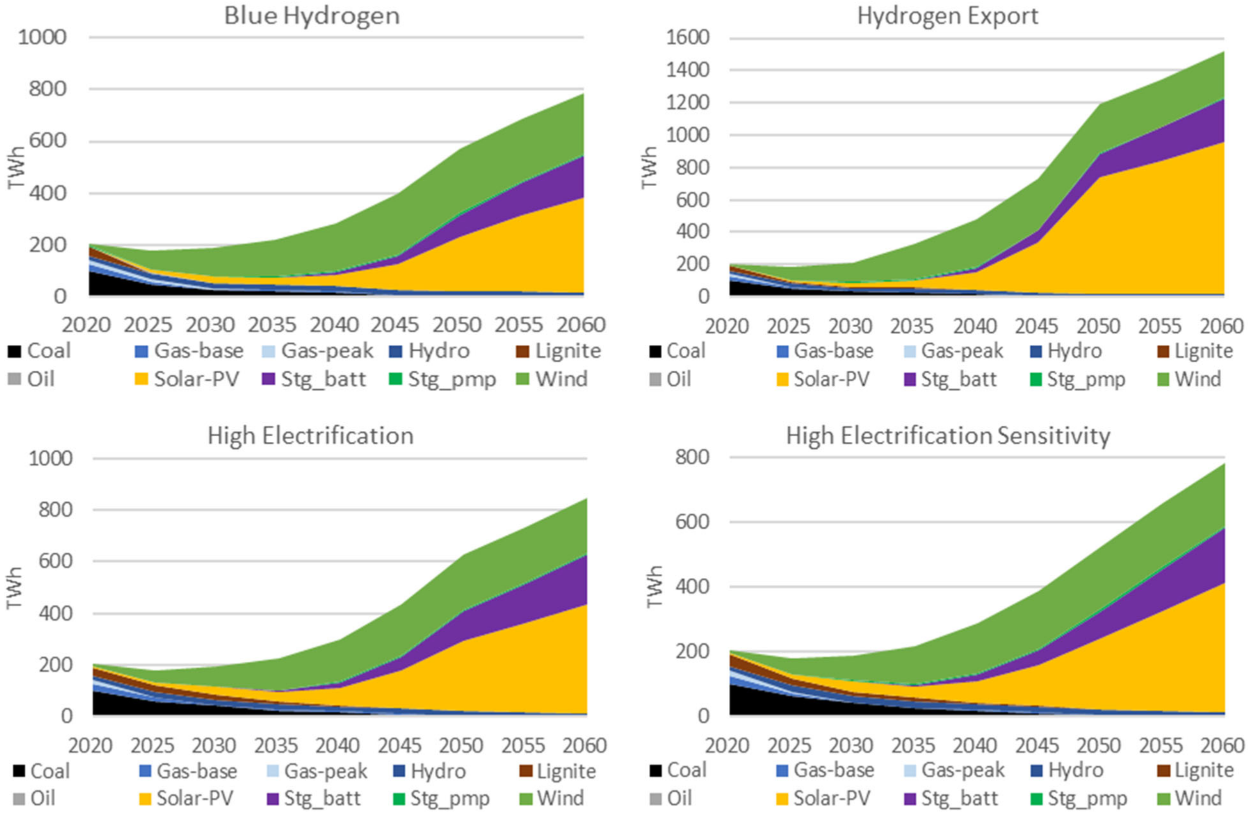

Figure 5-27: Power Generation Energy by technology for NEM

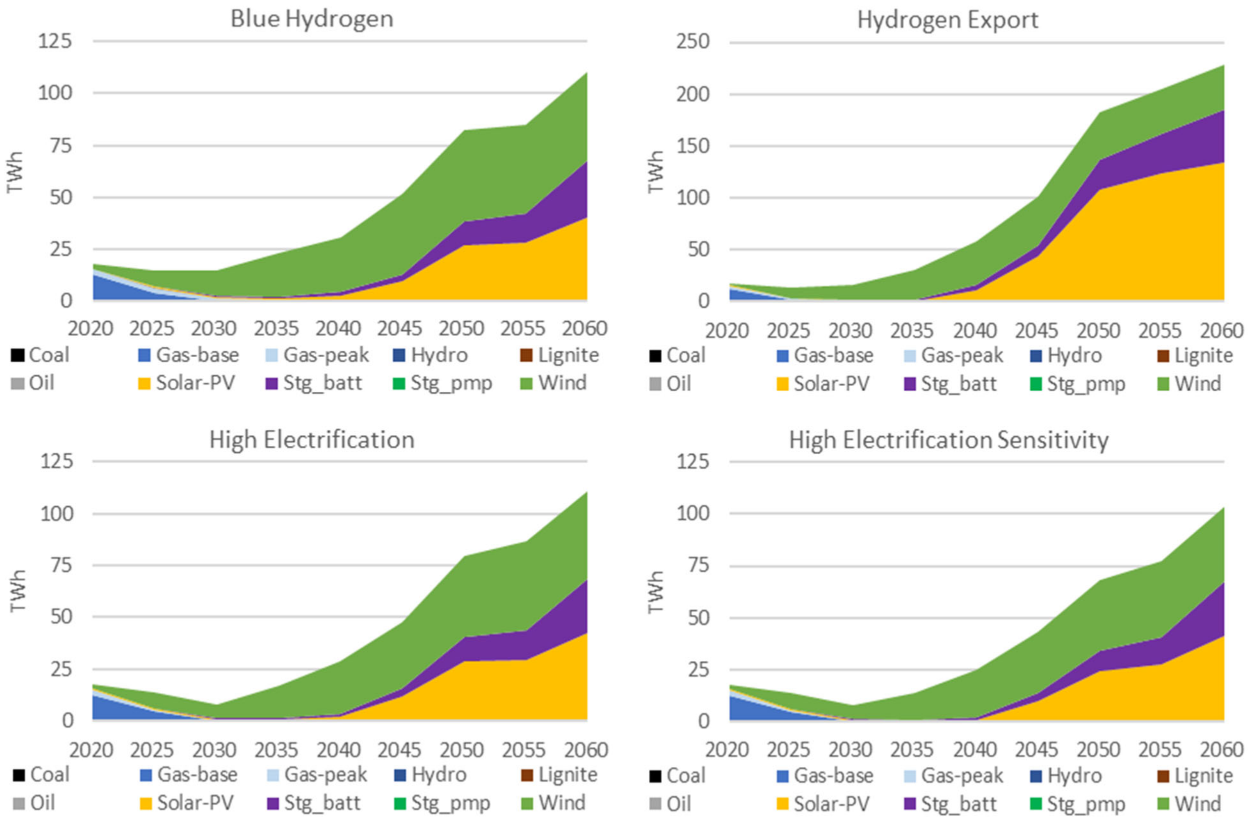

Figure 5-28: Power Generation Energy by technology for SA

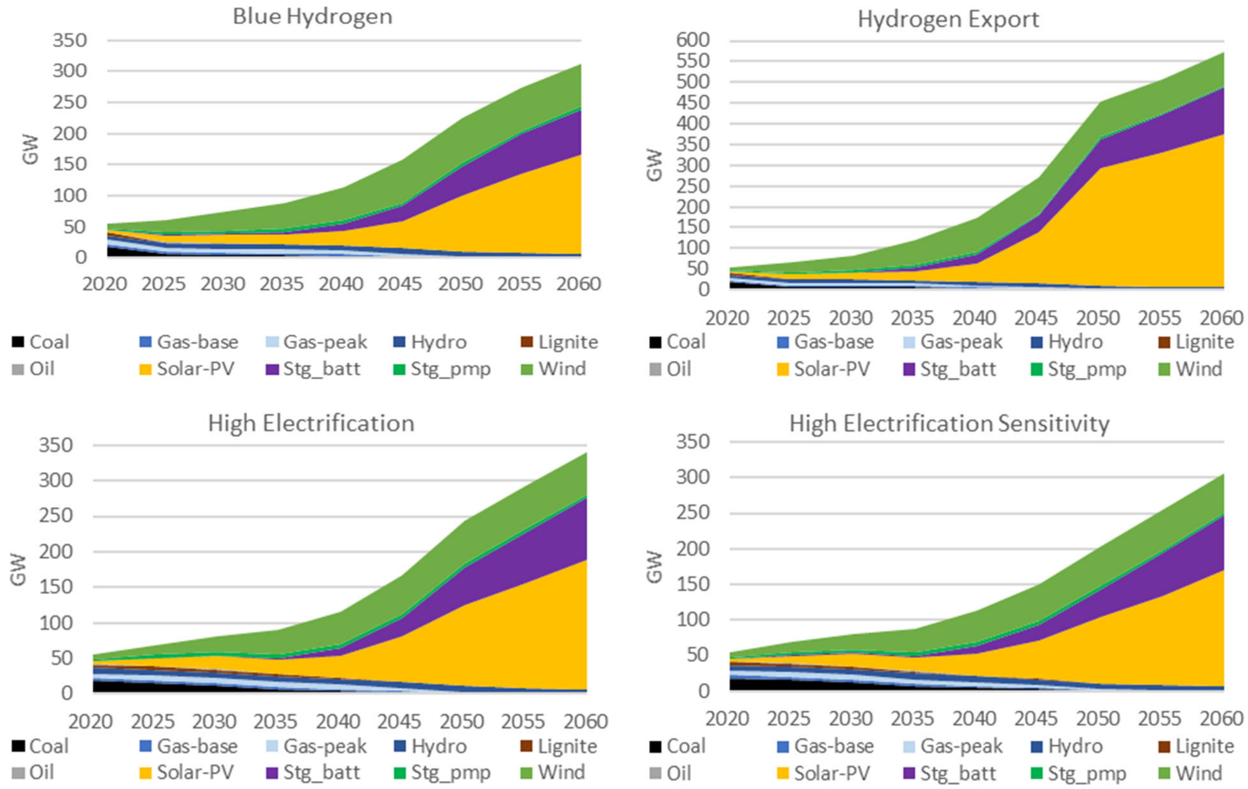

Figure 5-29: Power Generation Capacity by technology for Australia

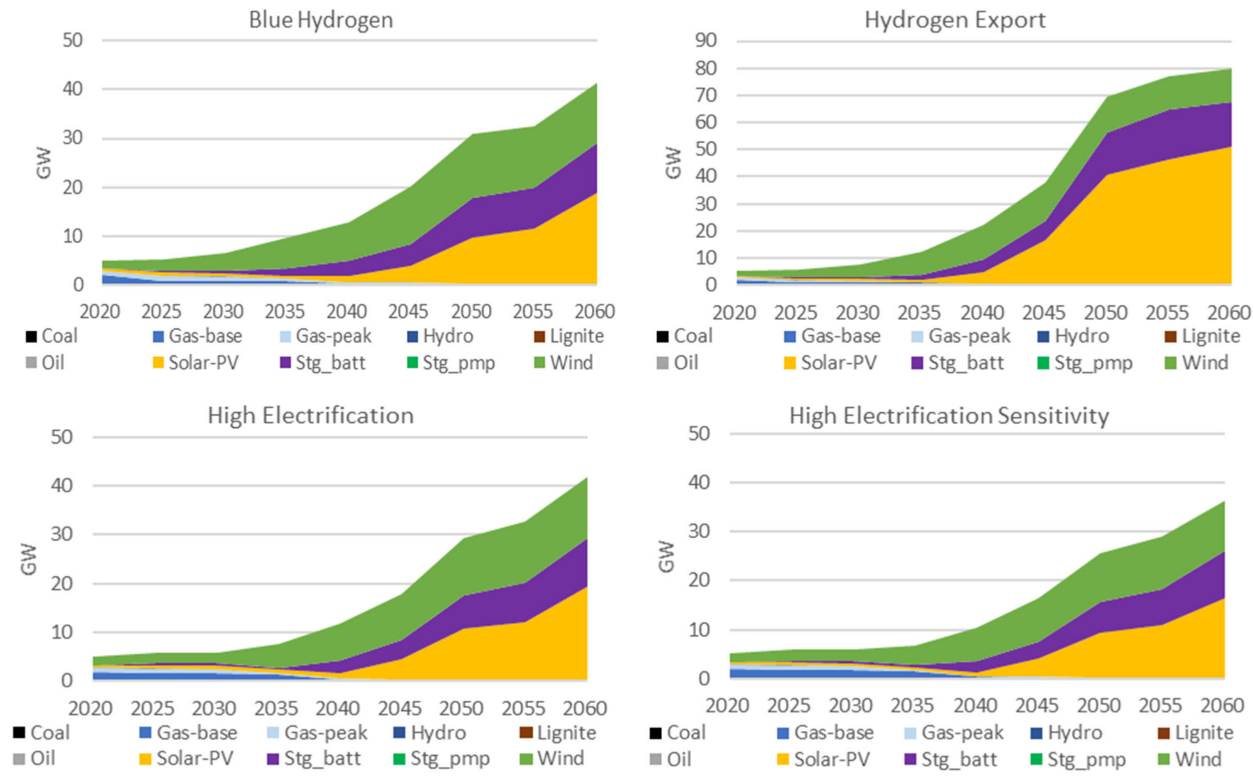

Figure 5-30: Power Generation Capacity by technology for SA

5.6.1.2 Rooftop Solar, Small-scale Batteries, Projected Storage Needs

Rooftop solar photovoltaics (RTPV) and small-scale battery projections are determined outside the AusTIMES model, as described in Appendix D, and are very similar across all three scenarios, with the capacity of solar in GW significantly exceeding that of distributed batteries.

Rooftop PV is projected to reach ~67GW nationally by 2060 in “Blue Hydrogen” and “High Electrification”, and a slightly higher ~83 GW in the “Hydrogen Exports” scenario. Nationally, distributed battery storage in 2060 is projected to range between ~7.6-12 GW across the scenarios with the greatest capacity in the “Blue Hydrogen” scenario and least in “High Electrification”. Similar patterns hold in South Australia with the exception that the greatest investment in distributed energy resource (DER) batteries is projected in the “High Electrification” scenario. By 2060, the capacity of rooftop PV in South Australia is the least in the “High Electrification” scenario at ~4.4GW, the greatest in the “Hydrogen Exports” scenario at ~6.8GW and ~5.7GW in the “Blue Hydrogen” scenario. Distributed battery capacity ranges between 340 and 620 MW.

