Australia's National Science Agency

Exploring climate risk in Australia

The economic implications of a delayed transition to net zero emissions

Technical Report

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1 Executive Summary

Climate change is recognised by central banks and supervisors as presenting significant risks to the global economy and in particular to the financial system. The risks are complex and uncertain in their scale, geographic scope, and timing, with the conditions experienced in the future and their severity dependent on current drivers such as policy settings, domestic and global markets, and atmospheric emissions.

For decision makers seeking to build an understanding of the spread of risks, scenario analysis is an important tool as it presents plausible long-term projections based on robust assumptions. To explore the impacts relevant to a global network of central banks, the Network for Greening the Financial System (NGFS) in 2021 released a set of six climate-related scenarios for use as a common starting place to examine physical and transition risks. In this report we contextualise two of these scenarios to Australia.

Exploring climate risk in Australia: The economic implications of a delayed transition to net zero emissions, is a first step towards quantifying the exposure of Australian economic sectors to climate-related risk through to 2050. Climate risks fall into three principal groups: physical, transition, and liability risk. Transition risks are the potential deterioration in profits and economic development as a result of policy, technological and/or social change. Physical risks are associated with climate hazards, which could be either chronic, arising from systematic gradual changes in the climate, or acute, as exemplified by extreme weather events. Liability risks are associated with litigation if organisations do not adequately respond to climate change impacts and climate change induced shifts in the regulatory environment.

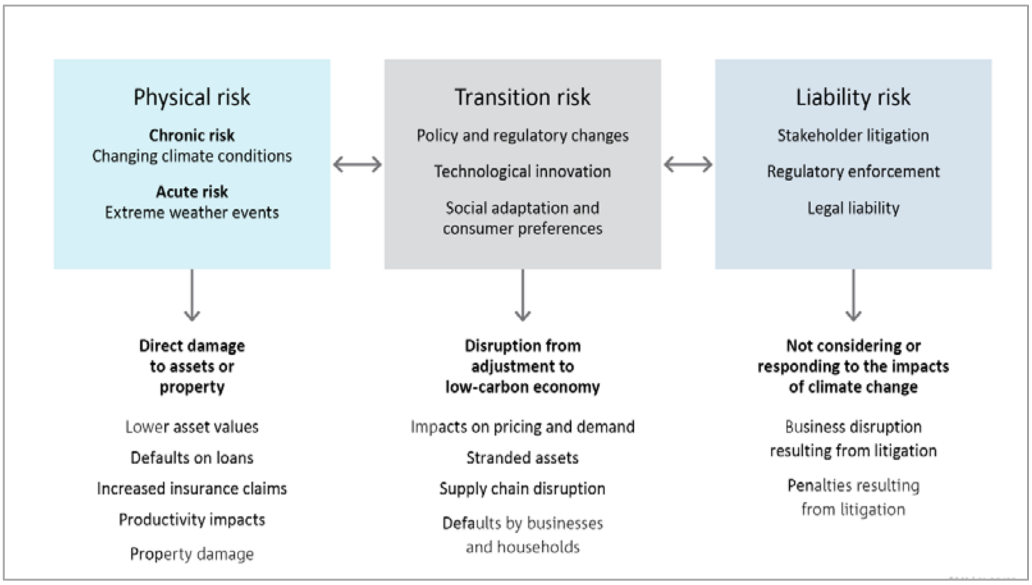

Figure 1 Overview of climate-related risks[1]

This report focuses primarily on transition risk and the potential economic consequences of rising global emissions, as well as presenting a view of an alternative future where net zero emissions targets are achieved by mid-century. It also considers limited impacts of physical climate risk: the impact of chronic temperature increase on productivity. This report does not consider the economic costs of other physical climate impacts; however, it is worth noting that such costs are expected to increase significantly, especially in the latter half of the century beyond the time frame considered in this report.

[1] Adapted from Overview of climate-related risks – Extracted from Prudential Practice Guide: Draft CPG 229 Climate Change Financial Risks, April 2021, APRA, (https://www.apra.gov.au/sites/default/files/2021-04/Draft%20CPG%20229%20Climate%20Change%20Financial%20Risks_1.pdf), and NGFS Climate Scenarios for Central Banks and Supervisors, June 2021 (https://www.ngfs.net/sites/default/files/medias/documents/ngfs_climate_scenarios_phase2_june2021.pdf)

Insights from scenario-based analysis

For the purposes of this report, two NGFS scenarios, *Current Policies* and *Delayed Transition* have been applied. The first considers the outcomes that may result from pursuing a business-as-usual trajectory featuring the current suite of policies and rising global greenhouse gas emissions. The second examines the conditions in which a transition to a low carbon economy is delayed until 2030. The second results in a more rapid transition of global economies towards net zero emissions over the period 2030 to 2050.

In both scenarios this is enabled by a decoupling of economic growth from emissions (Figure 2 and Figure 3) due to a combination of decarbonisation of key sectors and investment in carbon removal. Critically, the *Delayed Transition* scenario has a high reliance on negative emissions technologies to achieve net zero, rising to 9,000 $MtCO_2e$ by 2050. The challenges of deploying, scaling and commercialising negative emissions technologies should not be underestimated. Reliance on offsets could also serve to delay the transition to a low carbon economy if they are deployed in preference to decarbonisation or aid in transition reducing demand for negative emissions. This could create material economic risks for Australia. Likewise planning for, and failing to realise, this level of sequestration could result in a shock to emissions-intensive economies.

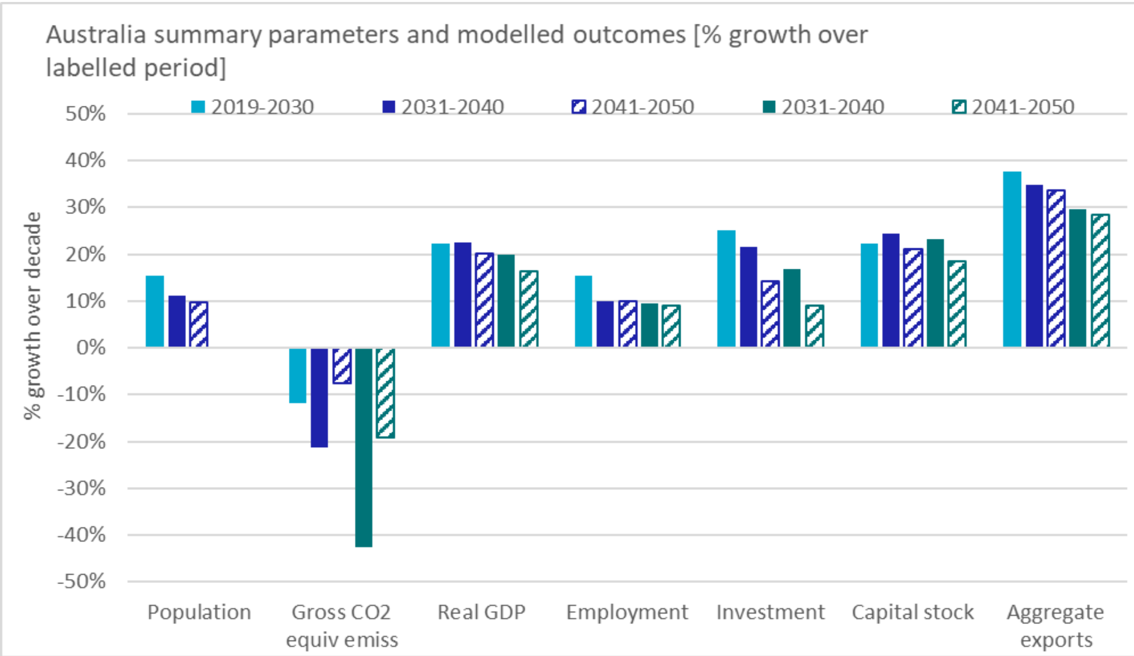

Figure 2 Summary of Australia-specific settings and modelled outcomes[2]

[2] Source: Population, emissions pathway NGFS; GDP, GDP per capita, Employment NiGEM for Current Policies, GTEM modelled outcomes for Delayed Transition; all other data GTEM for Current Policies, KPMG-EE for Delayed Transition.

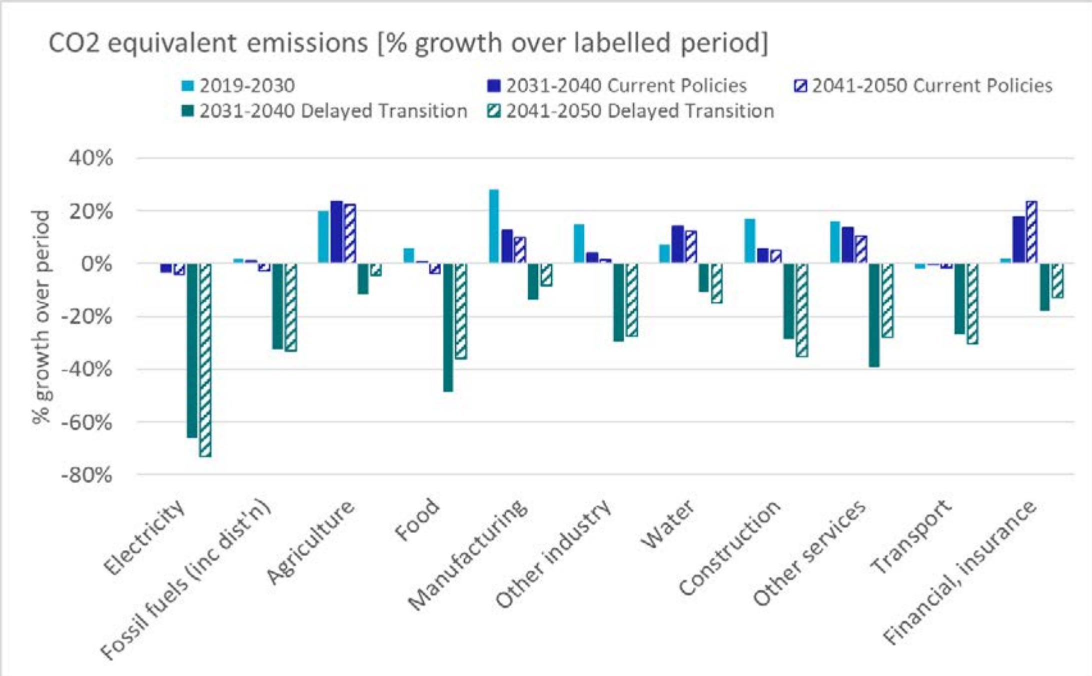

Figure 3 Percentage change in CO_2-equivalent emissions from 2019 to 2030 (common under both scenarios) and for current policies and delayed transition scenarios out to 2040 and 2050

The results indicate which industries may have greater opportunities or exposure to climate-related risk if the transition to a low carbon economy is delayed. The results highlight the exposure of Australia's key economic exports (Figure 4), which derive from emissions-intensive industries with hard-to-abate emissions sources (mining, manufacturing, and agriculture) and in the case of agriculture and mining, are also highly exposed to physical risk.

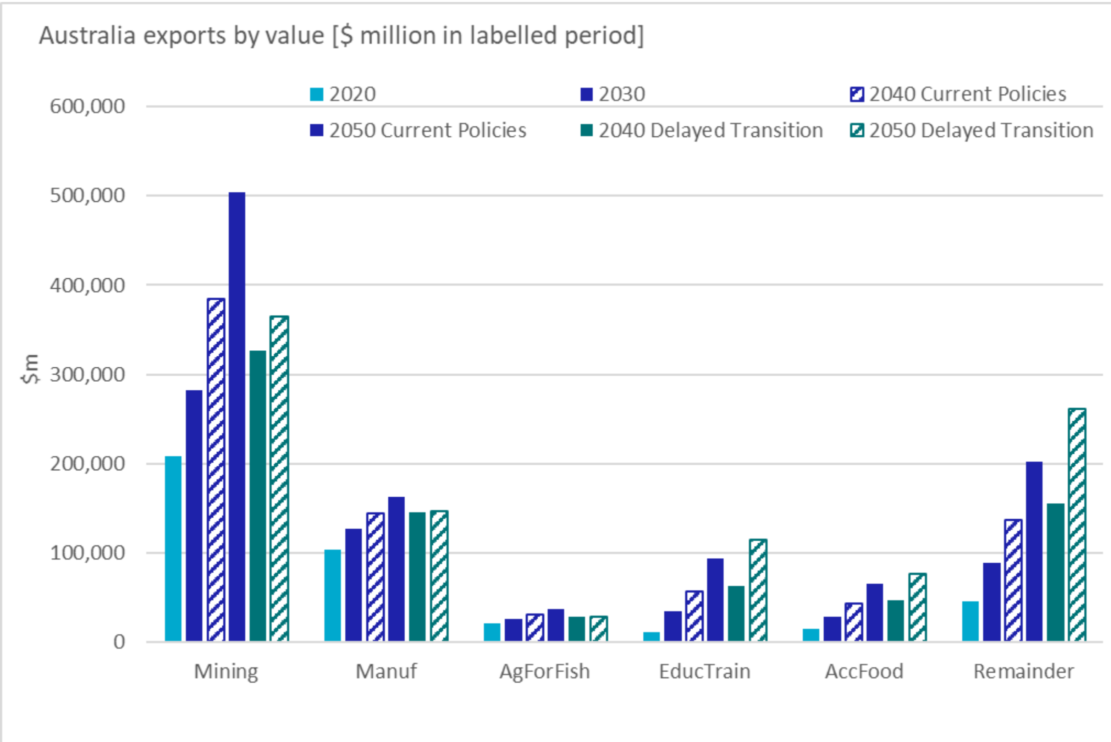

Figure 4 Export value and growth in Australia (in 2020 order of export value)

Fossil fuel intensive industries (fossil fuel sourced electricity, coal and gas production) decline the most, as expected, in the emission-constrained delayed transition scenario. This is driven by the delayed and then rapid transition to renewable energy sources, electrification and negative emission technologies. From a global perspective, Australia, as a major supplier of high-quality thermal coal and gas, is particularly exposed to potential declines in export demand. Declines in other industries are also observed across mining, mineral processing, and agriculture. Within these sectors the potential impacts are more nuanced:

- Coal mining and mineral processing, particularly ferrous metals, decline, yet the transition to a low carbon economy will require an increase in copper, nickel, lithium and other rare earth metals driven by batteries and electrification.
- Agriculture production will decline but increased demand combined with adaptation and resilience measures can mitigate economic impacts for crop and livestock production.
- Hydrogen presents a significant opportunity for use within industrial processes such as steel production and decarbonising across industrial and residential heating uses (not specifically modelled).

The analysis potentially understates some of the opportunities in emerging industries, such as hydrogen and commodities to facilitate low carbon industries. Service sectors tend to benefit and are projected to grow relative to current policies.

Aggregate increases in GDP tend to mask stagnating GDP growth per capita under current policies and a declining GDP per capita overall under a delayed transition. Declining real wages are reflected in falls in household income and consumption in most states and territories. Western Australia and the Northern Territory are clear exceptions, although they too are adversely impacted by a delayed transition relative to current policies. In both, household income and consumption are higher than today. Regional impacts within Australia are mixed. Queensland and New South Wales coal exports decline substantively, but Western Australian iron ore and other mining are projected to continue to grow.

However, these impacts could be mitigated. Higher short-term decarbonisation targets coupled with domestic policy certainty could assist to smooth the transition, avoid shocks, allow coordinated transition plans to be developed for the most vulnerable industries, and enable higher confidence to attract investment in emerging low emissions industries and technologies.

Value to the financial sector

This research helps investors to identify where they could conduct further analysis or engagement. It also provides companies with an understanding of risks to their sectors, allows areas of focus to be identified, and provides transparency on the information accessible to financiers, investors and insurers to support decision making. The data could be used to assess the sensitivity of an asset, sector, or portfolio to a delayed transition and implications for portfolio performance. Investors or financial institutions may wish to engage and work with their customers to better understand and reduce their climate risk exposure. If the climate risk exposure is systematic or non-diversifiable, the investor or financial institution may wish to alter their investment strategy. However, it is important to recognise that climate-related information should be used as a complement to other quantitative and qualitative information to inform a decision.

Next steps

Climate risk is a dynamic and complex issue. The variability in results from this relatively limited analysis illustrates the importance of considering risks that the financial sector and Australian business more generally are exposed to under differing emissions paths and policy settings. In providing this analysis it is our intent to catalyse conversations across a wide range of business sectors exposed to climate-related risks. The two scenarios considered do not address the full range of outcomes or economic impacts to Australia that might occur in the period to 2050. In the future they will need to be complemented with a set of scenarios (broader than the NGFS currently considers) to encapsulate different policy, market and technology, physical climate, and socioeconomic conditions.

As the transition to a low carbon economy accelerates, emissions-intensive sectors will decline while growth will be seen in renewables, electrification and alternatives. This analysis demonstrates, not unexpectedly, the elevated risks to emissions-intensive industries, particularly coal and to a lesser extent gas. Yet the narrow model selected (particularly limited to the middle of the road economic settings aligned with the NGFS scenarios) highlights that a more comprehensive transition risk assessment is warranted. The direction of this field is moving toward including more physically motivated, sector-specific, climate induced, chronic and acute damages. Furthermore, sophistication in analyses will continue to develop as new models, datasets and information evolve. Coincident and compound risks will need to be factored into risk assessment.

Clearly the challenge is to equip Australian businesses and institutions with knowledge, capability and capacity to engage with a rapidly evolving and sophisticated issue. Climate change impacts are an increasingly core component in investment risk appetite and decisions. This will require a shift in thinking, people and resources to address these issues.

2 Introduction and Context

Domestic and global markets, policy, atmospheric emissions, demographic and economic growth, and the response of the physical climate system are just some of the factors which will influence future climate risk to the finance sector and business more generally. In Australia, a significant economic contribution is made by industries exposed to climate-related impacts. For example, the agriculture sector is highly exposed to climatic shifts, and adaptation will be essential to maintain ongoing productivity in the sector. Other sectors, such as mining and offshore gas, are often located in areas exposed to physical hazards. Fossil fuel extraction industries are vulnerable to shifts in demand from global trading partners due to policy changes, social preference shifts and technological advances.

Understanding climate-related risks and mitigating them, as well as capitalising on new opportunities, is paramount to commercial decision making. Figure 5 outlines the range of transmission channels and the economic impacts.

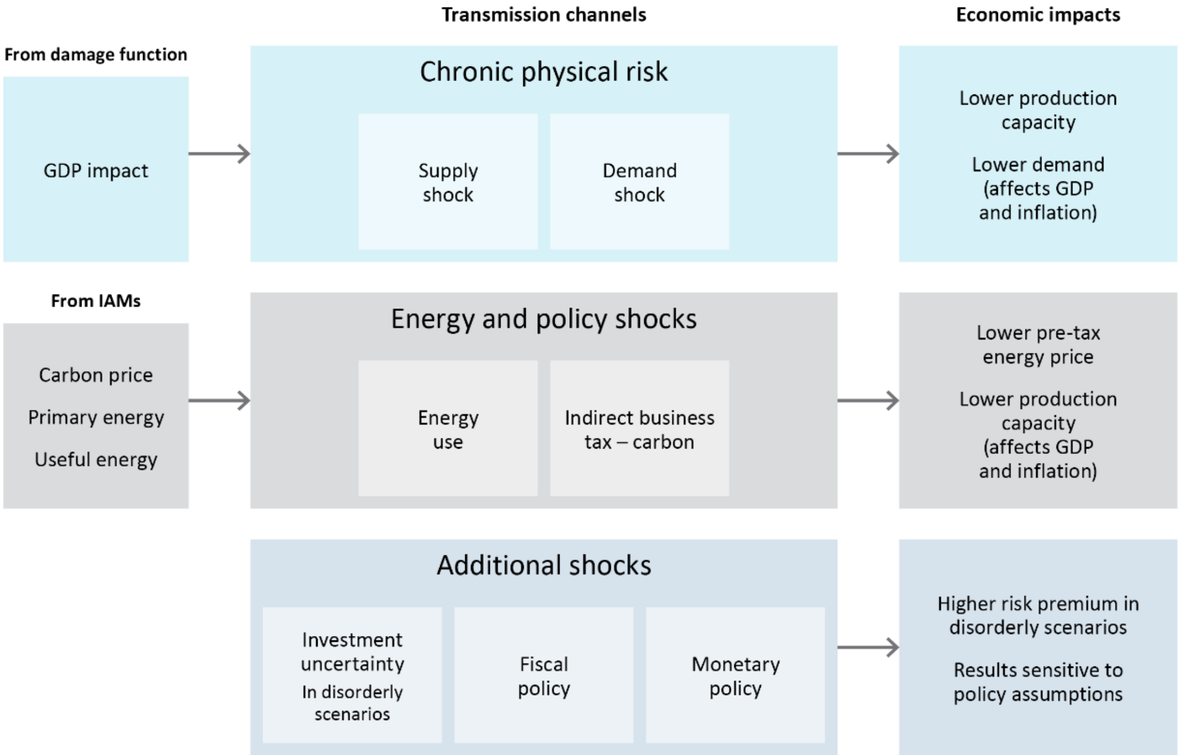

Figure 5 NGFS Climate scenarios phase 2 June 2021[3]

There are a number of key stakeholders. Underpinning current and future investment, the finance sector will play a pivotal role in financing mitigation, adaptation, and recovery from future climate impacts. The insurance sector also has a crucial role to play in underwriting damage to physical assets caused by climate-related impacts. Factoring climate risk and opportunity into these financial decisions, to complement the suite of existing inputs, will be critical to unlocking investment and ensuring risk is appropriately priced. Governments and other key infrastructure providers will need to be cognisant of both changes in production as a result of climate change and shifts in the demand mix for our exports. Similarly, major industries across Australia will need to consider whether shifting demand or production environments will require shifts in investment and strategy.

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

This study is a first step towards quantifying the exposure of the Australian economy to climate-related risk and highlighting some of the challenges of assessing this exposure. In this context climate risks are classified as physical, transition or liability as shown below in Figure 6. Liability risk is associated with the possibility of litigation if organisations do not adequately respond to climate change impacts.[4] Transition risk is related to potential deterioration in profits and economic development as a result of policy, technological and/or social change. Physical risks are those associated with climate hazards, which are in turn categorised as being either chronic, pertaining to systematic gradual changes in the climate; or acute, as exemplified by extreme weather events.[5]

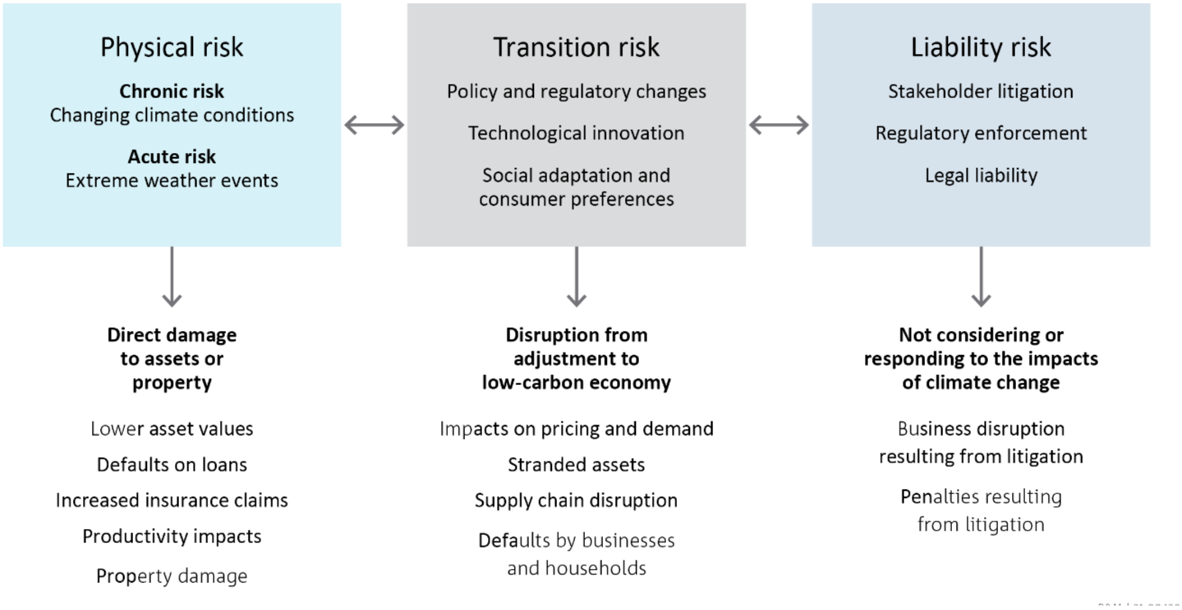

Figure 6 Overview of climate-related risks[6]

This report and its accompanying data focus on transition risk and some of the potential economic impacts arising from rising global emissions into the future, as well as the impact of an alternative future where net negative emission targets are achieved by mid-century. This analysis uses a multi-model approach tailored for an Australian context. It draws upon CSIRO's Global Trade and Environment Model (GTEM),[7] which explores transitional risk impacts globally and how these influence Australia through international linkages and trade impacts. We consider how these global changes influence sectoral and regional impacts on the Australian economy using KPMG's Computable General Equilibrium (CGE) energy and environment model (KPMG-EE). The impact of some chronic climate hazards are incorporated in GTEM, whilst the impact of acute physical hazards is referenced but not included in this activity. Whilst the approach pursued follows industry best practice, it is important to stress that not all types of physical hazards are incorporated into the modelling, nor all the possible ways the economy could be impacted or could adapt to these risks. We encourage others to continue to explore insights into physical risks and a wider range of economic impacts – positive and negative – in future work.

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[4] https://cpd.org.au/2021/04/directors-duties-2021/

[5] https://www.cmsi.org.au/

[6] Adapted from Overview of climate-related risks – Extracted from Prudential Practice Guide: Draft CPG 229 Climate Change Financial Risks, April 2021, APRA, (https://www.apra.gov.au/sites/default/files/2021-04/Draft%20CPG%20229%20Climate%20Change%20Financial%20Risks_1.pdf), and NGFS Climate Scenarios for Central Banks and Supervisors, June 2021 (https://www.ngfs.net/sites/default/files/medias/documents/ngfs_climate_scenarios_phase2_june2021.pdf)

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

3 Challenges and opportunities for the finance sector

To reach the Paris Agreement target, the global energy system alone is anticipated to require US$1,560 billion in investment annually by 2050, with an additional US$100 billion per annum for adaptation[8] in sectors such as agriculture and infrastructure. The financial sector has a unique challenge in this transition. To unlock this scale of investment in emissions mitigation and climate risk adaptation, the finance sector needs to understand and price both the opportunity and the risk. Risks and opportunities must be understood at scale, and across multiple industries. Investors will have different needs, and assessment of climate-related risk may incorporate both bottom up (by company) and top down (by sector) views. Geography is also an important consideration as Australian companies are increasingly exposed to regulatory risk from outside our borders, and policies such as the proposed European Carbon Border Adjustment Mechanism[9] demonstrate how transition risk may inevitably arise from interconnected markets.

Information asymmetry between companies and investors is a notable difficulty and the recommendations of the Task Force on Climate Related Financial Disclosures[10] will continue to make a transformational impact in addressing this challenge. However, ongoing tension is likely to remain between the depth of information sought by investors and the information that companies have the capacity and willingness to provide.[11]

Given current information asymmetry and the complexity of integrating climate risk at scale, particularly in investment portfolios and bank lending, platforms are emerging to assist with the evaluation of physical and transitional risk. These differ in their scope, from screening physical climate-related risk by location, to calculating financial metrics based on physical and transitional risk and opportunity. These platforms need to account for, or appropriately identify, these information risks.[12] It is also important to recognise that climate-related information will complement other quantitative and qualitative information used to inform decisions.

Advocacy and stewardship will be vital to increasing the climate literacy of executives, boards, investment analysts and decision makers, maturing companies' management of climate-related risk, and improving the quality of climate-related information received. These roles need to interpret and understand the reasonableness of information provided, compare approaches of different companies or sectors, and critically assess the evidence for a company's claims. In a dynamic and evolving climate risk landscape, these are skills that need to be developed and continuously enhanced over time.

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[8] https://www.ipcc.ch/site/assets/uploads/2018/02/WGIIAR5-Chap17_FINAL.pdf

[9] https://ec.europa.eu/info/sites/default/files/carbon_border_adjustment_mechanism_0.pdf

[10] https://www.fsb-tcfd.org/publications/#tcfd-recommendations

[11] More information on investor needs from company TCFD disclosures in Australia can be found in https://igcc.org.au/wp-content/uploads/2020/09/IGCCReport_Full-Disclosure_FINAL.pdf

[12] https://www.nature.com/articles/s41558-020-00984-6.epdf?sharing_token=KA_3fz0ShR9hqtb0XjVimdRgN0jAjWel9jnR3ZoTv0OSOZnKsSGMjP8867r_gOdtNaRkMlMK7aivZ2uhHDtFpU8uzvrzZHEujYqrZlJ5sTGgeE_X9odvXU60-2GY_AVrWtbp9ssBRiWWgCHv-o_hX-pTL0UJNJnCFyYVojc8eCI%3D

4 Future climate scenarios and the NGFS

Given that future climate risks are uncertain in their scale, geographic scope and timing, scenarios are useful tools to explore the possibility space to better understand and test potential impacts. Climate-related scenarios are commonly framed based on the level of atmospheric greenhouse gas emissions and assumed socioeconomic conditions, recognising that future emission levels and socioeconomic development are interconnected. For example, the Shared Socioeconomic Pathways (SSPs) and Representative Concentration Pathways (RCPs), which represent alternative socioeconomic and climatic futures respectively, were designed independently and later combined based on compatibility, recognising that achieving some RCPs would be more or less costly (if even possible) under different SSPs.

Recent work from the Network for Greening the Financial System (NGFS) applied six scenarios which *'provide a common starting point for analysing climate risks to the economy and financial system'*.[13] An important characteristic of these scenarios is that they are archetypal scenarios, framed around the physical and transition risks presented by climate change, and were designed to focus on the policy implications of responding to climate change. To better focus on the uncertainty of climate action these scenarios use the same overarching socioeconomic assumptions (Figure 7). The NGFS scenarios are a policy-oriented extension of the shared socioeconomic pathway 2 (SSP2),[14] referred to as the 'middle of the road' pathway. SSP2 assumes moderate population and GDP growth and moderate challenges to both climate change mitigation and adaptation. Some important implications of using the same overarching socioeconomic conditions are discussed in Box 2.

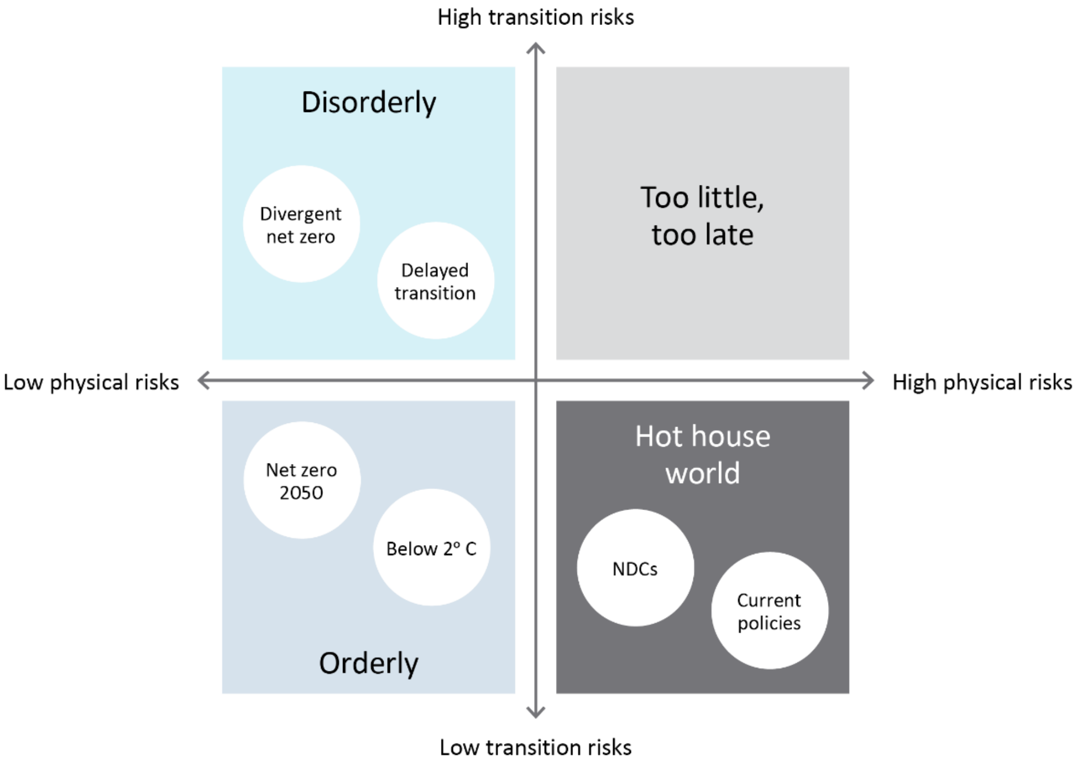

Figure 7 The six NGFS scenarios positioned according to transition and physical risk[15]

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[13] NGFS Climate Scenarios for central banks and supervisors, June 2021 (page 6).

[14] O'Neill, B. C., Kriegler, E., Riahi, K., Ebi, K. L., Hallegatte, S., Carter, T. R., Mathur, R., and van Vuuren, D. P. (2014). A new scenario framework for climate change research: the concept of shared socioeconomic pathways. Climatic Change, 122:387–400.

[15] See NGFS Climate Scenarios for central banks and supervisors, June 2021.

The six NGFS scenarios include one ‘current policies’ scenario representing business-as-usual and five counterfactual scenarios which explore differences in the extent, speed and timing of climate change mitigation scenarios, along with disorderly scenarios aiming to illustrate the economic impacts of a delayed and globally fragmented transition to a low carbon economy. For this modelling, assumptions have been applied from two NGFS scenarios to an Australian context: **current policies** and **delayed transition**. The current policies scenario presents a future with lower transition risks but high physical risks, albeit growing more severe beyond the model period, and the delayed transition scenario which offers a future with lower physical risks, but higher transition risks. The delayed transition scenario aims to understand the increase in transition risk when policy settings are changed with relatively short notice to force a rapid decarbonisation of the economy. Although these are just two of the NGFS scenarios, they have been selected to contrast higher physical and higher transition risks to the economy. As our focus is predominantly on transition risk, we focus our modelling on the transition period to 2050, when global economies are assumed to meet net zero in the delayed transition scenario. Transition risks are higher in the delayed transition scenario because the delay in action requires a greater cut in emissions over a shorter period than an orderly transition beginning now. Note, however, that our model framing means a common path until 2030 as a comparison rather than other scenarios.

Figure 8(a) illustrates the pathways of the global emissions, and Figure 8(b) the domestic Australian emissions (excluding emissions embedded in export products) for both scenarios. The representation of these scenarios in our modelling suite includes updated socioeconomic trends to account for the near-term impacts of COVID-19 based on International Monetary Fund growth projections.

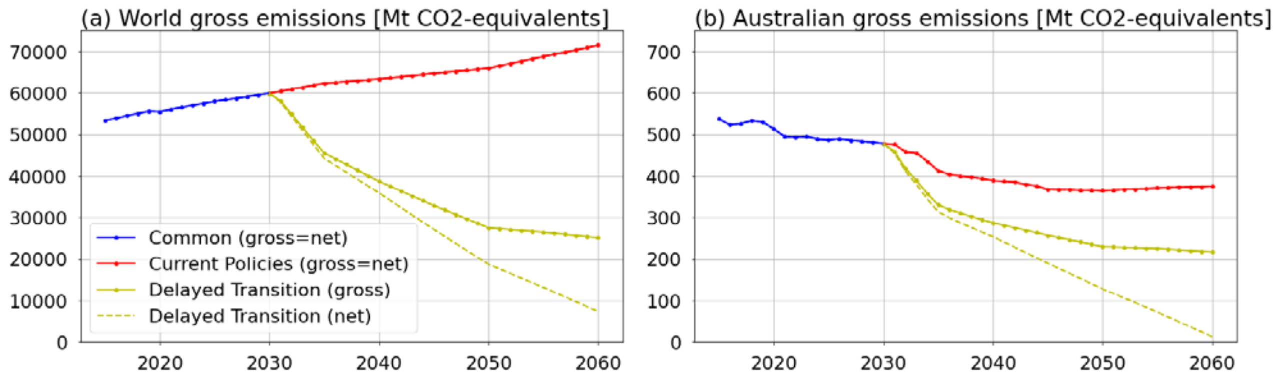


Figure 8 CO_2 equivalent emissions for Current Policies (red) and Delayed Transition (yellow) scenarios and the common period (blue) for (a) the entire world; and (b) Australia, not including emissions embedded into fossil fuel exports or any other exports for that matter. Note, these are only two of potentially many plausible scenarios.

Emissions in the current policies scenario are similar to representative concentration pathways (RCP) 4.5, which corresponds to a projected global average temperature increase of 0.9–2 °C during the model period and 2–3 °C by 2100. Emissions in the delayed transition scenario correspond most closely to RCP2.6, which projects a global average temperature increase of 0.4–1.6 °C and would limit global average temperature increase to less than 2 °C in 2100. [16] The temperature increase in the latter scenario is in alignment with the goals of the Paris Agreement, whilst the former is not.

