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Understanding Structural Change from Transitioning to a Low-Carbon Economy: An Integrated Multi-Model Approach for Australia

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Abstract

Continued climate change raises concerns on climate-related physical and transition risks. This study focuses on transition risk or the structural change related to decarbonisation. Specifically, we model the structural change associated with net zero emissions (NZE) for Australia along with global action to limit warming to 1.5°C by the end of the century. This scenario is implemented using a two-stage integrated approach that links two computable general equilibrium (CGE) models – one representing the world economy at a broad level and the other representing the Australian economy in greater detail. Results indicate that achieving NZE would contract the global and Australian economy. Global GDP is projected to fall by 5% and Australian GDP by 3.95%. Both globally and in Australia the capital and labour use falls. The NZE pathway is transformative for the energy sector but disruptive to other industries. Electricity generation increases by 1.45% per year as the Australian economy shifts from fossil-fuel-based energy to renewable energy. Economic activity of the non-energy sector contracts due to higher production costs related to the cost of abatement. Sensitivity analysis indicates that the GDP effects are rather sensitive to the speed with which NZE is reached.

Keywords

computable general equilibrium, model Integration, net-zero transition, Australia

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Understanding structural change from transitioning to a low-carbon economy: an integrated multi-model approach for Australia

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Abstract

Continued climate change raises concerns on climate-related physical and transition risks. This study focuses on transition risk or the structural change related to decarbonisation. Specifically, we model the structural change associated with net zero emissions (NZE) for Australia along with global action to limit warming to 1.5°C by the end of the century. This scenario is implemented using a two-stage integrated approach that links two computable general equilibrium (CGE) models – one representing the world economy at a broad level and the other representing the Australian economy in greater detail. Results indicate that achieving NZE would contract the global and Australian economy. Global GDP is projected to fall by 5% and Australian GDP by 3.95%. Both globally and in Australia the capital and labour use falls. The NZE pathway is transformative for the energy sector but disruptive to other industries. Electricity generation increases by 1.45% per year as the Australian economy shifts from fossil-fuel-based energy to renewable energy. Economic activity of the non-energy sector contracts due to higher production costs related to the cost of abatement. Sensitivity analysis indicates that the GDP effects are rather sensitive to the speed with which NZE is reached.

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Contents

1. Introduction....1
2. Economic modelling of climate change....4
3. Methodology....6
   3.1 Integrated modelling approach....6
   3.2 Core features of GTEM and ATEM....6
   3.3 GTEM-specific features....8
   3.4 ATEM-specific features....9
   3.5 Energy accounting....10
   3.6 Emissions accounting....10
   3.7 Carbon price mechanism....13
4. Simulation design....14
   4.1 The baseline: a business-as-usual economy....14
   4.2 The policy scenario: a NZE economy under 1.5° global target....15
5. Results and discussion....16
   5.1 Global results....16
   5.2 Australian results....17
   5.2.1 Emissions pathway....17
   5.2.2 Transformation in the energy system....19
   5.2.3 Macroeconomic effects....21
   5.2.4 Sectoral effects....22
6. Sensitivity analysis....22
7. Conclusion....24

References....25

Tables....28

Figures....30

1. Introduction

As concern about global warming has increased, the scientific focus has rapidly evolved from understanding the magnitude of climate change to developing and applying tools that manage the most pressing risks associated with it. Climate risks are typically classified as either physical or transition risk. Physical risk can be further classified as comprising chronic risks (e.g., temperature changes) and acute risks (e.g., floods, cyclones, bushfires). In contrast, transition risk arises from the structural change required to move towards a low carbon economy. This risk encompasses shifts in energy generation and use, transport modes, material flows, production technologies and consumption preferences. Scientists now recognise that understanding and managing this multifaceted economic transition will be one of the most important adaptations to climate change. This study explores the potential economic effects of global and Australian transition pathways to net zero emissions (NZE) using an integrated modelling approach.

Significant climate change continues to manifest as greenhouse gas emissions build-up in the atmosphere. According to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2023), cumulative net CO2 emissions equalled 2400 ±240 GtCO2 from 1850 to 2019 with 42% occurring between 1990 and 2019. Industrial greenhouse gases are dominated by carbon dioxide (CO_2) with methane (CHO), nitrous oxides (N_2O) and chlorofluorocarbons (CFCs) being less important. The largest contributors to these emissions are the burning of fossil fuels and industrial processes. The growth in greenhouse gas emissions has been associated with increasing global warming; global surface temperature is 0.84 - 1.10°C higher in the last two decades (2001-2020) relative to 1850–1900 (IPCC, 2023).