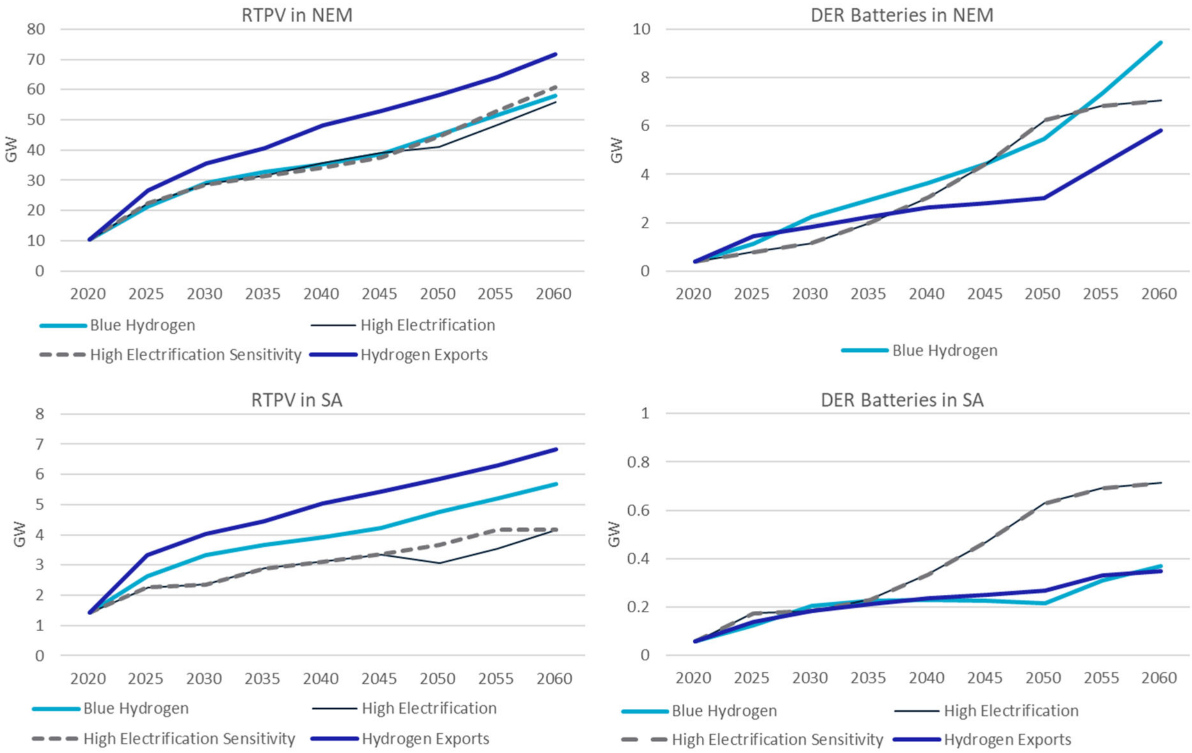

Figure 5-31: RTPV and DER Battery Capacity by scenario, for NEM and for SA

5.6.2 Power System Balancing, Spillage

In this project we did not perform short time scale power system balancing analysis. However, in other similar projects we have done such studies and found that the requirement for reliability of supply does not have a large impact on total system costs or the energy supply fuel mix (Campey et al. 2017, pp45ff, see also Appendix G and Section 5.2 of Graham et al. 2021c).

Open cycle gas power plants are low-cost generation technologies that are typically adequate to ensure sufficient generation capacity exists even during several days or weeks of low renewable resource availability. However, the low likelihood of such circumstances implies that quite small contributions, in terms of total energy contribution, from such backup technology are required. In principle, if a constraint on generation is 100% low emissions, these gas plants could be supplied by low emissions biogas. Gas generation capacity to meet periods of low renewable resources availability was not explicitly modelled, as it is expected to make relatively little difference to generation mix by total energy supplied (although it may represent a greater relatively difference to generation capacity.)

Any requirement to meet constraints on minimum inertia or fault current provision can be provided by the installation of synchronous condensers for a cost that is typically sufficiently modest that it makes very little difference to the least cost mix of generation (Reedman et al., 2021b, Section 7, see also Appendix H.) In the event that large-scale batteries, or inverter-based generators are installed with primary frequency response capability, these would still further reduce the requirement for synchronous condensers to provide for minimum inertia requirements.

5.6.3 Transmission Results, REZ Development

There are significant differences among scenarios in terms of transmission development both in South Australia, and nationally. Somewhat counterintuitively, the “High Electrification” scenario is projected to have the least transmission build, primarily because the demand for renewables to produce hydrogen by electrolysis is high in both the “Blue Hydrogen” and “Hydrogen Exports” scenarios (Figure 5-32).

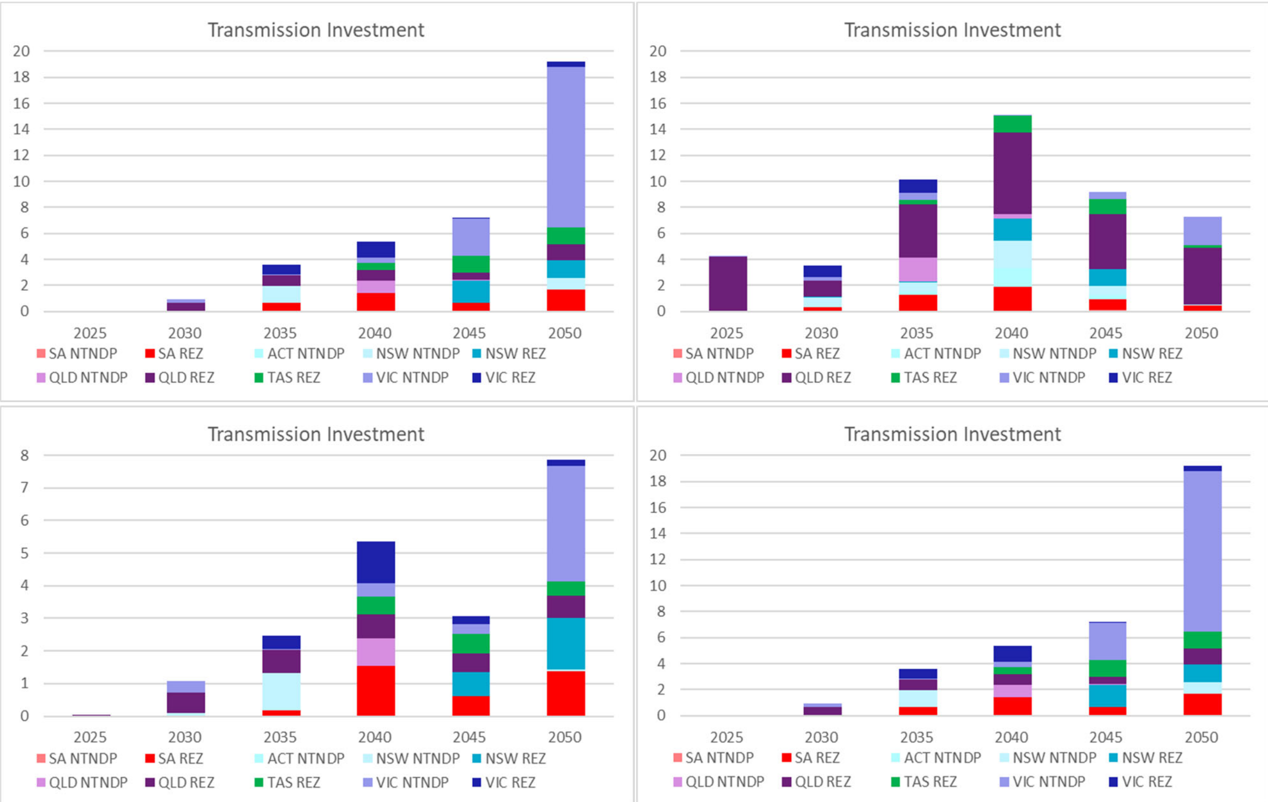

Figure 5-32: Projected transmission investment (GW): NTNDP interconnects and REZ developments, NEM region (Top Left: Blue Hydrogen, Top Right: Hydrogen Exports, Bottom Left: High Electrification – note scale, Bottom Right: High Electrification Sensitivity)

Nationally, more of the investment is in transmission to increase interconnection capacity as opposed to unlocking renewable energy zones. However, in South Australia, particularly later in the projection period, there is more investment in transmission to service renewable energy zones. Interconnection capacity enhancement in South Australia is similar in all scenarios, with more within South Australia (from the Adelaide region to the two other transmission regions) than between South Australia and nearby states (NSW and Victoria). Variation in transmission enhancement among scenarios is more pronounced for the renewable energy zone expansions. REZ Q8 (see AEMO 2021, Figure 46) is particularly higher in the “Blue Hydrogen” and “Hydrogen Exports” scenarios than in “High Electrification”, and REZ Q3, N1, N2, N3 are higher in the “Hydrogen Exports” scenario than in the other two.

5.6.4 Electricity wholesale costs

Electricity wholesale costs are projected to generally increase across the projection period in all states and all scenarios (Figure 5-33), ranging between $50-100/MWh. Costs are lowest in the high electrification sensitivity scenario, where there is less pressure on the expansion of electricity generation to provide for hydrogen electrolysis. Costs are lowest in Tasmania and Queensland and highest in Victoria and NSW, with those in South Australia towards the lower end of the range in all scenarios except “Hydrogen Exports”, where costs are more volatile in the NEM states excluding Queensland and Tasmania.

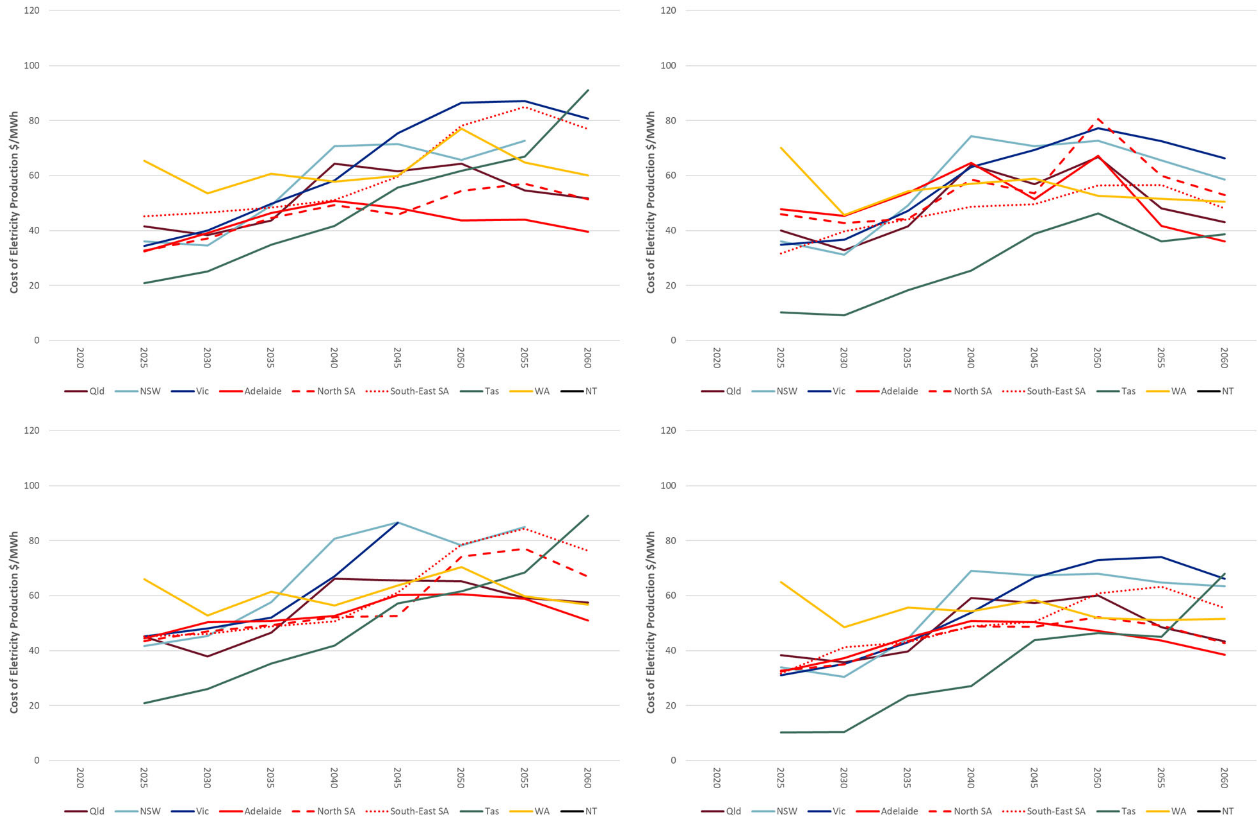

Figure 5-33: Projected electricity production costs, by state and SA region (Top Left: Blue Hydrogen, Top Right: Hydrogen Exports, Bottom Left: High Electrification, Bottom Right: High Electrification Sensitivity)

5.7 Emissions

Greenhouse emissions across all scenarios, both nationally (Figure 5-34), and in South Australia in particular (Figure 5-35), are projected to be significantly reduced in the power generation sector. These reach essentially zero by 2030 in South Australia as gas generation is replaced by renewables supported by battery storage, and by 2050 in the Rest of Australia. Total greenhouse emissions from the hydrogen generation sector are relatively small, and the temporal pattern of direct greenhouse emissions generation can be explained by the growth in hydrogen in the gas network and constraints on the hydrogen production process. In scenarios where hydrogen production is required to become primarily from renewable electrolysis, the greenhouse emissions from that sector eventually reduce significantly, being produced only by SMR with CCS. In the “High Electrification” sensitivity scenario, hydrogen is permitted to be produced by the lower cost SMR CCS process, and so greenhouse emissions from that sector increase commensurately over the projection period but are mostly captured.

Direct emissions from transport are also projected to be similar across scenarios, reducing significantly over time in all cases– though not being eliminated entirely. Indirect emissions are expected to be primarily from the use of electricity as a transport fuel, but these reach zero by the end of the projection period as the electricity sector decarbonises. Other indirect emissions in the transport sector are from the relatively small quantities of hydrogen transport fuel, which is produced via either SMR with CCS (in the Hydrogen scenario and the “High Electrification” scenario sensitivity). However, in the other scenarios greenhouse emissions from hydrogen production are almost non-existent, being derived from renewable electricity.

There is more scope for reduction in direct emissions from residential buildings rather than commercial buildings, given that commercial buildings are already significantly electrified in comparison. Overall, the direct emissions from commercial buildings are projected in all scenarios to increase slightly over the projection period at the national scale, and to decrease slightly in South Australia.

There remains a significant challenge in the reduction of direct emissions in industry. Although combustion (energy use) emissions in industry tend to be projected to decline to varying extents in all scenarios considered, process emissions – which are currently larger in quantity - are projected to increase slightly with the net result that total emissions from industry is expected to increase. The reduction in (energy related) industry emissions due to fuel switching away from coal and natural gas to solid biofuels, decarbonised electricity and hydrogen, is insufficient to compensate for the projected increase in process emissions owing to growth in industrial output by about 50%. Emissions intensity from industry is projected to decline, however, the rate of decline in intensity is insufficient to offset increases owing to industry growth. This applies both at the national scale and in South Australia in particular. Although emissions in industry indirectly from fuel use and directly from industrial process is not eliminated entirely over the modelled period, both are reduced substantially, even while economic growth result in increased total production (recall Figure 4-1 and Figure 4-2).

Approximately half of industry emissions are from agriculture – primarily sheep, cattle and dairy and of the remaining emissions, most are due to coal mining and gas extraction at the national scale, and in South Australia, due to gas extraction only. This report does not focus on agricultural emissions, as the majority by far in this sector are non-energy emissions. Negative emissions owing to biosequestration in Forestry and logging are assumed to be identical across all three scenarios. These are consistent with Commonwealth of Australia (2021) for Australia and Government of South Australia (2015, Figure 4), reaching 10% of 2005 emissions nationally (that is, reaching 620 Mt) and approximately 60Mt in South Australia, by 2050.