These emissions pathways, population trajectories and other prescribed factors (see Table 1) are used as inputs to the GTEM and KPMG models, which then simulate and downscale these broad global pathways and trajectories to more detailed sectoral and national scales relevant to decision makers. This process is described in general terms in Box 1, and how it is specifically implemented in this study in Section 5.

[16] https://www.wcrp-climate.org/wgcm-cmip/wgcm-cmip5

Box 1: Description of How Computable General Equilibrium Models Work

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

There are many IAMs in use, designed to explore different questions with varying degrees of representation of the economy, energy technologies, and land-use change, amongst other factors.[17] We adopt dynamic Computable General Equilibrium (CGE) models – which employ a more detailed focus on economic relationships – to simulate the global and domestic Australian economies. CGE models are quantitative economy-wide models comprised of a set of equations that describe how governments, firms, industrial sectors and representative households behave within an economy (or interacting economies), and how they could respond to changes in policy, technology, and availability of resources amongst other factors. The parameters in these equations are estimated based on historical economic statistics, observed behaviour, and economic theory. Typically, CGE models apply several key assumptions, including:

- Firms are in perfect competition, and are profit maximisers constrained by market prices and input costs;
- Households try to maximise the value of their expenditures (utility) constrained by market prices and their income; and
- Perfect information across all sectors, which allows for efficient allocation of capital across the economy.

The resources drawn from the environment and the impact of the climate on economic activity are also incorporated in the CGE framework adopted in GTEM, as illustrated for a given aggregate region in Figure 9. Each of the aggregate regions interacts with the other regions via trade flows and migration, as illustrated in Figure 10. All regions potentially contribute to global carbon emissions. These emissions influence the surface temperatures of each region via the greenhouse effect, which in turn influence economic activity via approximated chronic climate induced damages

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

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

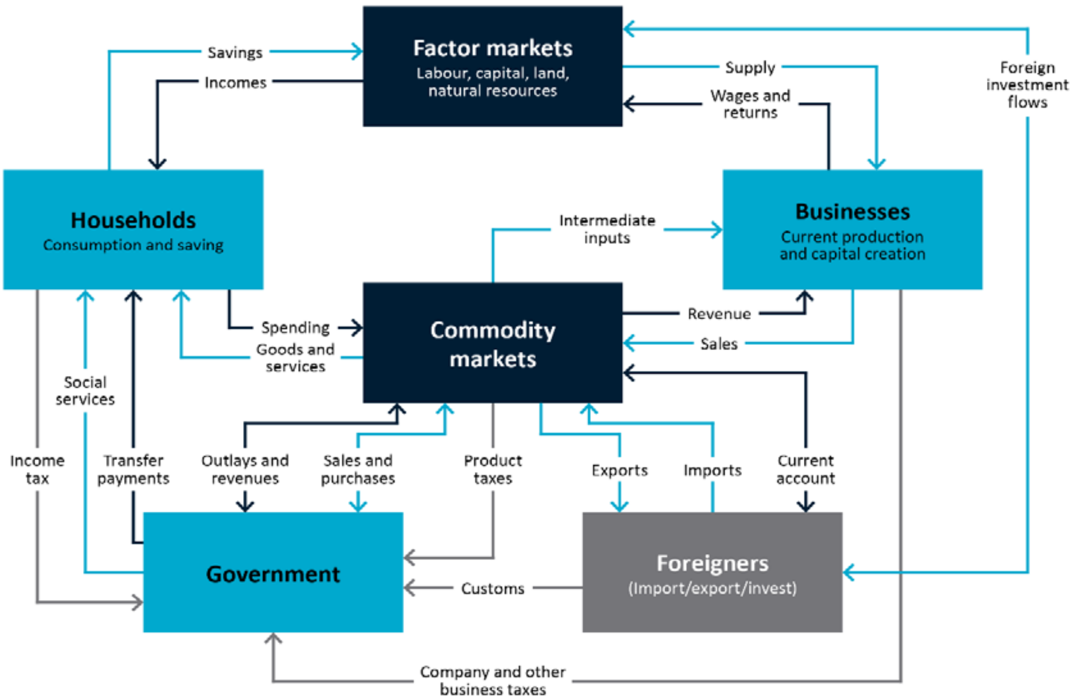


Figure 9 Interactions between agents within a given aggregate region in GTEM

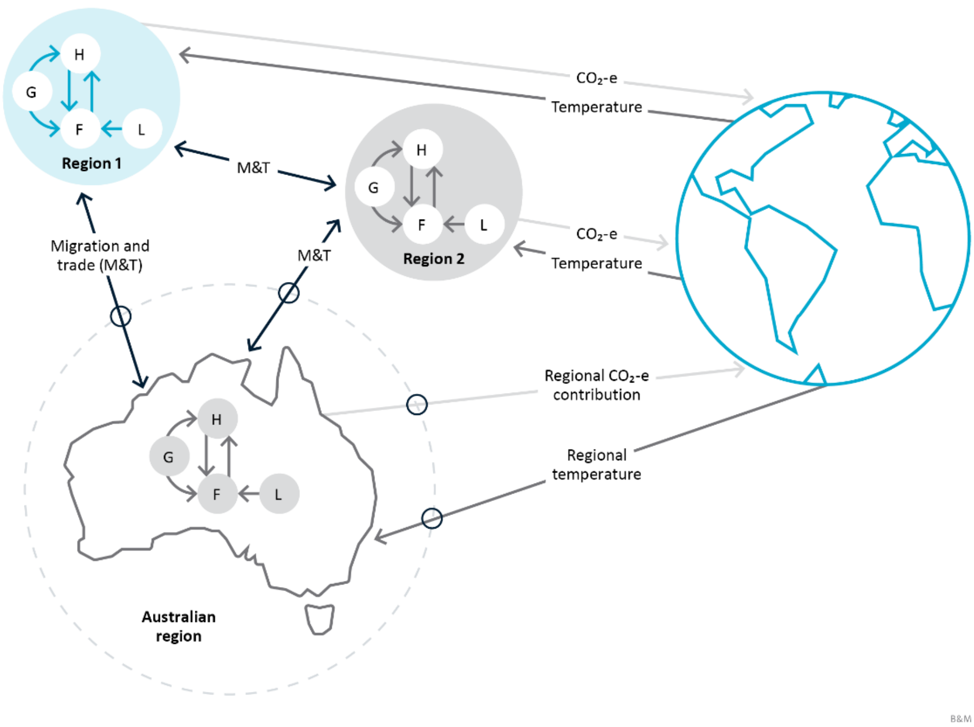


Figure 10 Interactions between the biophysical system (i.e. the Earth), and the aggregate regions. Only 3 of the 23 regions are illustrated for clarity. Each region is comprised of representative agents for the government (G), firms (F), household and tracks the harvesting of resources and land (L), temperature (ΔT) entering model via a productivity impact. The pink circles indicate where GTEM provides the boundary conditions for the national level CGE model.

5 The transition risk modelling approach applied in this study

The modelling framework is designed to tailor two NGFS Phase II scenarios to an Australian context to better reflect Australia's position in the global economy. GTEM is used to model the global macroeconomy, and the KPMG-EE model applies the global implications to Australian states and territories with a more detailed sectoral representation. The CGE form of these models allows a more contextualised and detailed examination of the financial transition risk on a small, open economy like Australia. The prescribed data required for each scenario has been adjusted for the short-term impacts of COVID-19. Country level prescribed data is acquired predominantly from the National Institute Global Econometric Model (NiGEM)[18] outputs prepared for the NGFS, which enables us to perform our own purpose-built regional aggregation. Figure 11 provides an overview of which NGFS models have informed this work.

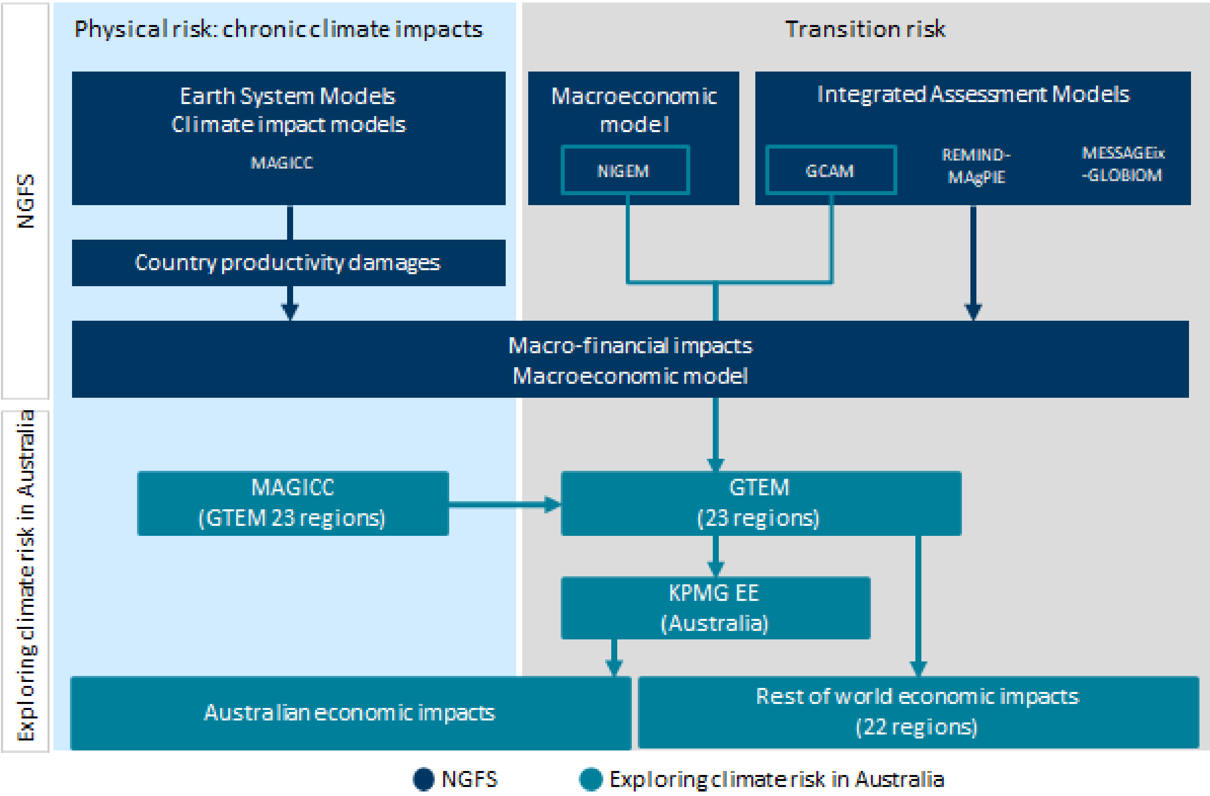


Figure 11 Overview of the models used in this assessment and their relationship to the NGFS model set. Adapted from NGFS scenarios phase II[19]

GTEM is a global model that combines approaches of three modelling traditions: integrated assessment models; computable general equilibrium models; and electricity supply models. Thus, it represents the nexus between climate, energy and the economy. The model, as applied in this study, simulates the global economy across 25 economic sectors (Section 6.1) and 23 countries and regions (Table 3), allowing for the analysis of Australia and its key trading partners. Climatic changes and associated regional economic damages are also applied in GTEM to reflect the spatial heterogeneity of projected climate impacts. These damages reflect limited impacts of chronic temperature change via reduced economy-wide total factor productivity. Global warming temperature trajectories are calculated for each emissions pathway using the

[18] https://nimodel.niesr.ac.uk/

[19] https://www.ngfs.net/sites/default/files/media/2021/08/27/ngfs_climate_scenarios_phase2_june2021.pdf

climate carbon cycle model MAGICC.[20] The regional temperatures required to calculate the above damages are calculated by calibrating this MAGICC output to global climate models runs with similar emissions pathways. For some variables there are differences in how the *Current Policies* and *Delayed Transition* scenarios are represented in GTEM. Table 1 summarises the treatment of certain key variables in each scenario.

Table 1 Treatment of key variables in GTEM

Variable	Current Policies Scenario	Delayed Transition Scenario
Emissions	Global CO_2e emissions from the NiGEM baseline scenario. Regional CO_2e Australian emissions consistent with the Australian Government Department of Industry, Science, Energy and Resources (DISER) projections[21] until 2030 and modelled from 2030 onwards.	Global CO_2e emissions from NGFS delayed transition GCAM5.3_NGFS scenario. Same treatment for Australia from 2031 onwards as the current policies scenario.
Surface temperature per region	Global temperatures calculated using MAGICC and regional averages calibrated using CMIP5 climate model outputs.	
Emissions permit trading	Not enabled	International trading enabled from 2031 onwards with regional permit allocations equal to emissions in 2030.
Electricity technology mix per region	The global electricity mix is adjusted to track GCAM5.3_NiGEM 2060 outcomes. In Australia the electricity technology mix is prescribed to be consistent with the business-as-usual AEMO Steady Progress Scenario[22] projections until 2050 for the National Electricity Market and CSIRO projections for the rest of Australia.	The global energy electricity technology mix is modelled from 2031 onwards. In Australia the technology mix is modelled subject to constraints to negative emissions technologies and prescribed levels of solar and wind.
Negative emissions technologies	Not enabled	Total negative emissions are limited to a maximum of half of the difference in gross emissions between the two scenarios, with the other half taken up by increased adoption of non-fossil fuel sources. This is conceptually similar to the NGFS approach except we do not specify the negative emissions as BECCS.

Using the GTEM outputs as inputs, the KPMG-EE model as applied in this study calculates the associated economic response for the states and territories within Australia and across 50 sectors (see Section 6.2). Changes in demand for Australia's exports by the rest of the world are transmitted from GTEM to KPMG-EE to form the key link between the two models.

In both the GTEM and KPMG-EE models, particular attention is placed on the technology bundle of the electricity generation sector, inclusive of carbon capture and storage (CCS), as this is critical for the

[20] http://www.magicc.org/

[21] https://www.industry.gov.au/data-and-publications/australias-emissions-projections-2020

[22] https://www.aemo.com.au/-/media/files/major-publications/isp/2021/2021-inputs-assumptions-and-scenarios-report.pdf?la=en

realisation of the modelled emissions pathways. The GTEM model is run with a 12-technology bundle across coal, oil, gas, nuclear, hydro, wind, solar, and all other renewables, with CCS technology options across coal, oil, gas and bioenergy. There are also four modelled negative emissions technologies including olivine, soda lime, artificial tree direct air capture, and bioenergy CCS, with their sole function being to extract carbon from the atmosphere. While these four negative emissions technologies have been modelled, we also recognise the suite of emerging technological options, as well as the role of sequestration in the natural environment including in vegetation, soils, and coastal environments. Box 3 outlines some challenges associated with negative emissions technologies that need to be considered when interpreting these results. The KPMG-EE model incorporates this same suite of electricity generation but excludes the negative emissions technologies. The suite of electricity generation is a key element of the analysis since each of these electricity generation technologies have vastly different carbon footprints.

Within GTEM, carbon trading is enabled in the delayed transition scenario. It is implemented with a single world carbon price with the assumption of international trade in emissions permits. Whilst the model assumes a price mechanism, this can in principle be imposed by a range of other (more or less efficient) measures within countries and regions, such as cap-and-trade, emissions reduction credits, the elimination of subsidies for fossil fuels, or environmental and clean standards and regulations (e.g. clean energy standards, or car efficiency standards). Within KPMG-EE the carbon price is represented by a series of ad valorem taxes on production and consumption that have been determined in GTEM. The carbon 'tax' is returned to households via a 'lump-sum transfer'. This leaves the government budget constant as a share of GDP. That is, the transition pathway is driven entirely by carbon prices and the lump-sum transfer removes the income effect of the carbon tax. Similarly, there are no carbon border adjustments or sectoral protection in KPMG-EE.

Other key differences in assumptions between GTEM and KPMG-EE relevant to the results include:

- Physical capital is perfectly mobile across sectors in GTEM but is industry-specific in KPMG-EE.
- Labour is perfectly mobile across sectors in GTEM but is occupation-specific in KPMG-EE. The latter has eight occupational groups each with a unique wage rate. Individual occupations are fully mobile across industries, but there is limited movement across occupational groups, reflecting the cost and time of retraining, relocation and other factors.
- The representation of the current and capital accounts in GTEM is such that there is zero initial debt, which then accumulates depending on the evolution of the current account; as such, debt servicing cost is low until debt accumulates. In KPMG-EE initial net foreign liabilities (NFL) reflect current Australian data. Thus, NFL servicing costs are significant from year 1. NFL as a proportion of GDP stabilise by 2050 via adjustment of the household saving rate.
- The budget balance for the composite government sector is adjusted so that government debt as a share of GDP stabilises by 2050. This is accommodated by (minor) movements in the average income tax rate.
- The KPMG-EE and GTEM models are run at a different sectoral resolution to balance the benefits of more detailed representation at the sectoral level against the additional computational complexity, calibration requirements, and time.

The differing treatment of physical capital and labour mobility mean there are higher costs of adjustment in the economy in KPMG-EE (due to lower intersectoral mobility of factors of production) relative to GTEM. The links from GTEM to the KPMG-EE model are scenario dependent, as summarised in Table 2.

Table 2 Treatment of key variables in KPMG-EE for each scenario

Variable	Current Policies Scenario	Delayed Transition Scenario
GTEM output applied to KPMG-EE	● Government consumption ● GTEM export demands applied to KPMG-EE shifts in export demands ● Population ● Climate damage ● Energy intensity in production and household consumption ● Electricity technology shares ● GDP, CPI ● Land and natural resource supply ● Cost, insurance and freight (CIF) import prices ● Employment ● Labour supply	● Government consumption ● GTEM export demands applied to KPMG-EE shifts in export demands ● Population ● Climate damage ● Energy intensity in production and household consumption ● Electricity technology shares ● Foreign income from emissions permit trading ● Changes in taxes on output, intermediate inputs and household consumption that reflect carbon tax ● Land and natural resource supply ● CIF import prices
Additional KPMG-EE settings	● Current account to GDP ratio stabilises at -1%, which stabilises the net foreign liabilities to GDP ratio at 34% ● Government budget to GDP ratio stabilises at -1%, which stabilises the government debt to GDP ratio at 31%. Small income tax shifts are implied within this setting.	● Current account to GDP ratio returns to Current Policies level by 2060 ● Government operating balance to GDP ratio remains at Current Policies levels via endogenous lump-sum transfer ● Unemployment rate fixed (same as Delayed Transition in GTEM) ● Coal production constrained to fall to 25% of Current Policies 2020 levels by 2050.

In summary, the KPMG-EE model provides greater sectoral resolution for Australia. It also allows the modelling to reflect initial conditions (such as the current account balance and net foreign liabilities) that are not present in GTEM. The lower intersectoral mobility of capital and labour and the resulting adjustment costs are also considered more specific to the realities of the Australian economy. For these reasons we do not provide GTEM Australia level results but only KPMG-EE outputs.

6 Results and caveats

In this project, we have applied an integrated assessment model incorporating a CGE approach to determine a set of regional technological and socioeconomic trajectories consistent with the NGFS emissions pathways for two scenarios: Current Policies, and Delayed Transition. GTEM is used to model the global economy aggregated into 23 bespoke regions (including Australia), to which chronic climate damages are applied according to bespoke regional warming trajectories for each emissions pathway. The national level KPMG-EE model provides more granular implications of each scenario for Australia by sector and by each state or territory, with international boundary conditions and interactions provided by the global GTEM results.

The global GTEM results are explored in greater detail in Section 6.1, followed by the national level KPMG-EE data in Section 6.2 and an exploration of state level effects in Section 6.3. A series of boxes are also provided describing the caveats and sources of uncertainty in the modelling process, and as an introduction to sector-specific risks and uncertainties beyond the scope of this modelling exercise.

For reasons outlined in Section 5, no Australian results are provided from GTEM as the results from the KMPG-EE are considered more appropriate to reflect the circumstances of the domestic economy. Soft coupling between the two models means that the Australian results from KPMG-EE will differ from GTEM where they are not constrained.

Box 2 Sources of uncertainty

Box 2: Sources of uncertainty

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

Uncertainty of socioeconomic settings – Projecting demographic and economic trends into the future is challenging, as they are highly interconnected, and changes in economic growth can have profound implications on population growth and vice versa. UN population projections have tended to overstate future growth, underestimating the decline in fertility rates observed over the past century. Nevertheless, these trends are not laws, and nothing ensures they will continue into the future. Furthermore, the SSPs were designed independently from climate change with the goal that they could be compatible with various climate change trajectories. As such, they do not explicitly consider potential climate change sensitivity and feedbacks to future economic growth, which may overstate future growth potential. The same prescribed population trajectories are also adopted in the delayed transition case, which does not capture any influence that changes to economic prosperity may have on population growth. Additionally, whilst we have corrected for near-term population implications of COVID-19, the long-term implications on economic openness, migration patterns, and changes to the nature of work and productivity are still highly uncertain and not explicitly accounted for. The politics of climate action are also intertwined with socioeconomic pathways. Futures where there is faster growth spurred by technological development, for example, will face lower costs to mitigate climate, than futures where economic growth is stagnant or being driven by carbon-based technologies. Futures with increasing fragmentation (SSPs 4 and 5, for example) will present more challenging worlds for collective action and increase the risk of miscalculations and overshooting to achieve climate targets.

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

Uncertainty of global and regional climate sensitivity – For a given emissions pathway the temperature response used in the CGE models is calibrated from complex physics-based models of the climate. Various climate models producing data for the International Climate Model Intercomparison Project (CMIP)[23] produce different global and local temperature responses. The spread in model results is such that there is significant overlap between each of the various emissions scenarios. The impact of climate change is summarised in an impact function based on changes to temperature, and therefore does not fully account for other changes caused by climate change, such as changing precipitation patterns or the effects of elevated CO_2, which can have profound sector-specific impacts.

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

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

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

6.1 Global GTEM results

The growth of the prescribed population trajectories is illustrated in Figure 12(a) by bars for an aggregate of the GTEM regions over the periods 2019–2030 (blue solid), 2030–2040 (orange hatched) and 2040–2050 (orange solid) along with Australia[24] (all 22 regions are reported in the appendices, Section 8.3). Recall, the same population trajectories are applied for both scenarios. A start year of 2019 was chosen in the first time period to avoid any distortions due to the COVID-19 induced recession in 2020 in comparing periods. Note Australia data is shown in Figure 12 (but not in later figures) as these model outputs are identical in both GTEM and KPMG-EE.

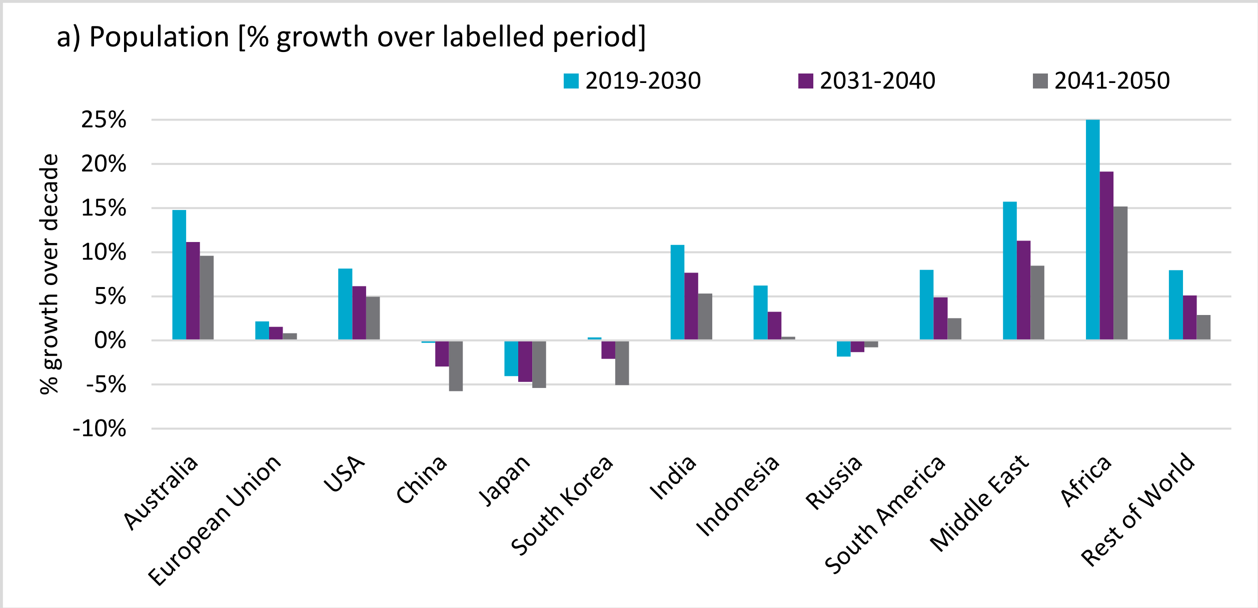
The percentage change in CO_2 equivalent emissions for the same regions is illustrated in Figure 12(b). Note, the emissions are the same for both scenarios over the common 2019–2030 period (blue solid), after which the two scenarios diverge, with current policies indicated by red bars, and delayed transition with yellow bars. In all cases the period 2030–2040 is hatched, and the 2040–2050 period is solid. This is the case for all other remaining diagnostic growth rates. Large percentage declines in CO_2 equivalent emissions are observed across all regions but again there is some variation – notably in Africa, South America, and Indonesia. The transition impact is always highest early in the transition (2030–2040) but remains much higher in some regions throughout (Japan, US, China, Russia, South Korea). African growth is population

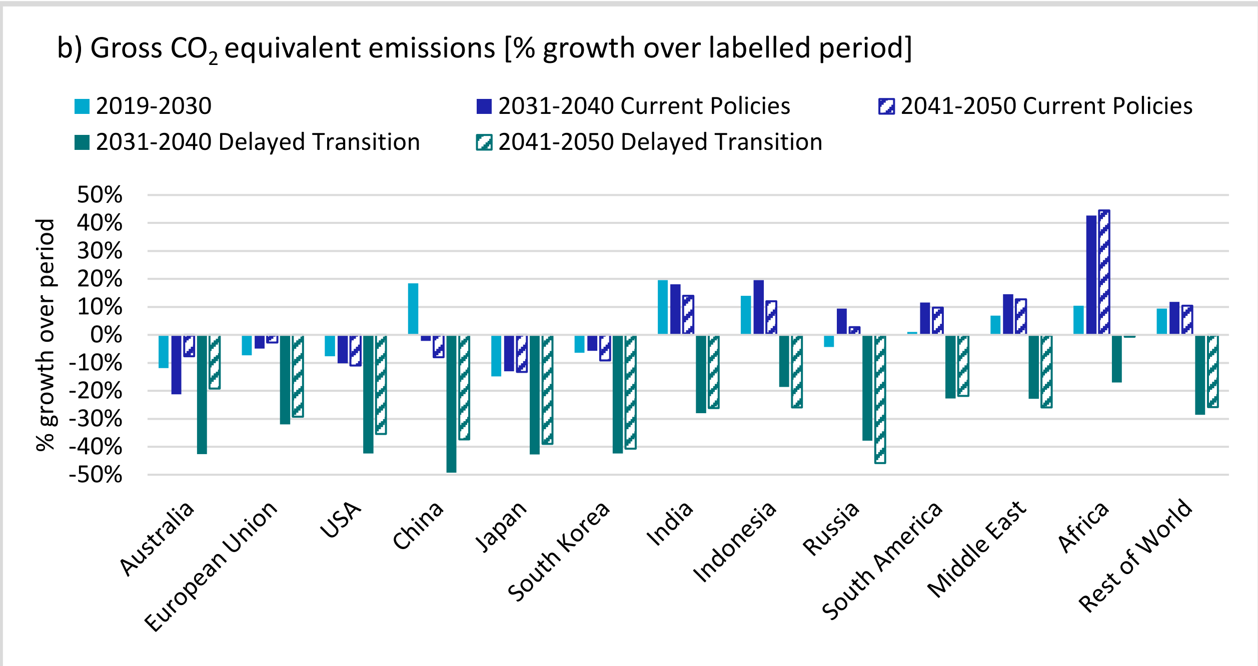
[23] https://www.wcrp-climate.org/wgcm-cmip

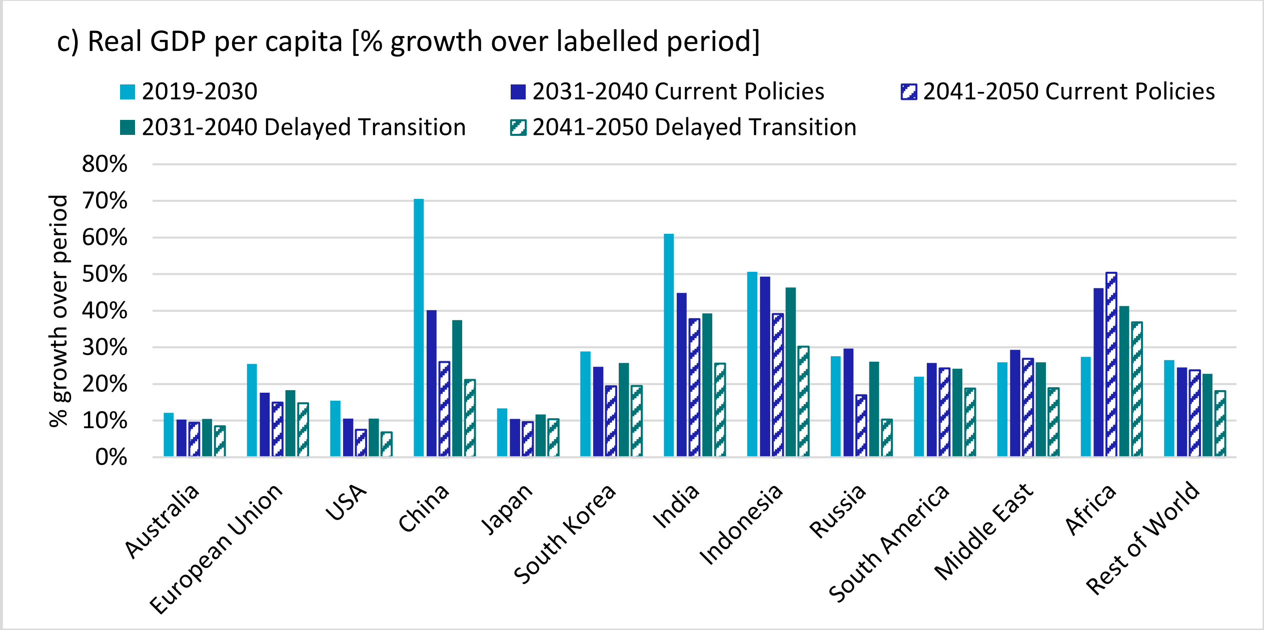
[24] Data for Australia is shown for exogeneous parameters but removed where KPMG-EE modelling provides a more contextualised endogenous result.

driven (note that this effectively disappears in per capita figures). Delayed transition emission reductions are the result of the induced carbon price in the GTEM framework. The carbon price impacts more heavily on carbon intensive sectors. Referring to Figure 8 (panel a), the gap between gross and net emissions is total negative emissions (~9 GT in 2050).

GDP per capita growth is illustrated in Figure 12(c). The growth is strong in Asia, initially in China and then spread throughout. Growth in Africa is largely population driven later in the model period. Delayed transition impacts are highest in Russia, India, China and the Middle East. Growth is generally lower in developed countries. Similarly, employment growth illustrated in Figure 12(d) indicates that outcomes under delayed transition are generally lower but some regions do markedly better than others (e.g. Australia, the United States, South America). Several regions show negative employment growth driven by an ageing population and declining labour force.







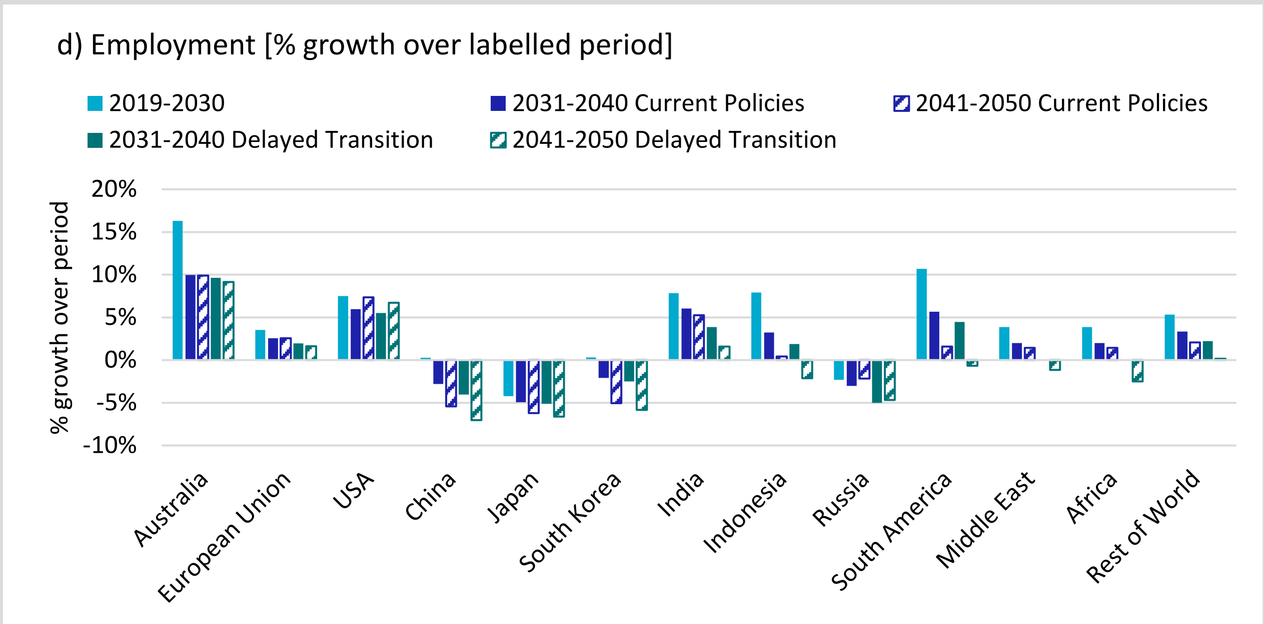
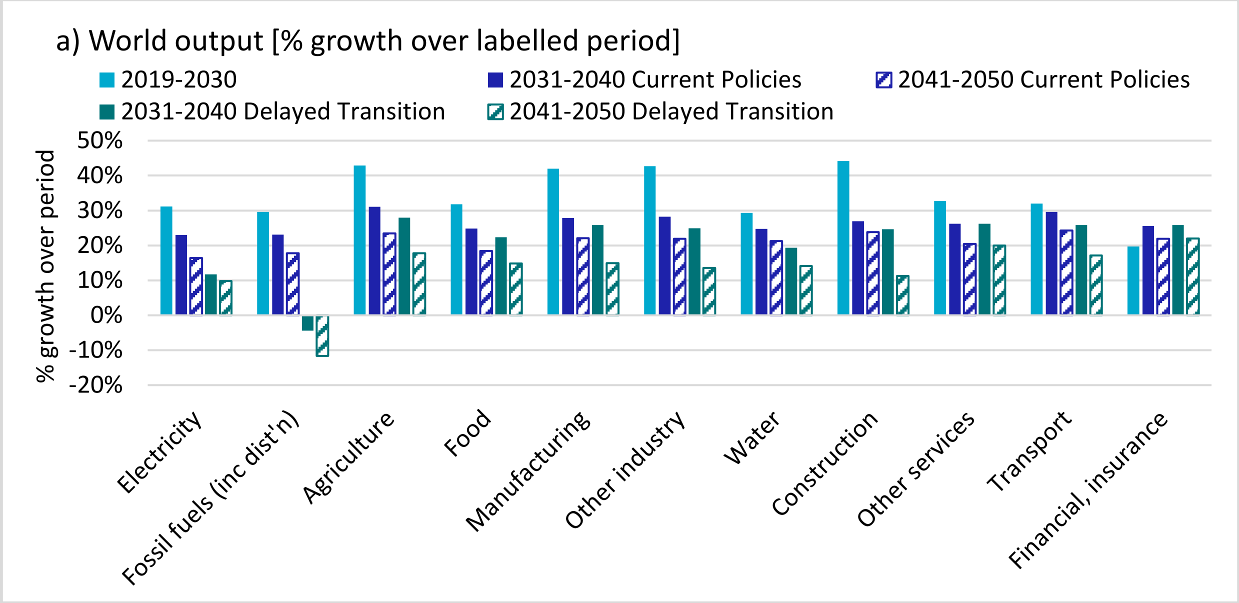


Figure 12 Percentage change from 2019 to 2030, and for current policies and delayed transition scenarios out to 2040 and 2050 for quantities: (a) population, note same for both scenarios in all years (2040, 2050); (b) CO_2-equivalent emissions; (c) GDP per capita; (d) employment.