If not mitigated, higher global temperatures will pose increasing economic, sociopolitical and environmental challenges such as sluggish industry growth, resource scarcity, vulnerable communities, and an increasing occurrence of catastrophic natural disasters. Most countries have adopted policies addressing the reduction of emissions in line with the Paris Agreement's long-term temperature goal to hold global warming under 2˚C and pursue efforts to limit this warming to 1.5˚C. Many countries have committed to decarbonise through their Nationally Determined Contributions (NDCs), and Long-term Strategies (LTSs) (Dafnomilis et al., 2023). These commitments are guided by the UN Framework Convention on Climate Change (UNFCCC) process, including the outcomes of the Kyoto Protocol and the adoption of the Paris Agreement. With ongoing efforts to establish a global carbon market, together with increasing awareness of consumers on value chain emissions and decarbonisation, countries with the ability to produce goods with a lower carbon footprint will generate a competitive advantage relative to international peers. Achieving this competitive advantage provides an incentive for countries to strengthen and implement their NZE policies either through their NDCs, LTSs and domestic policies.

Greenhouse gas emissions vary substantially across countries. Data from IPCC (2023) indicates that developed countries (e.g., Australia, Japan and New Zealand) have higher annual per capita emissions (13 tCO_2e per person) relative to the global average (6.9 tCO_2e per person) as compared to least developed countries (1.7 tCO_2e per person) and small island developing countries (4.6 tCO_2e per person). Global net CO_2 emissions in 2020 is about 57 $GtCO_2e$ based on median projection from the 6th IPCC report. Australia contributed about 490 Mt of CO_2e (or <1% of total global emissions) in 2020. Figure 1 shows the sectoral distribution of Australia's emissions. Key emitting sectors and sources are electricity generation (35% share), mining (22% share), agriculture (18%), household-based consumption (12%) and transport (6%). These statistics provide an initial indication of Australia's mitigation strategy. A central focus of decarbonisation of the energy sector as this makes up almost half of the country's CO_2 emissions due to the use of fossil fuels as an energy source. A NZE pathway for this sector largely involves transitioning from coal-fired power stations to renewable energy such as solar, wind and bioenergy.

Another focus of the mitigation strategy is enhancing the energy efficiency of buildings and improving the material efficiency of the construction sector. The rapid electrification of transport (e.g., electric and hydrogen fuel cell vehicles) and in other industrial sectors (e.g., iron and steel, and buildings) will also help reduce emissions. Another option is the deployment of carbon dioxide removal (CDR) technologies such as direct air capture and storage (DACCS), soil carbon sequestration, bioenergy with carbon capture and storage (BECCS) and enhanced mineralization. Although CDR technologies are relatively expensive, they have the potential to offset remaining emission from hard-to-abate sectors like agriculture and industrial emissions. Land use, land use change and forestry (LULUCF) activities are also expected to play a crucial role in limiting global warming to 1.5°C. Decarbonisation from LULUCF occurs through increasing sequestration in vegetation and soils. Changes in consumer behaviour and lifestyle choices, such as the shifts in diets towards low meat consumption, or low population growth could also help lower CO_2 emissions.

This study explores the economic effects of decarbonising the economy in line with a global warming outcome of 1.5°C. The scenarios are implemented over a 30-year period from

2021 to 2050 using a computable general equilibrium (CGE) framework heavily modified to capture all the important aspects of decarbonisation. Two CGE models are used to conduct our NZE scenario analysis. The first model is GTEM (Global Trade and Environment Model) representing the global economy with multiple regions. The second model is ATEM (Australian Trade and Environment Model) representing the Australian economy with greater sectoral resolution. Our analysis presents detailed results for the Australian economy, as well as broad results for the global economy. We conduct sensitivity analysis with respect to three parameters: (1) the timeframe of achieving net zero emissions (i.e., the speed of adjustment across technologies), (2) the cost of adopting lower-emissions-intensity technology, and (3) the productivity loss due to climate change.

Our study makes two contributions to the existing literature. First, it contributes to the understanding of how future energy and emissions profiles globally and in Australia are likely to affect the economy. The transition risk of climate change is an area of considerable debate among scholars and policymakers as it affects economic development. This paper sheds light on important policy questions. What is the economic cost of decarbonisation? Which sectors will be affected the most? What are the structural changes in the economy? Addressing these questions provides insights into the effective design of Australia's climate change policy, particularly the strategic development of sectoral pathways to net zero emissions.

Second, our methodology provides an integrated approach in modelling the economics of climate change. Our multi-model approach involves linking a global CGE model with a single-country model that allows the interaction of the domestic economy with the world economy. Such a coupling has the advantage of complementing the strengths of the two models. For example, global CGE models have multi-country representation of international trade and investment flows while national CGE models have greater sectoral resolution with more sophisticated assumptions on the intricacies of the domestic economy. To our knowledge, only a few studies have implemented this approach (e.g., Whitten et al., 2022 and Brinsmead et al., 2022). A critical limitation of the multi-model approach is the consistency of model assumptions and sectoral aggregation to properly account for the interactions between models. This consistency is more challenging to achieve for modellers who have constraints in modifying the models especially those developed by other organisations. In this study, we can reconfigure the modelling assumptions and databases of the models being used to achieve the required consistency for proper linking.