Remaining industries that are relatively large producers of emissions include steel manufacturing, other chemicals (including fertilisers and explosives), cement, refrigeration and air-conditioning and aluminium production. Across all three scenarios at the national scale, the trajectory of emissions from most of these sectors is projected to decrease somewhat, though with emissions from refrigeration and air conditioning declining more quickly to 2040 as restrictions on the use of refrigerant gases with a high greenhouse contribution are phased out.

In South-Australia there are small differences across scenarios. The high emitting industrial sectors are Steel production, Cement production, Other non-metallic minerals and Other chemicals. In the above sectors, process emissions are projected to decrease in all scenarios. Steel production, for example, is able to partially electrify with the recycling of scrap through electric arc furnace technology, and blast furnace production can eventually be replaced with Direct Reduction Iron processes that rely on natural gas or hydrogen as fuel.

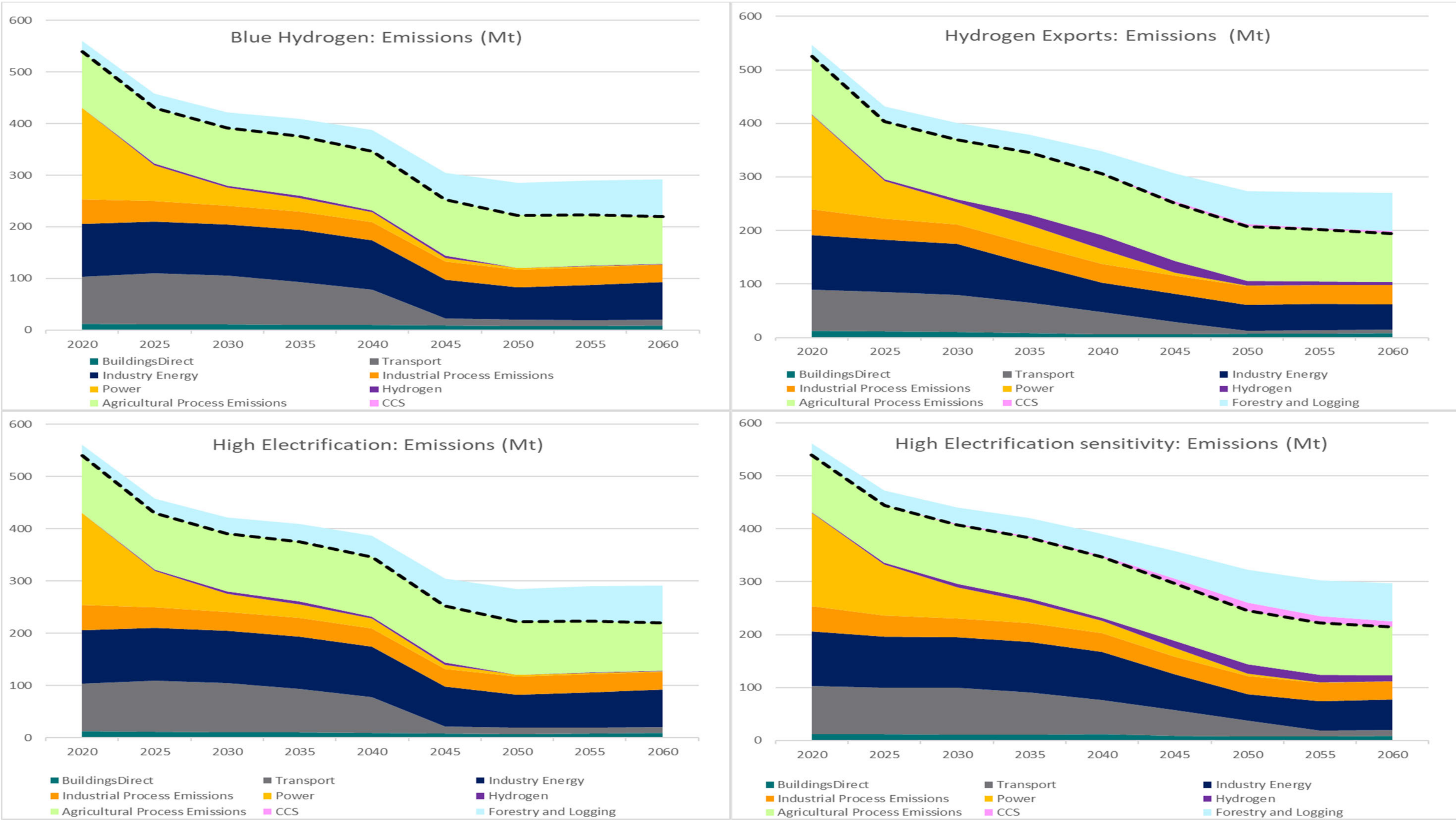

Figure 5-34: Projected Greenhouse Emissions: Australia (Top Left: Blue Hydrogen, Top Right: Hydrogen Exports, Bottom Left: High Electrification, Bottom Right: High Electrification Sensitivity)

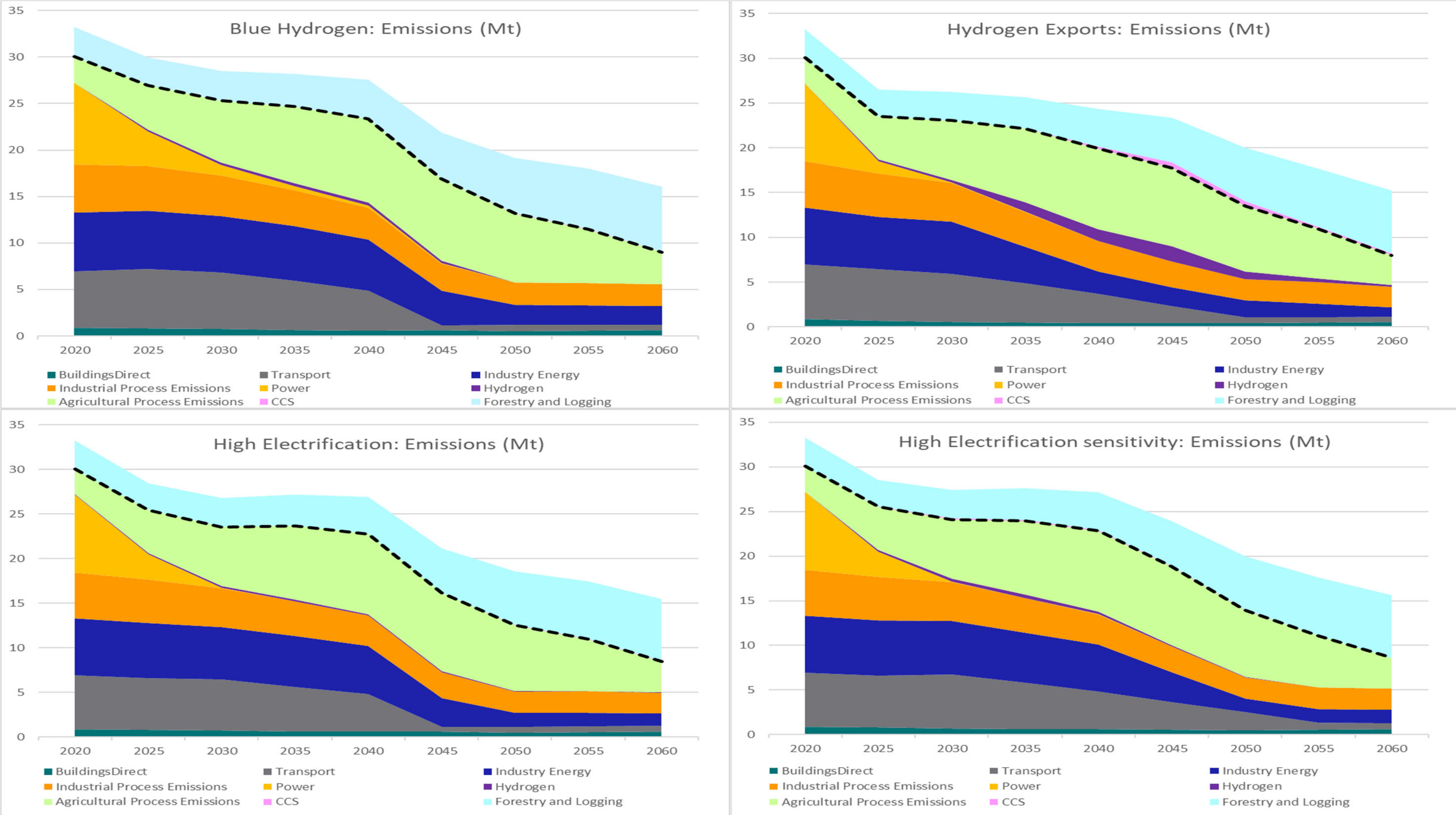

Figure 5-35: Projected Greenhouse Emissions: SA (Top Left: Blue Hydrogen, Top Right: Hydrogen Exports, Bottom Left: High Electrification, Bottom Right: High Electrification Sensitivity)

6 Appendices

Appendix A. Data sources and quantitative interpretation

Data sources and quantitative interpretation (see Table 6-1 below).

Technology Shifts

Electrification

- Represented by rate of return required on switching capital costs. Technological options data from ClimateWorks (2016) and Butler et al. (2020a, b)
    - Low (30%);
    - Medium (20%);
    - High (7%)

Renewables, batteries and EV costs, Electrolysis costs:

- From *Gencost 2021* (Graham et al. 2021c).
    - Low (Global NZE by 2050)
    - Medium (Global NZE post 2050)
    - High (Current policies)

SMR Costs

- From *Australia's Hydrogen Energy Strategy* (DISER 2019):
    - Low (cost reductions accelerated 10 years over the projection period)
    - Medium (nominal)
    - High (cost reductions delayed 10 years)

Hydrogen Distribution

- Based on https://www.australiangasnetworks.com.au/blended-renewable-gas Blended Gas project figures:
    - Low (a minimum of 10% by 2030, and 100% renewable by 2050),
    - Medium (10% by 2030, 20% by 2040 and 100% renewable by 2050),
    - High (10% by 2030 and 100% renewable by 2040)

Hydrogen Transmission

- Based on Hydrogen Distribution
    - Low (5% from 2030)
    - Medium (10% from 2030, 20% from 2040)
    - High (unconstrained)

Transport demand for gas

- Bureau of Infrastructure Transport and Regional Economics (2019)

Biogas availability

- DISER 2019

Table 6-1: All Scenario elements

Scenario Element		Driver/ Result?	Blue Hydrogen	High Electrification	Hydrogen Exports
Technological shifts	Electrification (rate of return required on switching capital costs)	D/R	Low (30%)	High (7%)	Medium (20%)
	Renewables costs (*Graham et al. 2021c)*	D	High (Current policies Scenario)	Low (NZE by 2050)	Medium (NZE post 2050)
	Batteries and EVs costs (*Graham et al. 2021c)*	D	High (Current policies Scenario)	Low (NZE by 2050)	Medium (NZE post 2050NZE post 2050)
	SMR costs (*Australia's Hydrogen Energy Strategy)*	D	Low (cost reductions accelerated 10 years)	High (cost reductions delayed 10 years)	Medium (nominal)
	Electrolysis costs (*Graham et al. 2021c)*	D	High (Current policies Scenario)	Low (NZE by 2050)	Medium (NZE post 2050)
	Hydrogen transmission	D	Medium (10% from 2030, 20% from 2040)	Low (5% from 2030)	High (unconstrained)
	Hydrogen distribution	D	Medium (10% by 2030, 20% by 2040 and 100% renewable: 2050)	Low (a minimum of 10% by 2030, and 100% renewable by 2050)	High (10% by 2030 and 100% renewable by 2040)
	Transport demand for gas	D	High	Low	Medium
	Biogas availability	D	High	Low	Medium
	Engagement with energy market	D	Low (Slow Change ISP Scenario)	High (High DER)	Medium (Fast Change)
Power Supply	Increased renewable supply	R	Medium	High	Medium
	Decline in thermal coal generation	D/R	High (permit early economic closure)	Medium (Expected shutdown year)	High (permit early economic closure)
	Increased DERs and DM	R	Low	High	Medium
	Increased storage	D/R	Low	High	Medium
	Electricity Prices	R	High	Low	Medium
	Power Transmission growth	D/R	Low	Medium	High
Emissions Policy	Emissions target stringency (Aust)	D	Medium (Existing Policies)	High (Existing policies with life extension)	Medium (Existing Policies)
	Emissions stringency (SA)	D	Medium (consistent with nationally determined contributions for STEPS)		
	Renewable subsidies	D	Low (Existing Policies)	Medium (Existing policies with life extension)	Medium (Existing policies with life extension)
Long-term demand drivers	Domestic gas affordability	D	Medium	Medium	Medium
	Industrial growth	D	Medium	Medium	High
	Hydrogen demand	D	Medium (Targeted Deployment)	Medium (Targeted Deployment)	High (Hydrogen: Energy of the Future)
	Energy efficiency	D			
	Economic growth	D	Medium	Medium	Medium
	Immigration	D	Australian Bureau of Statistics (Series B)		
	Discretionary Income	D	Medium	Medium	Medium

Customer engagement with Energy Market

- *AEMO Integrated System Plan* (AEMO 2021): Assumed uptake of distributed energy and electric vehicles in the consumer market.
    - Low (Slow Change ISP Scenario)
    - Medium (Fast Change)
    - High (High DER)

Power Supply

Renewable Supply, Centralised Energy Storage, Electrical Transmission Expansion

- Endogenous model result

Decline in thermal coal generation

- *AEMO Integrated System Plan* (AEMO 2021a and 2021b):
    - Low (permit end of life extensions)
    - Medium (Expected shutdown year)
    - High (permit early economic closure)

Uptake of distributed energy resources

- *AEMO Integrated System Plan* (AEMO 2021a and 2021b): Assumed uptake of distributed energy and electric vehicles in the consumer market.
    - Low (Slow Change ISP Scenario)
    - Medium (Fast Change)
    - High (High DER)

Uptake of energy efficiency measures

- Endogenous model result

Emissions Policy

Emissions target stringency (national)

- State and Federal government policies
    - Medium (Existing Policies)
    - High (Existing policies with life extension)
- Greenhouse gas emissions price equivalent policies
    - All (consistent with nationally determined contributions for STEPS)

Emissions target stringency (SA)

- *South Australia's Climate Change Strategy 2015-2050,* (Government of South Australia 2015): Medium (nominal)

Renewable Subsidies

- Low (Existing Policies)
- Medium (Existing policies with life extension)

Long Term Demand Drivers

Domestic gas affordability

- AEMO 2021a and 2021b

Industrial growth

- Steel, Hydrogen and Aluminium sectors
    - DISER 2019 and Energy Transition Hub 2019
- Other sectors
    - Endogenous model result based on economic growth
- Hydrogen demand
    - Export: DISER 2019: Medium ('Targeted Deployment' scenario), High ('Hydrogen: Energy of the Future' scenario)
- Domestic: Endogenous model result
    - Energy efficiency
        - Consistent with long term trends (Office of the Chief Economist 2020), ClimateWorks (2016), Butler et al. (2020a, b)

Economic growth

- KPMG-SD default projections

Immigration

- Australian Bureau of Statistics (Series B)

Discretionary Income

- KPMG-SD default projections

Appendix B. ABS standard geographical regions in South Australia

Table 6-2: Australian Bureau of Statistics classification of SA regions

South Australia	Statistical Area Level 4 (SA4)	Statistical Area Level 3 (SA3)
Greater Adelaide	Adelaide - Central and Hills	Adelaide City
		Adelaide Hills
		Burnside
		Campbelltown (SA)
		Norwood - Payneham - St Peters
		Prospect - Walkerville
		Unley
	Adelaide - North	Gawler - Two Wells
		Playford
		Port Adelaide - East
		Salisbury
		Tea Tree Gully
	Adelaide - South	Holdfast Bay
		Marion
		Mitcham
		Onkaparinga
	Adelaide - West	Charles Sturt
		Port Adelaide - West
		West Torrens
Rest of State	Barossa - Yorke - Mid North	Barossa
		Lower North
		Mid North
		Yorke Peninsula
	South Australia - Outback	Eyre Peninsula and South West
		Outback - North and East
	South Australia - South East	Fleurieu - Kangaroo Island
		Limestone Coast
		Murray and Mallee

Appendix C. Model descriptions

This appendix provides details of some of the models used in this report.