Figure 13 illustrates the model outputs broken down by sector groupings (all 25 GTEM sectors are reported in the appendices, Section 8.3). The sectors are ordered with electricity first, followed by fossil fuel intensive sectors, then the remainder. World output growth in terms of nominal USD is illustrated in Figure 13(a). Output growth is negative under the delayed transition scenario in the emissions heavy coal, oil and gas sectors. Price feedbacks lead to reduced electricity growth (also in some other sectors) compared to Current Policies.

As expected, emissions growth per sector in Figure 13(b) declines the most under the Delayed Transition scenario in fossil fuel intensive electricity, coal and gas, which barely change under Current Policies. There are also substantive Delayed Transition reductions in emissions in food and other industry (ferrous metals). Emissions growth by sector is smallest for crops and livestock, manufacturing and water – noting that the water sector also includes sewage with a substantive methane footprint. Crops and livestock emission price impacts are counteracted by rising incomes in middle income countries which feed back into higher food demand, particularly for livestock products. This is illustrated clearly in the purchaser price per sector

(Figure 13(c)) where livestock and coal prices increase the most – coal due to the embodied emissions price, and livestock due to a combination of embodied emissions and demand changes. Purchaser prices are inclusive of any carbon effects, hence revenue that the producer receives will be less than that represented here – especially for emissions-intensive sectors.



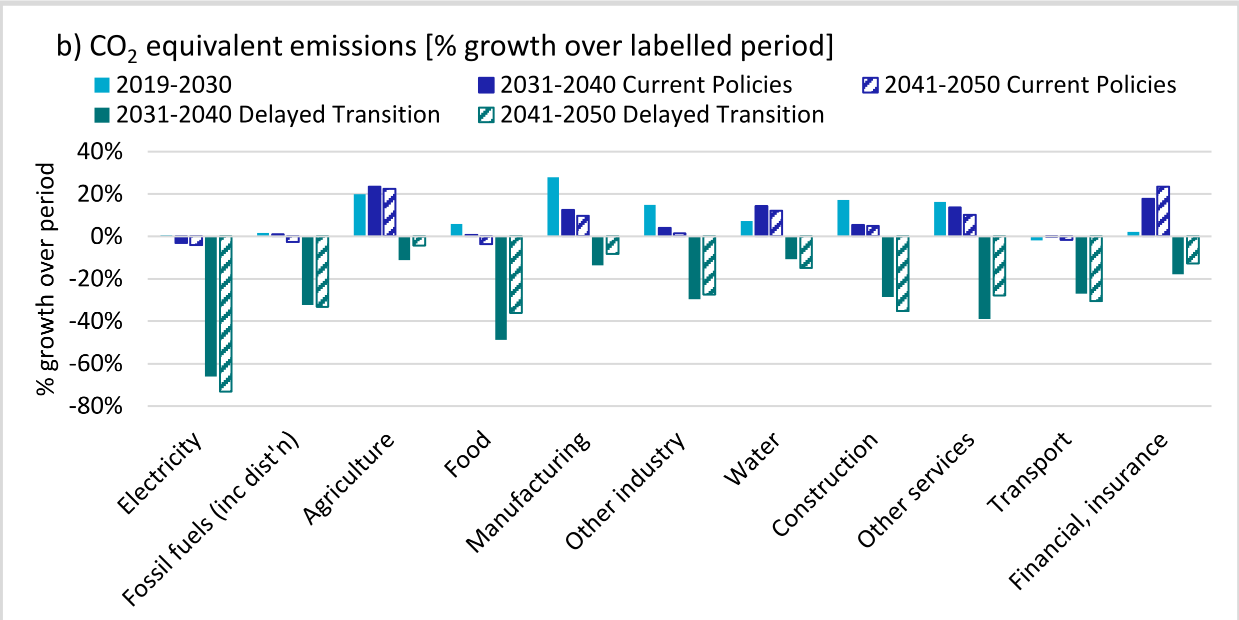


Figure 13 Per sector, for current policies and delayed transition scenarios, the percentage growth from 2019 to 2030, and from 2030 to 2040 and 2040 to 2050 in (a) world output; (b) CO_2-equivalent emissions; and (c) world purchaser price inclusive of carbon price. Australian exports in $ billions at 2030, 2040 and solid in 2014 USD.

The delayed transition emissions path is achieved in the GTEM model by the introduction of a single world carbon price (implying carbon trading across nations) within the GTEM model which then propagates through each sector according to the embodied carbon footprint in the model. In common with the NGFS approach, we include negative emissions technologies, allowing for approximately half of the emissions gap to be filled by these technologies. In contrast with NGFS, which limits negative emissions to BECCs in disorderly scenarios, we are agnostic on technology (see Box 3). GTEM carbon prices are similar to NGFS IAMs (with the exception of the REMIND-MagPIE high end price) at around $200 USD/t CO_2 in 2040 increasing to over $700 USD/t CO_2 in 2050 (Figure 14).

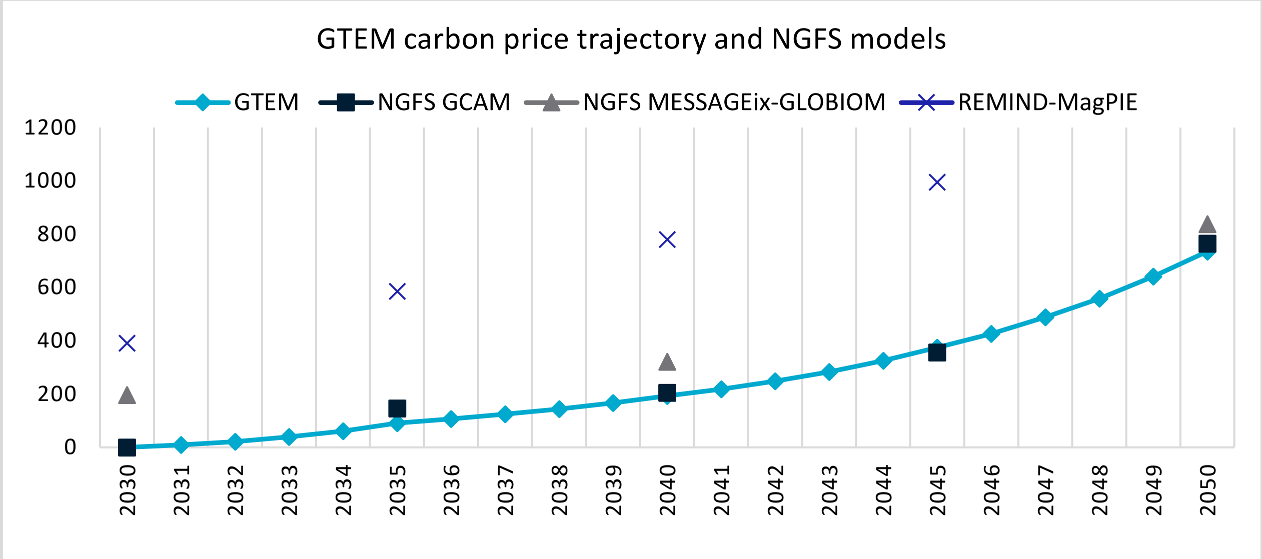
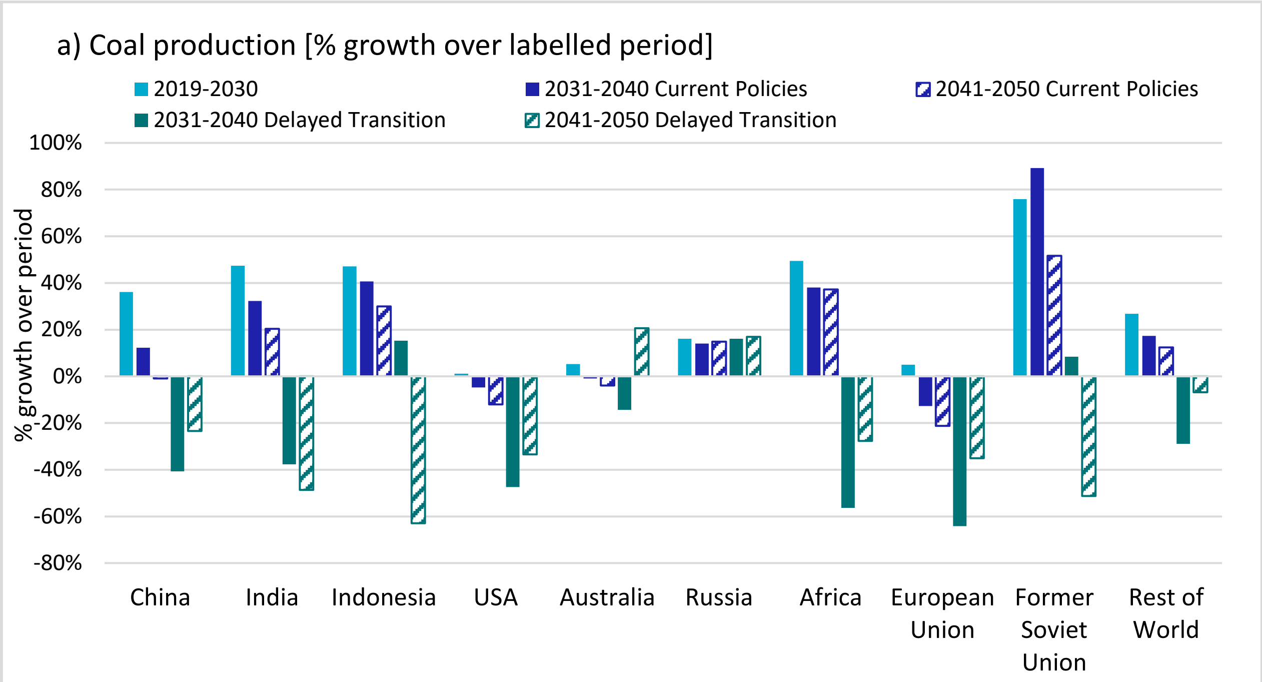


Figure 14 Delayed transition scenario world carbon price and comparison prices from NGFS models in 2014 USD/t CO_2

The impact of an emissions price in the delayed transition scenario dramatically reduces coal production – by far the highest emitting fossil fuel – across much of the world. Figure 15(a) shows large reductions in production across all major coal producers. On top of the modelled impacts, we can anticipate that there will also be additional domestic policy actions by both coal importing and exporting nations (not included in the GTEM model) that are likely to impact the quantum and value of coal exported (Figure 15(b)).



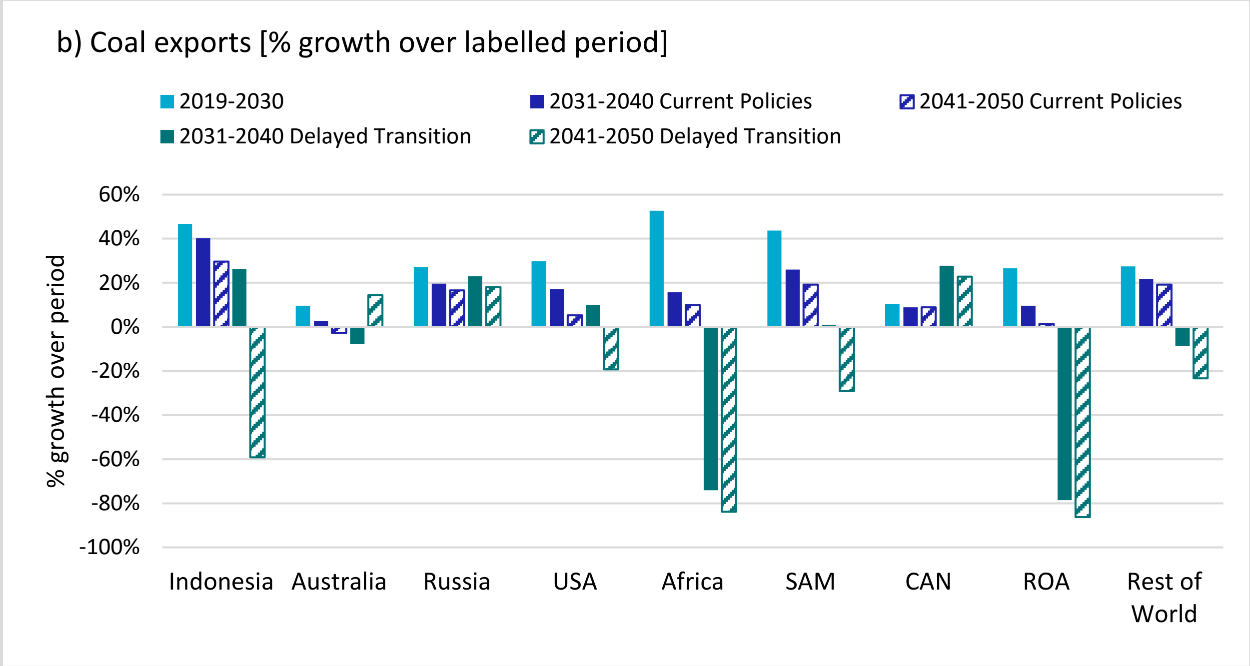
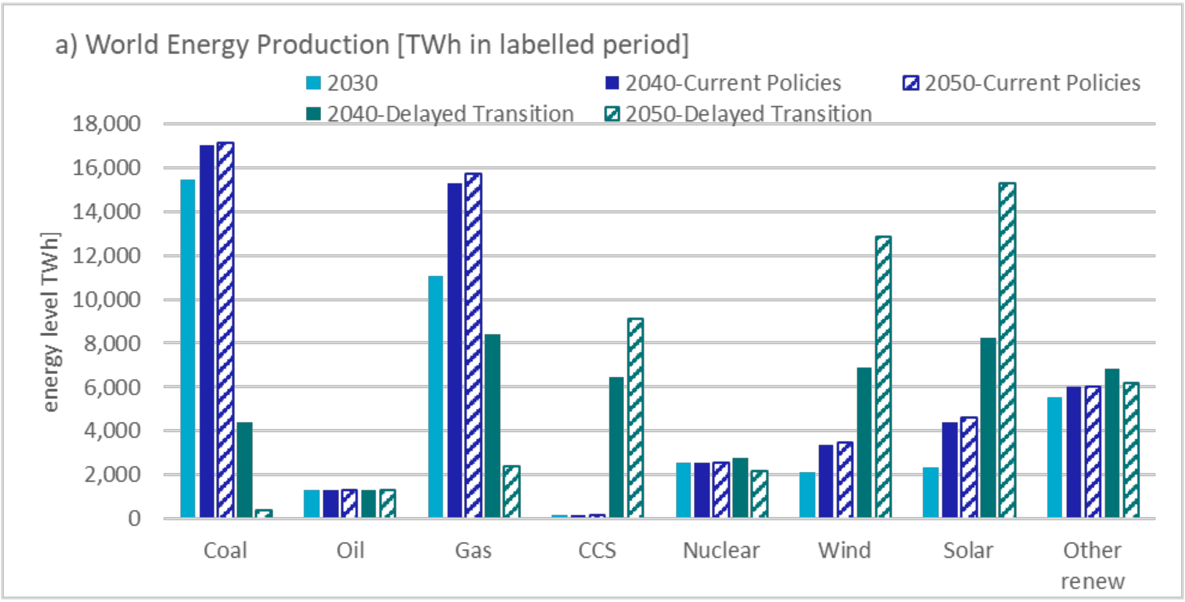
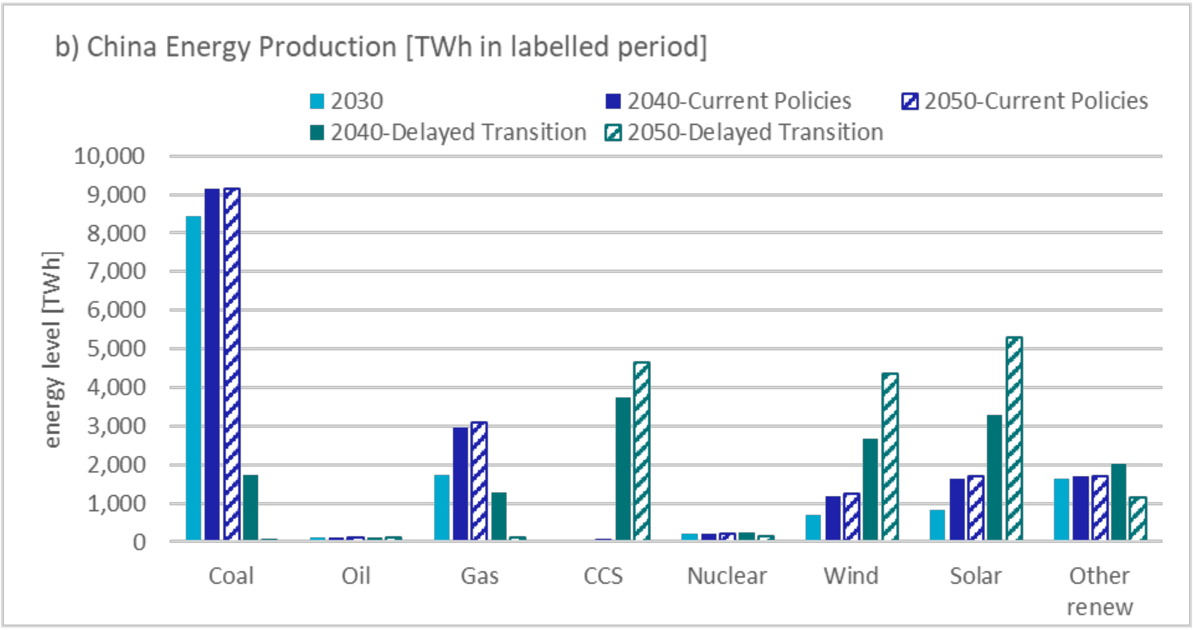


Figure 15 Per region, coal: (a) production percentage change from 2019 to 2030, and for current policies and delayed transition scenarios out to 2040 and 2050 for quantities: (b) export level in 2030, 2040 and 2050 for each scenario.

The levels of electricity generated by various technologies in specific years (2030, 2040, 2050), indicated by GTEM, are illustrated for the world, China, and USA in Figure 16(a), (b) and (c), respectively. Recall that the initial model is calibrated towards a similar electricity mix to the NGFS GCAM current policy scenario whilst the delayed transition is modelled. For all regions, the delayed transition scenario induces a rapid decarbonisation of the electricity sector via a shift from coal and gas towards wind and solar along with induced improvements in energy use efficiency. The US and China (the two largest total emitters) electricity sectors are significantly impacted by the delayed transition scenario forcing a rapid shift from coal to wind and solar. Carbon capture and storage associated with fossil fuels grows rapidly in the delayed transition scenario, but only to a relatively small portion of the future energy mix, especially when compared to the current fossil fuel contribution.





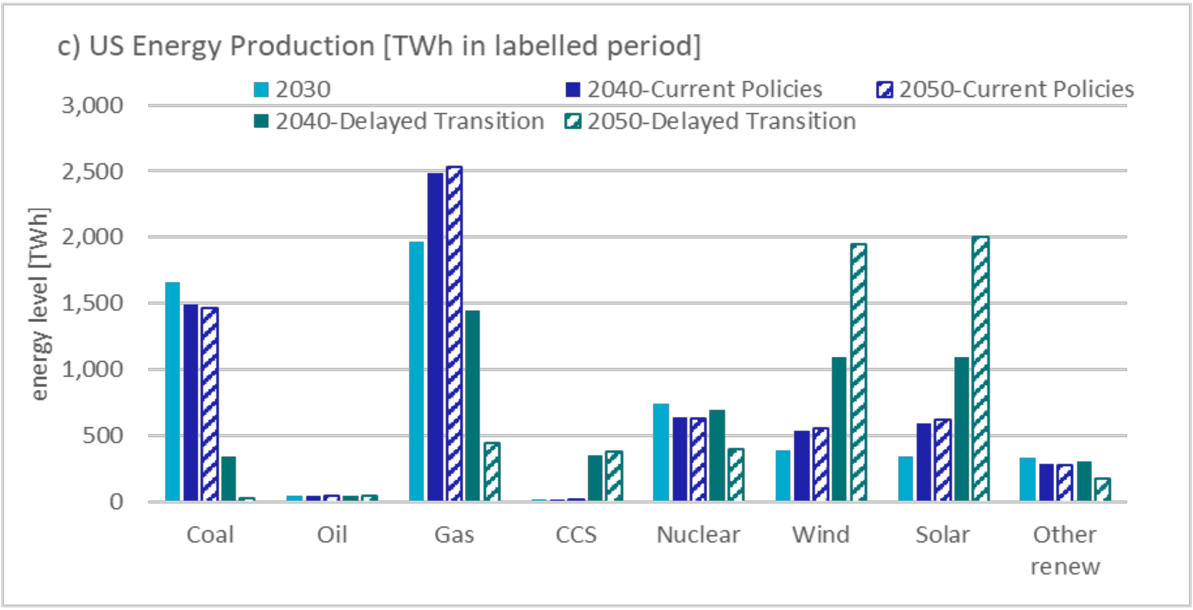
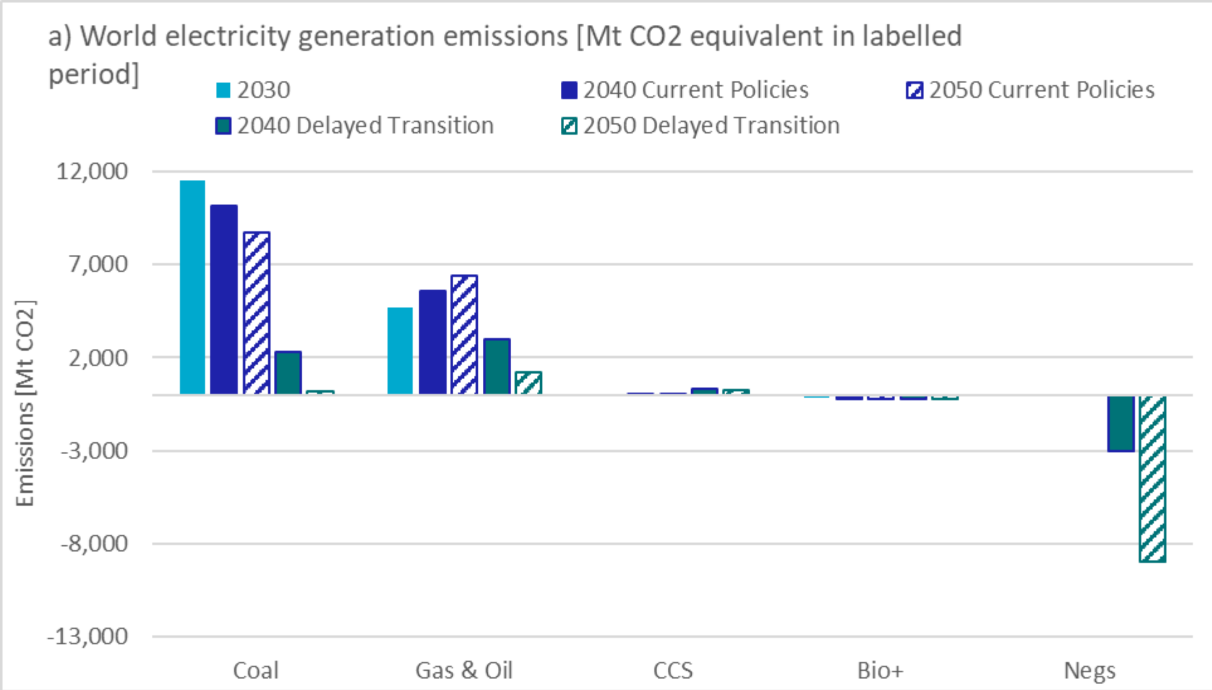
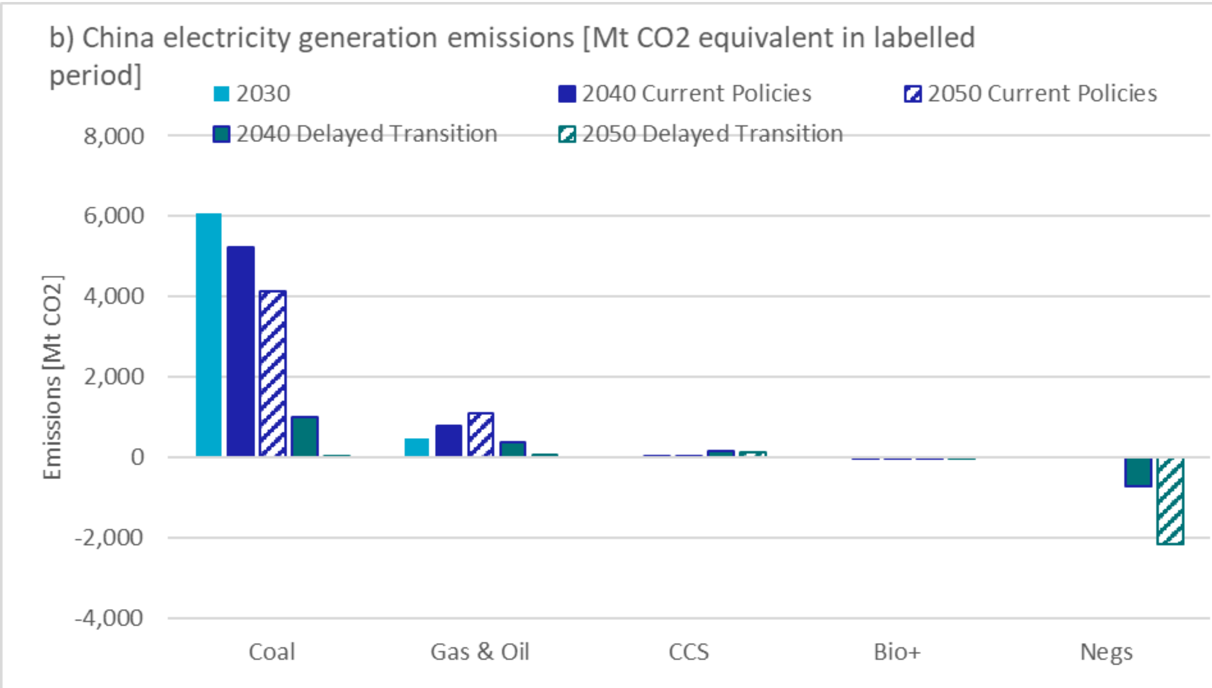


Figure 16 Energy production in TWh per technology at 2030 and for current policies and delayed transition scenarios at 2040 and 2050 for (a) the world; (b) China; and (c) USA.

The levels of emissions per technology are illustrated for the same set of regions in Figure 17. The rapid decarbonisation of the electricity sector leads to dramatically lower emissions from coal, and to a lesser extent gas, under the delayed transition scenario. Emissions from coal-fired electricity generation fall dramatically under the Delayed Transition in the US and China, in line with the rapid shift from coal and gas to wind and solar. Note, technologies with no emissions have been excluded from this figure (e.g. wind, solar, hydro, nuclear). We have included negative emissions in this figure to give an indication of their scale relative to the coal and gas shifts. These may be delivered by a range of activities including land-use change, industrial processes with emissions capture, or carbon capture from the atmosphere (see Box 3).


a) World electricity generation emissions [Mt CO2 equivalent in labelled period]
2030
2040 Current Policies
2050 Current Policies
2040 Delayed Transition
2050 Delayed Transition
12,000
7,000
2,000
-3,000
-8,000
-13,000
Emissions [Mt CO2]
Coal
Gas & Oil
CCS
Bio+
Negs


b) China electricity generation emissions [Mt CO2 equivalent in labelled period]
2030
2040 Current Policies
2050 Current Policies
2040 Delayed Transition
2050 Delayed Transition
8,000
6,000
4,000
2,000
0
-2,000
-4,000
Emissions [Mt CO2]
Coal
Gas & Oil
CCS
Bio+
Negs

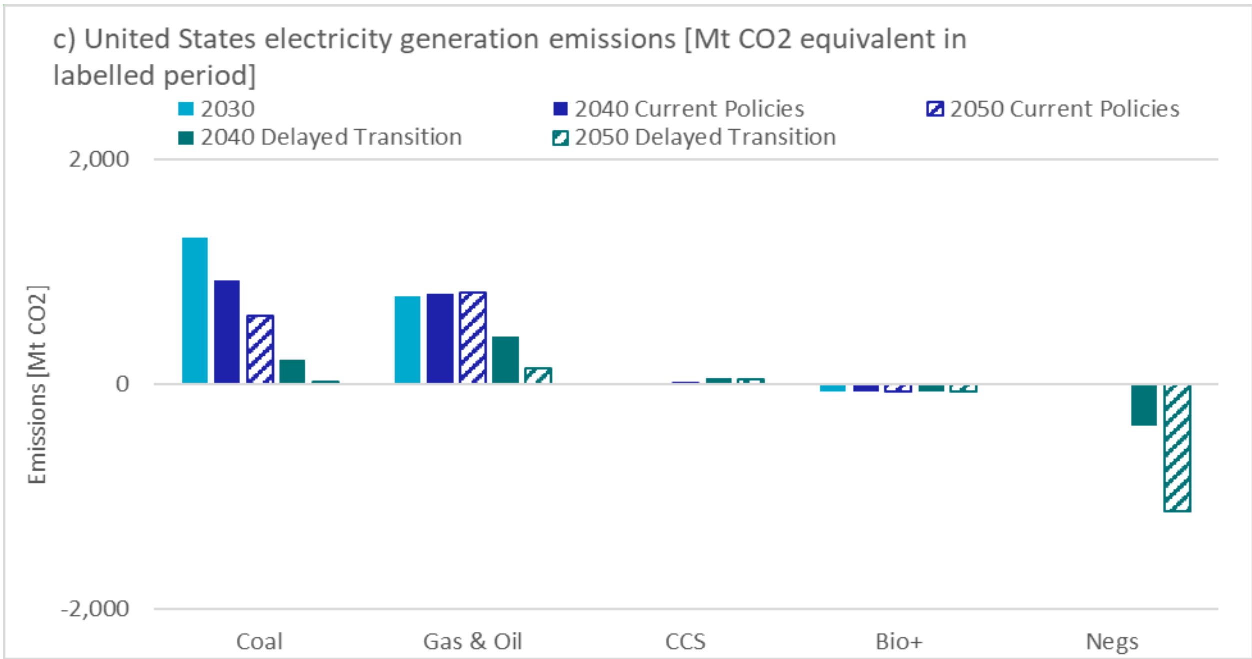


Figure 17 CO_2-equivalent emissions per energy technology at 2030 and for current policies and delayed transition scenarios at 2040 and 2050 for (a) the world; (b) China; and (c) USA. Technologies with no emissions have been excluded (e.g. wind, solar, hydro, nuclear).

6.2 Australian sectoral responses

Overall economic pathways for the Current Policies and Delayed Transition for the Australian economy are set out in Figure 18. Population settings are identical for both scenarios and match the Australian sociodemographic assumptions used in GTEM (Figure 18). Australian CO_2 equivalent emissions fall approximately twice as much under Delayed Transition than Current Policies. The consequences of having to drive a larger emission cut in a short period of time are reflected in the economic measures. There is a 5% GDP per capita difference in 2050 terms between the Delayed Transition and Current Policies scenarios, a 1% employment, 8% investment, 3% capital stock 3% and 8% export difference. Of course, differing transition pathways will generate differing pathways – a slower, orderly transition may cost less and improve future economic outcomes.

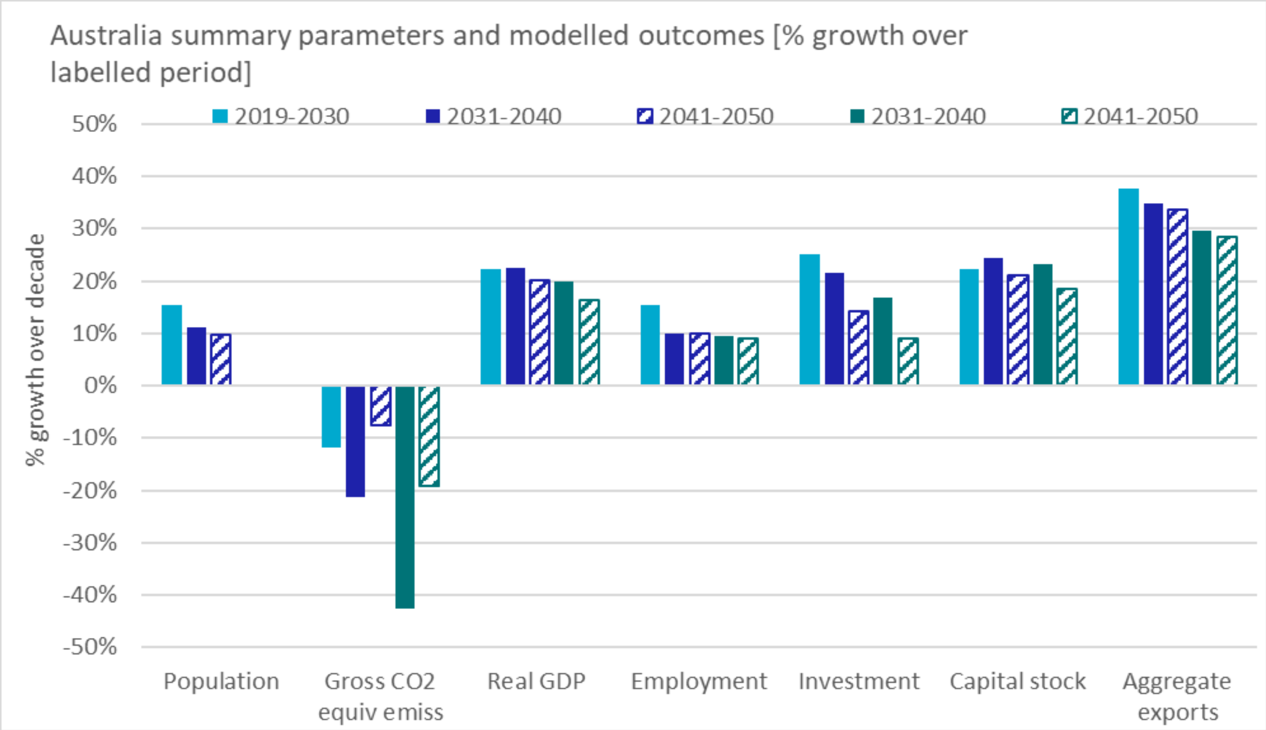


Figure 18 Summary of Australia-specific settings and modelled outcomes. Source: population, emissions pathway NGFS; GDP, GDP per capita, Employment NiGEM for Current Policies, GTEM modelled outcomes for Delayed Transition; all other data GTEM for Current Policies, KPMG-EE for Delayed Transition.

Australia's output growth is illustrated in Figure 19. Under the Delayed Transition scenario, output is constrained (relative to Current Policies) by emissions price impacts on the emissions-intensive agriculture, mining, and construction sectors. Mining is further constrained by the imposition of a coal production limit, reflecting an assumption that a range of political, economic, and business environment considerations will dramatically slow development of any new energy coal mines under the Delayed Transition scenario, with a consequent reduction in exports. This assumption is consistent with the impact on coal production worldwide under a Delayed Transition scenario in GTEM. Price feedbacks and wider efficiency improvements in the economy lead to reduced electricity demand and therefore output growth under Delayed Transition relative to Current Policies. Service sectors benefit most, including accommodation and food, and information, media and telecommunications.