2. Economic modelling of climate change

Achieving net zero emissions has consequences on industry activity, resource use and consumer demands. This means that any action taken to decarbonise the economy has an economic cost absent any environmental benefits of decarbonisation. The economic cost derives from the movement of capital and labour from high-emission-intensity industries to low- or zero-emissions intensity industries. Hence, one of the key challenges facing policymakers is identifying cost-effective ways of achieving a net zero economy. To inform policy makers, scientists and economists have developed a suite of tools known as integrated assessment models (IAMs). These tools combine knowledge from two or more domains into a single framework. For example, IAMs link different modules of the economy, energy and Earth systems (including land use and agriculture, and the climate). This integration approach enables the transmission of information, data or results across multiple systems to comprehensively evaluate the potential impacts of a policy such as climate abatement targets.

Several IAMs have contributed to the climate change assessment reports of the IPCC. The results of these models provide the basis for the baseline and mitigation scenarios in different countries. For example, in the 6th assessment report of the IPCC, a number of global-scale complex IAMs have contributed to the modelling of shared socioeconomic pathways across participating countries.[1] These IAMs consist of various sub modules to capture the economic and biophysical systems, e.g., a computable general equilibrium (CGE) model of the economy, the Model of Agricultural Production and its Impact on the Environment (MAgPIE), the Global Biosphere Management Model (GLOBIOM), and the Model for the Assessment of Greenhouse Gas Induced Climate Change (MAGICC).[2]

Macroeconomic modelling is an integral part of IAMs as it estimates the potential economywide impacts of climate policy while also considering the environmental aspects of climate change. In this section we discuss models that focus on the energy-environment-economy nexus, especially using the CGE framework. Based on the survey of Parson and Fisher-Vanden (1997), the early works of climate change modelling can be traced back to the 1970s through the coupling of Energy System Models (ESMs) with economic models

[1] For a comprehensive review of IAMs see Parson and Fisher-Vanden (1997), Loschel and Schymura (2013), and Elberry et al. (2024).

[2] These include the Model for Energy Supply Strategy Alternatives and their General Environmental Impact (MESSAGE) developed by the International Institute for Applied Systems Analysis (IIASA), the Integrated Model to Assess the Global Environment (IMAGE) developed by the Netherlands Environmental Assessment Agency, the Asia-Pacific Integrated Model (AIM) developed by research institutes in several Asian countries, the Global Change Assessment Model (GCAM) developed by the Pacific Northwest National Laboratory, the Regional Model of Investments and Development (REMIND) developed by the Potsdam Institute for Climate Research (PIK), and the World Induced Technical Change Hybrid (WITCH) model developed by a number of Italian organisations (CarbonBrief, 2024).

(Greenberger et al., 1983). This model integration approach helps identify potential synergies and trade-offs between different policy objectives, such as economic growth and emissions reduction (Elberry et al., 2024). A specific attribute of these early models is the accounting of energy-specific CO_2 emissions coefficients, which allowed the user to gauge emissions paths and economic costs associated with energy transition scenarios (Edmonds and Reilly, 1985; Nordhaus and Yohe, 1983; Wolf et al., 1981).

The evolution of the economic-energy models has been facilitated by advances in computing power and the increasing availability of data sets. Several modelling projects began to seek broader integration in climate assessments. Existing models that incorporate climate-economy or climate-energy submodules and damage functions include DICE/RICE (Nordhaus, 1994; Buonanno et al., 2003), WITCH (Bosetti et al, 2011), CETA (Peck and Teisberg, 1992), MERGE (Manne and Richels, 2005), and PAGE (Alberth and Hope, 2007). CGE models are also popular in climate change studies. These models apply the principles of general equilibrium theory in their depiction of the whole economy. They capture how different agents (e.g., governments, firms, investors, households and foreigners) behave within an economy as they respond to changes in policy, technological and social change. An et al. (2023) and Babatunde et al. (2017) have systemically reviewed the applications of CGE modelling in evaluating the impacts of decarbonisation policies. Models of this type include GTEM-C (Cai et al., 2015), GTAP-E (McDougall and Golub, 2009), MIT-EPPA (Jacoby et al., 2006), DEMETER (Gerlagh, 2008) and GEM-E3 (Capros et al., 2013) among others.

CGE-based IAMs attempt to represent the interactions between physical and economic systems by linking geophysical data with economic flows. Physical units in a geophysical model are converted to monetary values using market clearing prices in the economic model. The physical flows can be of different units, for example: terawatt-hour for electricity units, petajoules for energy units, tonnes of CO_2 equivalent for emissions, hectares or acres for land use, and different units of sectoral outputs (heads, kg, and other quantity measurements). Using a common unit of accounts (say, dollar values), the economic model converts or translates the changes in physical flows and market transactions into monetised values with prices driven by demand and supply factors. This monetisation makes different scenarios of NZE pathways comparable through their impact on economic values. Quantitative indicators of economic effects include gross domestic product (GDP), aggregate savings and investment, household consumption, the balance of trade and government tax revenue, sectoral value added, wages and commodity prices.