AusTIMES

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

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

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

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

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

Structural features

AusTIMES model has the following structural features:

- Coverage of all states and territories (ACT, NSW, NT, QLD, SA, TAS, VIC, WA)
- Time is represented in annual frequency (2015-2050)
- Demand sectors include agriculture (8 sub-sectors), mining (6 sub-sectors), manufacturing (19 sub-sectors), other industry (5 sub-sectors), commercial and services (11 building types), residential (3 building types), road transport (10 vehicle segments) and non-road transport (aviation, rail, shipping)
- Detailed representation of the electricity sector (detailed below "Electricity Sector")
- Five hydrogen production pathways including two electrolysis pathways: proton exchange membrane (PEM); and alkaline electrolysis (AE): steam methane reforming (SMR); SMR with carbon and storage (CCS); coal gasification with CCS.

Model inputs

AusTIMES has been calibrated to a base year of 2015 based on the state/territory level energy balance (Office of the Chief Economist 2016), national inventory of greenhouse gas emissions (DoEE, 2017), stock estimates of vehicles in the transport sector (ABS, 2016), data on the existing power generation fleet (ACIL Allen, 2014a; 2014b; AEMO, 2015; ESAA, 2016) and installed capacity of distributed generation (CER 2018, AEMO 2018).

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

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

Objective function

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

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

Where:

NPV: net present value of the total costs

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

d: general discount rate

REFYR: reference year for discounting

YEARS: set of years for which there are costs

R: region

While minimizing total discounted cost, the model must satisfy a large number of constraints (the so-called equations of the model) which express the physical and logical relationships that must be satisfied in order to properly depict the energy system. Details on these constraints are available in Part I of the TIMES model documentation.[6]

Electricity sector

In the TIMES framework, the power (electricity) sector is a transformation sector that converts forms of primary energy (That is, coal, natural gas, renewable resources) into electricity that is a derived demand of the end-use sectors outlined below. The electricity sector in AusTIMES has the following features:

- Electricity demand aggregated to 16 load blocks reflecting seasonal and time of day variation across the year
- 19 transmission zones: 16 NTNDP zones in the National Electricity Market (NEM); South-west Interconnected System (SWIS); North-west Interconnected System (NWIS); and Darwin Katherine Interconnected System (DKIS)
- Existing generators mapped to transmission zone at the unit-level (thermal and hydro) or farm-level (wind, solar)
- Renewable resource availability at Renewable Energy Zone (REZ) spatial resolution for solar, on- and off-shore wind and tidal resources and sub-state (polygon) spatial resolution for geothermal and wave resources in the NEM
- Trade in electricity between NEM regions subject to interconnector limits
- 29 new electricity generation and storage technologies: black coal pulverised fuel; black coal with 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 4 hours storage (PSH4); PSH with 8 hours of storage (PSH8); PSH with 12 hours of storage (PSH12); PSH with 24 hours of storage (PSH24); PSH with 48 hours of storage (PSH48); onshore wind; offshore wind; large-scale single-axis tracking solar photovoltaic (PV); residential rooftop solar PV; commercial rooftop solar PV; hot fractured rocks (enhanced geothermal); conventional geothermal; wave; tidal; hydrogen reciprocating engine; diesel reciprocating engine; small modular nuclear reactor; battery with 2 hours of storage; battery with 4 hours of storage; battery with 8 hours of storage.
- Current policies: national large-scale renewable energy target; Northern Territory, Queensland, Tasmania and Victoria Renewable Energy Targets; Small-scale renewable energy scheme; NSW Energy Security Target.

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

End-use sectors

Industry

Energy use in industry is significant and therefore is disaggregated into a number of sub-sectors. The mapping of AusTIMES to ANZSIC industry subsectors is displayed below (Table A-1).

Table A- 1: Mapping of AusTIMES to ANZSIC industry subsectors

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

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

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

- Projections of sectoral activity developed through the *Pathway to Deep Decarbonisation Project* (ClimateWorks Australia, ANU, CSIRO and CoPS, 2014), drawing on results of CGE analysis by the Centre of Policy Studies at Victoria University.
- Asset-level assumptions for alumina, aluminium, steel and petroleum refining facilities.
- Recent trends of changes in energy use by sector, drawing on historical data from the Office of the Chief Economist (2017)

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

Demand for Australian energy exports are based on *International Energy Agency* scenarios. AusTIMES can implement energy efficiency and electrification of technologies based on capital costs, equipment lifetime and fuel costs, if it is economically attractive. Assumptions on costs and savings are derived from the *Deep Decarbonisation Pathways Project* (CWA, ANU, CSIRO and CoPS, 2014) and *Industrial Energy Efficiency Data Analysis Project* (CWA, 2013). The total electrification allowed can be limited to reflect the levels expected in the scenarios.

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

Residential buildings

The stock of buildings is sourced from the *Residential Buildings Baseline Study* (EnergyConsult, 2015), 2016 ABS *Census* data, 2016 ABS populations and dwellings projection, *Australian Energy Statistics*, and the *Low Carbon High Performance* report (CWA, 2016).

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

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

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

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

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

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

Commercial buildings

The stock of buildings is sourced from the *Commercial Buildings Baseline Study* (Commonwealth of Australia 2012), *Australian Energy Statistics*, and the *Low Carbon High Performance* report (CWA, 2016).

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

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

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	Gas
Law court	Water heating	Hydrogen
Office	Appliances	
Public building	Lighting	
Retail	Equipment	
Supermarket		
School		
Tertiary		
Data centre		
Aged care		

All commercial buildings experience a business-as-usual efficiency improvement at no cost. Additional 'best practice' energy efficiency and electrification options are available, at an additional incremental cost. Should 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 (CWA ,2016).

Transport

The transport sector is a significant and growing component of Australia's greenhouse gas emissions. AusTIMES has a very detailed representation of road transport. The road transport segments, vehicle classes, and fuel categories are listed below (Table A-4).

Table A- 4: Road transport segments, vehicle classes, and fuel categories

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

Key inputs are ABS data on vehicle stock (ABS, 2016a), average kilometres travelled (ABS, 2017), Bureau of Infrastructure Transport and Regional Economics (2019) and *Australian Energy Statistics* data (OCE, 2017) on fuel use, NGA emission factors for fuel (DoEE, 2017), population/GSP projections, assumptions around future vehicle costs and efficiency improvements (Graham et al., 2021a), oil price projections (International Energy Agency, 2020) and production costs on biofuels (Campey et al., 2017). The delivery price of electricity and hydrogen for road transport is endogenously determined within AusTIMES.

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

There is less detailed representation of non-road transport, implemented on a fuel basis. The market segments and fuel categories are listed below (Table A-5).

Table A- 5: Non-road transport market segments and fuels

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

Key inputs are Bureau of Infrastructure Transport and Regional Economics (2019) and Australian Energy Statistics data (Office of the Chief Economist, 2017) on fuel use, National Greenhouse Accounting emission factors for fuel (DoEE, 2017), population/GSP projections, assumptions around activity and fuel efficiency improvements, oil price projections (International Energy Agency, 2020) and production costs on biofuels (Campey et al., 2017). The delivery price of hydrogen for rail and shipping is endogenously determined within AusTIMES.

Key outputs at a state/territory level include fuel consumption (PJ) and greenhouse gas emissions (kt).

Agriculture

Energy use in agriculture is minimal although emissions are significant. The mapping of AusTIMES to ANZSIC industry subsectors is displayed below (Table A-6).

Table A- 6: Mapping of AusTIMES to ANZSIC agriculture subsectors

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

Agriculture activity growth projections were developed through the *Pathway to Deep Decarbonisation Project* (CWA, ANU, CSIRO and CoPS, 2014), drawing on results of CGE analysis by the Centre of Policy Studies at Victoria University. CWA hosts the ongoing multi-year initiative Land Use Futures, which focusses specifically on the Agricultural sector. While not integrated into AusTIMES, emerging findings from this work can be drawn upon to sense-check assumptions or results as required.

Carbon forestry

Agriculture activity growth projections were developed through the *Pathway to Deep Decarbonisation Project* (Climateworks Australia, ANU, CSIRO and CoPS, 2014), drawing on results of CGE analysis by the Centre of Policy Studies at Victoria University. CWA hosts the ongoing multi-year initiative Land Use Futures, which focusses specifically on the Agricultural sector. While not integrated into AusTIMES, emerging findings from this work can be drawn upon to sense-check assumptions or results as required.

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

Appendix D. DER Adoption Model

DER Adoption Model

Adoption projections method overview

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

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

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

Trend model

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

$$X_{m=f(month\ in\ sequence, month\ of\ year\ dummy\ variable)}$$

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

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

Adoption in consumer technology markets

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

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

In Section 2.1 we highlighted the general projection approach including some examples of the types of demographic or other factors that could be considered for inclusion. We also indicate an important interim step, which is to calibrate the adoption curve at appropriate spatial scales (due to differing demographic characteristics and electricity prices) and across different customer segments (due to differences between customers' electricity load profiles which are discussed in Appendix C).

Once the adoption curve is calibrated for all the relevant factors, we can evolve the rate of adoption over time by altering the inputs according to the scenario assumptions[7]. For example, differences in technology costs and prices between scenarios will alter the payback period and lead to a different position on the adoption curve. Non-price scenario assumptions such as available roof space in a region will result in different adoption curve shapes (particularly the height at saturation). Data on existing market shares determines the starting point on the adoption curve.

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

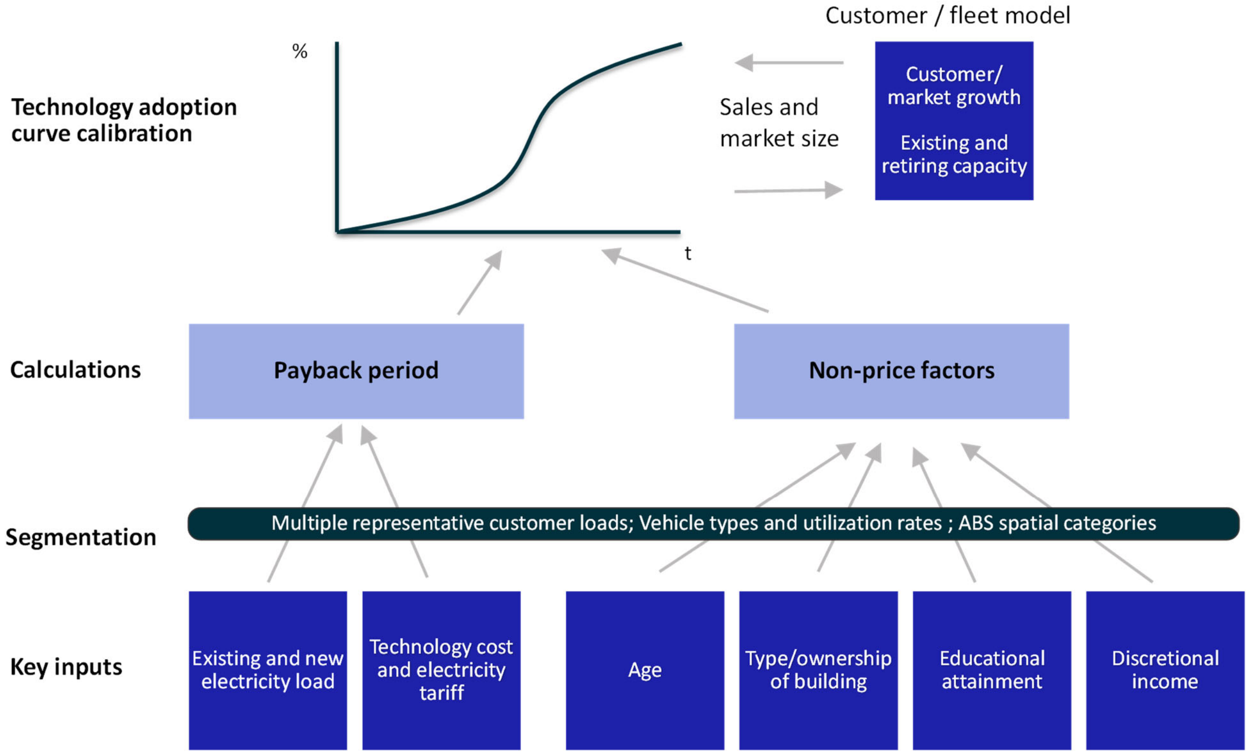


Figure 6-1: Adoption model methodology overview

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

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

Appendix E. Ports

Table 6-3: Maximum production based on port capacity and 5% workforce (dark blue workforce limited, light blue port capacity limited)

		Maximum production in 2050 (Mtpa)				
Port	Available Port Capacity[8]	PEM H2	PEM H2 + DRI Steel	PEM H2 + DRI & EAF Steel	PEM H2 + DRI & EAF & CHR Steel	Aluminium Smelter
Newcastle	147.53	3.51	12.94	4.56	2.54	0.64
Port Hedland	363.92	0.54	2.00	0.70	0.39	0.10
Melbourne	7.70	7.70	7.70	7.70	7.70	7.70
Esperance	2.14	0.09	0.34	0.12	0.07	0.02
Fremantle (Inc Kwinana)	8.42	8.42	8.42	8.42	8.42	2.38
Dampier & Ashburton	127.80	0.48	1.77	0.62	0.35	0.09
Geraldton	0.54	0.32	0.54	0.42	0.23	0.06
Abbot Point	28.94	1.97	7.27	2.56	1.43	0.36
Gladstone	77.26	1.08	4.00	1.41	0.78	0.20
Mackay	1.05	1.05	1.05	1.05	1.05	0.36
Townsville	2.13	1.54	2.13	2.00	1.11	0.28
Brisbane	2.75	2.75	2.75	2.75	2.75	2.75
Hay Point	118.32	1.97	7.27	2.56	1.43	0.36
Botany Bay	0.02	0.02	0.02	0.02	0.02	0.02
Eden	0.09	0.00	0.00	0.00	0.00	0.00
Port Kembla	7.10	1.76	6.49	2.29	1.27	0.32
Adelaide	1.12	1.12	1.12	1.12	1.12	1.12
Darwin	0.45	0.45	0.45	0.45	0.45	0.33
Bell Bay	1.99	0.59	1.99	0.77	0.43	0.11