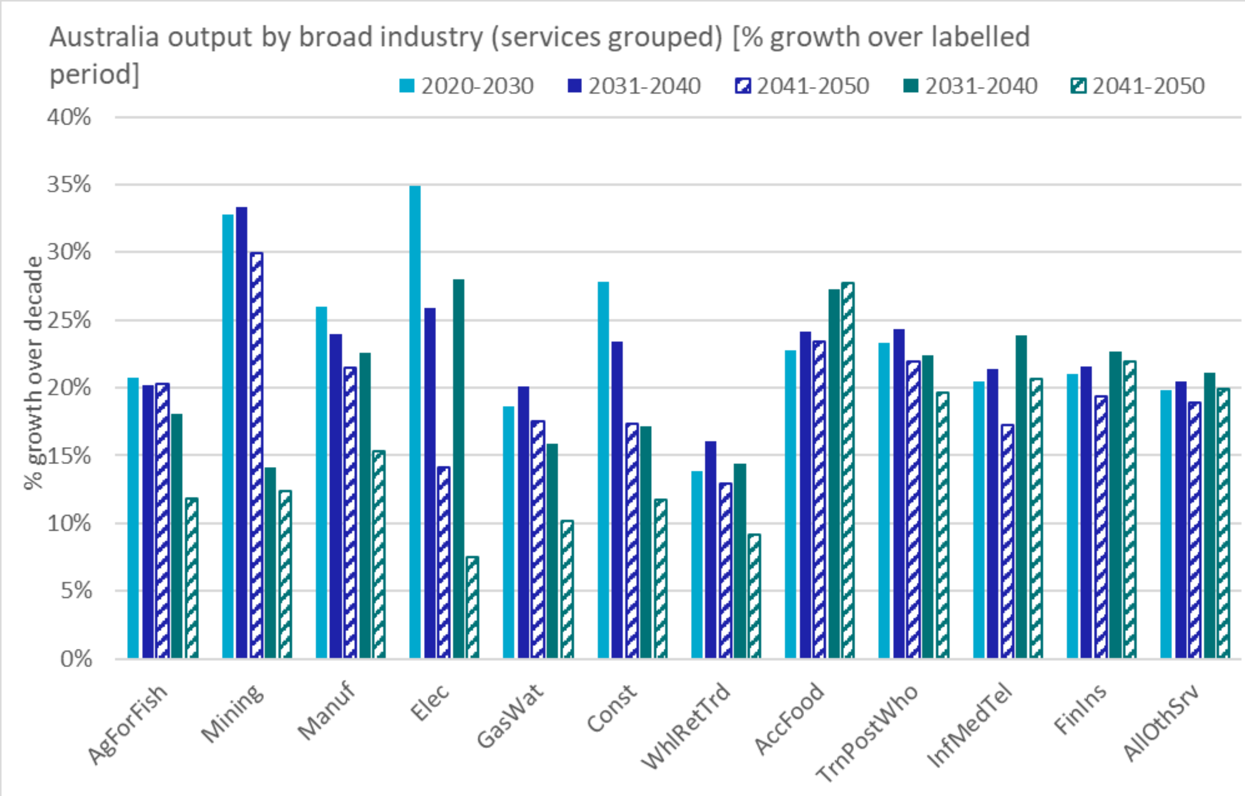
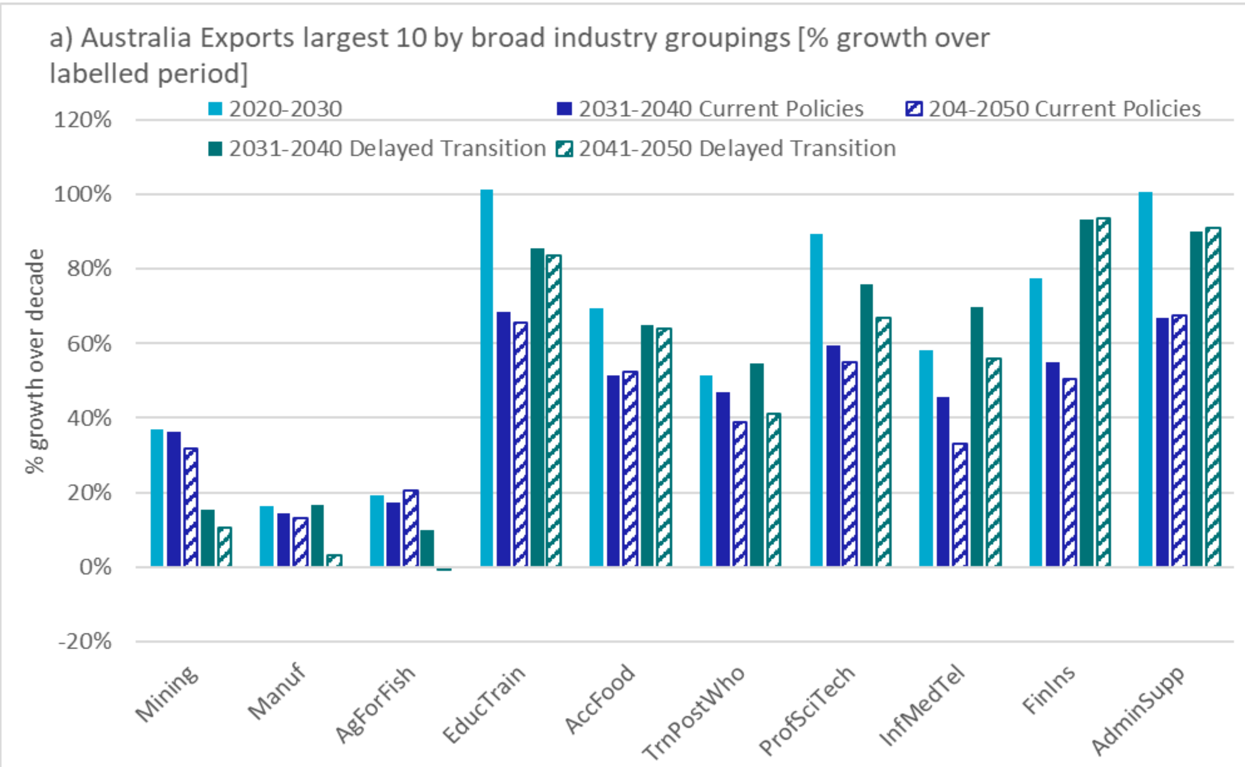


Figure 19 Sectoral growth in Australia. Service sectors are grouped. Detailed results in appendix.

The growth in exports is illustrated in Figure 20 for the ten largest broad industry groups (>95% of current exports by value). Exports under the Delayed Transition scenario contrast sharply with Current Policies for large important sectors in mining, agriculture, and in the later transition manufacturing. Service-oriented sectors grow more (relative to Current Policies), especially finance and insurance services, but also all other service sectors. Growth in service sector exports (Figure 20(b)) approximately compensates for the reduction in mining and agriculture by value as illustrated previously.



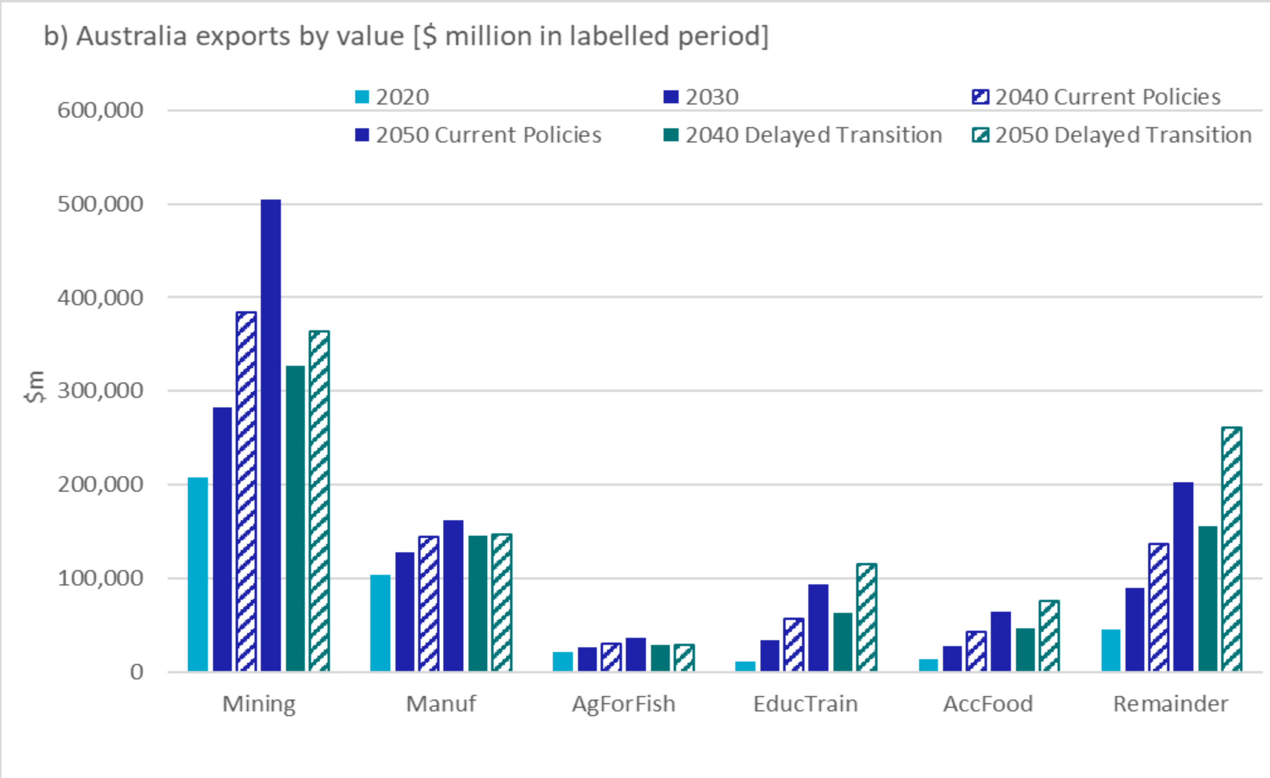


Figure 20 Export value and growth in Australia (in 2020 order of export value)

More detailed information can be found in the appendices, Section 8.4.

6.2.1 Electricity sector

Generation source and emissions for the Australian electricity sector are shown in Figure 21. A rapid shift from fossil fuels to renewables is already predicted to occur over the coming decades in Australia with little difference between the Current Policies and Delayed Transition scenarios. Decarbonisation of the grid is driven by retirement of the ageing coal-fired generation fleet as it becomes more challenging to operate this infrastructure reliably and cost effectively. Concurrently, a shift is underway from a centralised one-way power supply system towards an increasingly decentralised, two-way system. Drivers of this change include:

- Replacement of the coal-fired generation fleet with more decentralised renewable electricity generation capacity.
- Increased renewable energy installations driven by households and businesses.
- Mechanisms allowing large energy users to reduce their electricity demand when supply is constrained.

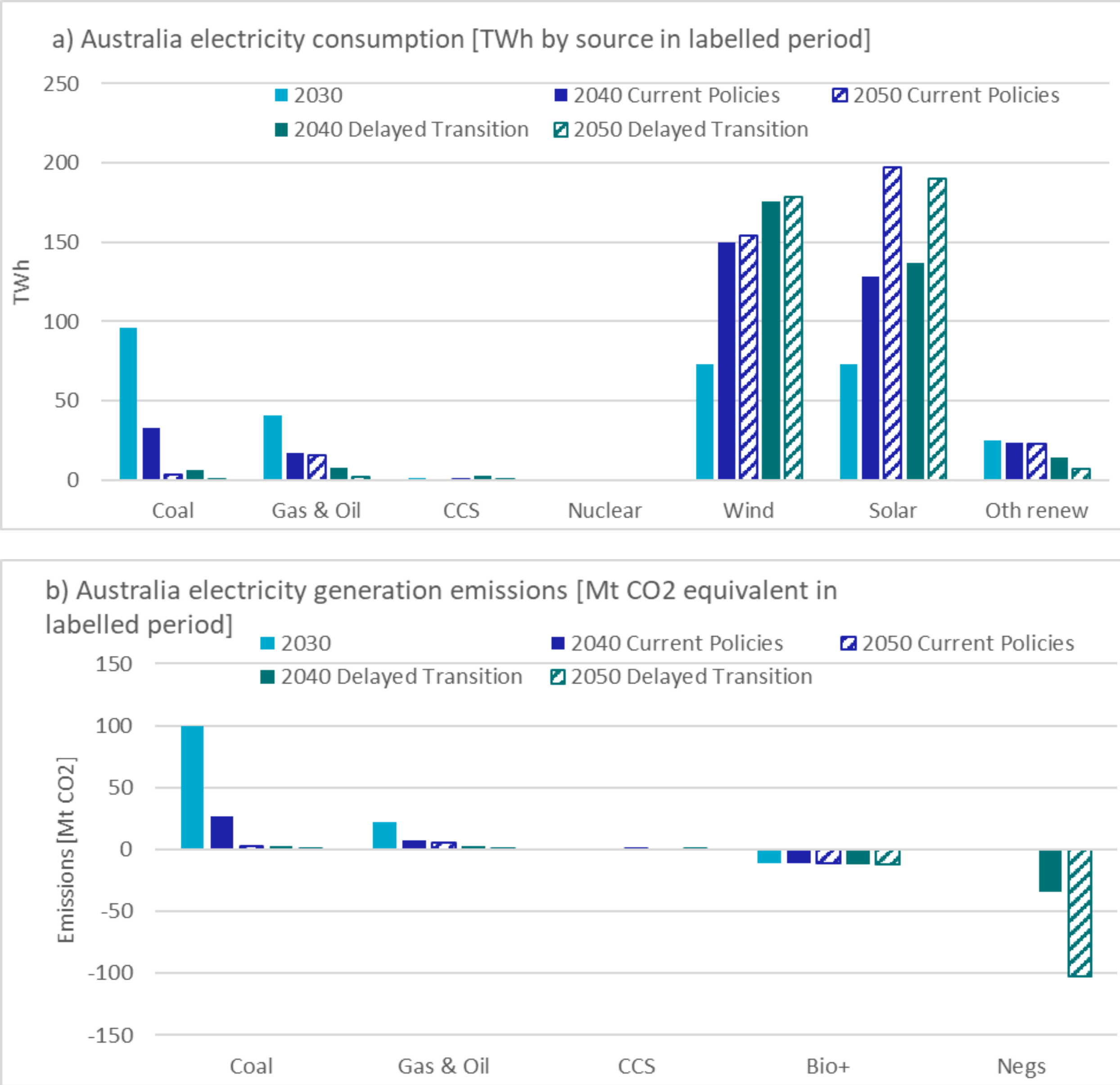


Figure 21 Australian electricity source and emissions. Source: GTEM modelling using AEMO steady progress for Current Policies, modelled for Delayed Transition.

The rapid shift to renewables presents significant challenges for the operation of the electricity system, including the ability to balance demand and supply, as well as frequency and voltage and a growing pool of demand response resources. Due to the pace of change, concerns have been raised about the inadequacy of market signals to encourage investment in support system security, including transmission infrastructure and fast response dispatchable capacity.

For the finance sector the electricity sector presents an opportunity for investment in new generation, storage, and electricity infrastructure assets, but also increases the risk of stranded assets, particularly in a delayed or disorderly transition. There is also substantial uncertainty around future electricity demand as the economy decarbonises. Electrification of transport (light and heavy vehicles), domestic and commercial buildings, and international export of electricity[25] are emerging options. Significant investment is also being made into the development of a renewable hydrogen industry[26] that, if successfully deployed at scale,

[25] https://suncable.sg/australia-asia-power-link/

[26] https://www.industry.gov.au/data-and-publications/australias-national-hydrogen-strategy

could provide opportunities for better utilisation of renewable energy domestically and international export opportunities.

The GTEM model:

- Assumes the Australian electricity sector decarbonises relatively rapidly under current policies consistent with the AEMO steady progress scenario for the National Electricity Market (NEM)[27] and CSIRO electricity technology projections for Western Australia and the Northern Territory.
- Does not account for the energy storage and other infrastructure investment that may be needed to support the decarbonisation of the grid.
- Incorporates electrification of the transport and manufacturing sectors but does not reflect electrification potential for other sectors such as commercial and residential buildings.
- Does not assume a renewable hydrogen industry is realised at scale.

Box 3 Negative emissions and carbon capture technologies

Box 3: Negative emissions and carbon capture technologies

As the world decarbonises there will be greater demand for offsets that remove emissions from the atmosphere rather than emissions avoidance activities that inherently measure their emissions reduction from business-as-usual-levels. Greater priority and value will be given to emissions removals that are long lasting and have a low risk of reversal.[28] To date, offsets originated in Australia have been dominated by projects which sequester emissions in vegetation, many of which are inherently short term (maintained for 25 or 100 years) and have a risk of reversal (either after the permanence period has expired, or through disturbance such as bushfires). However, many of these projects provide valuable ecosystem services, social and economic co-benefits and, assuming that robust additionality and permanence criteria are maintained, are likely to continue to play an important role in decarbonisation in Australia.

The NGFS scenarios assume that negative emissions will be delivered from a mix of technological solutions and biological sources (such as revegetation or reforestation) and do not include direct air capture with CCS (DACCS).[29] Technological solutions are at various levels of technical and commercial maturity. Some have existing proven applications (for example, direct air capture in industrial applications using flue scrubbers, and gas injection for enhanced oil recovery in the oil and gas industry) and some are the subject of research and development. They can be grouped into three general categories:

1) Capture of CO_2 for use (e.g., in the food and beverage industry).

2) Capture and geological storage of CO_2 (e.g., direct air capture using 'artificial trees' or bioenergy with carbon capture and storage (BECCS)).

3) Sequestration of CO_2 in a stable mineral form (e.g., olivine).

All have advantages and disadvantages in their application. Some key challenges for Australia include: geographic location of the emissions source and suitable CO_2 use or sequestration locations may require costly transport infrastructure and reduce lifecycle emissions benefits; social licence issues; high cost; and technological challenges. Given the nascent development of many of these sequestration technologies, and their cost, these technologies may be most commercially attractive to

[27] National Electricity Market covers NSW, VIC, QLD, SA, TAS and ACT.

[28] https://www.smithschool.ox.ac.uk/publications/reports/Oxford-Offsetting-Principles-2020.pdf

[29] https://www.ngfs.net/sites/default/files/ngfs_climate_scenario_technical_documentation_final.pdf

address emissions in hard-to-abate sectors. It will also be contingent on the ability to bring nascent sequestration options to commercialisation at scale and at costs per tonne of CO_2e abated, which can compete with structural decarbonisation options.

Currently approximately 11.5 mtCO_2e is sequestered per annum in Australia (9 MtCO_2e from sequestration in vegetation and soils[30] and 2.5 MtCO_2e on average from the Gorgon project).[31] To align with the NGFS assumptions, the delayed transition scenario modelled assumes sequestration using negative emissions technologies that grows to 9,000 MtCO_2e by 2050. This has three critical implications:

It suggests that the cost of these technologies can compete with emissions reduction in industries such as transport, manufacturing, electricity generation, and commercial buildings. In particular, the modelling does not incorporate fuel switching (e.g., electrification) in commercial and residential buildings, which would result in negative emissions technologies being deployed over these emissions reduction alternatives.

It assumes that negative emissions technologies become cost competitive over time in line with an assumed growth path consistent with the increase in carbon price in the analysis.

It implies that there is no reputational pressure for industries utilising fossil fuels and other heavy emitters to maximise their decarbonisation activities before using offsets.

Given the nascent development of many of these sequestration technologies, and their cost, and risks, the delayed transition scenario does not represent the full spread of risk to emissions-intensive sectors, particularly in circumstances where the transition to a low carbon economy is rapid and globally uncoordinated. This could increase the risk of stranded assets but also increase the opportunity for investment in decarbonisation solutions.

6.2.2 Agriculture

The agriculture sector is an integral part of the Australian economy with a footprint across more than half of the continent, contributing almost 2% of value added, and 3% of employment. It furthermore contributes to national and international wellbeing through the production of food, fibre, and other biomaterials. The sector is a major producer of surplus, supplying around 90% percent of domestic food consumption[32] even as it exports around 70% of total value of agricultural, fisheries, and forestry production.[33] The agriculture sector is also a significant user of natural resources, accounting for 55% of land use and 25% of water extraction,[34] and as such is particularly exposed to a wider range of potential climate impacts than other sectors, many of which cannot be incorporated explicitly in this study due to limited data and sector aggregation.

The sector is substantively impacted under the delayed transition scenario across production, exports and gross operating surplus (Figure 22). The main impacts of the delayed transition are via livestock on the

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30 http://www.cleanenergyregulator.gov.au/ERF/project-and-contracts-registers/project-register

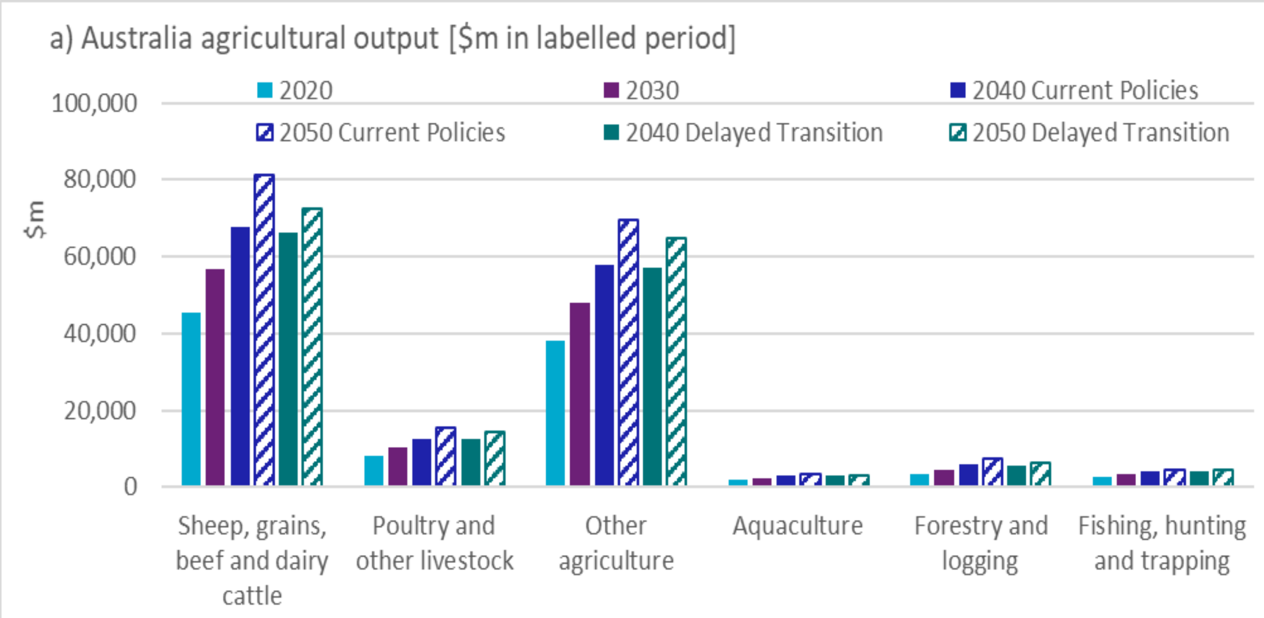
31 Which is under the target of 4 MtCO_2e per annum due to operational challenges https://australia.chevron.com/news/2021/co2-injection-milestone

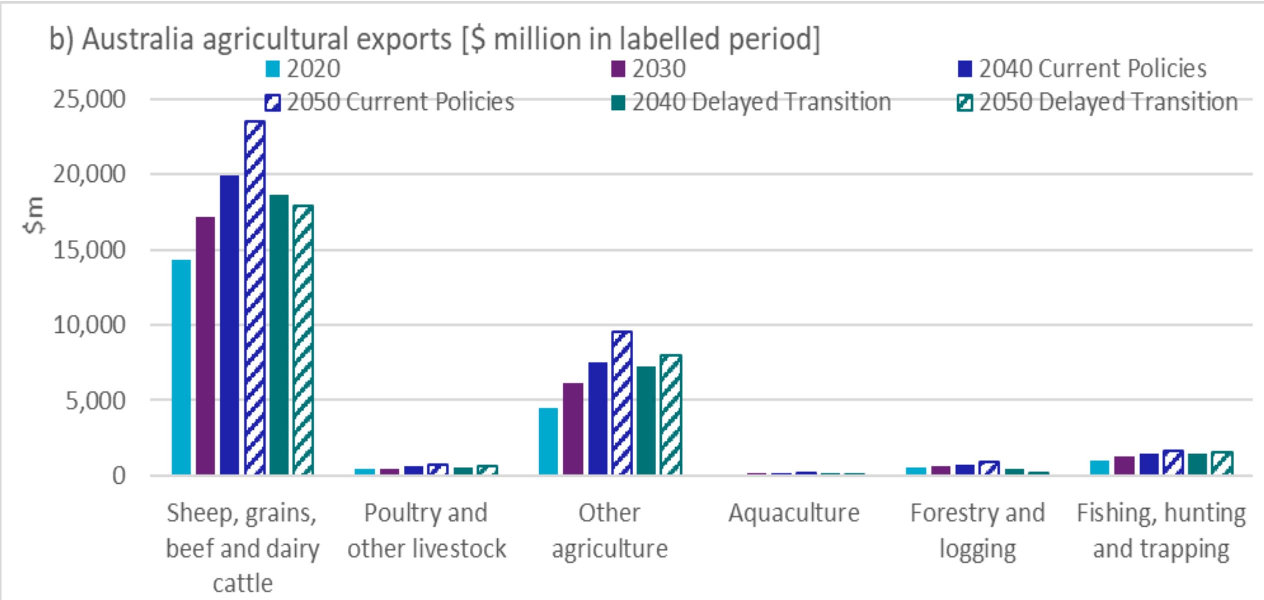
32 Ridoutt, B. G. et al. Australia’s nutritional food balance: situation, outlook and policy implications. Food Secur. 9, 211–226 (2017).

33 ABARES (2021) Snapshot of Australian Agriculture 2021. Canberra.

34 ABARES (2021) Snapshot of Australian Agriculture 2021. Canberra.

sheep, grains, beef and dairy cattle sector inclusive of exports. Profitability impacts on the sheep, grains, beef and dairy sector are larger than production and export impacts as shown in panel (c), being about a third lower relative to Current Policies by 2050 with a lesser impact across other agricultural sectors.





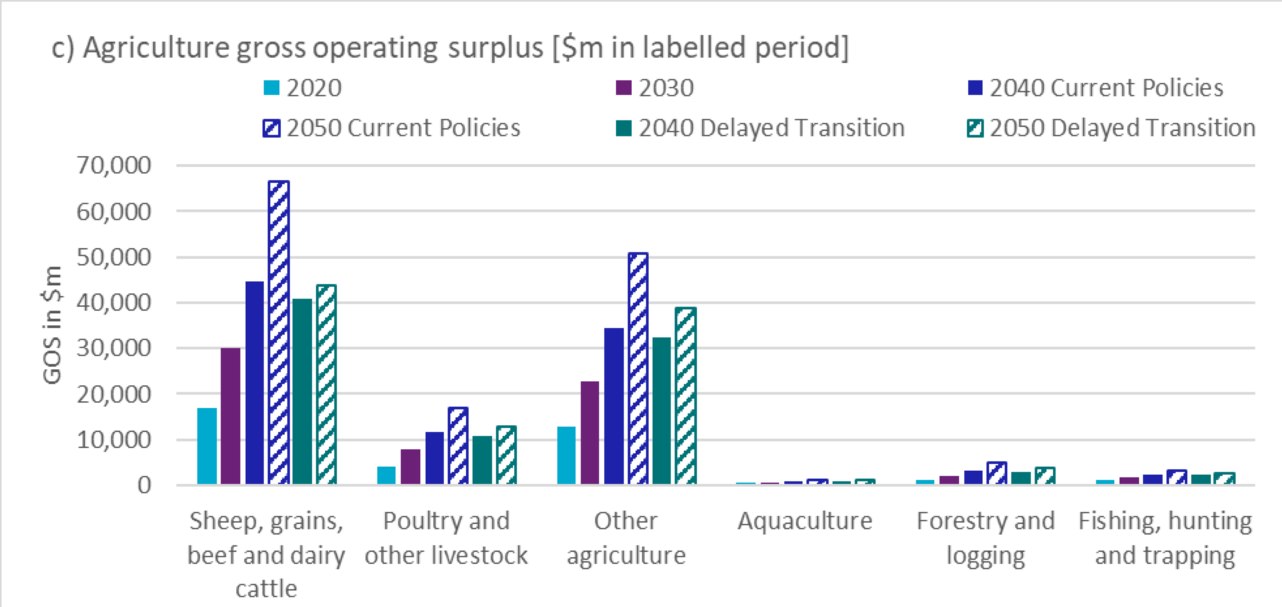


Figure 22 Australian agriculture production, exports and gross operating surplus. Source: KPMG-EE modelled outputs.

Modelled impacts in the GTEM and KPMG-EE do not specifically include a range of risks that will impact the Australian agricultural sector. Changing precipitation patterns will test both rainfed and irrigated production systems, as increased variability will complicate water storage and management. Elevated CO_2 has the potential to mitigate some of the negative impacts of rising temperatures on crop productivity through CO_2-fertilisation. However, greater availability of carbon will change the chemical composition of many crops, with potential negative implications on nutrition (reduced mineral content) and crop quality (reduced protein content, increased toxicity).[35] Rising sea levels not only threaten coastal infrastructure but may degrade important agricultural land. Rising temperatures and changing water availability will also threaten livestock productivity across a range of dimensions.[36]

Global diets spurred by increased affluence have transitioned towards more western diets, characterised by greater environmental footprint of food production (i.e., more animal products and processed foods). However, shifting social preferences and increased awareness of health and environmental impacts of diets may lead to different dietary choices in the future that reduce the environmental footprint of food consumption. This could include healthier diets as well as the development of novel food technologies (e.g., alternative proteins, circular food systems, cellular agriculture, vertical farming, etc.), which while not included in this modelling exercise could substantially alter the linkages between food production and natural resource use and alter the sector's climate risk profile.[37]

6.2.3 Mining, oil and gas

The mining, oil, and gas industries have underpinned significant economic growth in Australia in recent decades and form part of our most important export industries. However, as the economy decarbonises the outlook for these industries, their opportunities, and challenges, will be substantially impacted as

[35] Beach et al. (2019). Combining the effects of increased atmospheric carbon dioxide on protein, iron, and zinc availability and projected climate change on global diets: a modelling study. The Lancet Planetary Health, 3(7), e307–e317. https://doi.org/10.1016/S2542-5196(19)30094-4. Myers et al. (2014). Increasing CO_2 threatens human nutrition. Nature, 510(7503), 139–142. https://doi.org/10.1038/nature13179

[36] Godde et al. (2021). Impacts of climate change on the livestock food supply chain, a review of the evidence. Global Food Security, 28, 100488. https://doi.org/10.1016/j.gfs.2020.100488

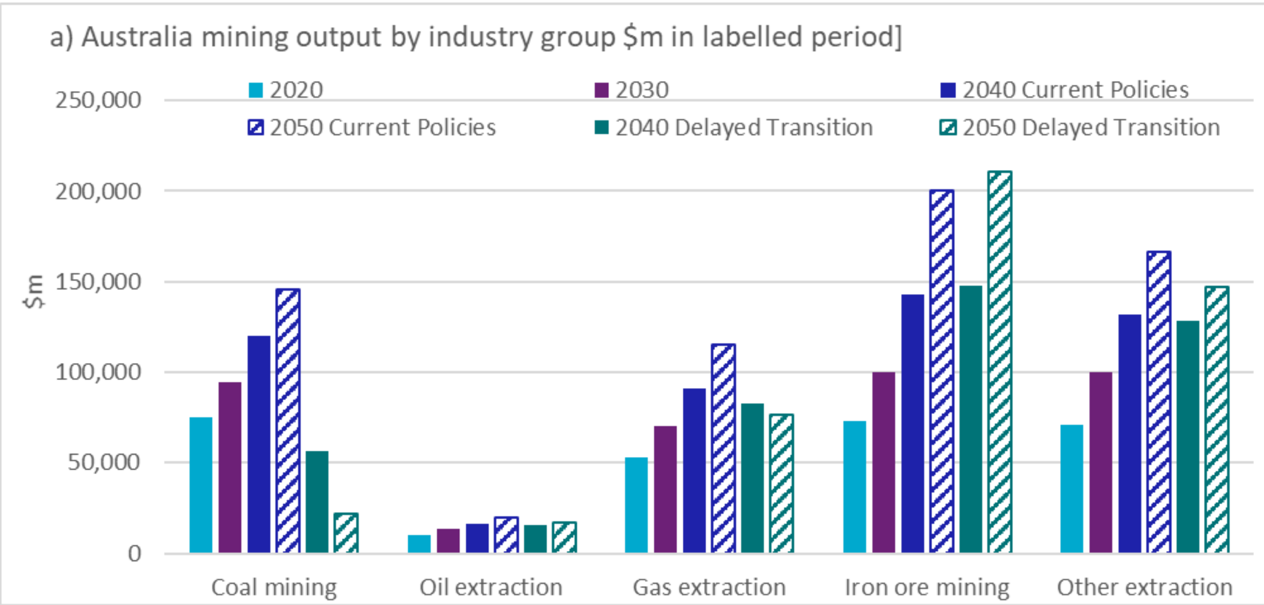
[37] Herrero et al. (2020a). Articulating the effect of food systems innovation on the Sustainable Development Goals. The Lancet Planetary Health. https://doi.org/10.1016/S2542-5196(20)30277-1. Herrero et al. (2020b). Innovation can accelerate the transition towards a sustainable food system. Nature Food, 1(5), 266–272. https://doi.org/10.1038/s43016-020-0074-1

illustrated in Figure 23. The transition provides significant economic opportunity in some mining subsectors (for example nickel, copper, lithium, and rare earths) to underpin renewable energy assets, energy storage, and electricity transmission infrastructure. However, it also comes with the challenge of transforming energy and emissions-intensive operations with non-trivial environmental impacts to businesses which can legitimately play their part in achieving a net zero economy through decarbonisation of their operations and value chains. The increased adoption of net zero targets in the sector suggests this is becoming a key driver of social licence to operate and a lever for attracting investment. Large growth in these sectors is an opportunity which is only partly captured in our modelling.

Sectors for which there are low emissions substitutes (such as energy – or thermal – coal) are the most sensitive to stronger decarbonisation requirements domestically and internationally. Domestic demand for energy coal falls in response to the decarbonisation of our electricity grid. Export decline is driven by a combination of falling world demand for coal along with countries continuing to exploit their energy coal reserves for their domestic or export use. It is important to recognise that the Current Policies scenario assumes our export partners do not strengthen their decarbonisation efforts which, based on the annual ratchet mechanism recently implemented for Paris Agreement Nationally Determined Contributions and the focus on the role of fossil fuels, may be less likely to occur. Rather, the failure of Australia to decarbonise our emissions-intensive industries in line with international expectations could put us at a competitive disadvantage as countries apply imposts through legislation and trade agreements, and scope 3 emissions become increasingly important.

Almost all of Australia's metallurgical coal is exported. The modelling assumes continued but declining export of metallurgical coal, which is used in applications such as the production of iron and steel, under Delayed Transition. Significant investment is being made in low emissions alternatives (such as renewable hydrogen) for these production processes but current technical and commercial challenges facing both hydrogen and metals production will need to be surmounted to enable these alternatives to be deployed at scale.

In Australia, natural gas plays a role in electricity generation, for heat (both space heating and industrial heat applications), and as a reductant in industrial processes. The role of gas in the electricity sector will depend on when and how some of the challenges to that sector are addressed. Implications for gas use in electricity generation and manufacturing are discussed separately. Australia is also the largest exporter of liquified natural gas, and therefore will be influenced by the speed of decarbonisation of the largest importers: Japan, China, South Korea and India.[38]



[38] https://www.statista.com/statistics/274529/major-lng-importing-countries/

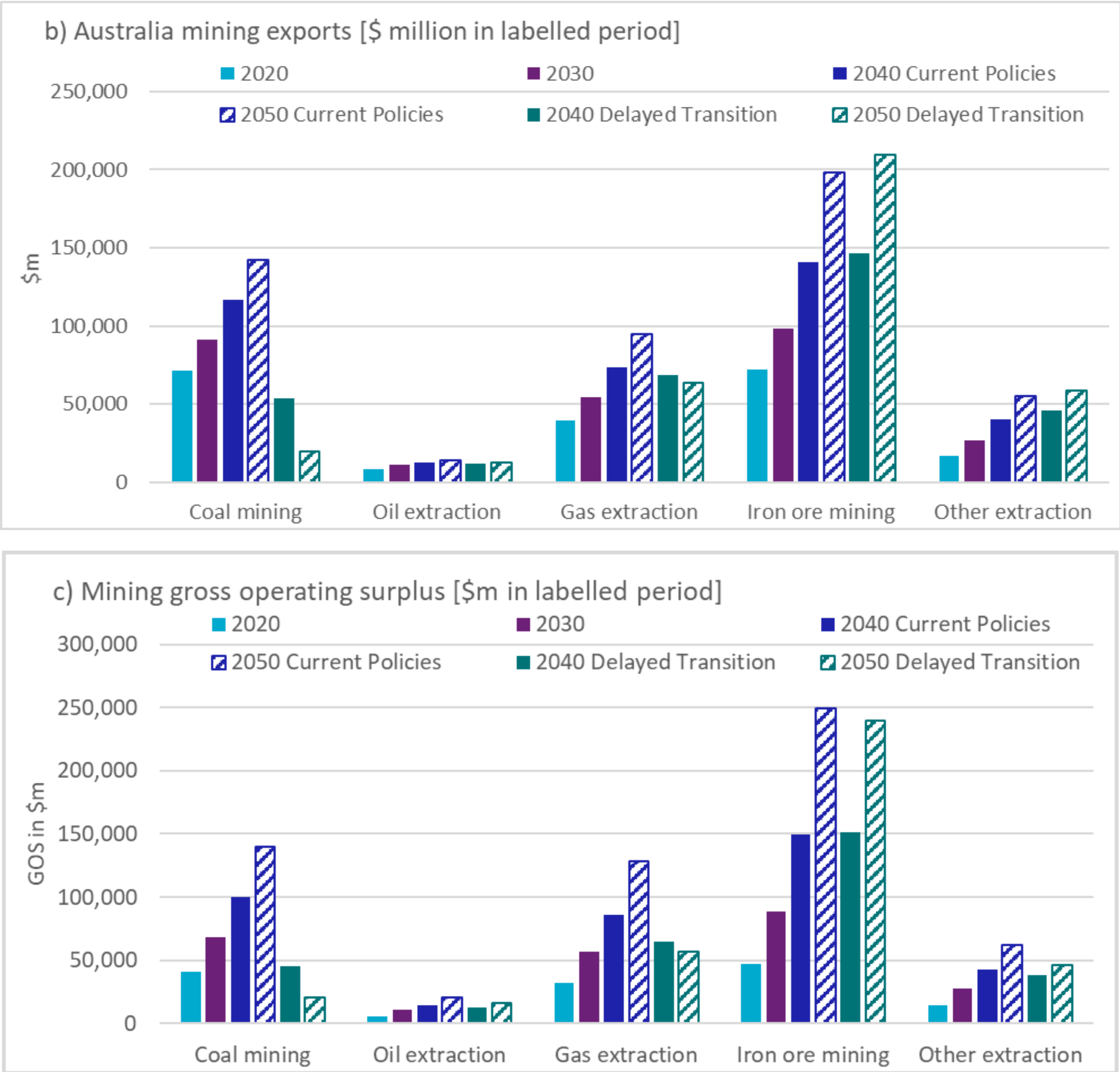


Figure 23 Australian mining production, exports and gross operating surplus. Source: KPMG-EE modelled outputs.