3. Methodology

3.1 Integrated modelling approach

This study applies an integrated assessment modelling (IAM) framework that combines knowledge from biophysical models into two economic models – the Global Trade and Environment Model (GTEM) and the Australian Trade and Environment Model (ATEM). GTEM and ATEM are CGE models specifically designed for the analysis of climate change policy with an emphasis on the energy-environment-economy nexus. The strengths of the two models are complementary. GTEM has a multi-regional representation of international trade and investment but with limited sectoral detail. ATEM has a detailed representation of the domestic economy but treats the rest of the world as exogenous. By linking these two models we can adequately represent the realities of the Australian economy at the domestic and global level. This coupling is essential as international investment and trade have a significant influence on the Australian economy, e.g., coal is a major export commodity in Australia. Capturing the global demand for coal and other fossil-fuels is important for our analysis as the pathway to NZE is characterised by an extensive shift away from fossil-fuel-based energy.

The modelling framework is implemented in two stages as illustrated in Figure 2. In stage 1 we run GTEM to implement a global emissions pathway that limits global warming to 1.5°C. The total greenhouse gas emissions budget is consistent with the IPCC's IMP-Ren scenario in IPCC (2022). We also impose energy targets based on the International Energy Agency's World Energy Outlook (IEA, 2021), LULUCF estimates from the GLOBIOM model, and temperature changes model from the MAGICC model. This first pass generates the macroeconomic effects of the global NZE scenario. In stage 2 we extract GTEM results that represents the global setting for Australia, such as exports, imports, foreign investment, and global fuel demands. These results are fed into ATEM to form the link between the Australian and global economies. Under such a global setting, we run ATEM with additional forecasts representing the future path of the domestic economy and net zero emissions targets. This second pass generates detailed and fine-tuned results of the economic effects for Australia. The modelling inputs for GTEM and ATEM are further elaborated in Section 4.

3.2 Core features of GTEM and ATEM

GTEM and ATEM belong to the CGE class of numerical macroeconomic models. As illustrated in the upper panel of Figure 3, CGE models capture all the flows in the economy by representing different agents such as households, firms, government and foreigners. These economic agents make decentralised decisions on their consumption or production activities but are interconnected through upstream and downstream flows of commodities and factor inputs. Moreover, the lower panel of Figure 3 shows the interaction between the economic and biophysical systems in our CGE framework. All economic agents potentially contribute to carbon emissions as they draw resources from the environment. These emissions influence the surface temperatures of a country or region via the greenhouse effect, which in turn influence economic activity via approximated climate-induced damages (e.g., the change in temperature ΔT enters the model via a productivity shock).

Both models are Walrasian general equilibrium models possessing the features of optimisation theory (i.e., revenue maximisation or cost minimisation by economic agents), market clearing conditions (i.e., demand equals supply) and zero pure profit conditions (i.e., revenue of firms is equal to their cost of production). More specifically, defining features of the theoretical structure of both models include:

- optimising behaviour by households and firms in the context of competitive markets with explicit resource and budget constraints;
- the price mechanism operates to clear markets for commodities and capital;
- marginal costs are equal to marginal revenues in all activities;
- the labour market operates with a degree of friction so that some labour is always unemployed but the rate of unemployment is held constant in the long-run; and
- firms face costs in adjusting their capital and labour inputs.

The model theory is calibrated with real-world data to quantify behavioural responses such as the following:

- price and wage adjustments driven by resource constraints;
- tax and government spending adjustments driven by budget constraints;
- input substitution possibilities in production; and
- responses by consumers, investors, foreigners and other agents to changes in prices, taxes, technological changes and taste changes.

Although the core theoretical underpinnings of GTEM and ATEM are consistent, there are notable differences in some assumptions such as the treatment of physical capital and labour mobility. More specifically, physical capital is perfectly mobile across sectors in GTEM but is industry-specific in ATEM. Labour is perfectly mobile across sectors in GTEM but is occupation-specific in ATEM. 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 differing treatment of physical capital and labour mobility means that there are higher costs of adjustment in the economy in ATEM (due to lower intersectoral mobility of factors of production) relative to GTEM.

3.3 GTEM-specific features

GTEM is a dynamic model of the global economy with a bilateral representation of international trade (Cai et al., 2015). For this study, the global economy is represented by 20 countries or country groupings and 36 industrial sectors (see Appendix, Table A1). The regions interact with each other via trade flows and foreign investment. The initial data inputs to GTEM are the IO tables and related data drawn from the GTAP 10 data base (Aguiar et al., 2019). This is a global data base produced by the Global Trade Analysis Project (GTAP), which accounts for bilateral trade patterns, production, consumption, investment and the intermediate use of commodities and services. The aggregation of household savings in all regions represents global investment, which is allocated across regions based upon the slow elimination of differences in regional rates of return on capital. Thus, regional saving can be allocated either domestically or internationally. In contrast, other factors of production (land, labour, natural resources) are internationally immobile.

The GTEM database also contains supplementary data on energy and greenhouse gas emissions. These data are adjusted for consistency with national and global data on energy sources and emissions by region and sector.