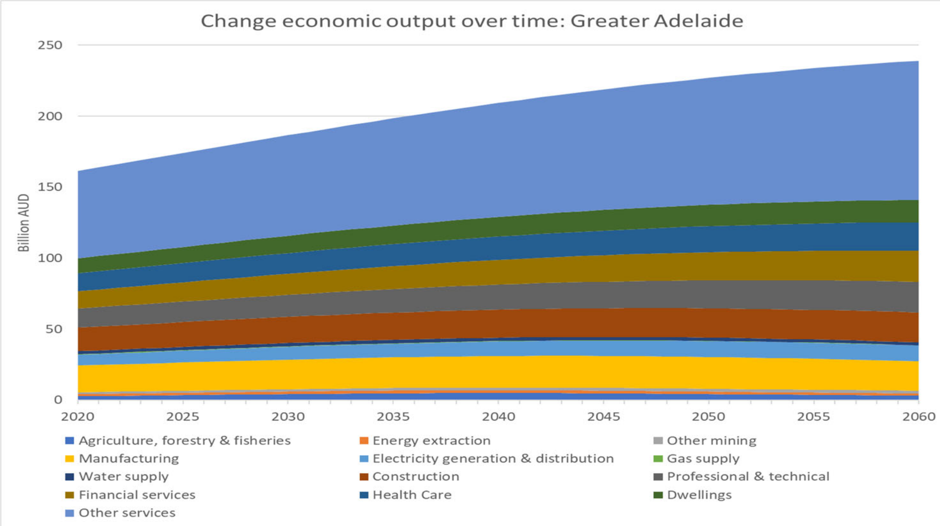
[8] Data from https://www.portsaustralia.com.au/resources/trade-statistics

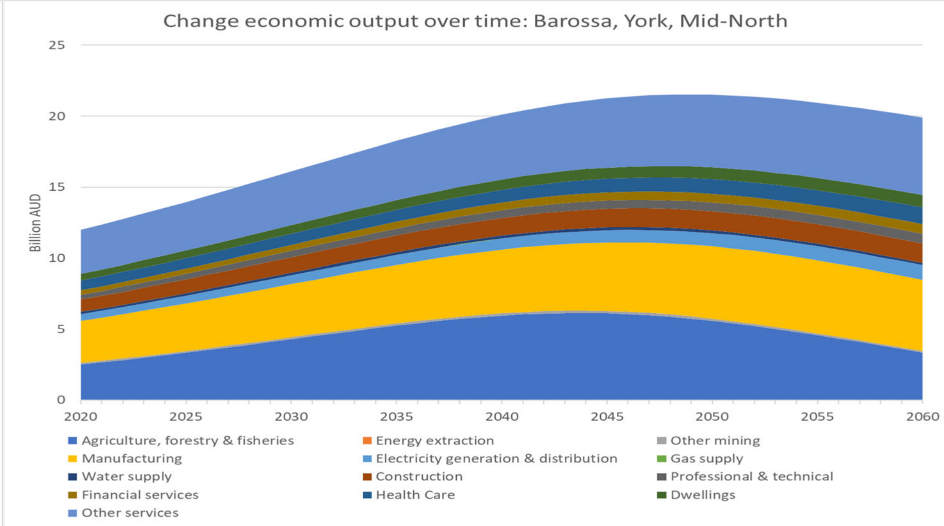
Table 6-4: Maximum production by NEM transmission zone (limited by port capacity – dark blue - and 5% of workforce – light blue)

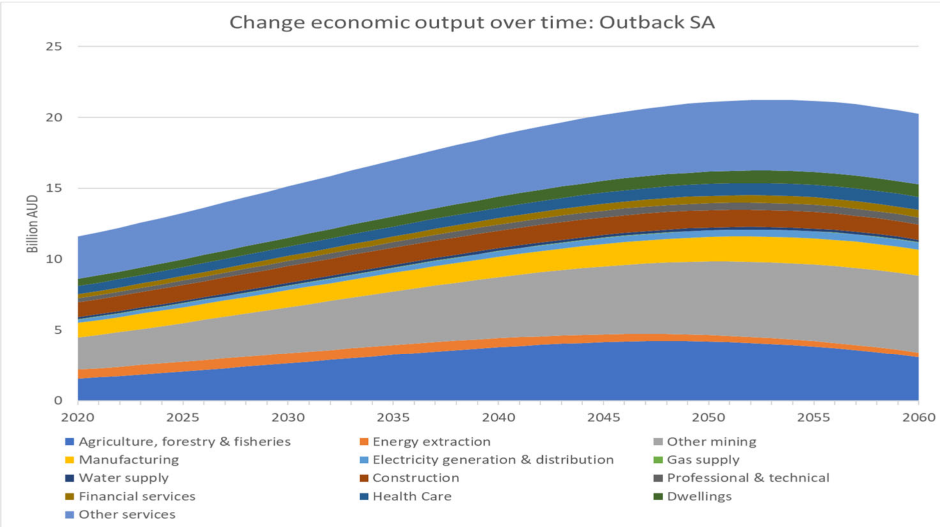
		Maximum production in 2050 (Mtpa)				
NEM Transmission Zone	Total Available Port Capacity[9]	PEM H2	PEM H2 + DRI Steel	PEM H2 + DRI & EAF Steel	PEM H2 + DRI & EAF & CHR Steel	Aluminium Smelter
Adelaide (ADE)	1.12	1.12	1.12	1.12	1.12	1.12
Canberra (CAN)	0.09	0.00	0.00	0.00	0.00	0.00
Central Qld (CQ)	77.26	1.08	4.00	1.41	0.78	0.20
Darwin-Katherine (DKIS)	0.45	0.45	0.45	0.45	0.45	0.33
Melbourne (MEL)	7.70	7.70	7.70	7.70	7.70	7.70
Central NSW (NCEN)	154.65	5.28	19.45	6.86	3.83	0.98
North Qld (NQ)	150.44	6.53	17.72	8.16	5.01	1.36
North-West Inter-connected System (NWIS)	492.26	1.34	4.31	1.74	0.97	0.24
South-East Qld (SEQ)	2.75	2.75	2.75	2.75	2.75	2.75
South-West Inter-connected System (SWIS)	10.55	8.51	8.76	8.54	8.48	2.40
Tasmania (TAS)	1.99	0.59	1.99	0.77	0.43	0.11

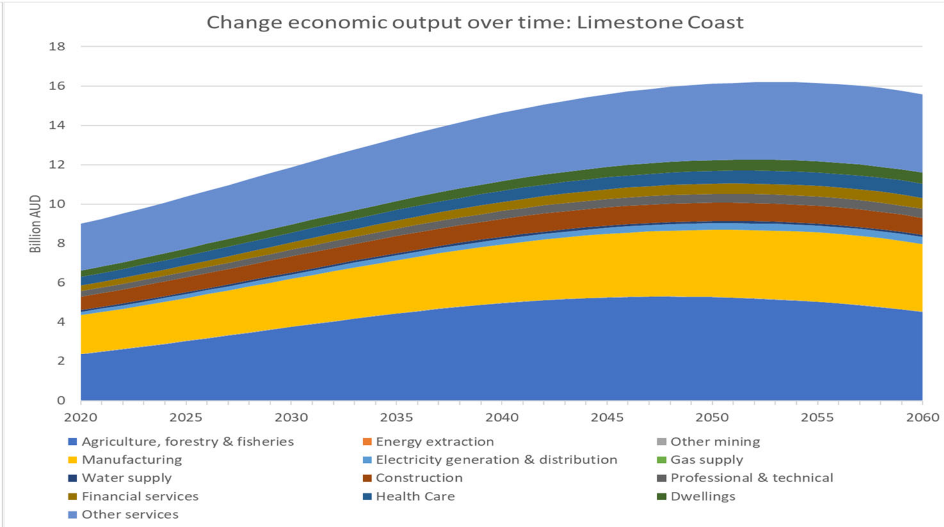
[9] Hayward, Jenny; Palfreyman, Doug (2022): Data: H2 exports from ports. v1. CSIRO. Data Collection. https://data.csiro.au/collection/csiro:53302

Appendix F. Economic projections









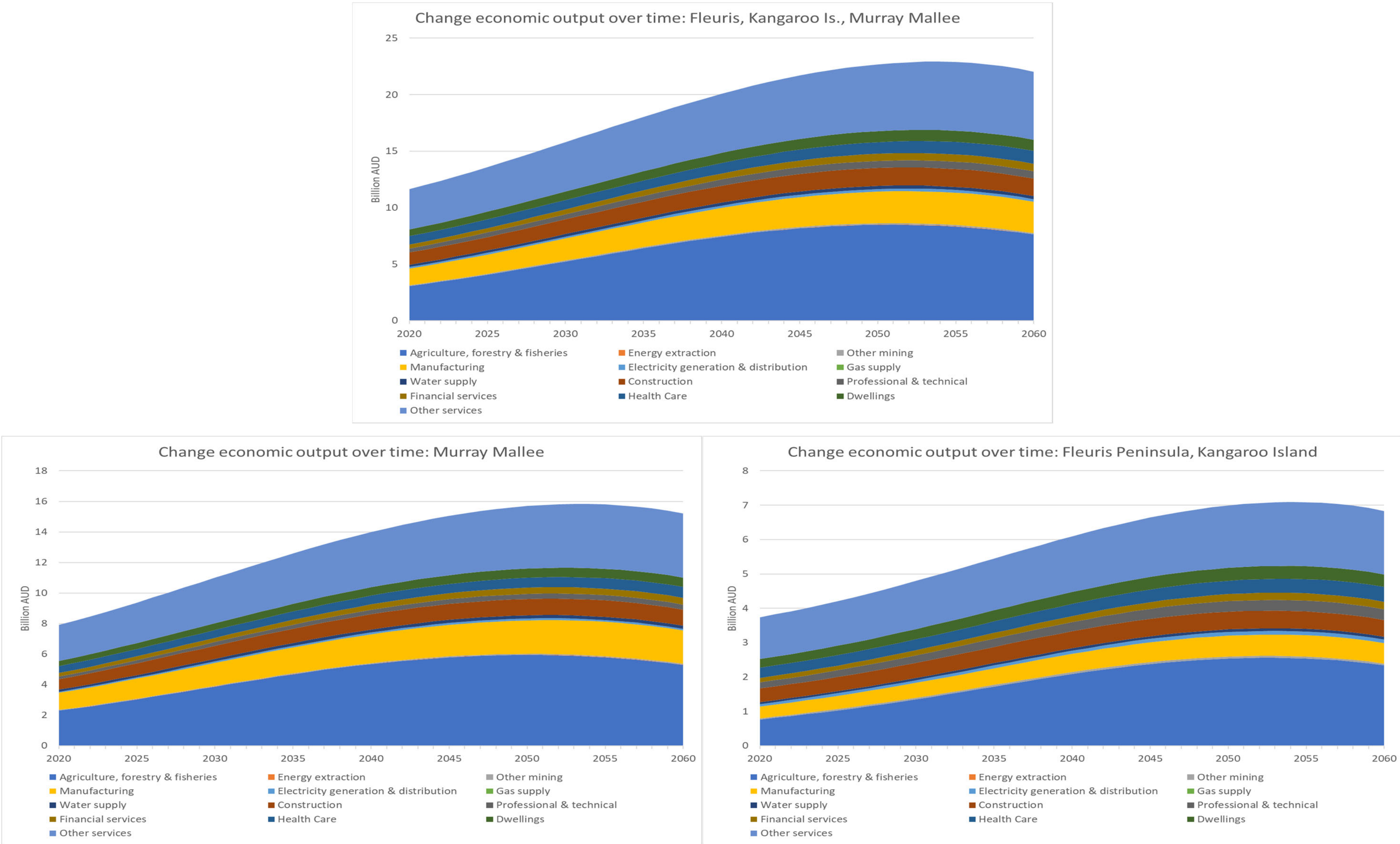
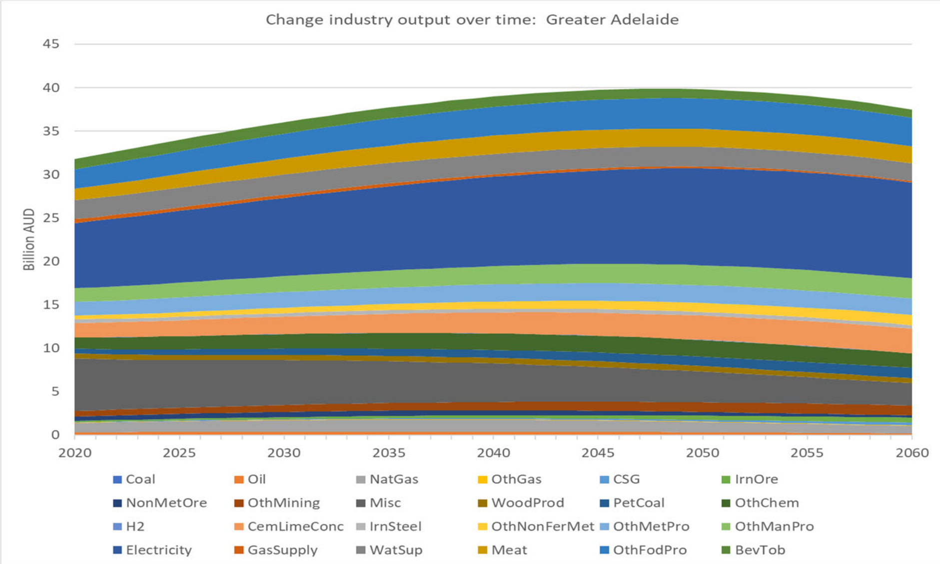
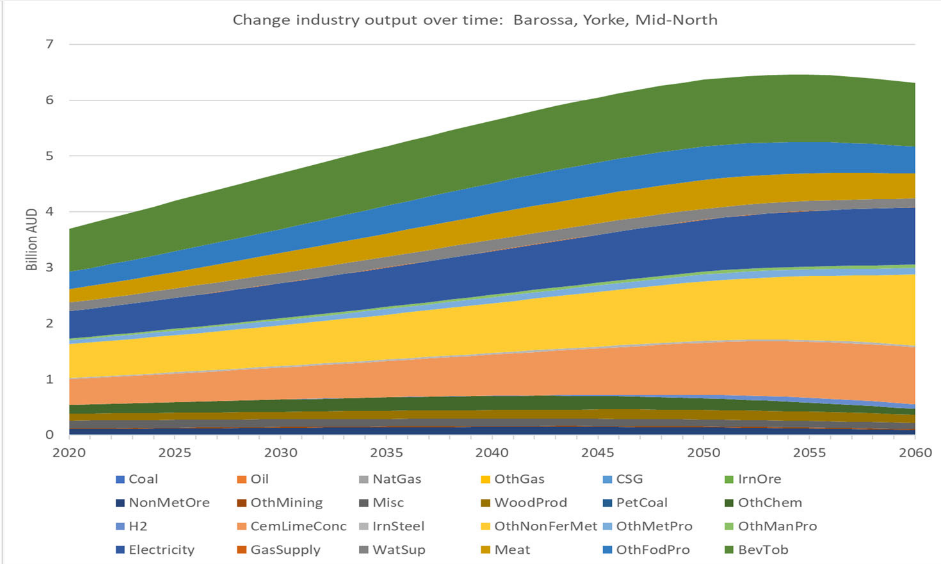
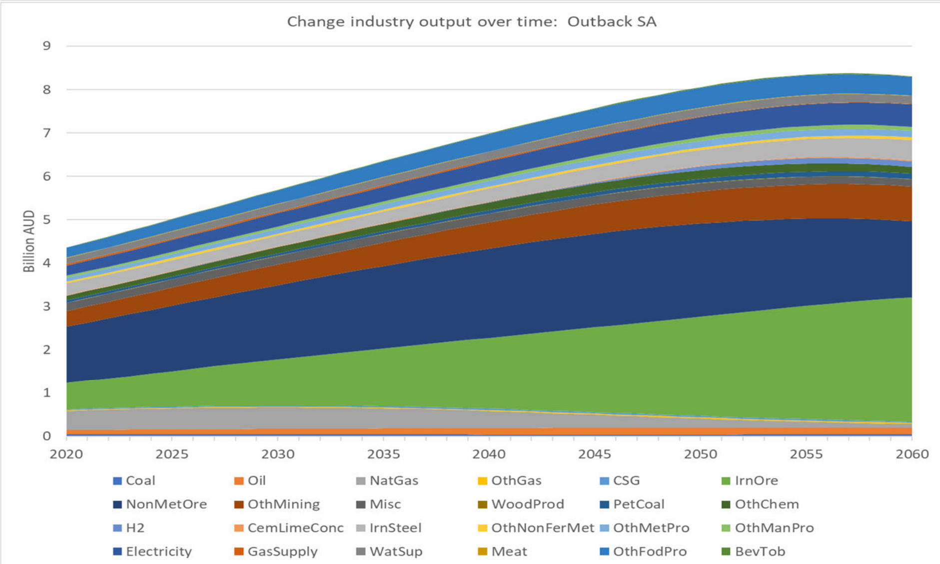