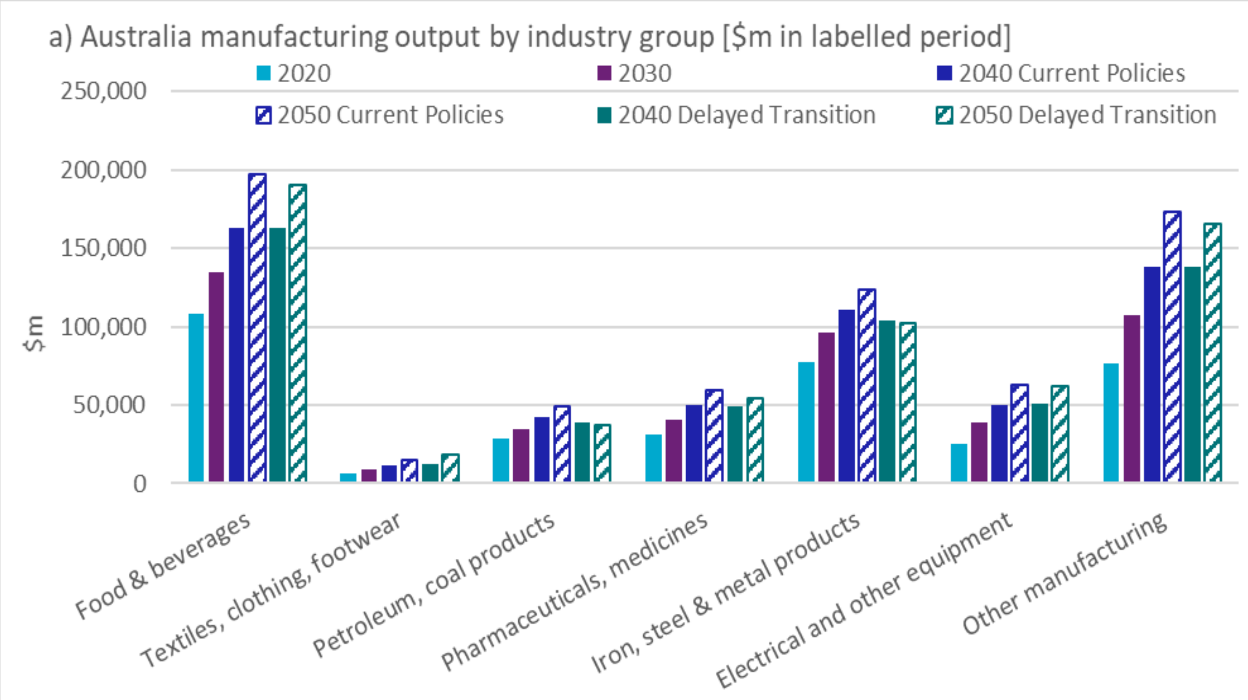
6.2.4 Manufacturing sector

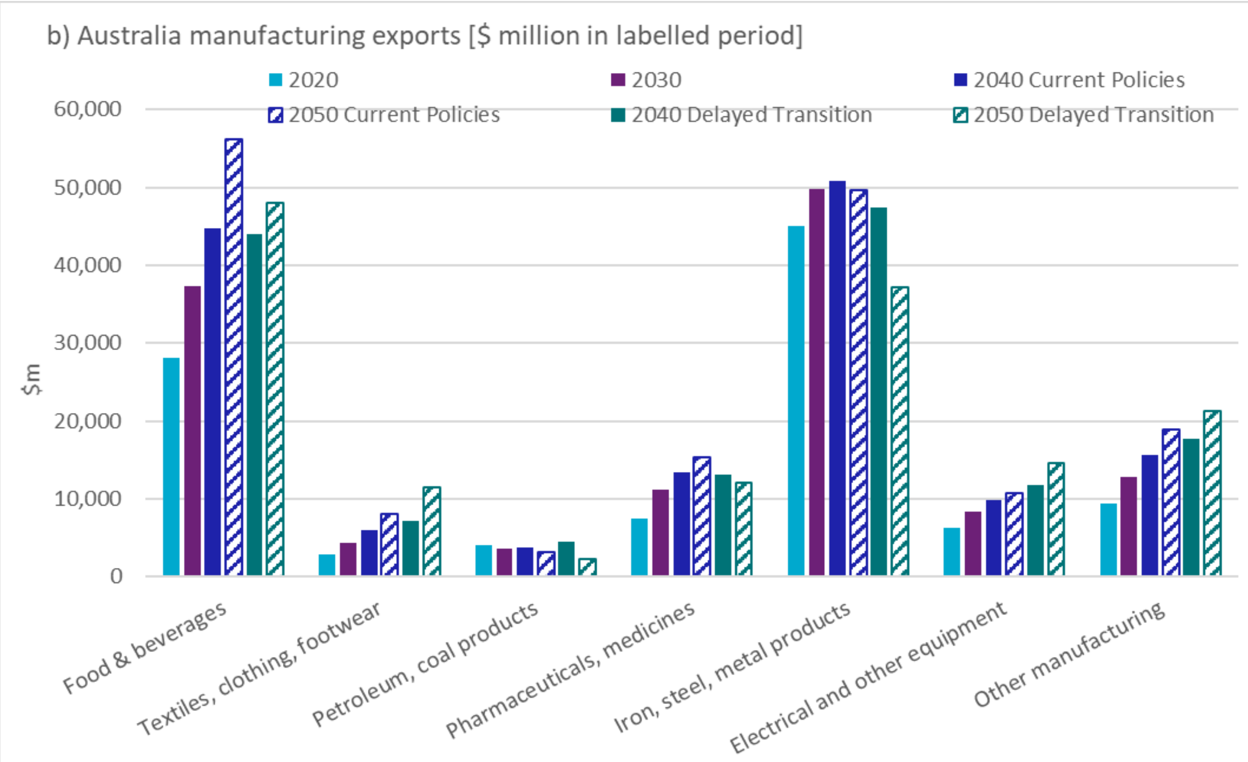
Manufacturing is exposed to transition risk from direct emissions, and indirectly via embodied carbon and energy costs. Australian emissions-intensive manufacturing spans cement production, steel and mineral processing – generally these sectors are the most impacted by a decarbonisation transition (Figure 24). As a first step, switching from coal to gas will provide partial decarbonisation for the remaining cement mills and alumina refineries.

In the Australian manufacturing sector, natural gas plays a significant role in industrial heat applications and as a reductant in industrial processes. Displacement of gas for heating and in industrial applications is likely to be driven by cost and decarbonisation objectives, and is easiest to substitute in low heat applications, whereas the high temperature industrial demands will be dependent on gas. Some applications currently using natural gas could potentially utilise renewable hydrogen, subject to the successful commercialisation of that industry.

Hydrogen's commercialisation pathway requires reduction in both energy and production costs to be widely adopted. Additional upgrades, from pipelines and compressor upgrades to updated end-use customer applications, such as burners in furnaces, will be required along the value chain to support a hydrogen fuel supply. The penetration of hydrogen will also have the potential to further decarbonise the manufacturing sector as a feedstock. Steel production has the potential to utilise hydrogen as a feedstock (and dislodge metallurgical coal) to further reduce emissions. Given these complexities, hydrogen is not specifically included in the modelling.

Food, beverages, textiles, pulp and paper industries are small contributors to the overall emissions profile, with the ability to shift towards biomass and biogas energy in a low carbon economy.





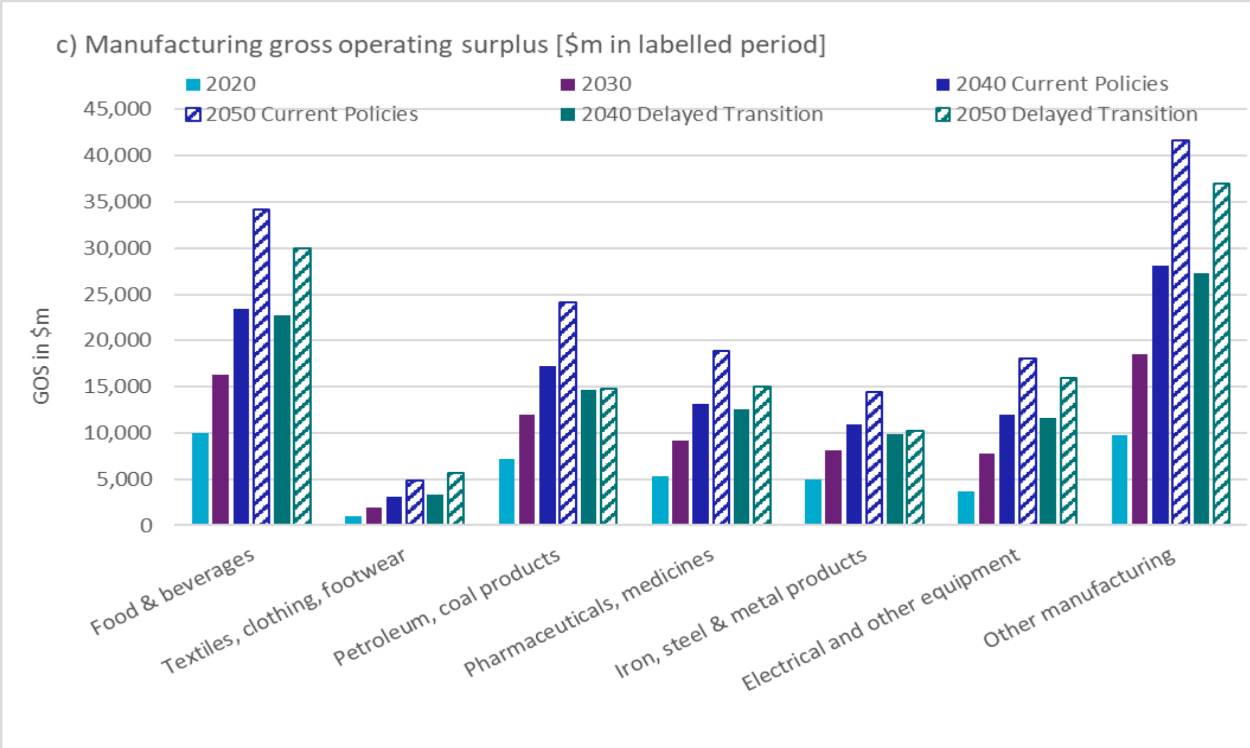
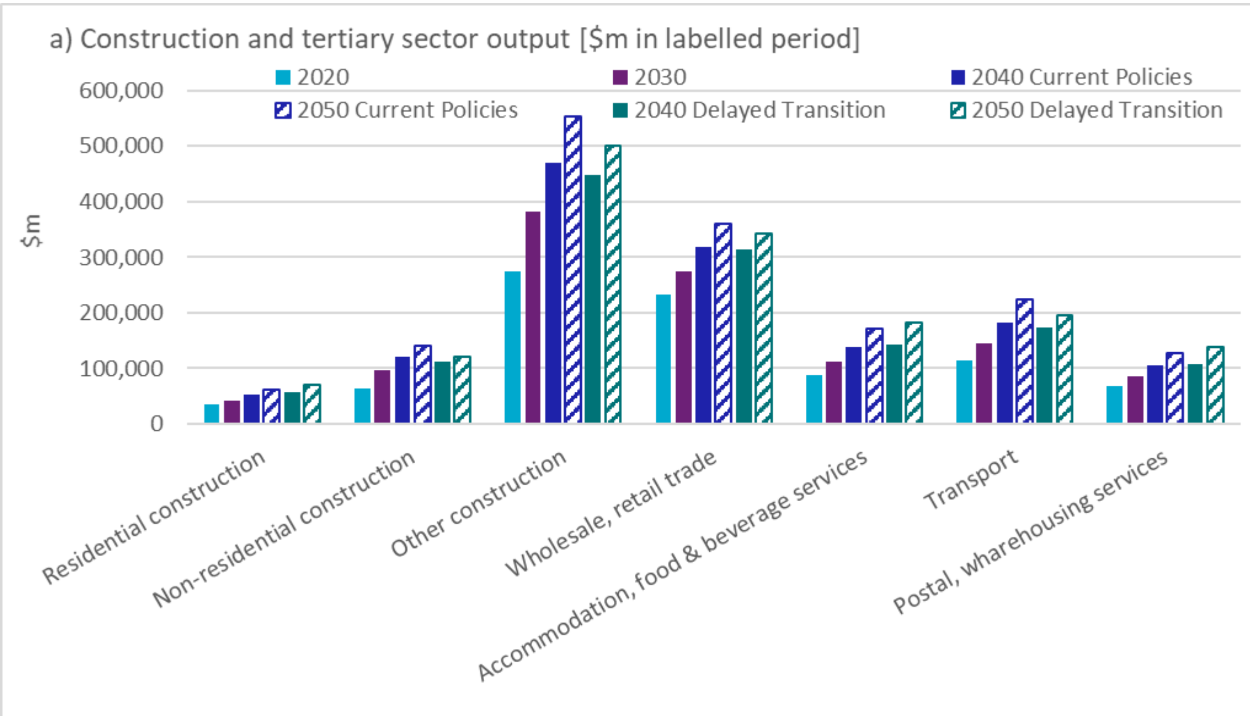


Figure 24 Australian manufacturing production, exports and gross operating surplus. Source: KPMG-EE modelled outputs.

6.2.5 Other sectors

Construction and transport are emissions exposed due to embodied energy in construction materials and fuels in the transport sector. Construction sector differences between Current Policies and Delayed Transition are substantive, particularly for the other construction segment (major infrastructure and commercial construction) (Figure 25). Analysis suggests minimal impacts of delayed transition on tertiary parts of the Australian economy. Transport impacts are minimal except for a decrease in air transport exports (not shown). Wholesale, retail, accommodation, and food and beverage services show little impact.



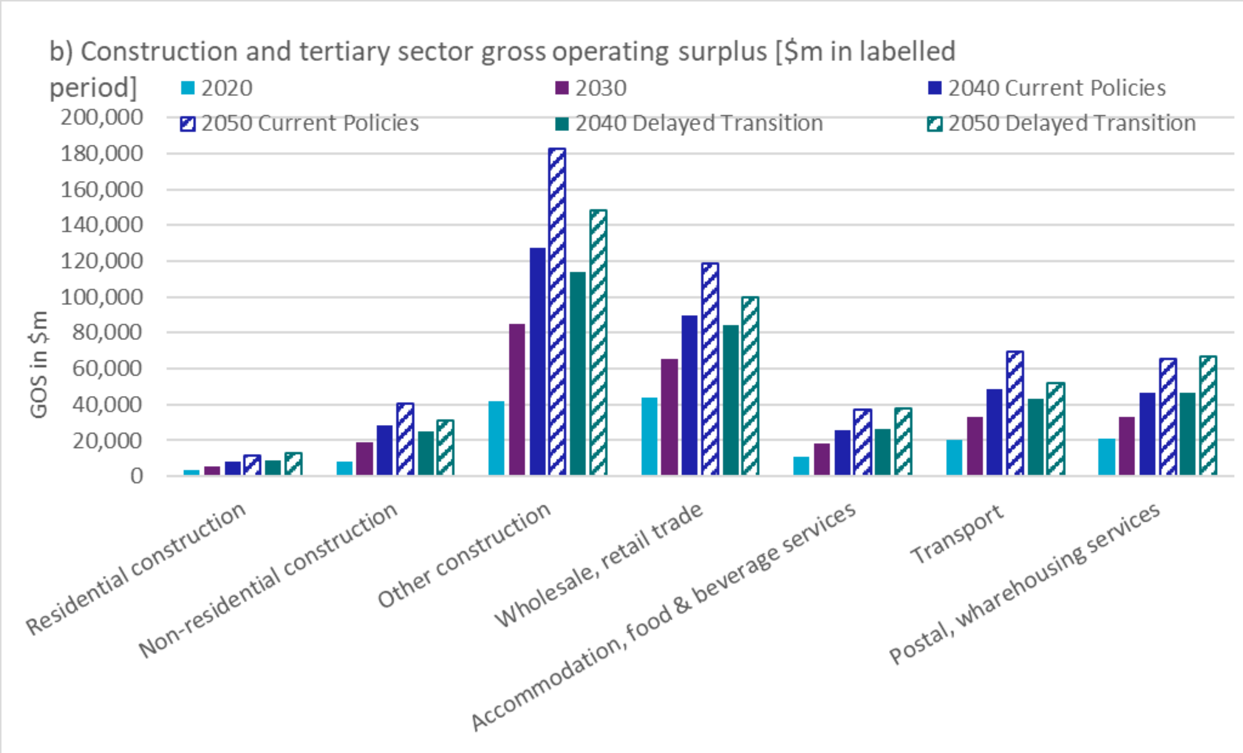


Figure 25 Construction, tertiary sector production and gross operating surplus. Source: KPMG-EE modelled outputs.

For the remaining seventy percent of the Australian economy, comprising a range of service sectors, government, health, and research and development activities there is little difference in modelled trajectories under current policies compared to a delayed transition scenario. Service sector exports are higher across a range of categories, reflecting the shift away from fossil fuel exports whilst retaining the need to service net foreign debt.

6.2.6 Household impacts and residential housing

Within the Australian economy a key risk for the financial sector is the impact on different parts of their portfolio. For example, around 60% of domestic banks' loan portfolios apply to residential housing, and a further 33% to businesses (dealt with above). Some of the pathways impacting on households are shown in Figure 26, indicating lower per capita GDP growth under delayed transition along with lower growth in per capita income. The effects of a delayed transition on households are even more negative if carbon tax revenue is not returned to households (for example, via tax cuts or transfers), leading to a decline in household consumption once net saving is considered.

In the Delayed Transition scenario our treatment of the labour market is to impose an unemployment rate consistent with the Current Policies scenario. This means that changes in demand for labour due to the carbon tax will be reflected partly as a change in employment and labour supply and mostly as a change in the real wage rate; this reflects the assumption of an inelastic supply of labour consistent with international and Australian evidence.[39] As the effect of the carbon tax is to reduce labour demand, in the Delayed Transition scenario we observe a fall in employment and much larger fall in the real wage rate.

An alternative treatment of the unemployment rate in the Delayed Transition scenario is to allow for nominal wage rigidity in the short run, and variation in the unemployment rate and complete wage flexibility in the long run, with the unemployment rate returning to same level as the Current Policies

[39] Bargain O, Orsini K, Peich A. Labor supply elasticities in Europe and the US. IZA discussion paper No. 5820. Bonn: Institute for the Study of Labor; 2011. Dandie, S. and Mercante, J. (2007), 'Australian labour supply elasticities: comparison and critical review', Treasury Working Paper 2007-04, Australian Government, Canberra.

scenario. This is a common approach in macroeconomic modelling.[40] Typically, the changeover point from rigid to flexible nominal wage rates is when the policy under evaluation (the carbon tax) is fully implemented. However, in this analysis the carbon tax continues to rise until 2050. Given the absence of an obvious changeover point, we choose to maintain the unemployment rate at Current Policies level for the duration of the Delayed Transition scenario.

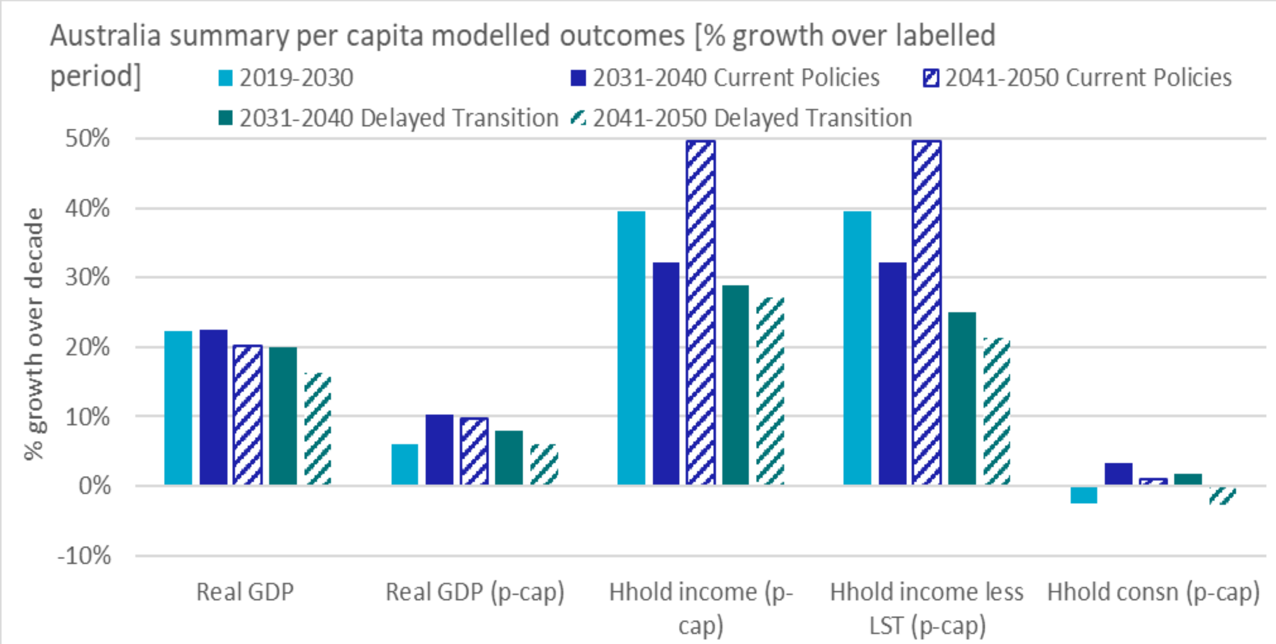


Figure 26 Summary outcomes per capita for Australia. Source: KPMG-EE modelled outputs.

Risk pathways relate to the capacity of households to repay mortgages, with consequent implications for the financial sector. Repayment risks can be impacted through both transition risks to income and physical risk impacts. Transition risks will be highest for those regions most exposed to rapid structural changes as the economy decarbonises (see Section 6.3). Urban areas, including residential housing, will be subject to a range of chronic and acute physical risks as the impacts of climate change are increasingly felt. Chronic risks are mostly driven by exposure to heat and the costs of increased energy use for cooling. Sea-level rise is both a chronic risk and acute risk when combined with rainfall and changes to flood risk placing more homes at risk, alongside increased bushfire and storm damage risks. These physical climate risks have not been taken into account in this modelling.

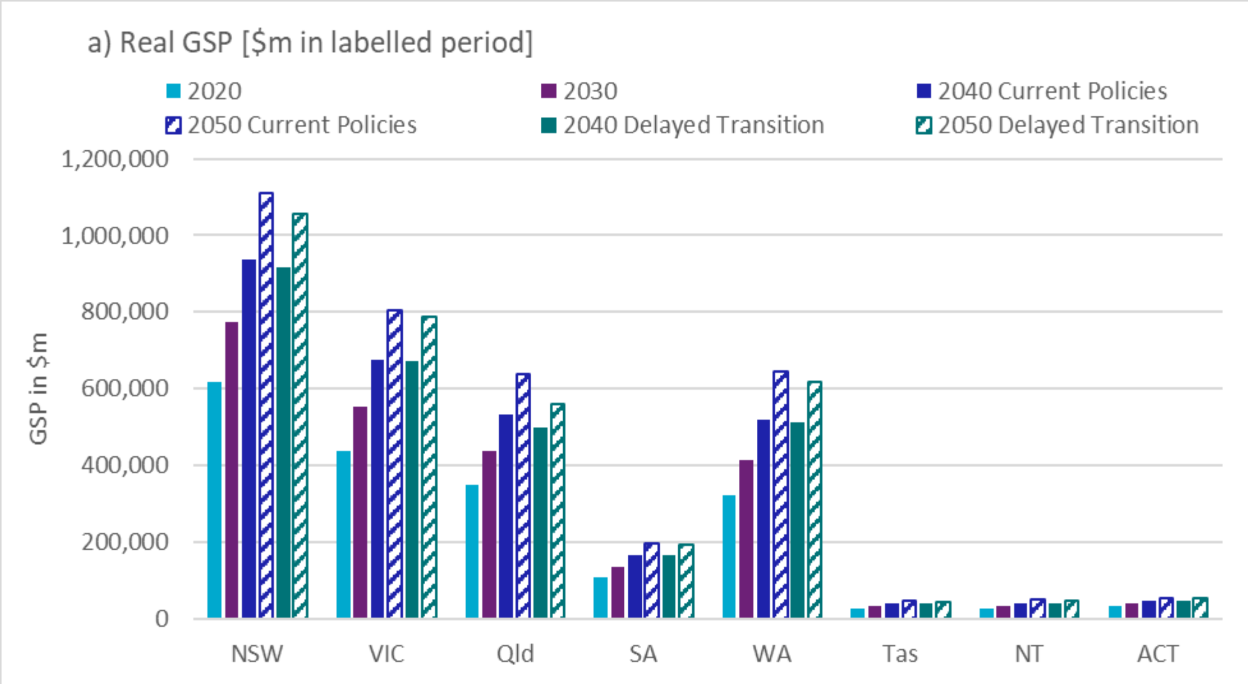
Complicating the impacts of climate change is the renewed focus on regionalisation in Australia driven by a range of lifestyle and affordability factors alongside preference shifts, in part driven by the impact of the COVID-19 pandemic. Taken to extremes, these shifts have the potential to leave some urban assets 'stranded', or at least overvalued, whilst the growth of regional populations is likely to take place in areas exposed to climate risk through the factors identified above.

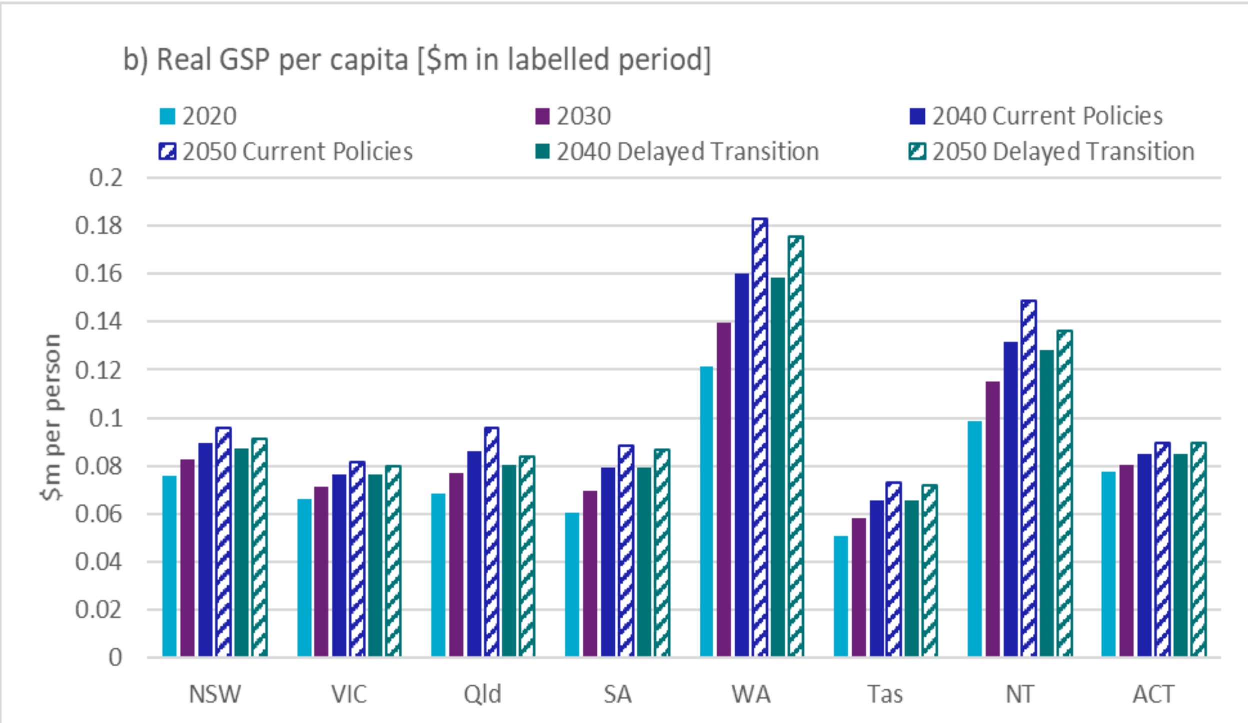
6.3 A varying impact across Australia

The economic implications of the Current Policies scenario, contrasted with the Delayed Transition scenario, indicate substantial differences across states and key industries. Rapid decarbonisation under the Delayed Transition scenario delivers lower gross state product than under Current Policies in all states

[40] See, for example, the NiGEM model (https://nimodel.niesr.ac.uk/).

except the ACT. However, Queensland's GSP is the most impacted due to the size of its export coal industry relative to the wider state economy (Figure 27). Although NSW coal exports are similarly exposed, coal mining forms a much smaller proportion of the overall economy. Longer term employment effects play out through labour-force participation, which falls slightly in most states (or some 220,000 people overall).





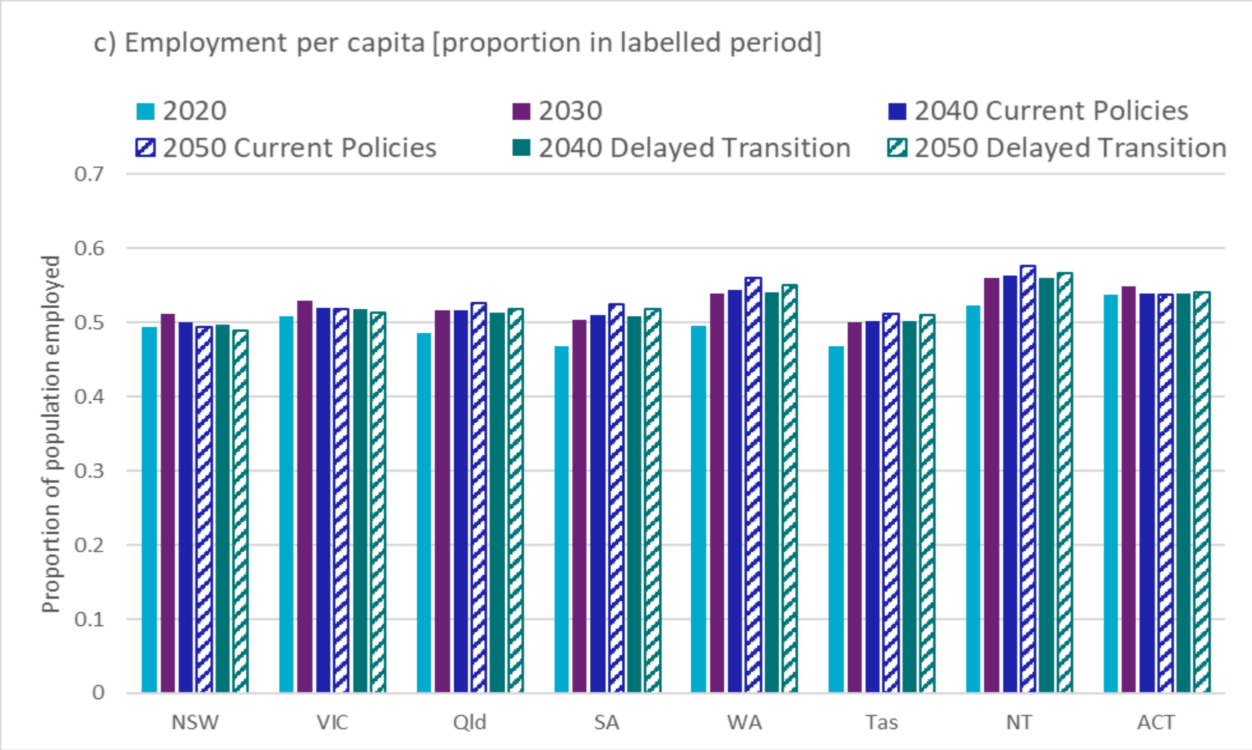
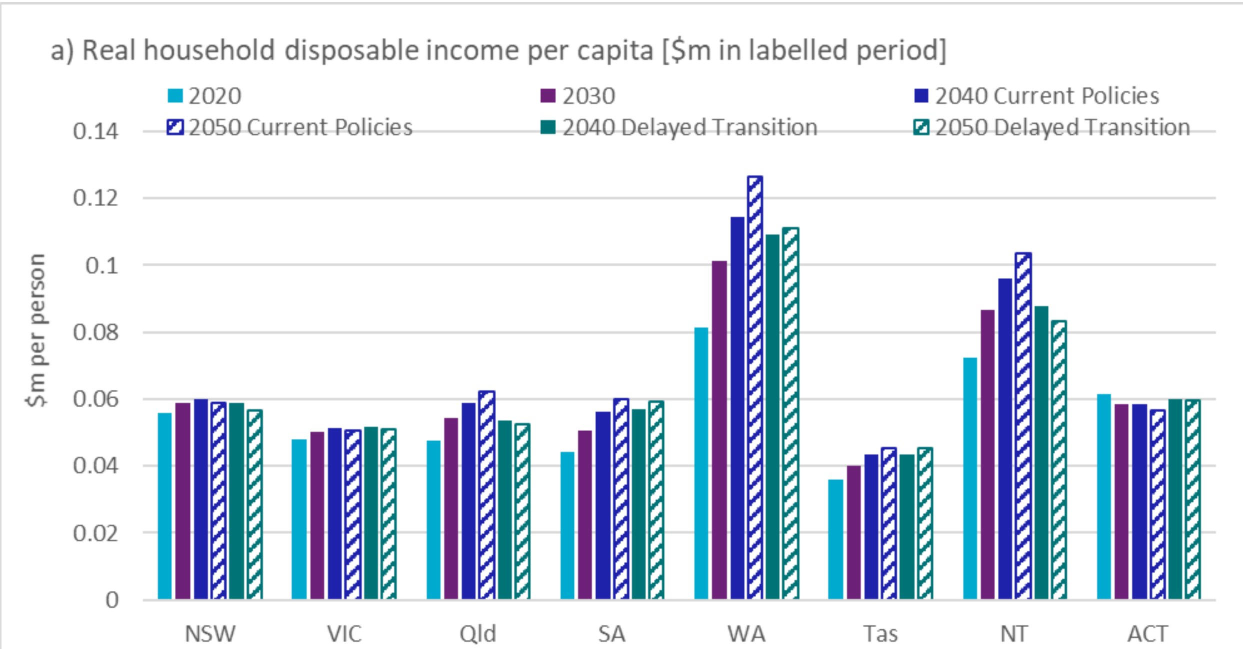
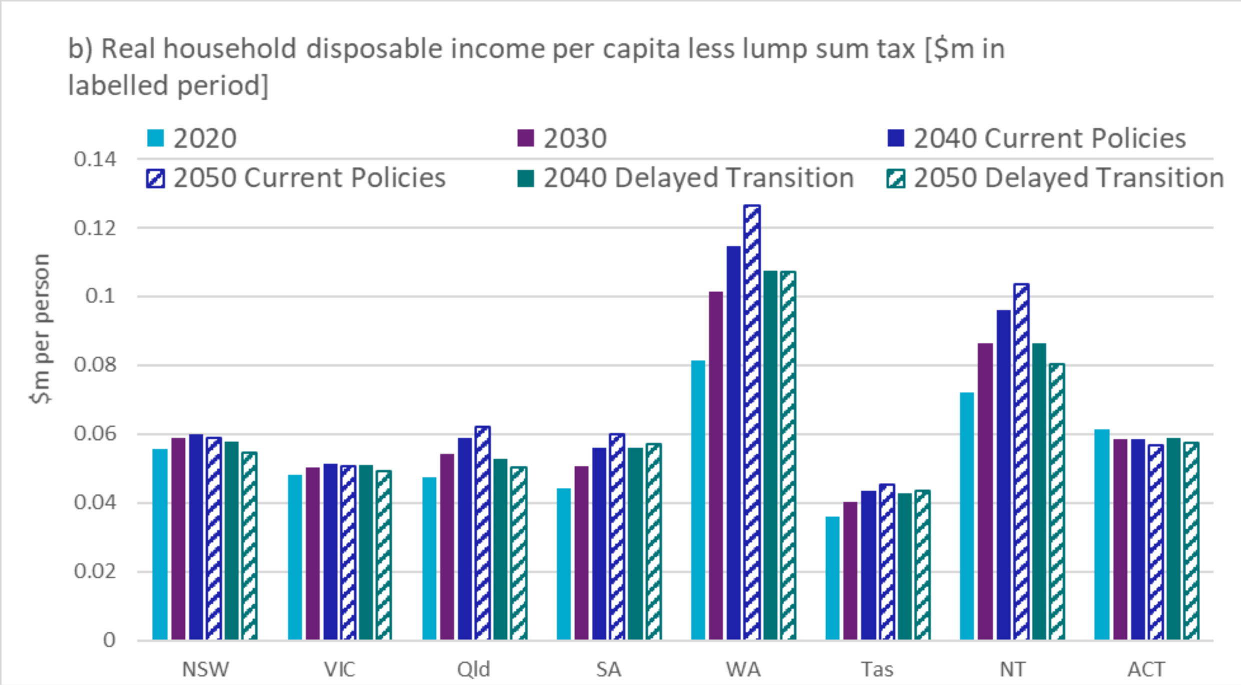


Figure 27 Real gross state product and real gross state product and employment per capita

Differences in impact play out most strongly through household consumption and disposable income. Falling real wage rates (not shown) under Delayed Transition lead to lower real household disposable income per capita in most states, particularly in export-exposed Queensland, WA and NT (Figure 28). Similarly, per capita household consumption is lower under the Delayed Transition in all states (except the ACT), but most particularly in Queensland and the NT. Note, however, that the largest differences in household consumption under a Delayed Transition relative to current 2020 incomes are in NSW, Victoria and the ACT (~-10%) whereas in other regions household income and consumption increase over time irrespective of the transition scenario.