GTEM combines the top-down macroeconomic representation of a CGE model with the bottom-up engineering details of energy production along with a representation of greenhouse gas emissions by sector. The model features detailed accounting of global energy flows that are embedded in traded energy goods. More specifically, GTEM differentiates “technology bundle” (TB) industries (such as electricity, iron and steel, and land transport) from other industries. Each TB industry consists of a bundle of heterogeneous and competing technologies, and an assembling service that unifies products of all technologies into a homogeneous industrial output. For example, the electricity industry has three emission-intensive technologies (coal, oil and gas), nine emission-free technologies (nuclear, hydro, wind, solar, biogas, other bioenergy, waste, hydrogen, and other renewables), and four low-emission technologies (carbon capture and storage for coal, oil, gas, and bioenergy). This detailed representation of electricity technologies is essential for modelling the switch from carbon-intensive fossil fuel to cleaner energy sources.

3.4 ATEM-specific features

ATEM is a dynamic single-country model of the Australian economy. A key feature of the model is the detailed treatment of the energy sector. Mining activities are divided into 13 industries to explicitly represent the extraction of coal, oil, gas, and ores. Petroleum and coal products are distinguished by 14 types, each of which represents individual industries in the manufacturing sector. Electricity is produced by 20 industries representing different types of generation technologies. ATEM has 159 sectors in its standard form. For this study, we aggregated the database into a more manageable size of 65 sectors without losing the relevant details of important sectors (see Appendix, Table A2). This aggregation is needed to easily map results between the two models and to enhance computational efficiency especially for dynamic simulations with a long forecast period.

To further characterise the energy sector, ATEM represents the production technology of industries through a nested structure. At the top level of the nest firms choose a CRESH combination of the non-energy composite and the primary factor-energy composite. This means that energy goods are treated separately from other intermediate goods and services in production and are complementary to primary factors. At the second level firms choose a CRESH combination of the energy composite (i.e., an aggregate of electricity technologies and primary fuels) and the primary factor composite (i.e., an aggregate of hired labour, owner-operator labour, capital, land, and natural resources). At the third level firms choose a CRESH combination of eight occupations that form the hired-labour composite. At the bottom level firms choose a CES combination of domestic and imported intermediate inputs.

The key data input in ATEM are input-output (IO) tables produced by the Australian Bureau of Statistics (ABS, 2020). The IO tables quantify the flows of goods and services from producers to various uses, i.e., intermediate inputs used in the production of commodities or creation of capital assets, and consumption by households, the government or foreigners. The input-output tables also quantify the flows associated with primary factor inputs such as labour, capital, land and natural resources. ATEM also contains auxiliary data on energy flows and greenhouse gases (GHG) emissions. Data on the energy usage of industries and households are sourced from the ABS' Energy Accounts (ABS, 2020b). This captures the amount of energy consumed by each user for a particular type of fuel. Data on emissions is sourced from the national GHG inventory (DCCEEW, 2021)[3]. These data capture different types of gases (CO_2, CH_4, H_2O and other gases) emitted across sources such as fuel combustion, fugitive emissions, industrial processes, agriculture, and LULUCF.

Another novel feature of ATEM is the use of recently estimated parameters on import-domestic substitution, household demand, and intermediate input substitution. These parameters are econometrically estimated using Australian data, thereby making the quantified economic impacts of ATEM more robust. See Clements et al. 2021, 2022) and Mariano et al. (2021) for details of the estimated elasticities used to calibrate ATEM.

3.5 Energy accounting

Both GTEM and ATEM account for the physical units of energy embedded in energy goods. These energy flows are modelled by applying the appropriate coefficients that represent the physical quantities of energy (in petajoules) for each type of fuel (coal, oil, gas, petroleum products, hydrogen, bioenergy, renewable electricity) across users (industry, households, government and exports). The physical energy units are linked to the IO flows of coal, oil, gas, petroleum, hydrogen, bioenergy and electricity. Formally, this is represented in the model as

$$N_{isu} = Q_{isu} \cdot \xi_{isu} \qquad i \in \mathrm{COM},\ s \in SRC,\ u \in USR. \qquad (1)$$

where the physical quantities (N_{isu}) of energy i from source s (domestic or imported) used by user u (industries or households) track the IO flow of that energy good Q_{isu}, i.e., a quantity variable determined in the production technology nest. The energy intensity coefficient ξ_{isu} is exogenous or assumed fixed. As the IO flows of the energy good Q are determined by market clearing conditions, any changes in the price of energy will induce behavioural responses in the model that will affect the level of energy usage (physical quantity flows N). For example, a higher tax on fossil fuels will increase the price of fossil fuel energy (e.g., coal) relative to non-fossil-fuel energy (e.g., solar), thereby inducing a switch in demand towards the cheaper fuel. Improvements in energy efficiency due to technological change are also captured in the model through exogenous changes in the energy intensity ξ of production and consumption.