Figure 6-2: South Australia Gross Regional Product projections: baseline


Change industry output over time: Greater Adelaide
Billion AUD
0 5 10 15 20 25 30 35 40 45
2020 2025 2030 2035 2040 2045 2050 2055 2060
Coal Oil NatGas OthGas CSG IrnOre
NonMetOre OthMining Misc WoodProd PetCoal OthChem
H2 CemLimeConc IrnSteel OthNonFerMet OthMetPro OthManPro
Electricity GasSupply WatSup Meat OthFodPro BevTob


Change industry output over time: Barossa, Yorke, Mid-North
Billion AUD
0 1 2 3 4 5 6 7
2020 2025 2030 2035 2040 2045 2050 2055 2060
Coal Oil NatGas OthGas CSG IrnOre
NonMetOre OthMining Misc WoodProd PetCoal OthChem
H2 CemLimeConc IrnSteel OthNonFerMet OthMetPro OthManPro
Electricity GasSupply WatSup Meat OthFodPro BevTob


Change industry output over time: Outback SA
Billion AUD
0 1 2 3 4 5 6 7 8 9
2020 2025 2030 2035 2040 2045 2050 2055 2060
Coal Oil NatGas OthGas CSG IrnOre
NonMetOre OthMining Misc WoodProd PetCoal OthChem
H2 CemLimeConc IrnSteel OthNonFerMet OthMetPro OthManPro
Electricity GasSupply WatSup Meat OthFodPro BevTob

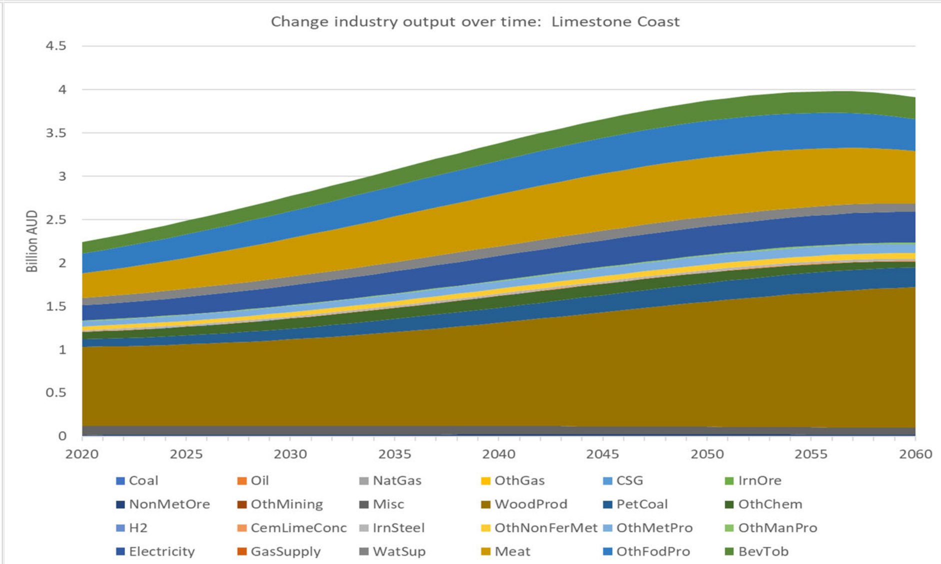

Change industry output over time: Limestone Coast
Billion AUD
0 0.5 1 1.5 2 2.5 3 3.5 4 4.5
2020 2025 2030 2035 2040 2045 2050 2055 2060
Coal Oil NatGas OthGas CSG IrnOre
NonMetOre OthMining Misc WoodProd PetCoal OthChem
H2 CemLimeConc IrnSteel OthNonFerMet OthMetPro OthManPro
Electricity GasSupply WatSup Meat OthFodPro BevTob

Figure 6-3: South Australia economic projections: baseline Mining and Manufacturing

Appendix G. Renewable energy zones and transmission developments

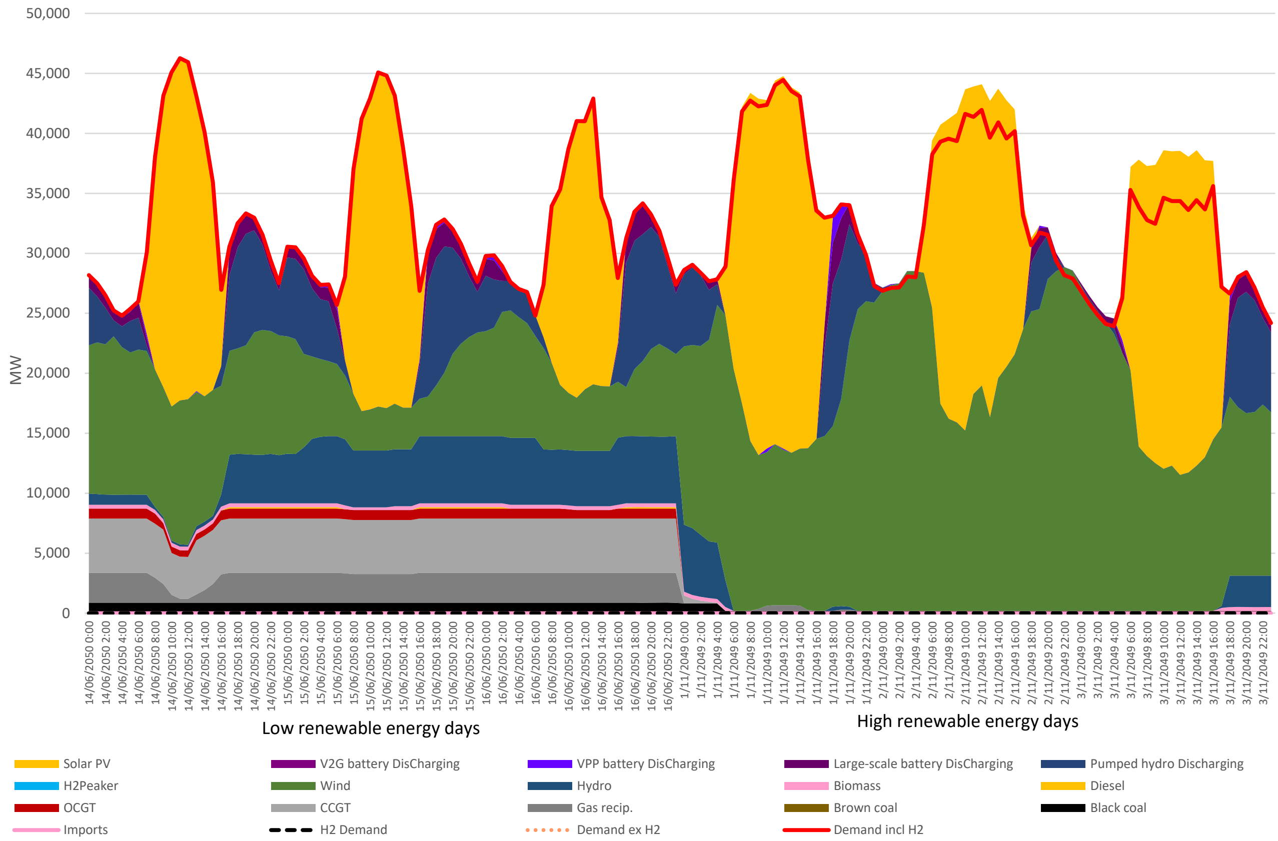


Figure 6-4 Low and high renewable energy days, NEM, Scenario "A"

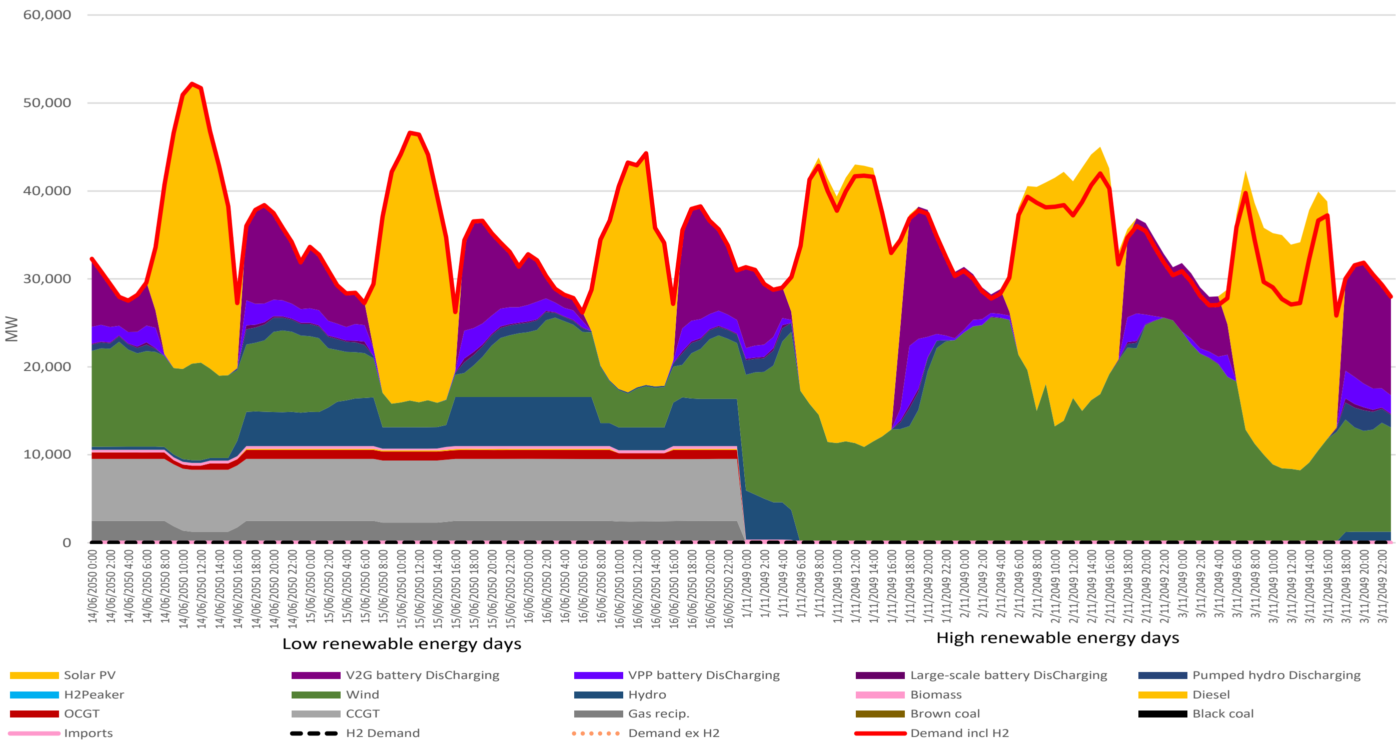


Figure 6-5 Low and high renewable energy days, NEM, Scenario "B"

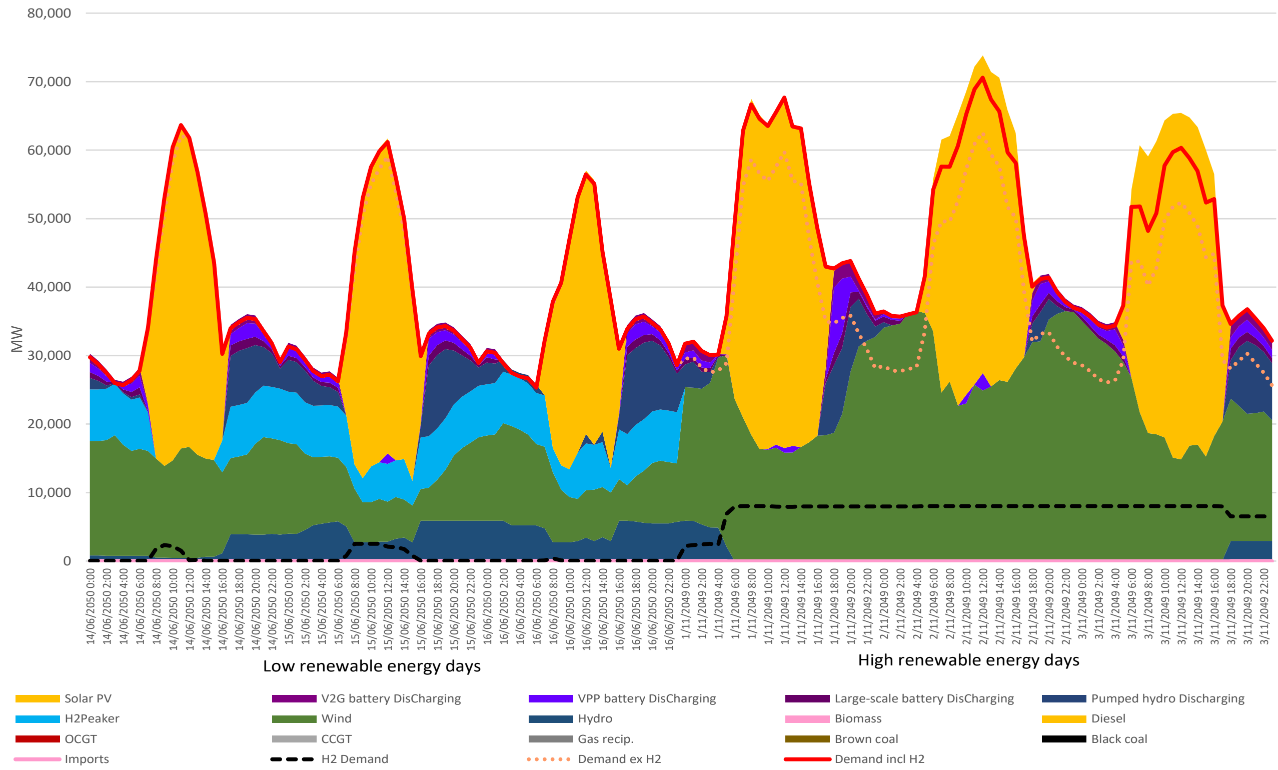


Figure 6-6 Low and high renewable energy days, NEM, Scenario "C"