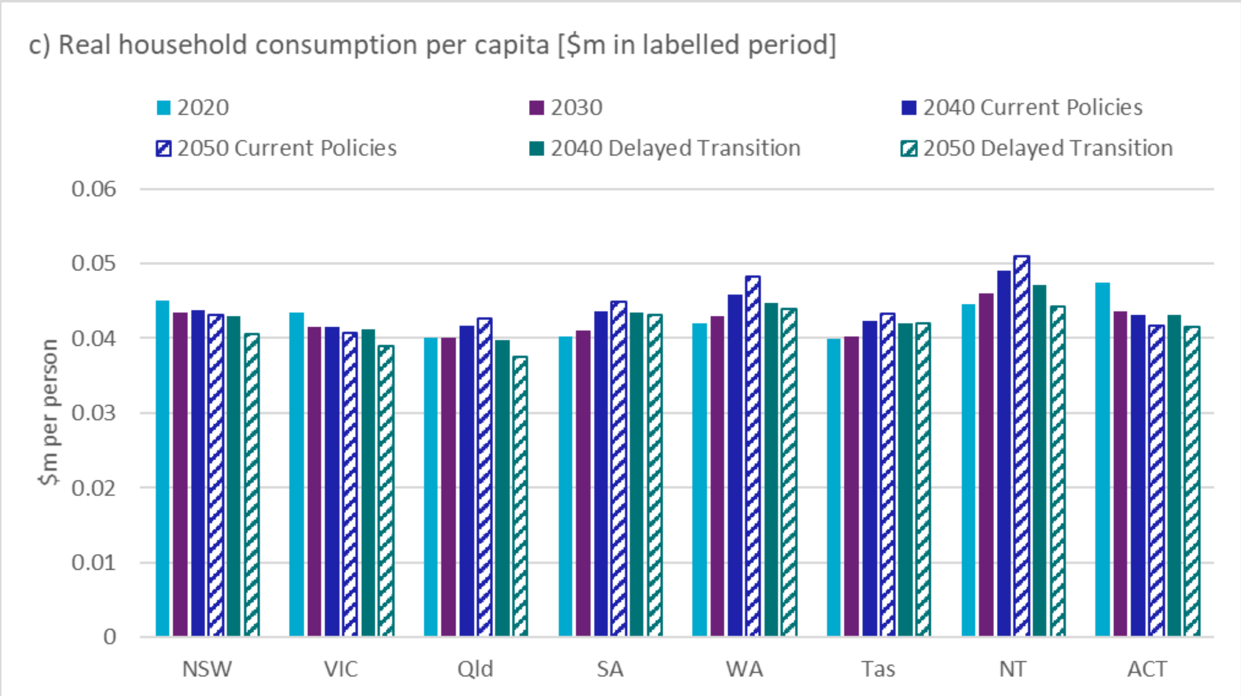
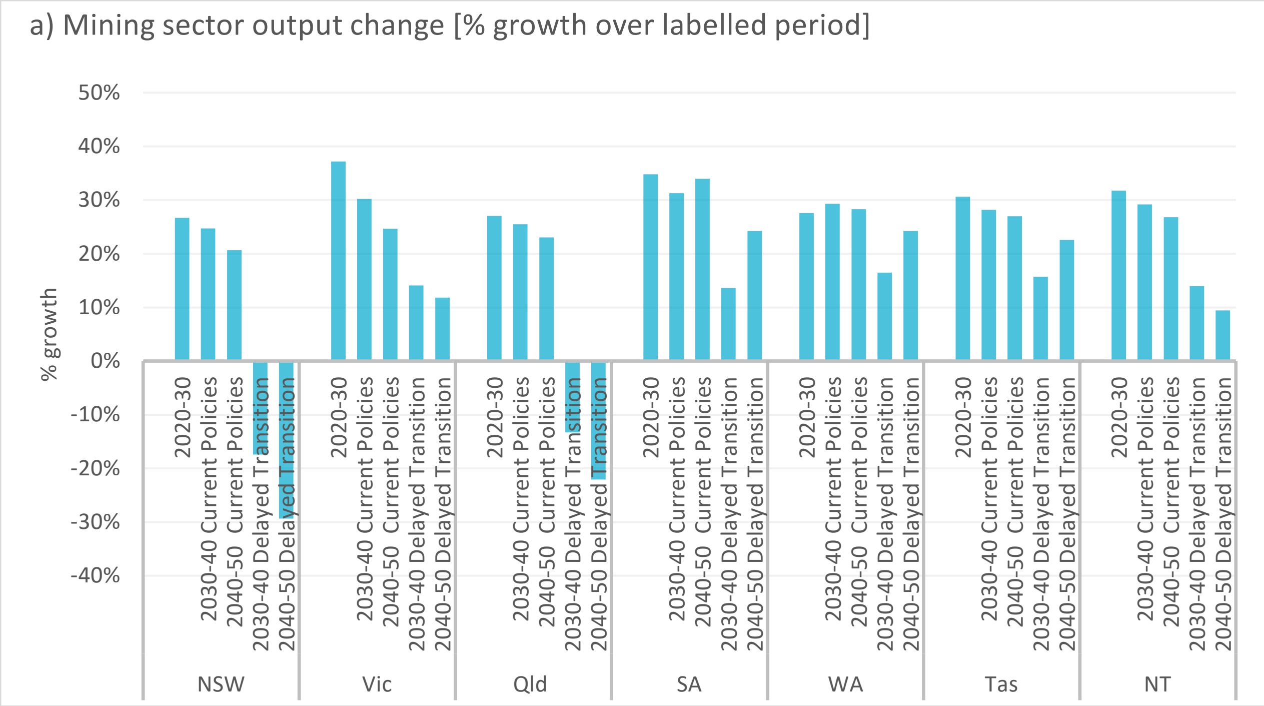


Figure 28 Real gross state product and real gross state product and employment per capita

Sectoral effects are also more nuanced at the regional level. Mining impacts reflect the lower coal exports under the Delayed Transition scenario and dramatically lower Queensland and NSW output (Figure 29(a)). Agricultural, manufacturing and construction impacts are consistently lower under the Delayed Transition scenario across regions relative to Current Policies (Figure 29(b), (c), (d)) – although agriculture and construction are both subject to a range of acute climate risks not explored in this modelling. Low emission, service-oriented sectors, which dominate employment in Australia, are initially impacted in the 2030–2040 period, but then rebound to similar or higher levels of growth than Current Policies (Figure 30(a), (b), (c)).[41]

[41] Regional results for all sectors shown in appendices.


a) Mining sector output change [% growth over labelled period]
50%
40%
30%
20%
10%
0%
-10%
-20%
-30%
-40%
% growth
2020-30
2030-40 Current Policies
2040-50 Current Policies
2030-40 Delayed Transition
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NSW
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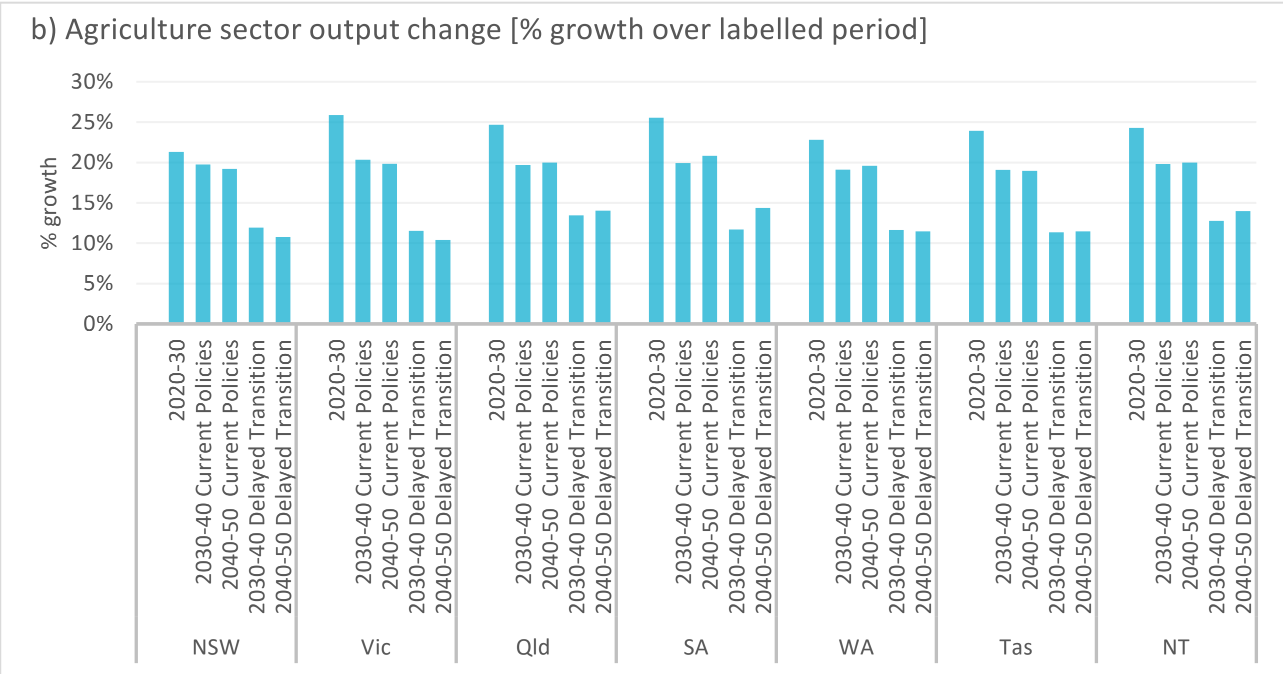
b) Agriculture sector output change [% growth over labelled period]
30%
25%
20%
15%
10%
5%
0%
% growth
2020-30
2030-40 Current Policies
2040-50 Current Policies
2030-40 Delayed Transition
2040-50 Delayed Transition
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SA
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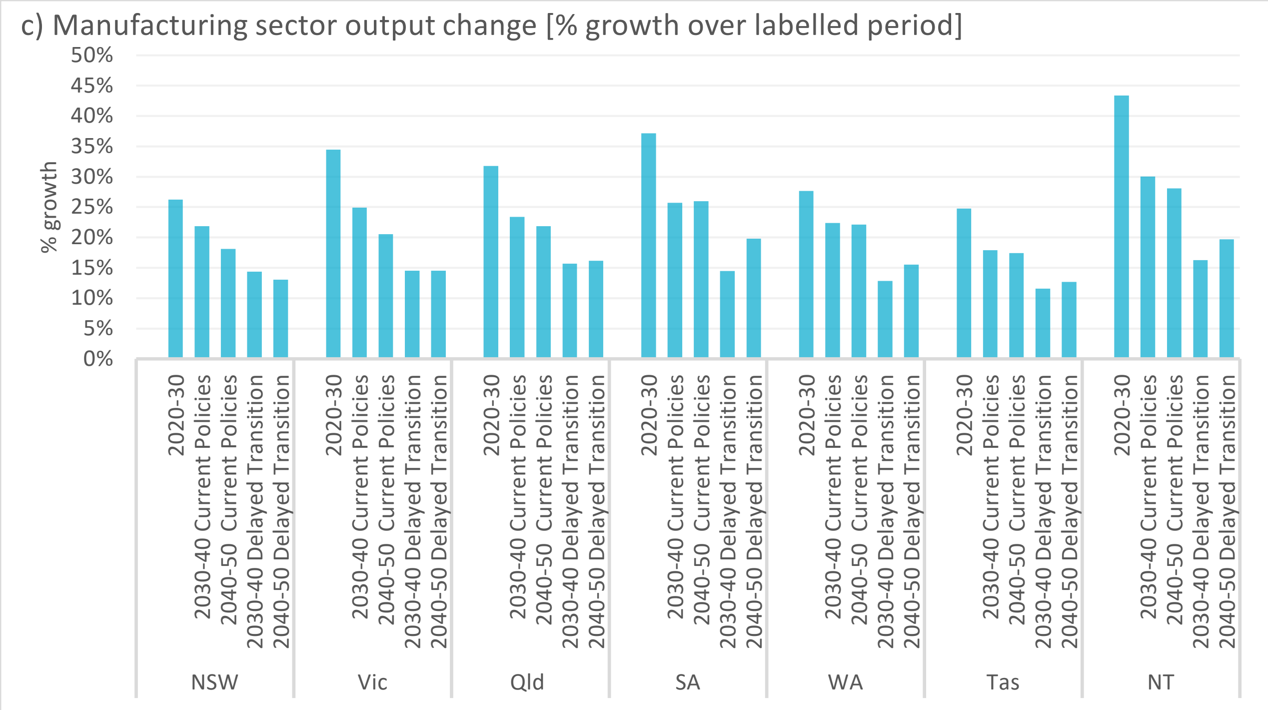
NT



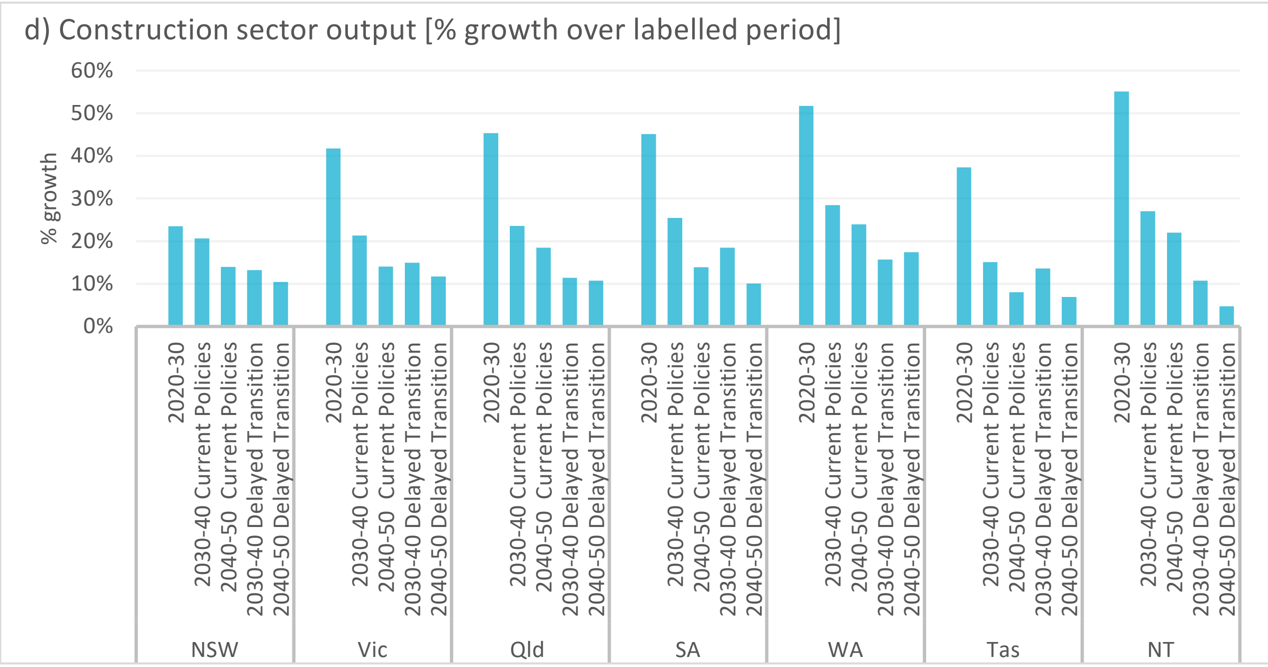
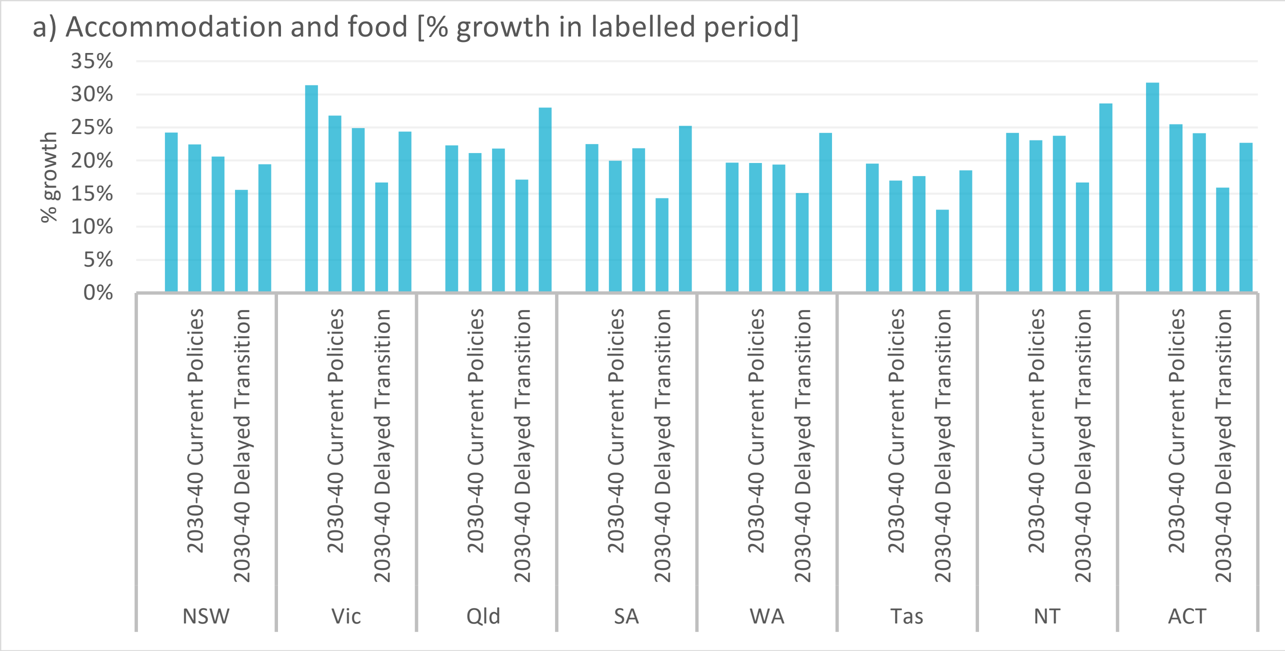
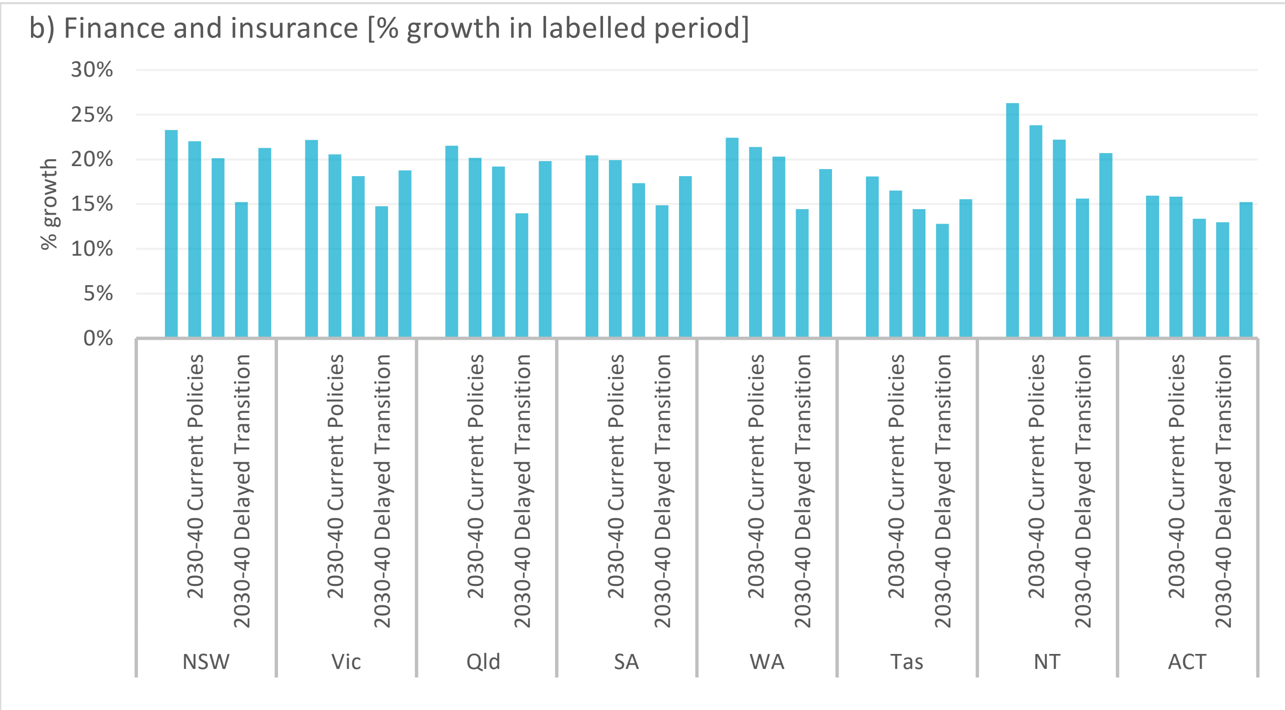


Figure 29 Mining, agriculture, manufacturing and construction output shifts across regions (KPMG-EE model outputs, ACT not shown)


a) Accommodation and food [% growth in labelled period]
% growth
35%
30%
25%
20%
15%
10%
5%
0%
2030-40 Current Policies
2030-40 Delayed Transition
NSW
Vic
Qld
SA
WA
Tas
NT
ACT


b) Finance and insurance [% growth in labelled period]
% growth
30%
25%
20%
15%
10%
5%
0%
2030-40 Current Policies
2030-40 Delayed Transition
NSW
Vic
Qld
SA
WA
Tas
NT
ACT

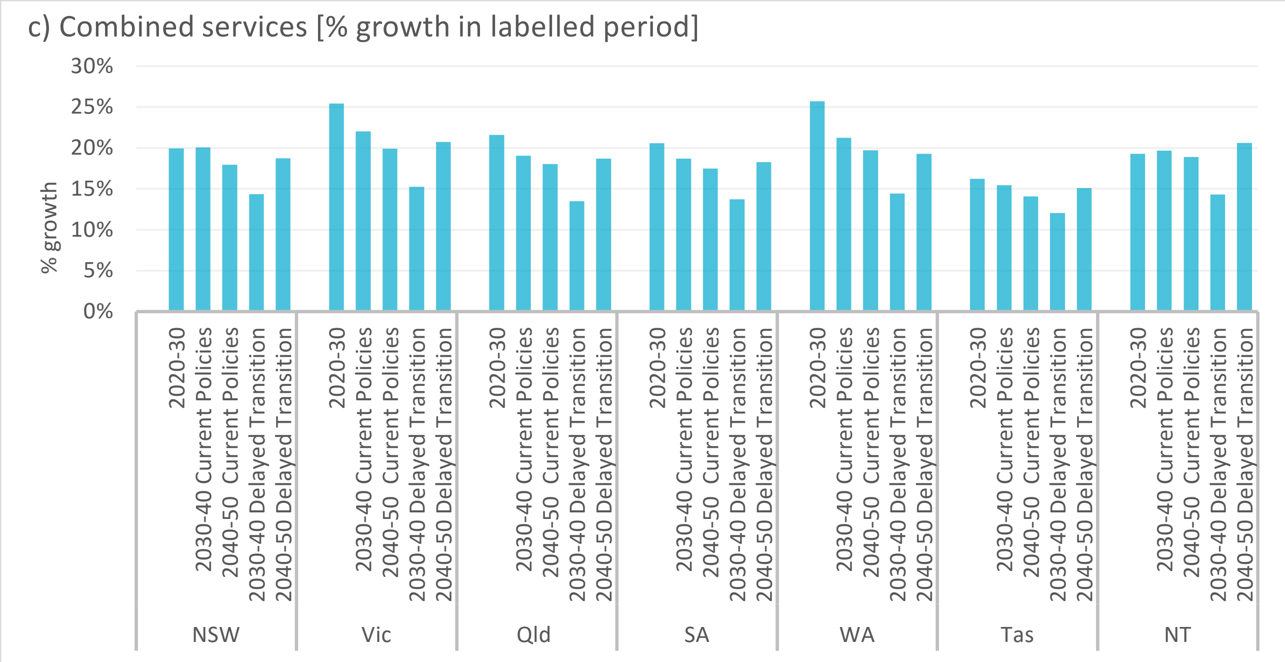


Figure 30 Accommodation and food, finance and insurance and combined services[42] (KPMG-EE model outputs, ACT not shown)

More detailed information about sectoral implications in States and Territories can be found in the appendices, Section 8.5.

[42] Combined services include information, media and telecommunications, rental, hiring and real estate, professional, scientific and technical services, administration and support services, public administration and safety, education and training, health care and social assistance, arts, recreation and other services.

7 Concluding remarks and future directions

The NGFS scenarios aim to provide a common starting place to examine physical and transition risks – particularly focusing on the finance sector. As a first step in understanding the application of the NGFS to Australia, two scenarios, *Current Policies* and *Delayed Transition*, were selected to examine the transition and chronic physical impacts on the Australian economy to 2050 across the Australian economy. These model results also inform the direction, but not the speed or other policy shifts that may be implemented, as Australia moves towards realising its net zero by 2050 commitment.

7.1 Sector impacts

The analysis provides a first step to identify which industries may have greater opportunities or exposure to climate-related risk if the transition to a low carbon economy is delayed. Fossil fuel intensive industries (fossil fuel sourced electricity, coal and gas production) are the most adversely impacted, as expected, in the emission-constrained Delayed Transition scenario. This is driven by the delayed and then rapid transition to renewable energy sources, electrification and negative emission technologies. From a global perspective, Australia, as a major supplier of high-quality thermal coal and gas, is particularly exposed to potential declines in export demand.

Declines in other industries are also observed across emissions-intensive mining, mineral processing, and agriculture. Within these sectors the potential impacts are more nuanced:

- Coal mining and mineral processing, particularly ferrous metals, decline, yet the transition to a low carbon economy will require an increase in copper, nickel, lithium and other rare earth metals driven by batteries and electrification[43]
- Agriculture production will decline but increased demand combined with adaptation and resilience measures can mitigate economic impacts for crop and livestock production
- Hydrogen presents a significant opportunity for use within industrial processes such as steel production and decarbonising across industrial and residential heating uses (although not modelled here).

Substantial growth and transition are demonstrated in renewable energy sources, accompanied by continuing improvements in energy efficiency in electricity usage, presenting a range of opportunities across the economy. Furthermore, the analysis potentially understates some of the opportunities in emerging industries, such as hydrogen and commodities to facilitate low carbon industries, but also does not incorporate important chronic and acute risks to some sectors and regions such as shifts in rainfall and sea level rises.

The analysis also illustrates that impacts will vary across Australia. Sectoral impacts of rapid decarbonisation in the coal industry particularly impact Queensland and to a lesser extent NSW, yet the overall economic impacts on household income and consumption are highest relative to current levels in NSW and Victoria and only to a lesser extent Queensland. This type of variability in sectoral and overall economic impact illustrates the need to differentiate between sectoral risk to business and more general changes in risk to household finance.

7.2 Key insights for the global and Australian economy

Transition to a low carbon economy will require substantive transformation of the global and Australian economy. Australia is highly exposed to global trade and our emissions-intensive exports are vulnerable to the energy transition plans of global economies. Australia's net zero 2050 target provides a clear economic

[43] https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions

signal for decarbonisation, however Australia's current 2030 target of 26–28% reduction on 2005 emissions levels would leave significant decarbonisation required in the latter two decades. Higher short-term ambition coupled with domestic policy certainty could assist to smooth the transition, avoid shocks, allow coordinated transition plans to be developed for the most vulnerable industries, and enable higher confidence to attract investment in emerging low emissions industries and technologies. It may also help support the long lead time to develop alternative exports such as minerals necessary to support transition.

For emissions-intensive industries, the potential divergent outcomes highlight substantive transition risks. Rapid decarbonisation of the global electricity sector impacts coal, as the highest emitting fossil fuel, and to a lesser extent gas, as wind and solar energy generation increases. Methane emissions in the agricultural sector are also a key risk to Australia. Similarly, future analysis should consider the disruptive technology impacts and risks from rapid electrification across the economy.

The modelling highlights the high reliance on negative emissions technologies to achieve net zero under the delayed transition scenario rising to 9,000 $MtCO_2e$ by 2050. Whilst this modelling is technology agnostic, the challenges of deploying, scaling and commercialising negative emissions technologies should not be underestimated. Challenges include technical and commercial maturity, Australia's geographic spread means emissions sources suited to direct capture may be far from potential underground storage locations, and at risk of cost and yet to be developed technology requiring significant research and development.

Reliance on offsets could serve to delay the transition to a low carbon economy if they are deployed in preference to decarbonisation and structural abatement. This could create material economic risks for Australia. Likewise planning for, and failing to realise, this level of sequestration could result in a shock to emissions-intensive economies.

7.3 What else needs to be done?

This analysis investigates the implications of two NGFS scenarios on Australia. It does not take into account the range of transition risks under different socioeconomic settings, levels of ambition domestically or globally, or investigate an orderly pathway to net zero. This model selection has numerous consequences for the insights. It may underestimate the transition risk to a low carbon economy for the Australian financial sector. To improve understanding, the modelling approach will need to be expanded to test:

- **A broader range of socioeconomic settings** – the NGFS considers one of five SSPs from IPCC's AR6 report, the 'middle of the road' scenario (SSP2). Extension to a wider range of SSPs will provide a more comprehensive view of transition risks within the market. Failure to consider the suite of SSPs could provide false security to the financial sector.
- **Acceleration of the rate of transition** – both scenarios considered in this analysis assume business-as-usual conditions globally until 2030. Earlier or faster transition to net zero economies will accelerate the rate of change and risks to exposed sectors whilst slower, more orderly transitions slow the rate of change for exposed sectors but may be incorporated. Similarly, while this analysis focused on a transition through 2050, a longer assessment period would allow for greater consideration of growing chronic and acute physical risks from climate change.
- **Different integrated assessment models (IAMs)** – use of different underlying IAMs (which differ in their inherent assumptions and how they are tuned) would provide a range of outcomes that may reveal different insights into the nature of transition risk.
- **Sensitivity of results to different sequestration assumptions** – the NGFS results have a high reliance on technical and biological sequestration options, which should be tested for their sensitivity to understand risk to emissions-intensive industries.

Continual improvements to modelling are recommended to capture:

- Interconnection between transition and physical risks with updated damage functions
- Carbon border adjustment mechanisms or carbon tariffs

- Supply chain limitations of a rapidly expanding renewable sector (e.g. rare earth elements, cobalt, lithium)
- Migration policies
- Feedbacks to regional economies.

Climate risk is a dynamic and complex issue across many sectors of the Australian economy. As the transition to a low carbon economy accelerates, emissions-intensive sectors will decline with renewables, electrification and alternatives providing attractive growth opportunities. This first step analysis demonstrates, not unexpectedly, the elevated risks to emissions-intensive industries, particularly coal and to a lesser extent gas. Yet the narrow model selected (particularly limited to SSP2-aligned NGFS) highlights that a more comprehensive transition risk assessment is warranted. The direction of this field is moving toward including more physically motivated, sector-specific climate induced chronic and acute damages.[44] Furthermore, sophistication in analyses will continue to develop as new models, datasets and information evolve. Coincident and compound risks will need to be factored into risk assessment. Bringing these risks and opportunities into future work will provide more informative results of downscaled and sector-specific effects and the adjustment options available to Australian firms and regions.

Clearly the challenge is to equip industry, governments and other civil society actors with knowledge, capability and capacity to engage with a rapidly evolving and sophisticated issue. As an example, climate change impacts are an increasingly core component in financial institutions' risk appetite and investment decisions, and ought to be considered as such. This will require a shift in thinking and investment in time, people and resources to address these issues in that sector and elsewhere across the Australian economy.

[44] Inter-sectoral impact model intercomparison project (ISIMIP).

8 Appendices

8.1 GTEM model specifications

This report applies the CSIRO version of the Global Trade and Environment Model (GTEM) to understand the global economic implications of climate risk. GTEM is a dynamic global CGE model that has been designed to analyse the energy-carbon-environment nexus. The GTEM model data and theory is described in detail by Cai et al. (2015). This section provides a brief overview of GTEM partly based on Cai et al. (2015) and also describes the model developments that postdate Cai et al (2015).

Overview

GTEM has been applied to a wide range of climate and environmental issues including climate mitigation (Garnaut, 2008) and food security (Scealy et al., 2012). GTEM is a multi-region multi-sector, dynamic computable general equilibrium model. GTEM is calibrated to reproduce economic and energy patterns in the initial year (2014) as captured by the GTAP 10 database (Aguiar et al., 2019) and greenhouse gas emissions as prescribed for RCP4.5. The underlying GTAP 10 database can be aggregated into different regional configurations in order to study specific questions; here the database is aggregated to 23 regions and 25 sectors (see Table A 1 and Table A 2) based on their significance to the global economy and importance to Australian trade.

Producer behaviour

Each sector in the economy (represented by a nested CES production function) produces goods and services that are used for private or government consumption, investment, intermediate demand or exported. Each sector uses as inputs commodities that can be produced domestically or imported and primary factors: land, natural resources, labour and capital. Both land and natural resources are treated as sector-specific factor endowments that are largely immobile across sectors. More specifically, agriculture, livestock production and forestry biomass, are all constrained by available land. Coal, oil, natural gas and other mining products are subject to finite natural resource constraints as well as decreasing extraction efficiency. Labour grows according to demographic and labour force participation assumptions and is constrained by the available working population, which is suppled exogenously to GTEM as part of the population growth trajectories. The growth over time of a region's capital stock is modelled differently to other primary factors. The capital stock changes over time according to the level of investment minus the level of depreciation of existing capital.

International trade and investment

Regions are linked by bilateral trade flows in each commodity. For each region, total imports of each commodity are sourced from each of the other regions according to the relative prices of commodities from each region. Commodities are assumed to be geographically differentiated, so that each region will purchase from a diversity of sources and can potentially be an exporter and importer of the same commodity, in accordance with observed trade patterns.

Regions are also linked by foreign income flows generated by net debt. Debt in each region accumulates over time according to the gap between savings, which fund the expansion of a region's capital stock or of a foreign region's capital stock, and investment, which may need to be partially funded by foreign borrowing if domestic savings is inadequate.

Electricity technologies

A distinctive feature of GTEM is that electricity generation is modelled by an energy technology bundle that can represent a wide range of electric energy. Here we distinguish 12 electricity technologies: see Table A 3.

Table A 1 GTEM regional aggregation

Region key	Description
AUS	Australia
NZL	New Zealand
OCN	Rest of Oceania
CHN	China, Hong Kong
JPN	Japan
KOR	South Korea
REA	Rest of East Asia: Mongolia, Taiwan
ROA	Rest of Asia: Brunei Darussalam, Cambodia, Lao Peoples Democratic Republic, Malaysia, Philippines, Singapore, Thailand, Viet Nam, Rest of Southeast Asia, Bangladesh, Nepal, Pakistan, Sri Lanka, Rest of South Asia
IDN	Indonesia
IND	India
CAN_XNA	Canada, Rest of North America
USA	USA
MEX	Mexico
SAM	South America: Argentina, Bolivia, Chile, Colombia, Ecuador, Paraguay, Peru, Uruguay, Venezuela, Rest of South America, Costa Rica, Guatemala, Honduras, Nicaragua, Panama, El Salvador, Rest of Central America, Dominican Republic, Jamaica, Puerto Rico, Trinidad and Tobago, Caribbean
BRA	Brazil
EU15	Austria, Belgium, Demark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, Netherlands, Portugal, Spain, Sweden, United Kingdom
EU12	Bulgaria, Cyprus, Czech Republic, Estonia, Hungary, Latvia, Lithuania, Malta, Poland, Romania, Slovakia, Slovenia
ROEUR	Rest of Europe: Croatia, Switzerland, Norway, Rest of EFTA, Albania, Belarus, Ukraine, Rest of Eastern Europe, Rest of Europe, Turkey
RUS	Russia
FSU	Former Soviet Union: Kazakhstan, Kyrgyzstan, Tajikistan, Rest of Former Soviet Union, Armenia, Azerbaijan, Georgia
MDE	Middle East
AFR	Africa
ROW	Rest of World

Greenhouse gases

GTEM produces estimates of global emissions for the following greenhouse gases: carbon dioxide, methane, nitrous oxide, and a range of fluorinated gases. The global path of these gases has been exogenously imposed for consistency with the relevant NGFS scenarios.