3.6 Emissions accounting

Another important feature of GTEM and ATEM is the accounting of GHG emissions. Consistent with the Australian Greenhouse Gas Inventory (DCCEEW, 2021), the model has a comprehensive representation of GHG emissions (i.e., CO_2, CH_4, N_2O and F-gases) and their

[3] The department publishes a series of comprehensive reports and databases that account for Australia's greenhouse gas emissions from 1989-90 onwards. The National Greenhouse Accounts fulfils Australia's inventory reporting requirements under the United Nations Framework Convention on Climate Change (UNFCCC) and the Paris Agreement.

sources. The emission of each gas has a common unit of measure - 'carbon dioxide equivalent' (CO_2e). Normalising emissions by using a common unit makes it computationally convenient to aggregate all gas-specific emissions into a composite variable. There are three broad categories of emission sources represented that relate to consumption and production: (1) combustion-based emissions, (2) output-based emissions and agriculture, and (3) agriculture, forestry and other land use (AFOLU) emissions.

First, combustion-based emissions are directly linked to fossil fuel use of the representative household and each producing industry and their respective emission intensities. This is represented in the model as

$$M_{isug}^{F} = Q_{isu} \cdot \varepsilon_{isug}^{F} \qquad i \in FUELCOM,\ s \in SRC,\ u \in USR,\ \mathrm{g} \in GHG \qquad (2)$$

where M_{isug}^{F} is CO_2e emissions, Q_{isu} is the quantity of energy and ε_{isug}^{F} is the emission intensity, i.e., one intensity for consumption and one intensity per industrial sector per energy commodity. For household consumption the emission intensities are exogenous. For industrial use the emission intensities respond to carbon-price-induced technological change drawing on Popp (2002). The industry emission intensity is represented as:

$$\varepsilon_{isug}^{F} \propto (\mathrm{C}_{iu}/\mathrm{P}_{u})^{-\eta} \qquad i \in FUELCOM,\ s \in SRC,\ u \in IND,\ \mathrm{g} \in GHG \qquad (3)$$

where $\mathrm{C}_{iu}/\mathrm{P}_{u}$ is the share of input-based carbon price mark-up in the price level of industry, and the positive parameter η represents the elasticity of carbon-price-induced technological change in emission intensities. To introduce some cost associated with the endogenous changes in emission intensity, the following mechanism is implemented:

$$A_{iu}^{F} = -\gamma_{iu}^{F} \cdot \varepsilon_{isu}^{F} \qquad (4)$$

where γ_{iu}^{F} is a parameter that governs the degree to which emission intensity ε_{isu}^{F} can be reduced by foregoing technical efficiency in the use of intermediate inputs A_{iu}^{F}. For example, setting $\gamma_{iu}^{F} = 10$ implies that a 1% decline in the emission intensity requires 0.1% decline in associated technical efficiency.

Second, output-based emissions include process-based emissions (i.e., those relating to industrial processes that chemically or physically transform materials such as cement production) and fugitive emissions (i.e., the release of GHG emissions during the extraction, processing, transformation and delivery of fossil fuels to the point of final use). Output-based emissions are linked to industry output and emission intensities. This is represented in the model as:

$$M_{jg}^{O} = Q_j \cdot \varepsilon_{jg}^{O} \qquad j \in IND,\ g \in GHG, \qquad (5)$$

where M_{jg}^{O} is emissions from industry i's production of gas g, Q_i is the amount of output produced, and $\varepsilon_{jg}^{O} \propto \left(\mathrm{C}_j/\mathrm{P}_j\right)^{-\eta}$ is the emission intensity. Similar to equation (4), the cost of reducing output-based emission intensities is

$$A_j^{O} = -\gamma_j^{O} \cdot \varepsilon_j^{O} \qquad (6)$$

where γ_j^{O} is the parameter that governs the magnitude of output-augmenting technical efficiency loss A_j^{O} associated with the reduction in output-based emission intensity ε_j^{O}.

Third, AFOLU emissions are treated differently depending on the relevant activity. Combustion-based emissions by agricultural industries are treated as described above for other industries via equation (2). Non-combustion emissions by agricultural industries are linked to the use of primary factor inputs and emission intensities. For example, N_2O emissions from livestock are proportional to the sectoral use of capital (as a proxy for the scale of farming) and the N_2O emission intensity, which responds to carbon-price-induced technological changes. Forestry and other land use emissions are also represented but do not respond to any endogenous model mechanism. The evolution of these emissions over time are exogenously specified in the model using external information from official projections, expert judgement or output from another model (e.g., GLOBIOM).

In both the GTEM and ATEM models, particular attention is placed on the technology bundle of the electricity generation sector as this is critical for the realisation of the modelled emissions pathways given its major contribution to aggregate emissions (see Figure 1). There are 12 electricity technologies including coal, oil, gas, nuclear, hydro, wind, solar, a composite other renewables sector, and CCS technologies for coal, oil, gas and bioenergy. The suite of electricity generation technologies is a key element of the analysis since each technology has a vastly different carbon footprint. Five negative emissions technologies are also modelled including olivine, soda lime, direct air capture, bioenergy CCS and carbon plantings. The sole function of these technologies is to extract carbon from the atmosphere. They use intermediate goods and factor inputs but do not produce any output. Their level of activity is part of *net* emissions, which affects the carbon price in the economy.