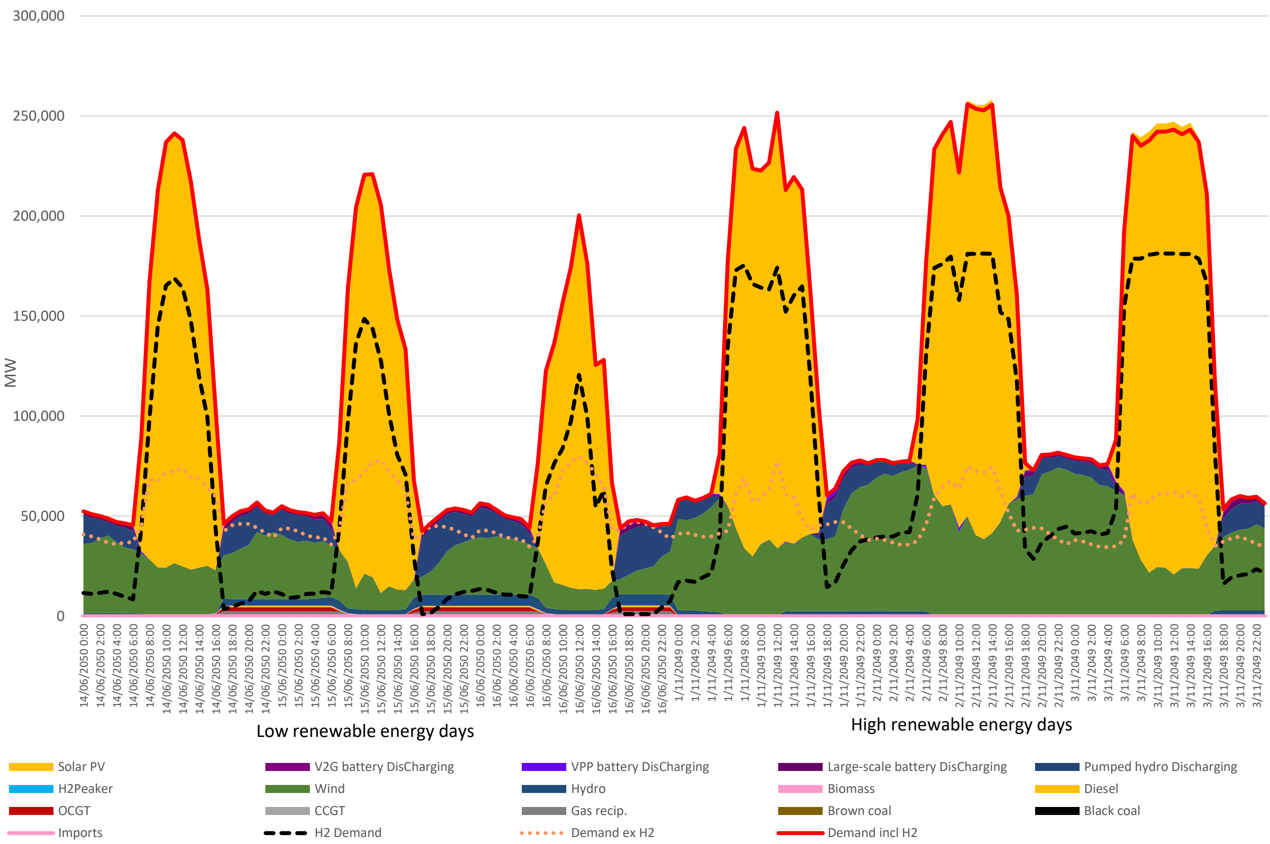
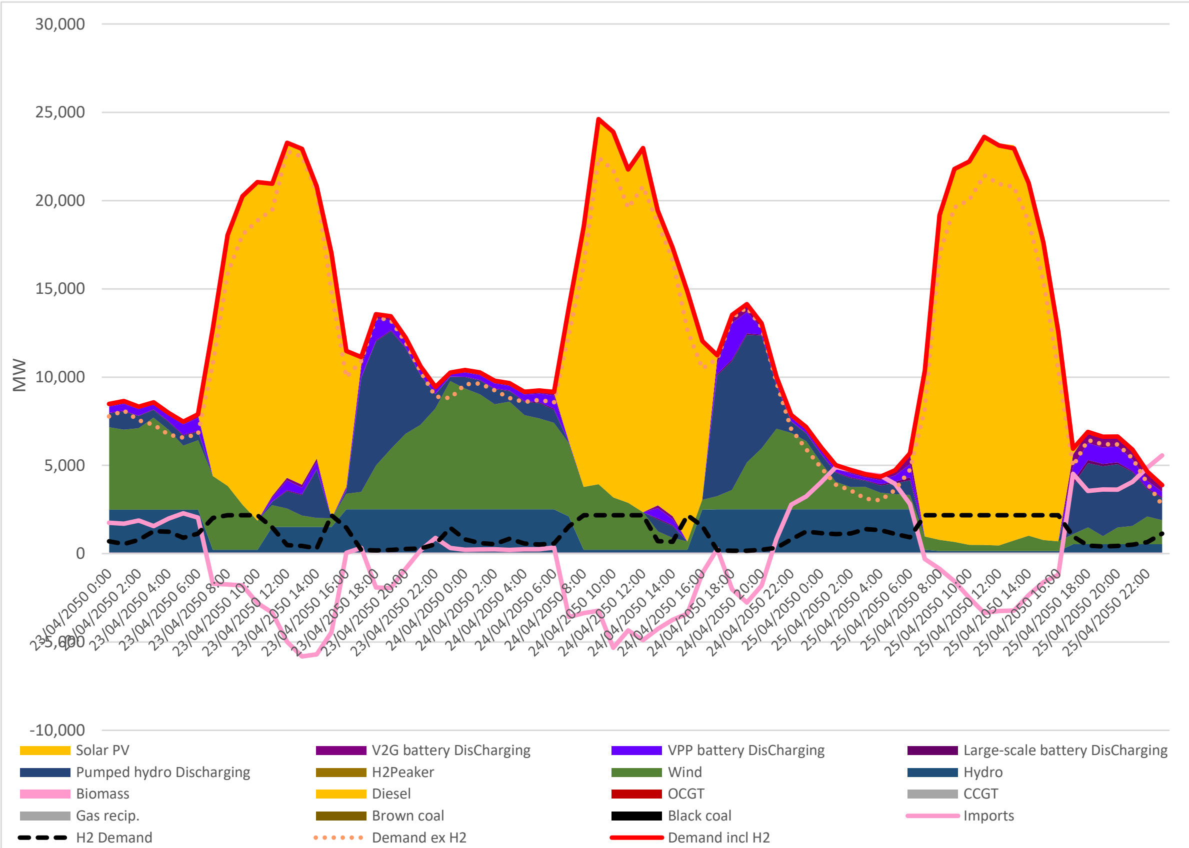
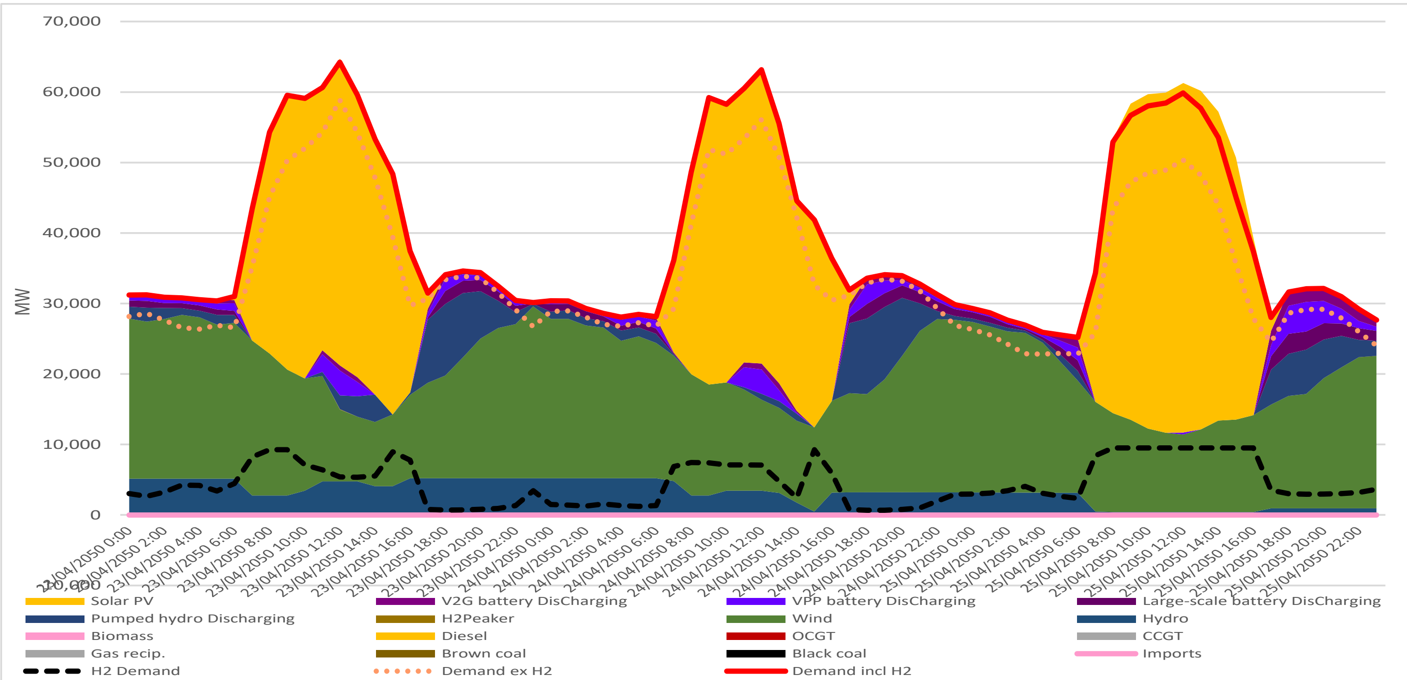


Figure 6-7 Low and high renewable energy days, NEM, Scenario “D”