Negative emissions technologies

A major recent development to GTEM has been the addition of negative emissions technologies (NET): see Table A 4. Dean (2011) provides guidance on the nature and cost structure of NET. In GTEM, negative emissions technologies are treated as extra categories of final demand rather than as industries that produce and sell outputs to other industries and final demanders. This approach is consistent with NET being investment activities that add to the carbon budget just as conventional investment adds to the stock of capital. The typical GTEM treatment of NET investment activities is that they are driven by the carbon price. However, in this work a global path for NET investment activities (measured in terms of CO_2-e sequestration) has been exogenously imposed for consistency with the relevant NGFS scenarios.

Table A 2 GTEM sectoral aggregation

Commodity key	Description
CROPS	Crops: Paddy rice; Wheat; Cereal grains; Vegetables, fruit, nuts; Oil seed; Sugar cane, sugar beet; Plant-based fibre; Crops
LSTK	Livestock: Bovine cattle, sheep and goats, horses; Animal products; Raw milk; Wool, silk-worm cocoons
FRS	Forestry
FISH	Fishing
COL	Coal
OIL	Oil
GAS	Gas
OMN	Other extraction
FOOD	Food: Bovine meat products; Meat products; Vegetable oils and fat; Dairy products; Processed rice; Sugar; Food products; Beverages and tobacco products
MANU	Manufacturing: Textile; Wearing apparel; Leather products; Wood products; Paper products, publishing; Metal products; Computer, electronic and optical products; Electrical equipment; Machinery and equipment; Motor vehicles and parts; Transport equipment; Manufacture
P_C	Petroleum, coal products
CHM	Chemicals
CRP	Basic pharmaceutical products; Rubber and plastic products
NMM	Other mineral products
I_S	Ferrous metals
NFM	Other metals
ELY	Electricity
GDT	Gas manufacture, distribution
WTR	Water
CNS	Construction
SVCE	Trade; Accommodation, Food and service activities; Warehousing and support activities; Communication
OTP	Other transport
WTP	Water transport
ATP	Air transport
OFI_INS	Financial services; Insurance

Table A 3 GTEM electricity technologies

Electricity Technologies
coal
oil
gas
nuclear
hydro
wind
solar
all other renewables
CoalCCS
OilCCS
GasCCS
BioenergyCCS

Table A 4 GTEM negative emissions technologies

Negative Emissions Technologies
Artificial trees (direct air capture)
Soda lime
Olivine
Bioenergy with CCS

Climate-economy interactions

For the scenarios analysed here, the climate-economy interactions are modelled using the MERGE damage function (Manne and Richels, 2004). The MERGE function combines three distinct elements of the response of a regional economy to climate warming in a single function. These are first, the degree of climate change, as represented by the surface air temperature, at which economic activity ceases; second, the resilience of the economy to this warming; and third, the capacity of the region to avoid the damage by paying for adaptation or regional mitigation measures. The damage function calculates region-specific economic loss factors. These are linked to an index of primary-factor-augmenting technical change. The link is specified so that a rise in regional average temperature leads to a loss in economic wellbeing through a decline in factor productivity across all sectors.

8.2 KPMG-EE model specifications

Overview

The KPMG-EE model is used in this work to understand how global changes captured by the GTEM model influence sectoral and regional impacts in the Australian economy. KPMG-EE is a dynamic CGE model of the Australian economy with a focus on energy and the environment. The core data, theory and parameters of KPMG-EE is based on the model formally presented in Verikios et al. (2021). Below we provide an overview of KPMG-EE particularly aspects not captured in Verikios et al. (2021).

In basic form, KPMG-EE distinguishes 114 sectors and commodities based on the 2017-18 input-output tables published by the Australian Bureau of Statistics - see ABS (2020). Primary factors are distinguished by 114 types of capital (one type per industry), nine occupations, two types of land, and natural resource endowments (one per industry).

KPMG-EE models the economy as a system of simultaneous equations that represent interrelated economic agents operating in competitive markets. Economic theory specifies the behaviour and market interactions of economic agents, including consumers, investors, producers, and governments. These agents operate in domestic and foreign goods markets, and capital and labour markets. These relationships are represented in detail in the diagram below.

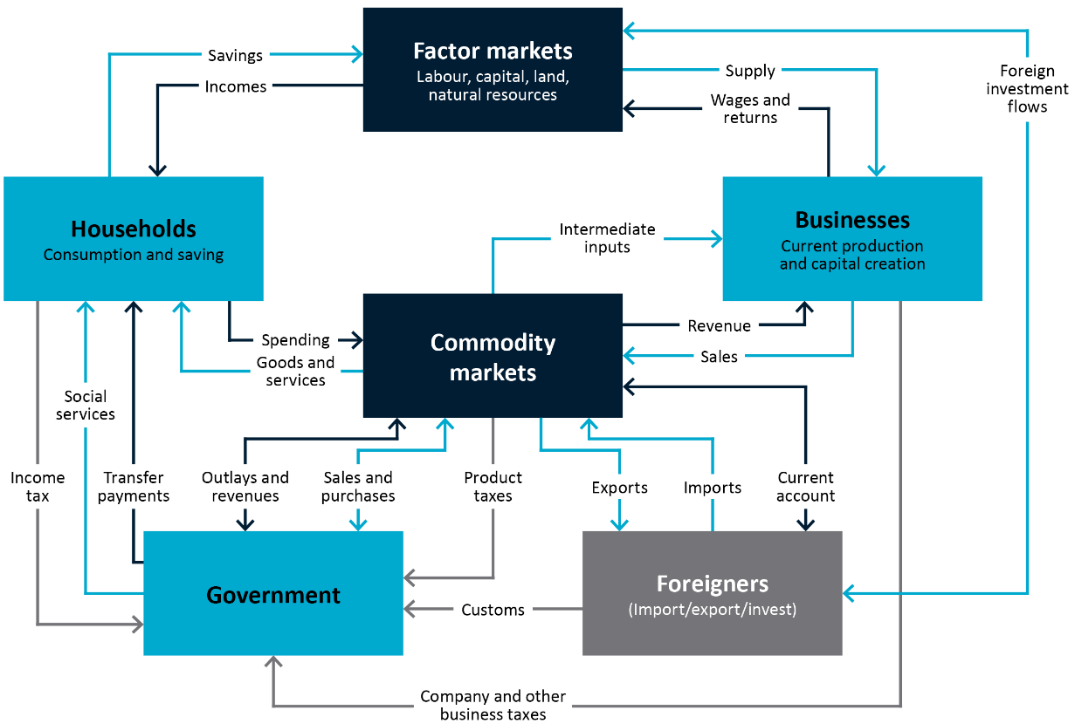


Figure A 1 KPMG- EE model

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

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

Producer behaviour

A representative firm in each sector produces a single commodity. Commodities are distinguished between those destined for export markets and those destined for domestic markets. Production technology is represented by nested CRESH functions (Hanoch, 1971) allowing a high degree of flexibility in the parameterisation of substitution and technology parameters. Energy goods are treated separately to other intermediate goods and services in production and are complementary to primary factors.

Labour market

The supply of labour is determined by a labour-leisure trade-off that allows workers in each occupation to respond to changes in after-tax wage rates thus determining the hours of work they offer to the labour market. The overall supply of labour is normalised on working-age population. In standard form, labour supply is represented by 8 broad occupations that map to ANZSCO (Australian and New Zealand Standard Classification of Occupations) 1-digit occupations. The 1-digit occupations map to the 5 skill levels identified in ANZSCO. In each region, the supply of and demand for labour by occupation determines the occupational wage rate. Each labour type can move across industries in a region given occupational wage rates. Thus, labour supply and demand are occupation-specific but not industry specific.

Household behaviour

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

Investment behaviour

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

Calibration

The key data inputs to KPMG-EE are input-output (IO) tables. The tables quantify 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 IO tables also quantify the flows associated with primary factor inputs: labour, capital, land, and natural resources. In KPMG-EE, the data inputs are combined with the model’s theoretical structure to quantify behavioural responses, including:

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

Behavioural responses relating to household demand and import-domestic substitution are driven by parameters estimated using Australian data; see Verikios et al. (2021), sections 16 and 17.

Sectoral and regional detail

In this work we apply KPMG-EE with 51 sectors and eight regions, see Table A 5 and Table A 6. The eight regions represent the Australian states and territories. KPMG-EE represents each region as a separate economy linked by interstate flows of commodities, investment, and labour. The IO and other data for each region is created from national IO and other data using a combination of industry shares in employment or labour hours and commodity-specific consumption shares to split industries, investment and government and private consumption across regions. This process also applies unpublished ABS trade data and census data. The shares are sourced from ABS (2020b, 2020c, 2020d).

Table A 5 KPMG sectoral aggregation

Sectoral key	description
ShpGrnBfDy	Sheep, grains, beef and dairy cattle
PolOthLiv	Poultry and other livestock
OthAg	Other agriculture
Acqua	Aquaculture
ForLog	Forestry and logging
FshHntTrp	Fishing, hunting and trapping
Coal	Coal mining
Oil	Oil extraction
Gas	Gas extraction
IrnOre	Iron ore mining
OthMin	Other extraction
Food	Food
Bev	Beverages
TCF	Textiles, clothing, footwear
Wood	Wood products
PulPapPrn	Pulp, paper, printing
PetCoal	Petroleum, coal products
BasChm	Pharmaceuticals, medicines
ChmRubPlas	Chemical, rubber, plastics

NonMetMin	Non-metallic mineral products
IrnStl	Iron, steel
OthMet	Other metal products
TrnEq	Transport equipment
ElcOthEq	Electrical and other equipment
OthMan	Other manufacturing
Elec	Electricity
GasSup	Gas supply
WatSew	Water, sewerage, drainage
ResCon	Residential construction
NonResCon	Non-residential construction
OthCon	Other construction
WhlRetTrd	Wholesale, retail trade
AccFodBev	Accommodation, food & beverage services
RoadTrn	Road transport
RailTrn	Rail transport
WatOthTrn	Water, other transport
AirTrn	Air transport
PstWhr	Postal, warehousing services
InfMedTel	Information, media, telecommunications
Fin	Finance
InsSup	Insurance
RntHreRE	Rental, hiring services, real estate
Dwell	Ownership of dwellings
PrfSciTch	Professional, scientific, technical services
AdmSup	Administrative, support services
PubAdm	Public administration, order, safety
EduTra	Education, training
HeaResSoc	Health, residential, social services
ArtRec	Arts, recreation
OthSrv	Other services

Table A 6 KPMG regional aggregation

Region key	description
WA	Western Australia
SA	South Australia
NT	Northern Territory
QLD	Queensland
NSW	New South Wales
ACT	Australian Capital Territory
VIC	Victoria
TAS	Tasmania

A key feature of KPMG-EE is a detailed representation of electricity technologies. In this work we explicitly represent 11 electricity technologies, see Table A 7. Each of these technologies represent individual industries. However, each electricity industry produces the same commodity (electricity). This represents a joint production approach to representing multiple electricity technologies. Note that this differs from the technology bundle approach in GTEM where each technology bundle essentially represents a satellite model and database.

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

- The Australian Government: Australian Energy Statistics (see https://www.energy.gov.au/government-priorities/energy-data/australian-energy-statistics),

- The Australian Energy Market Operator (see https://www.aemo.com.au/), and
- CSIRO (e.g., Graham et al., 2020).

Table A 7 KPMG electricity technologies

Electricity Technologies
oil
gas
hydro
wind
solar
all other renewables
CoalCCS
OilCCS
GasCCS
BioenergyCCS

8.3 GTEM region and sector model output summary for all regions/sectors

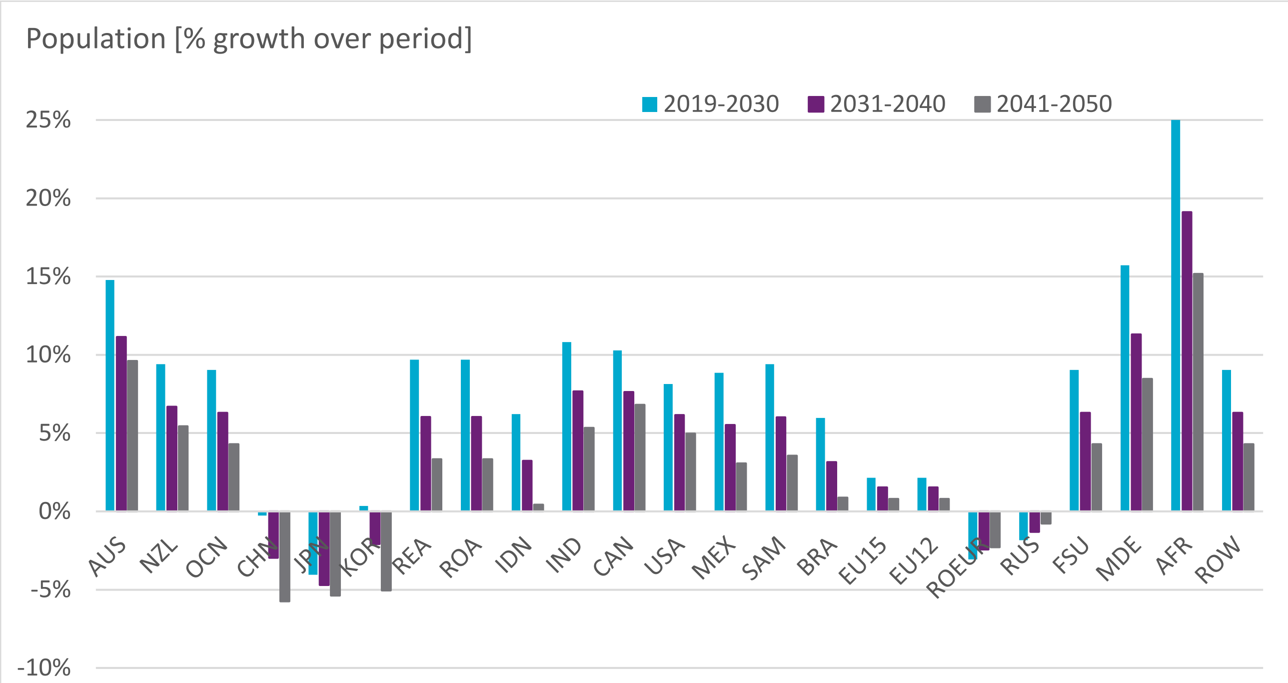


Figure A 2 Population growth by region

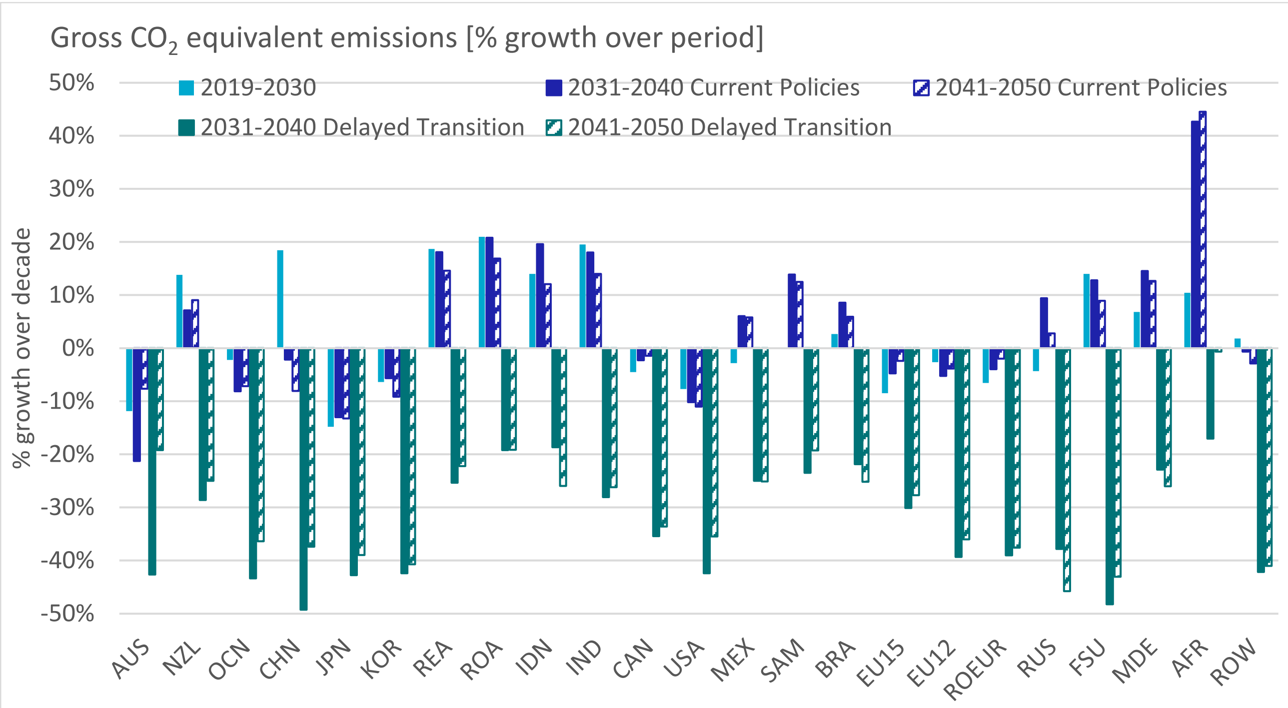


Figure A 3 Gross CO_2 equivalent emissions by region

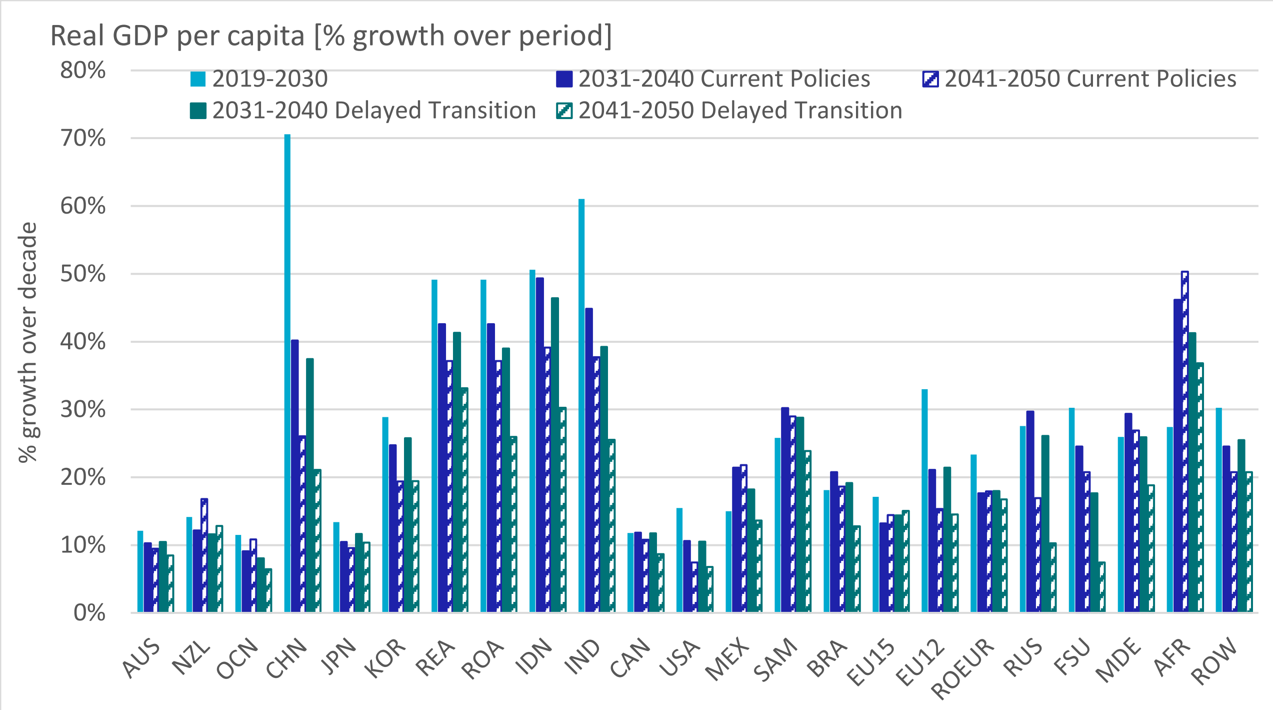


Figure A 4 Real GDP per capita by region

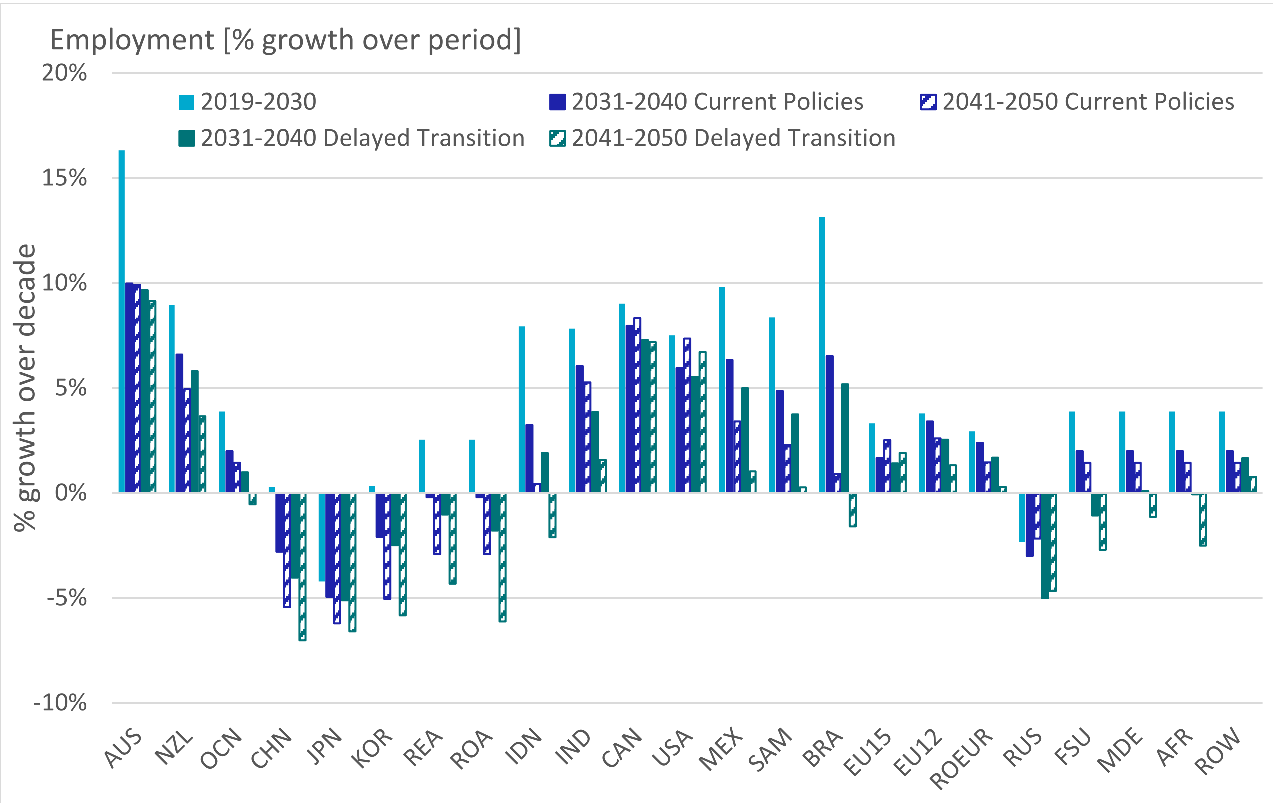


Figure A 5 Employment by region

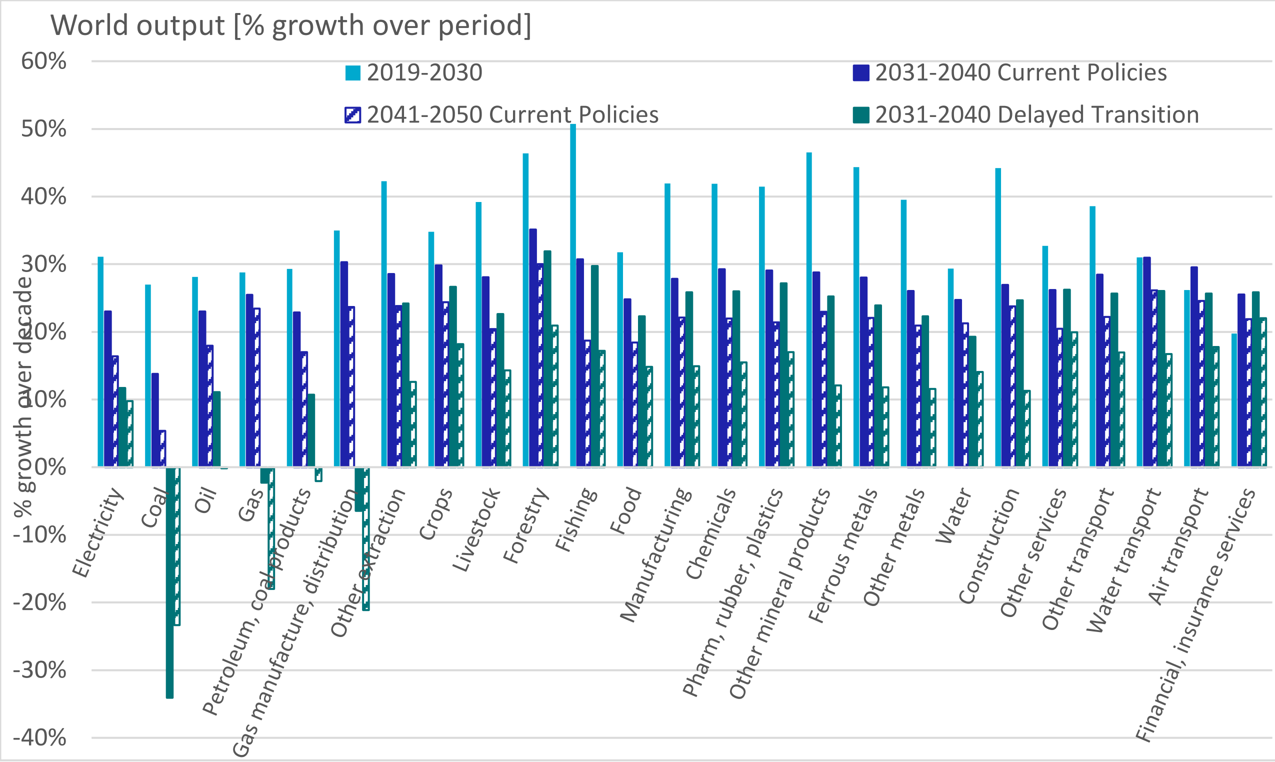


Figure A 6 World output by sector

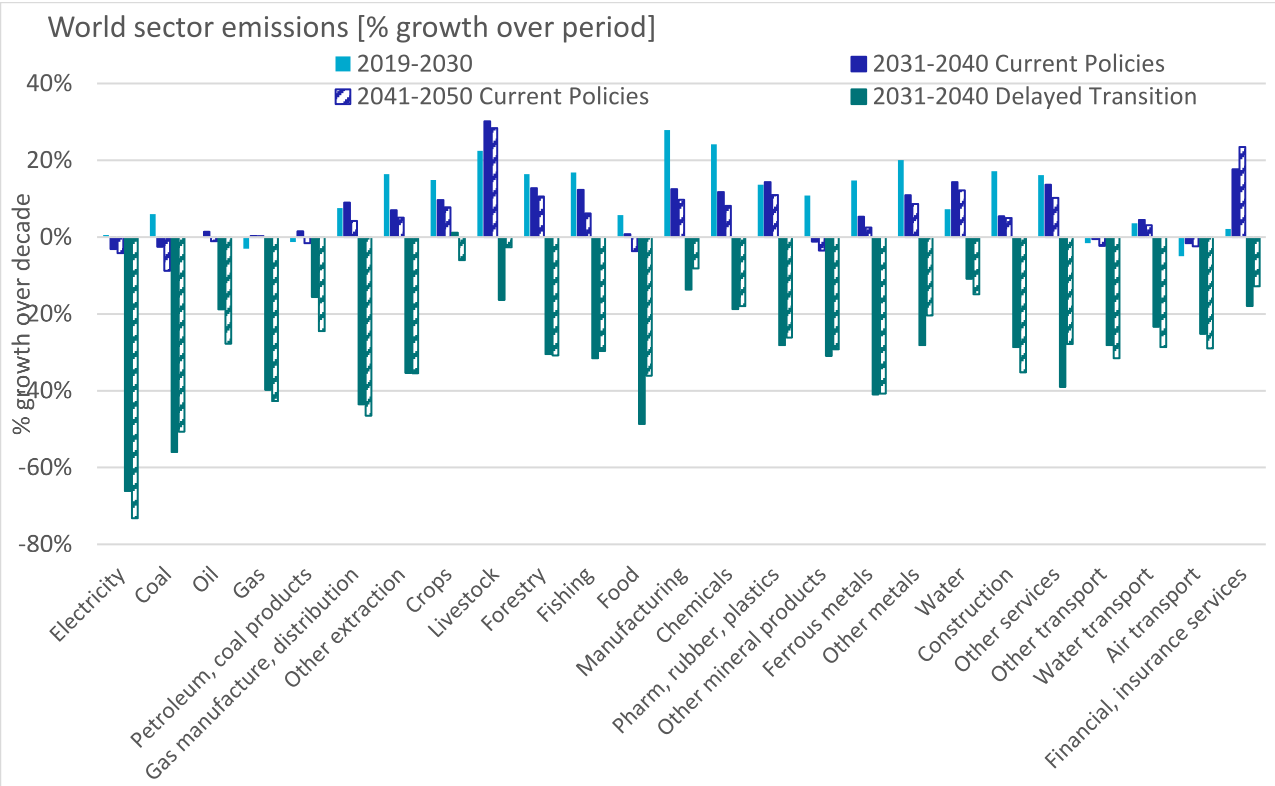


Figure A 7 World emissions by sector

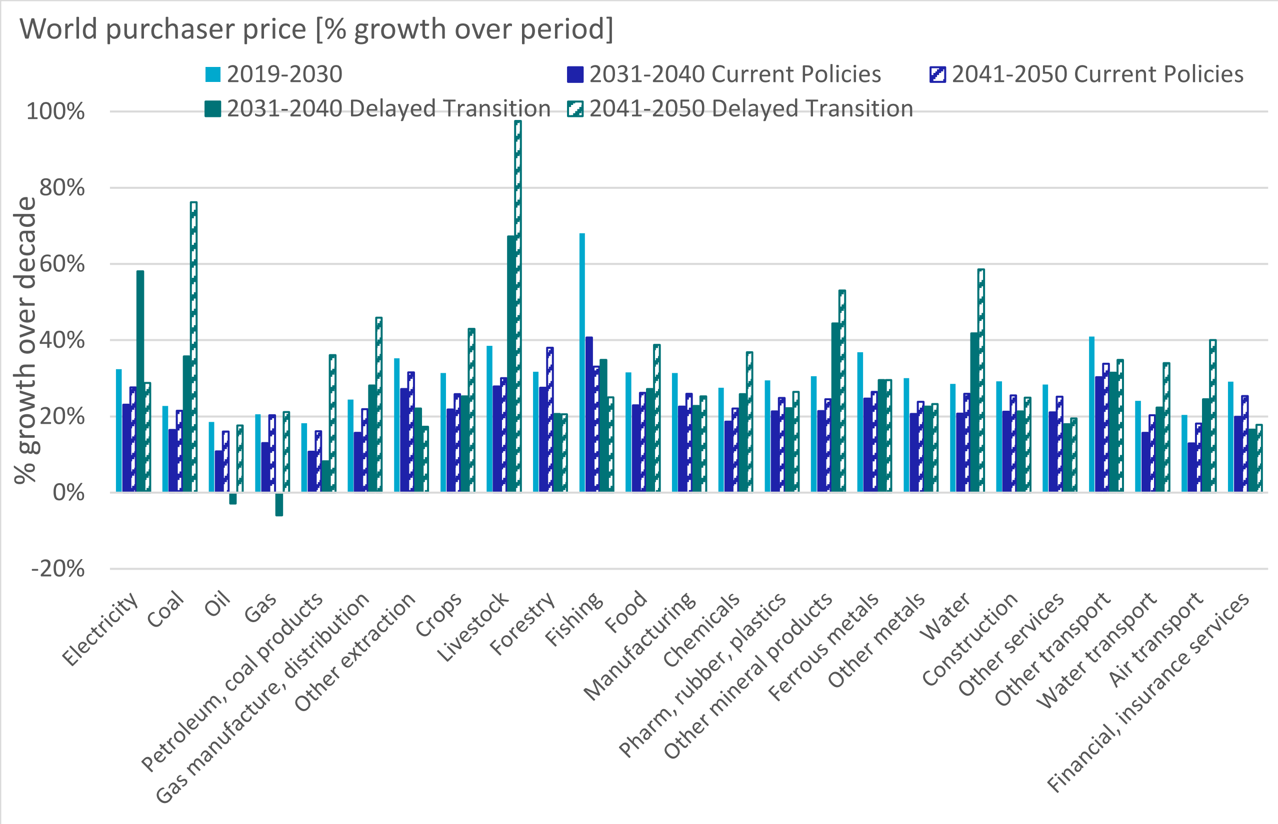


Figure A 8 World purchaser price by sector

8.4 KPMG-EE national model output summary

In this section we provide results for broad industry groups and more detailed results for sectoral splits not reported previously. We do not duplicate results specifically previously reported (excepting where subsets of whole groups were previously reported such as broad industry groups).