3.7 Carbon price mechanism

A carbon price is endogenously determined in the model for an exogenously specified level of GHG emissions.[4] This price is defined as a specific tax rate (*T*) expressed in dollars per tonne of CO_2e, which is consistent with the model database where (i) nominal values are in millions of dollars (US$ in GTEM, A$ in ATEM), and (ii) the quantity of emissions (*E*) are in mega tonnes (Mt) of CO_2e. Taking the ratio of these two coefficients (*T/E*) gives a dollar price per tonne of CO_2e. The revenue (R) generated from a specific carbon tax (*T*) on emissions (*E*) is represented in general form as

$$R = T \times E \tag{7}$$

The carbon price is converted into an *ad valorem* tax rate on a range of activities that cause emissions and this raises the price of commodities used in those activities thereby influencing their consumption and production. The *ad valorem* equivalent tax (*V*) is defined as a proportional tax on the value of the economic activity that raises the same amount of revenue as the *specific* tax *T*. Algebraically, this is represented as

$$V = R/Y \times 100 \tag{8}$$

where *V* is the *ad valorem* tax, *R* is the revenue raised from the specific carbon tax and *Y* is the value ($P \times Q$) of the economic activity corresponding to the relevant flow (e.g., industry output, household consumption, government consumption). Substituting (8) into (7) and explicitly defining Y as price times quantity (PxQ) gives:

$$V = T \frac{E}{P \times Q} \times 100 \tag{9}$$

Via equation (9), a tax on emissions can be modelled by shocking the exogenous *specific* tax rate T and allowing the quantity of emissions E to endogenously respond. Alternatively, an emissions trading scheme can be modelled by making the quantity of emissions *E* exogenous and shocking it while allowing the *specific* tax rate *T* to be determined endogenously.

Moreover, the model includes a closure mechanism that determines the use of the carbon tax revenue, i.e., whether it is received by households or becomes part of government revenue. The default closure assigns the revenue to households. That is, the carbon 'tax' is returned to households via a 'lump-sum transfer'. This leaves the government budget constant

[4] Note that this carbon price can be gas-specific or gas generic. Furthermore, the modelled carbon price can be interpreted as a shadow price or an observed price; both types of price are represented in an identical fashion in an economic model and this should not be confused with the policy used to achieve emissions targets, i.e., price or non-price intervention.

as a share of GDP. Hence, the transition pathway to net zero emissions is driven entirely by carbon prices and the lump-sum transfer removes the income effect of the carbon tax.

4. Simulation design

Scenario analysis is an important tool to understand the plausible long-term projections of the economic effects of NZE. In this study, we use the integrated CGE framework described above to explore the potential consequences of Australia's NZE trajectories on the economy. In simulating the effects of NZE, we run each CGE model twice to represent a baseline scenario and a policy scenario. Each of these two simulations project a future path of the economy. The baseline is a business-as-usual scenario with the emissions trajectory endogenously responding to current policies whereas the policy scenario projects an alternative path of the economy where the NZE target is achieved. The economic impact of the NZE target is measured by the deviation of economic variables from their baseline values. The following subsections provide details of the baseline and policy scenarios.

4.1 The baseline: a business-as-usual economy

Table 1 summarises the treatment of key variables in the baseline scenario. First, macroeconomic forecasts are developed by combining the latest NIGEM baseline with population and GDP forecasts from Oxford Economics as reported in the IEA's *Net Zero by 2050* report (IEA, 2021a). The macroeconomic forecasts include regional population, regional labour supply, regional GDP, regional employment and the global consumer price index (CPI) (see Appendix, Table A2). The global settings for Australia are endogenously determined in GTEM and these are imposed in ATEM, e.g., shifts in export demands, import and export price indices, global investment, capital stock and rates of return.

In GTEM the global CO_2 emissions pathways are imposed in the baseline via shifts in emission intensity. This includes the global emissions pathway for selected sectors such as electricity, basic chemicals, iron and steel, land transport, water transport, and air transport based on the STEPS scenario from the IEA's *World Economic Outlook* report (IEA, 2021b). Some regional emission pathways are also imposed on electricity emissions. We also inform GTEM with global and regional AFOLU CO_2e emissions pathways in the baseline using inputs from GLOBIOM (Frank et al., 2021). The baseline forecast on global fossil fuel output including the electricity output and technology mix are derived from IEA (2021b) (see Appendix, Tables A4 and A5).