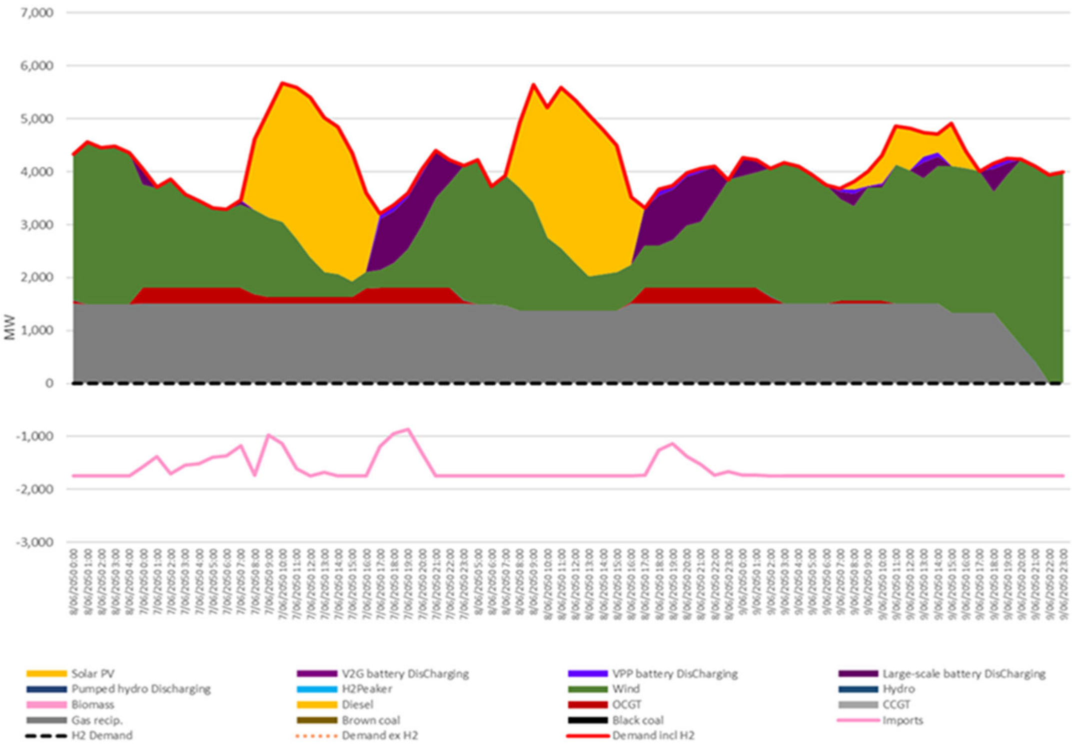


(a) Scenario "B" : 23-25 April 2050

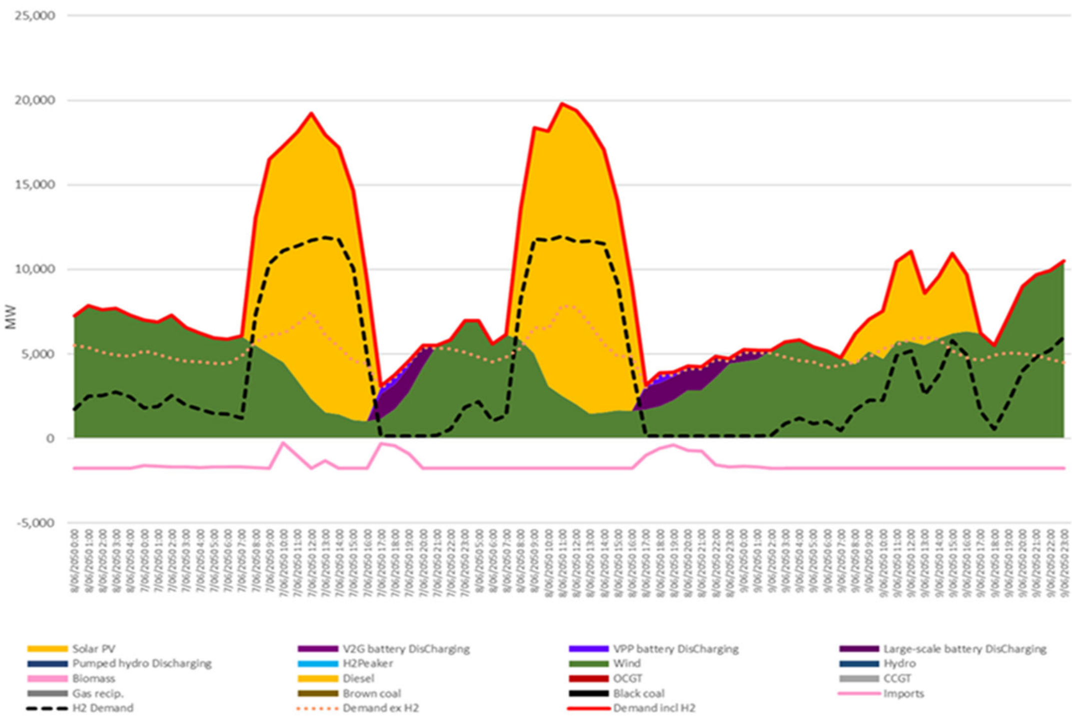


(b) Scenario "C": 23-25 April 2050

Figure 6-8: High variability three-day period, NEM



(a) Scenario “B”: 23-25 April 2050



b) Scenario “D”: 23-25 April 2050

Figure 6-9: High variability three-day periods, two alternative scenarios, SA

Appendix H. Inertia and fault current investigation

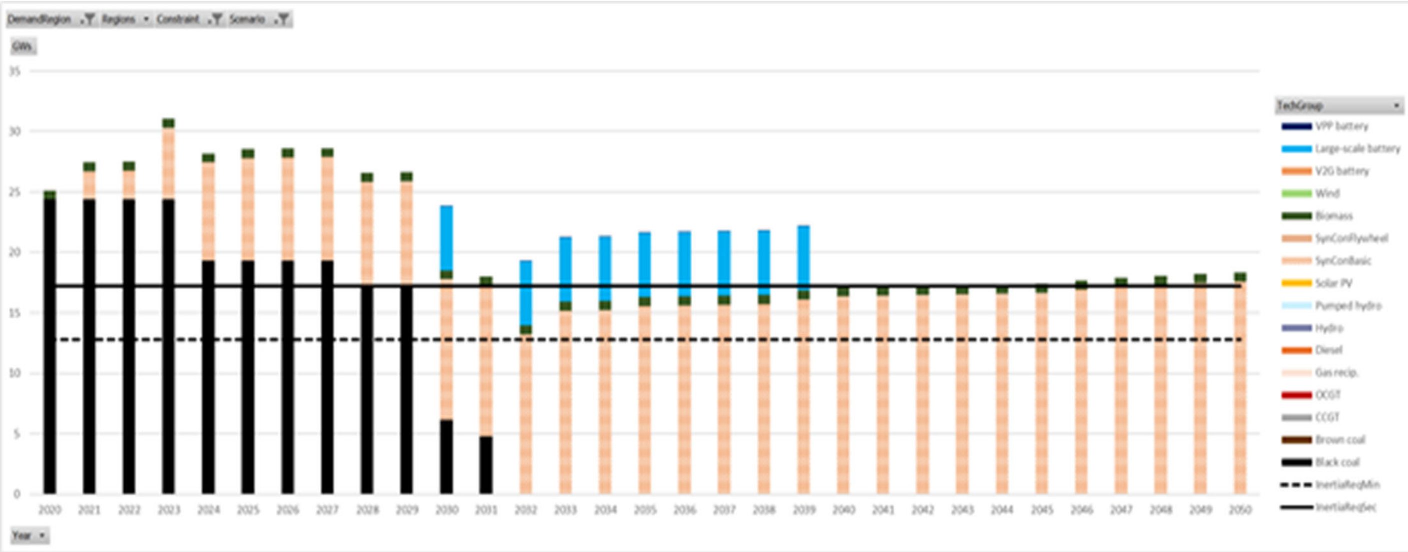


Figure 6-10: Scenario "A", Inertia – QLD (solid line shows minimum requirement)

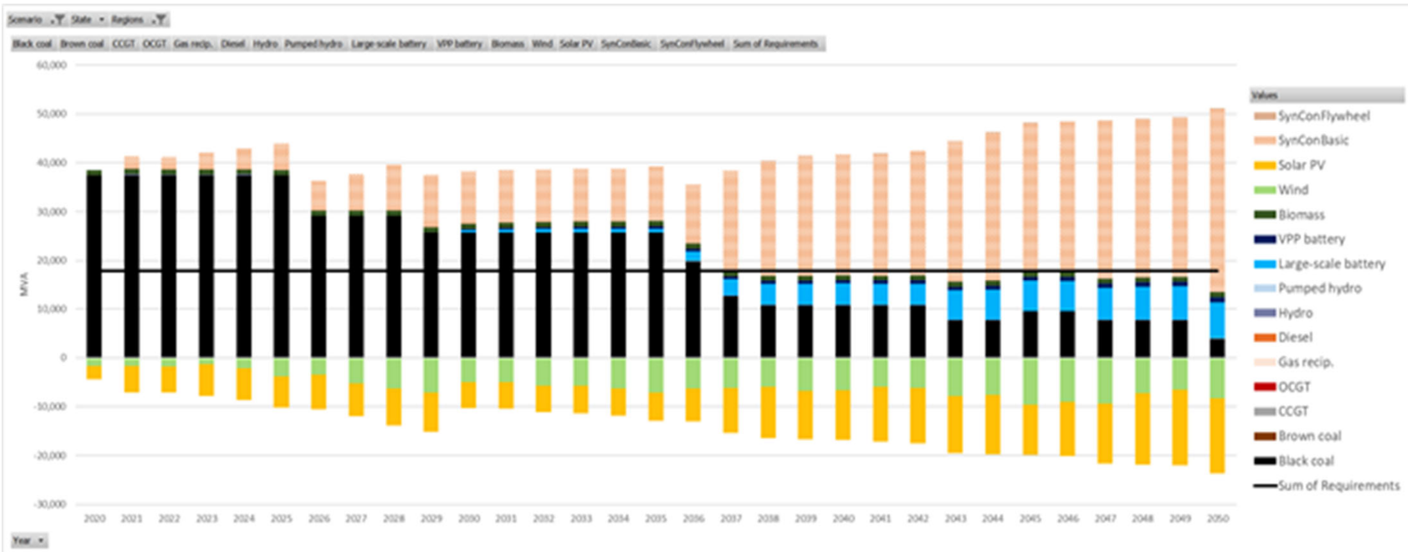


Figure 6-11: Scenario "A", Fault Current - QLD

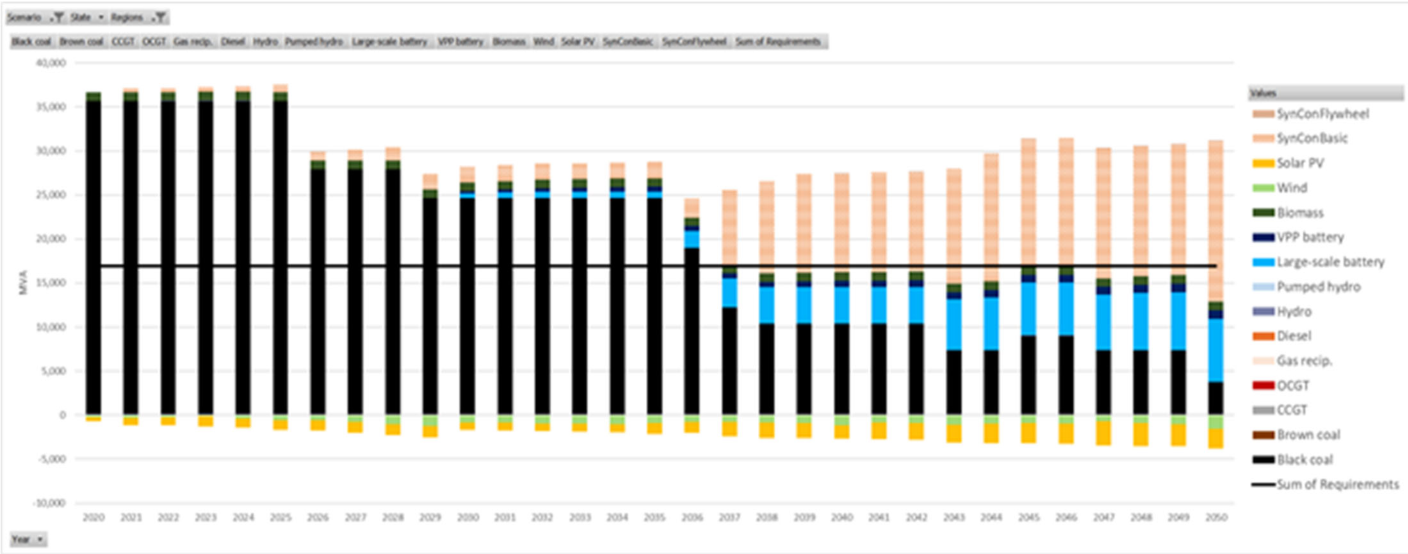


Figure 6-12: Scenario "B", Fault Current : QLD Transmission Zones only

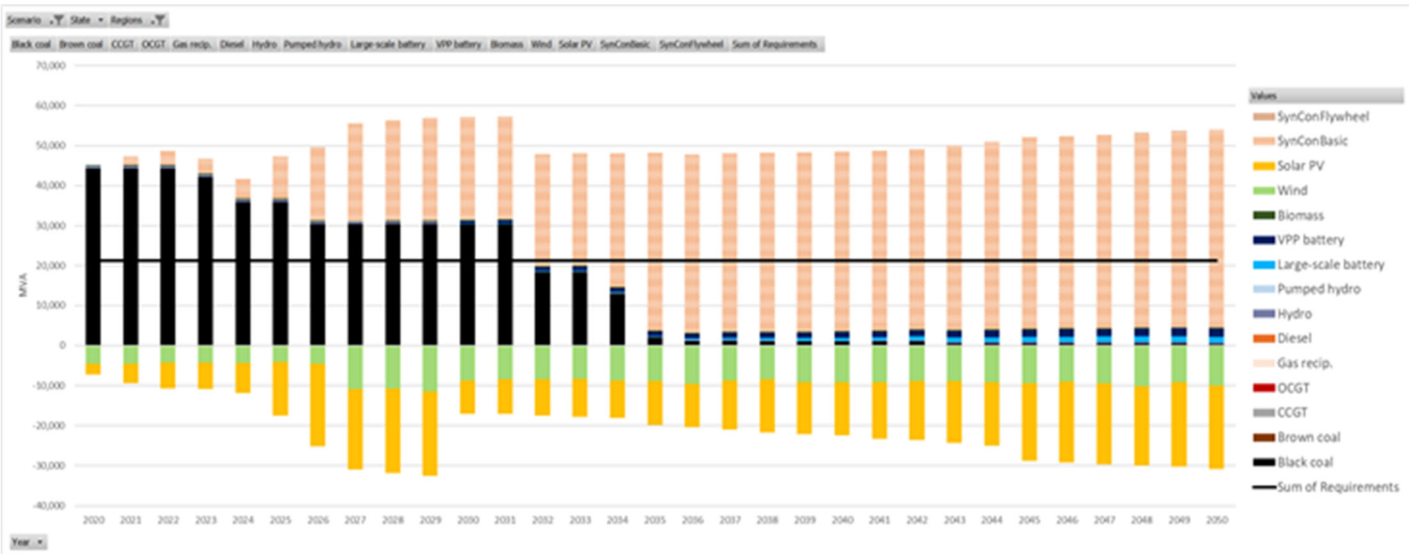


Figure 6-13: Scenario "A", Fault Current – NSW

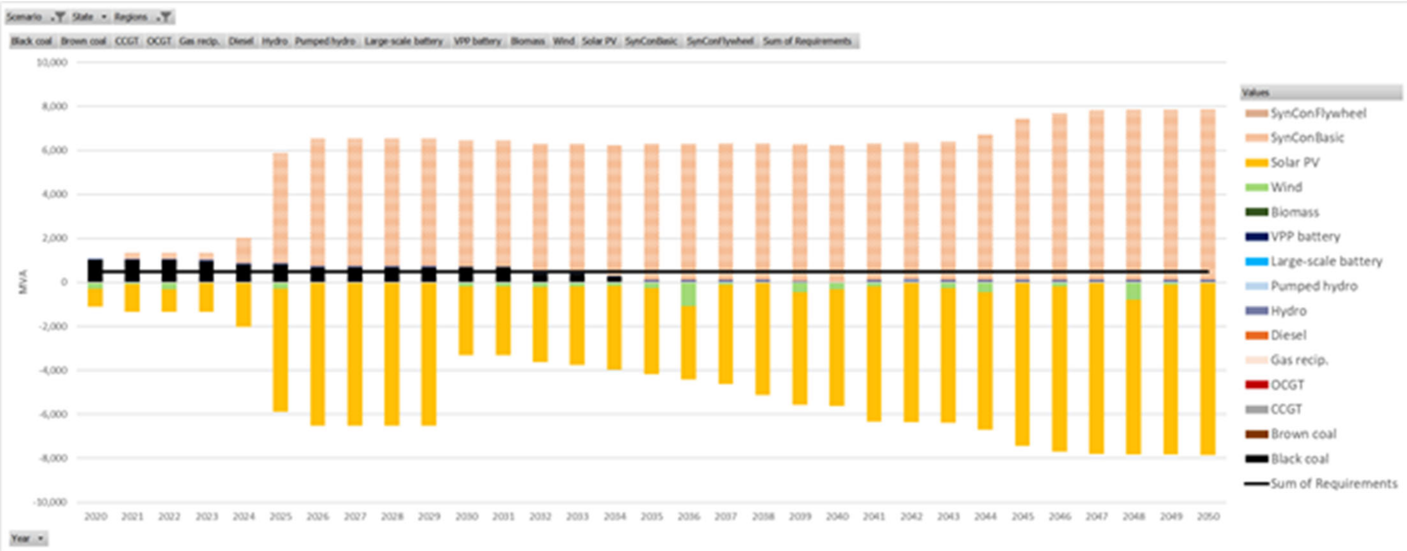


Figure 6-14: Scenario "A", Fault Current – Renewable Energy Zone N3 in NSW

Figure 6-10 and Figure 6-11 show synchronous condenser investment in Queensland sufficient to meet inertia and fault current requirements (requirements are in the solid line). The binding constraint is the inertia requirement, and the fault current requirements (which are imposed on a sub-state regional scale) are then exceeded. Figure 6-12 shows available fault current in Qld regions that are provided from Qld transmission regions alone (even though in principle, fault current provision in NSW can service adjacent Qld zones). Figure 6-13 shows fault current provision in NSW sufficient to meet requirements – again provided by synchronous condensers that are sufficient to meet inertia requirements. Figure 6-14 focuses on a single renewable energy zone: N3. The general conclusion from Figure 6-10 to Figure 6-14 is that synchronous condensers are a low cost backstop technology that can provide both inertia and fault current to support inverter based generators.

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