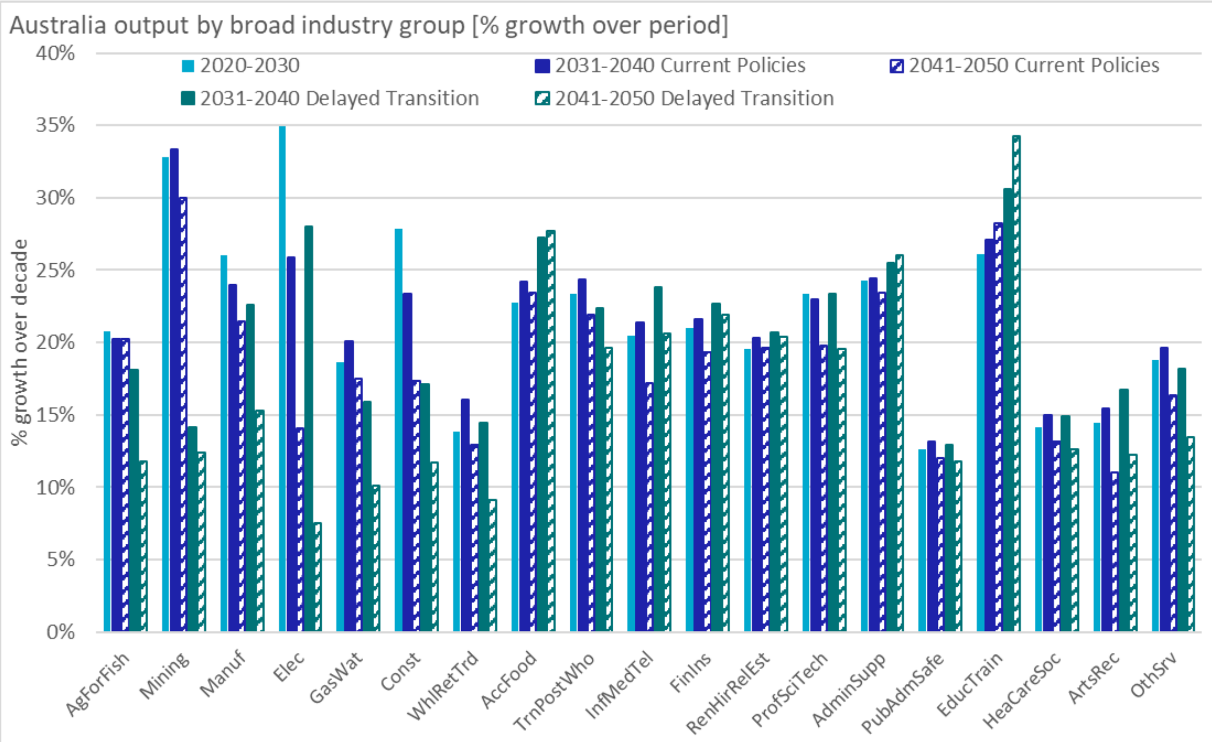


Figure A 9 Australia output by broad industry group

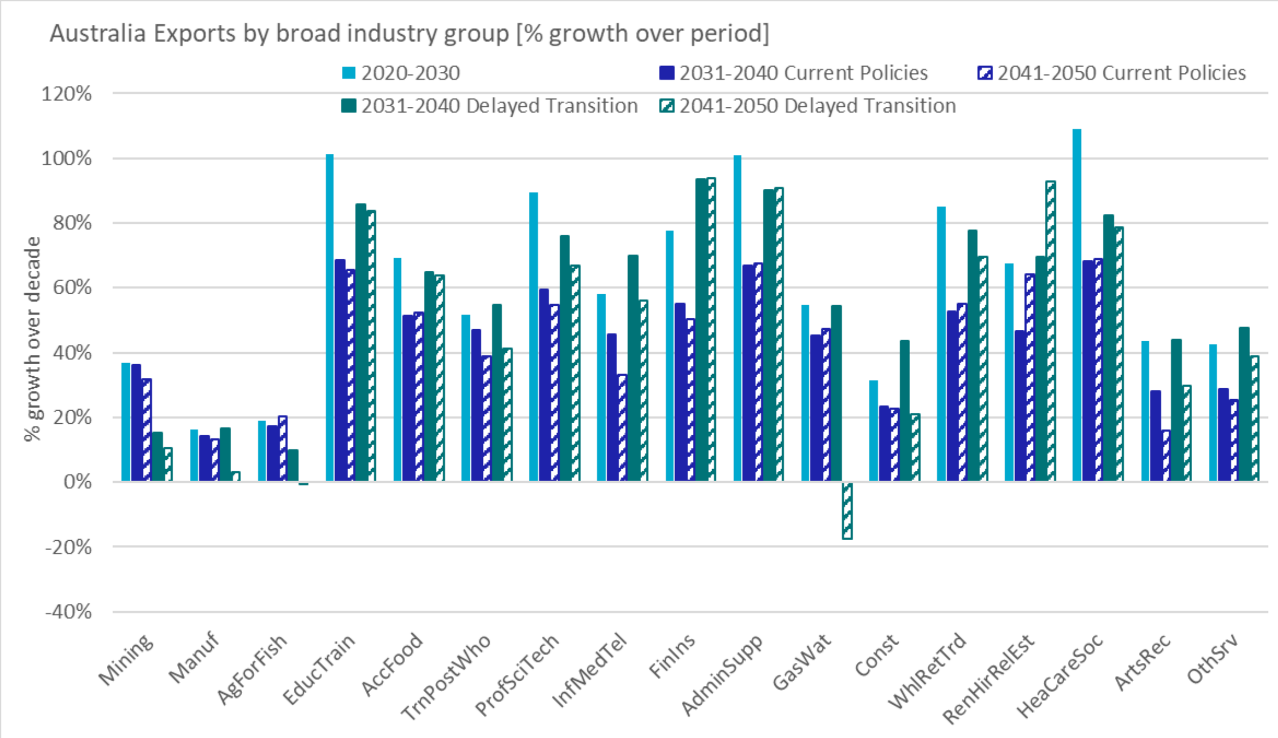


Figure A 10 Australia exports by broach industry group

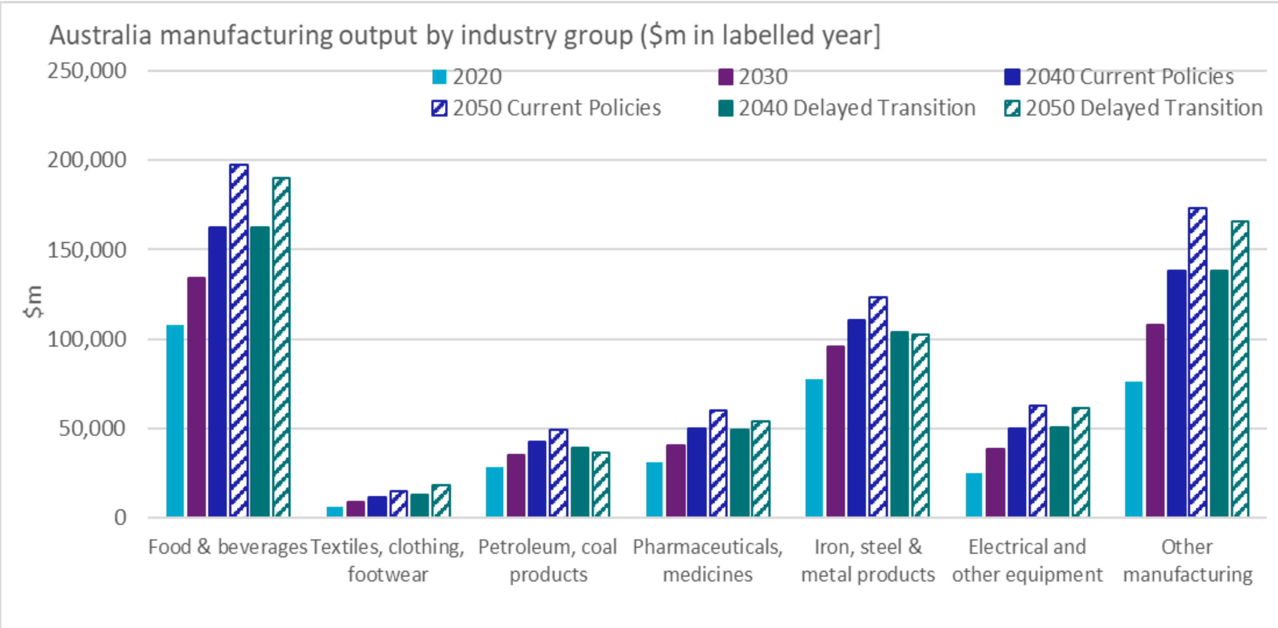


Figure A 11 Australia manufacturing output by industry group

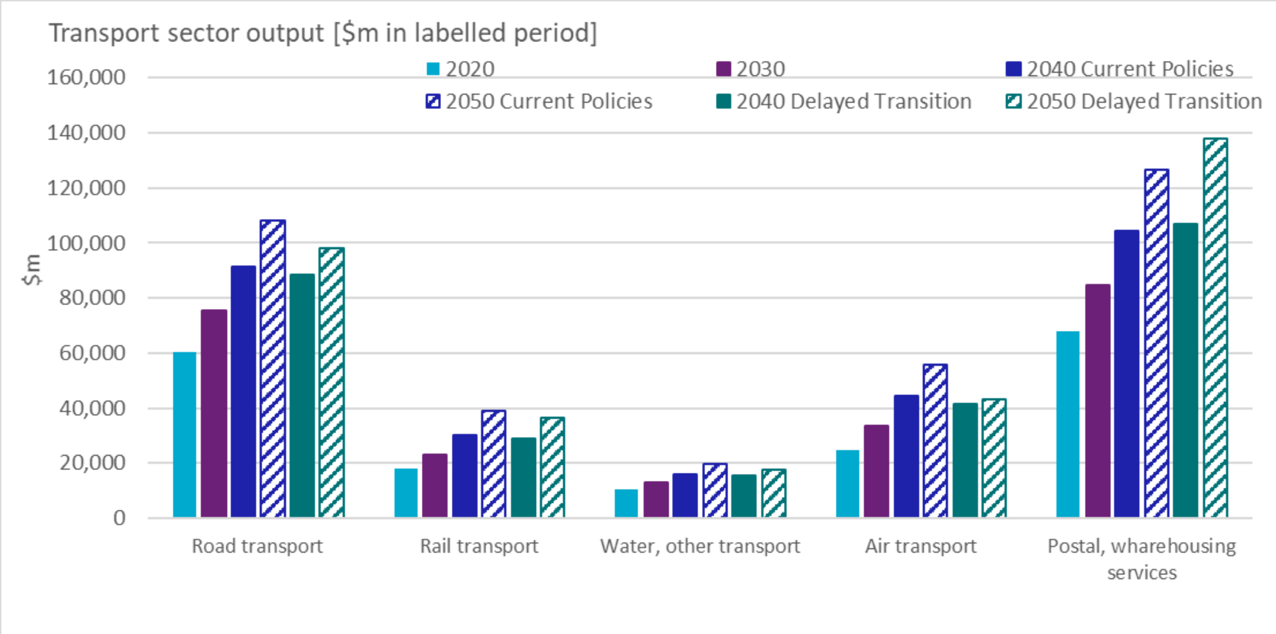


Figure A 12 Transport sector output by group

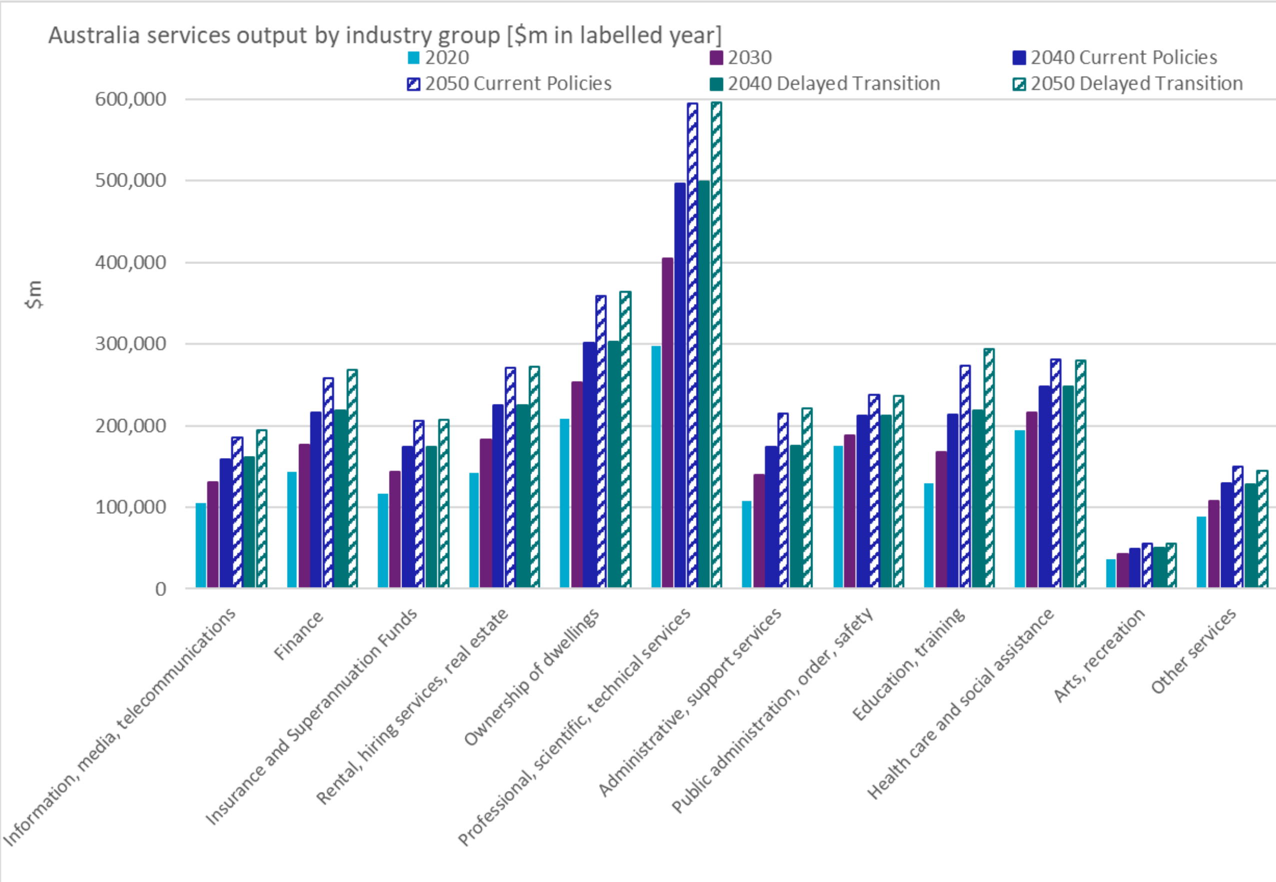


Figure A 13 Australia services output by industry group

8.5 KPMG-EE regional model broad industry output summary

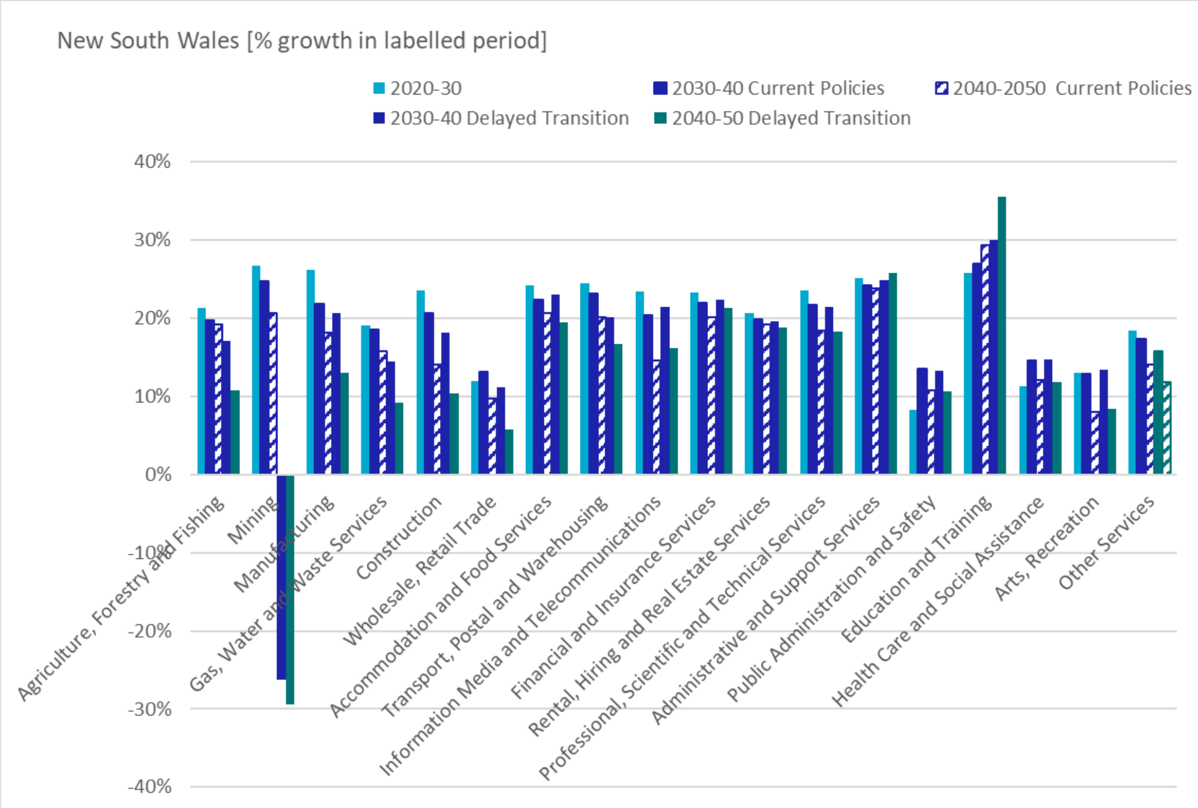


Figure A 14 New South Wales growth by sector

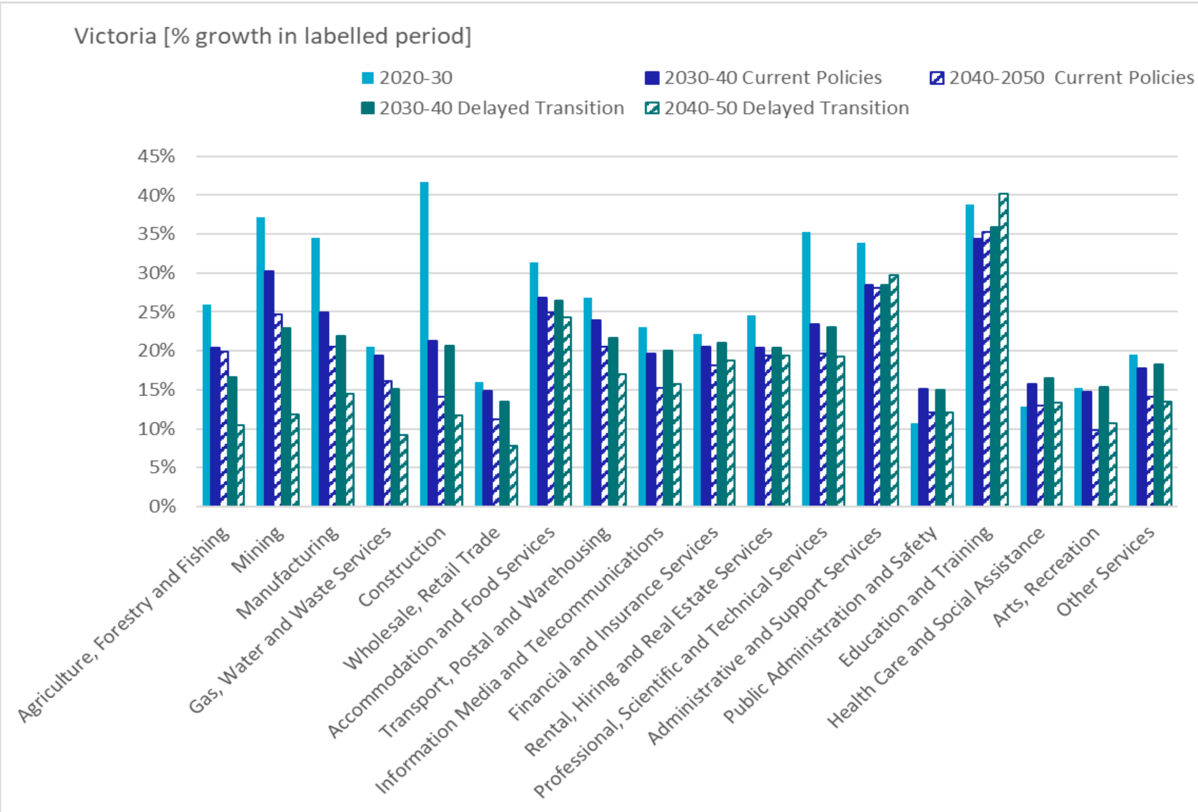


Figure A 15 Victoria growth by sector

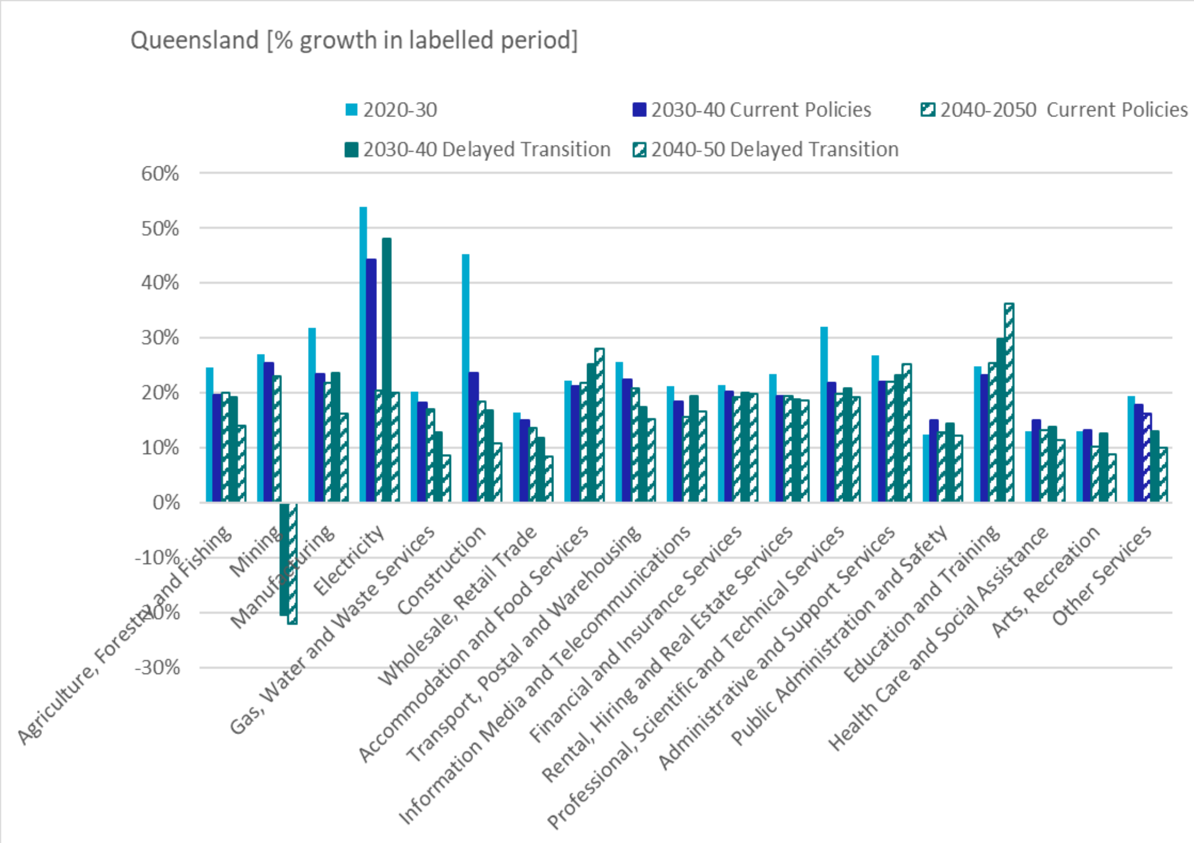


Figure A 16 Queensland growth by sector

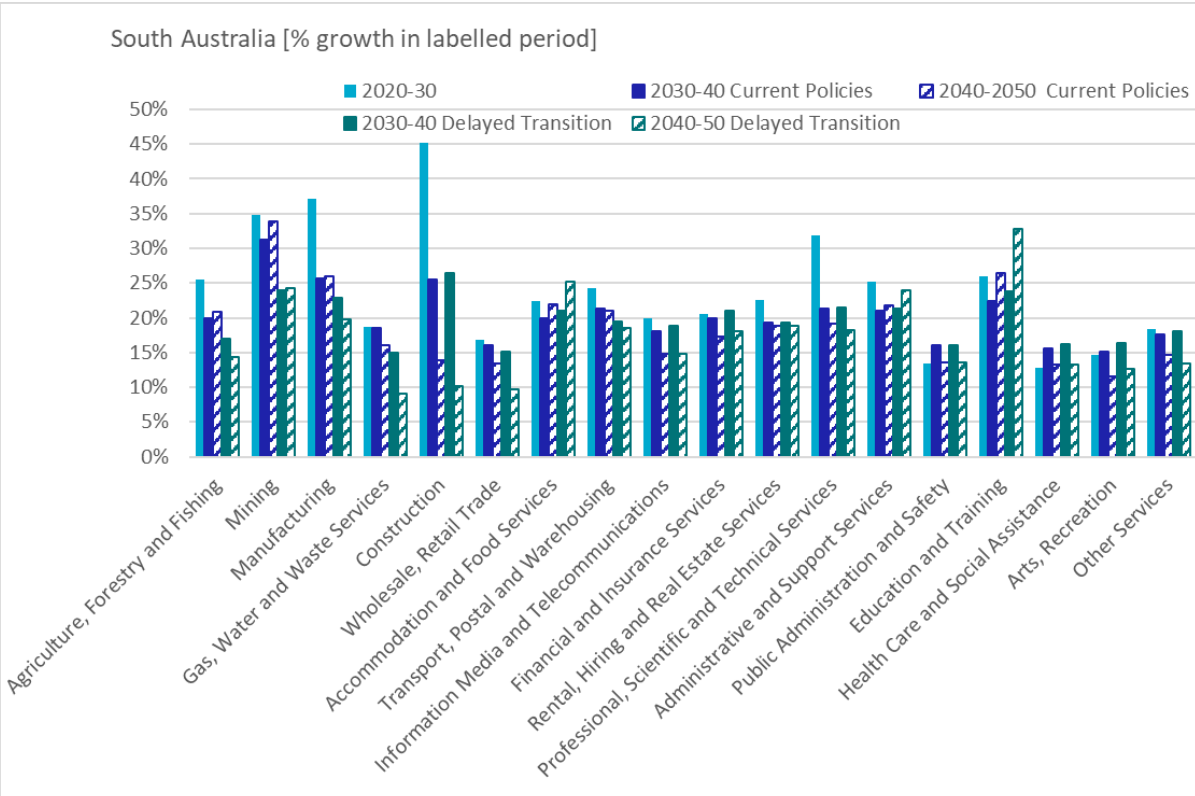


Figure A 17 South Australia growth by sector

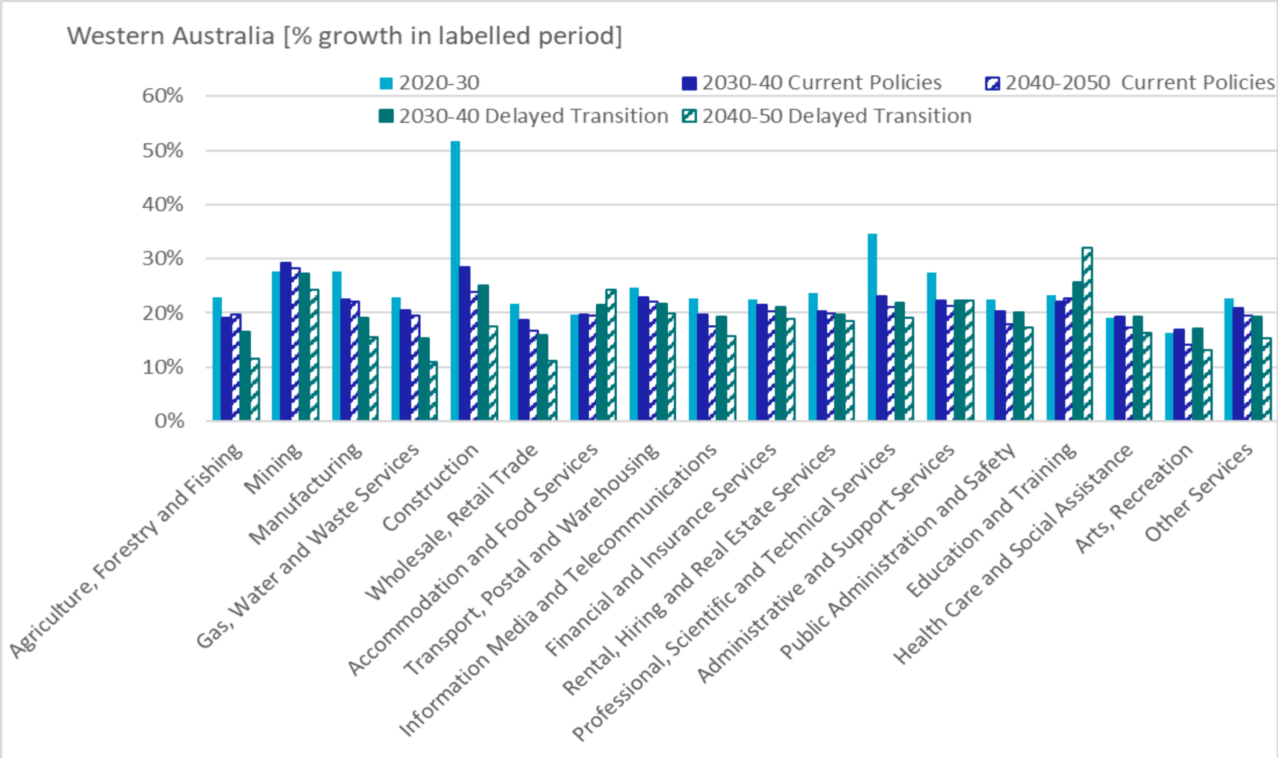


Figure A 18 Western Australia growth by sector

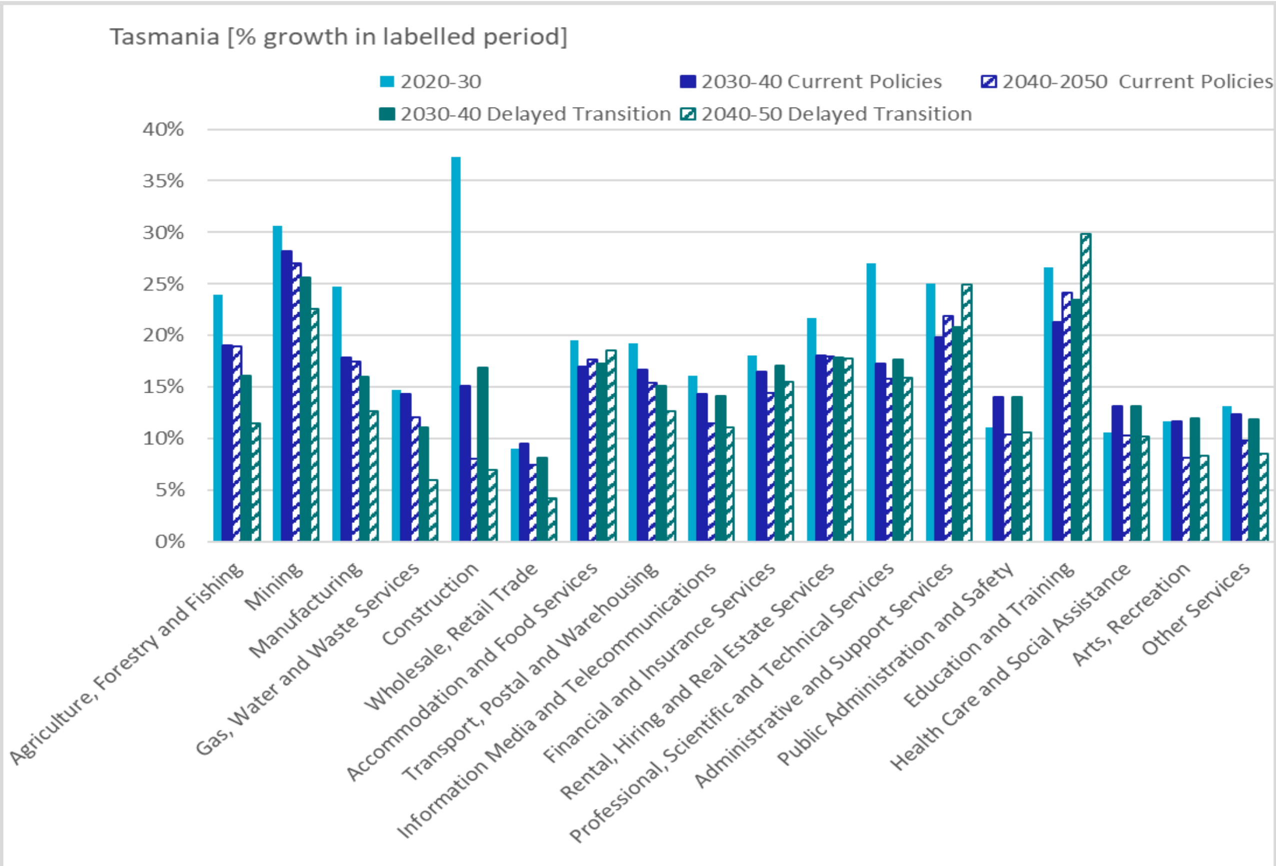


Figure A 19 Tasmania growth by sector

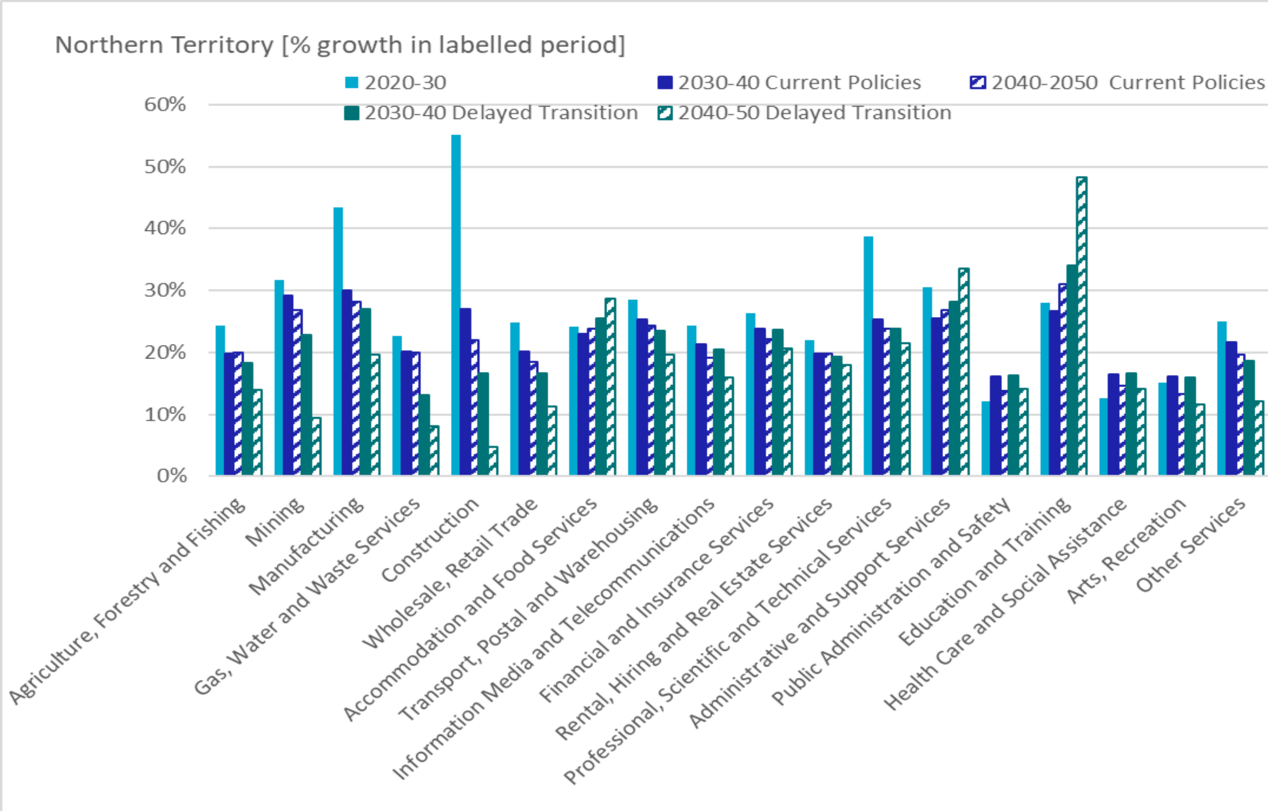


Figure A 20 Northern Territory growth by sector

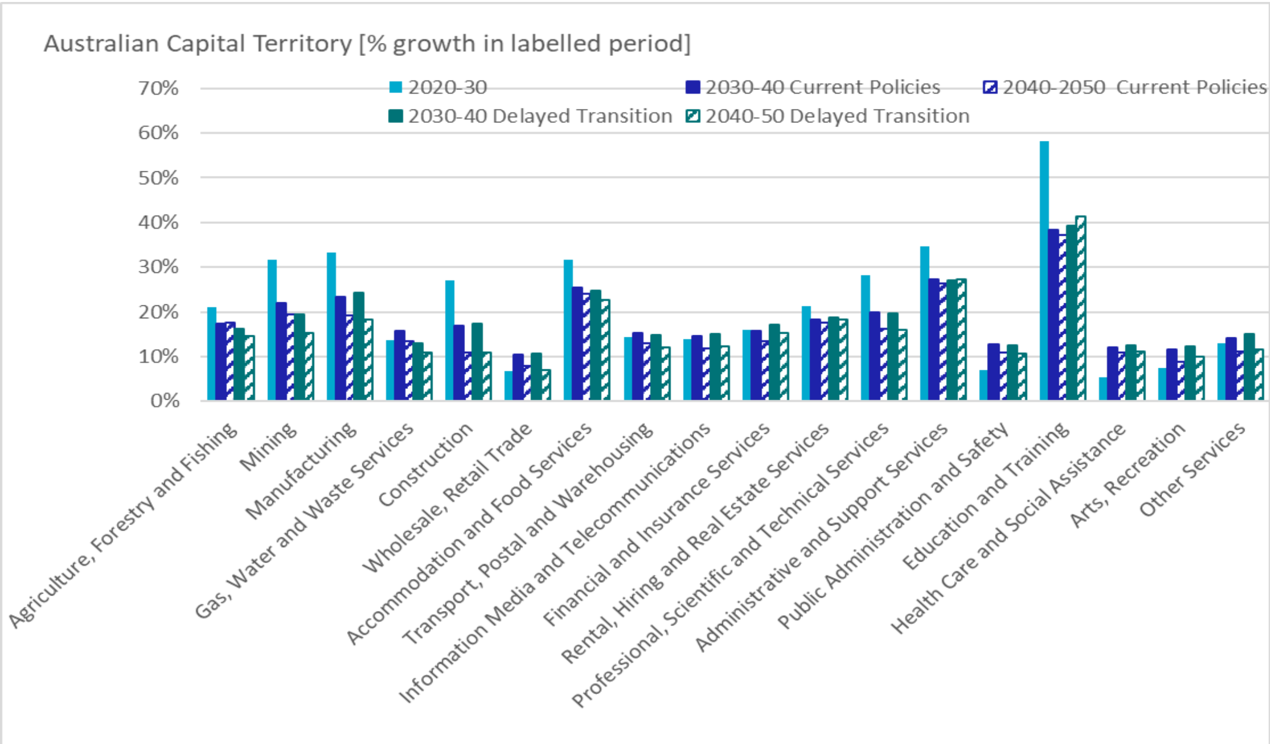


Figure A 21 Australian Capital Territory growth by sector

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