In ATEM, Australia's net emissions are exogenously imposed in the baseline via shifts in emission intensity. This includes broad sectoral pathways in the agriculture, transport and electricity sectors based on projections in DISER (2021). Australia's electricity output and technology mix pathway is also implemented based on the latest projections from AusTIMES (Verikios et al, 2024). In terms of energy efficiency, we impose a 1.5% annual energy efficiency improvement for households and firms. We also assume a 0.5% annual energy efficiency improvement in the iron and steel, non-ferrous metals, and all transport sectors. These energy efficiency assumptions represent the autonomous annual improvement of energy efficiency. In addition, the baseline assumes a starting carbon cost of US$10 per tonne of CO_2e in low-income regions and US$20 in high-income regions to reflect the shadow prices influenced by current global climate policies.

Changes in regional temperature are also imposed in GTEM and ATEM. These calibrate the climate damage function that governs the relationship between total factor productivity loss and chronic temperature change. Global warming temperature trajectories are calculated using the climate carbon cycle model MAGICC.

4.2 The policy scenario: a NZE economy under 1.5° global target

Table 2 summarises the treatment of key variables in modelling the policy scenario. At the global level, a net GHG emissions budget (827Gt CO_2e) is imposed in GTEM with the global emissions pathway consistent with the Illustrative Mitigation Pathway of heavy reliance on Renewables (IMP_Ren) scenario in the IPCC (2022). The fossil fuel output, electricity output and technology mix are also implemented in GTEM and these inputs are consistent with the NZE scenario in the IEA (2021b). For Australia, we transmit the policy pathway of the world GDP price index, CIF import price and FOB export price from GTEM to ATEM. Australia's emissions pathway is also exogenously constrained. With initial CO_2e emissions of 465 Mt in 2020, Australia is projected to reach net zero by 2040, and the economy progresses to a negative emission path with a net residual of -115 Mt CO_2e by 2050. In addition, to reflect the energy transition in the NZE scenario, we impose projections of total electricity output and technology mix based on Verikios et al. (2024). We also impose an extra 0.5%-1% annual efficiency improvement in the use of fossil fuels globally and in Australia.

In both models, the NZE path in the policy scenario is achieved through endogenous changes in the carbon price that represent the marginal cost of abatement. This carbon price is converted into a series of ad valorem taxes on production and consumption. As the carbon price affects the activity of different economic agents, the model endogenously quantifies the effects on GDP, employment, CPI, sectoral output and other economic variables. The carbon ‘tax’ is returned to households via a ‘lump-sum transfer’ by making the government budget constant as a share of GDP. This assumption implies that the transition pathway is driven entirely by carbon prices and the lump-sum transfer removes the income effect of the carbon tax.

5. Results and discussion

This section presents the modelling results from the two models. GTEM generates the broader economic results at the global level as the model captures interregional linkages in the world market. ATEM provides detailed and fine-tuned results of the economic effects for Australia as the model has more precise specification of the domestic economy.

5.1 Global results

Figure 4 shows the global net emissions pathways in the baseline (BAU) and policy (NZE) scenarios. In 2020, global net emissions were 57,846 Mt CO_2e. As the global economy operates under BAU conditions, net emissions fall to 49,512 Mt by 2050 or about 14% is abated over the 30-year period. Under the NZE scenario, the global economy decarbonises more rapidly reducing net emissions to 5,048 Mt by 2050, that is, 91% lower than in 2020. Comparing the two scenarios, achieving NZE leads to more global CO_2e abatement by 90% relative to the baseline at the end of the forecast period. The NZE pathway is achieved through endogenous changes in the carbon price that represent the marginal cost of abatement. As evident in Figure 4, the NZE emissions pathway increasingly deviates from the baseline pathway. Higher decarbonisation requires a marginal cost of abatement or carbon price relative to the baseline. This is indicated by the positive non-linear price trend in Figure 4.

Table 3 provides the global economic effects between the BAU and NZE scenarios. In general, the world economy receives a negative shock under NZE scenario compared to the baseline. The direct effect of pricing emissions is a rise in consumer prices. In the baseline, the global CPI has an average annual increase of 2.36% over the forecast period. In the NZE pathway, CPI growth is slightly higher at 2.54% per annum (pa). Higher consumer prices lead to a reduction in output and consumption. The results show that the global GDP is 0.17% lower in the NZE scenario relative to the baseline. Lower economic growth leads to lower employment and capital growth: both global employment and capital growth fall by 0.11% per year on average under the NZE scenario relative to the baseline. Figure 5 presents macroeconomic results across six broad regions. Overall, there is a higher reduction in economic activity for low- and middle-income countries relative to higher income countries.

Countries in the Middle East and African region experience the largest contraction in GDP growth (-0.43% pa) and employment (-0.16% pa). Asian countries experience smaller reductions in GDP (-0.24% pa) and employment (-0.11% pa) growth. Meanwhile, OECD countries experience the smallest contraction in economic activity with GDP growth falling only by 0.07% and employment growth by 0.05% relative to baseline.

Figure 6 shows the transformation in the global energy mix as driven by the carbon price. Pricing emissions provides a financial incentive for economic agents to decrease the use of emission-intensive fuels and encourages the economy to invest, develop and adopt more energy-efficient practices and technologies. In 2020 fossil fuels are a major energy source. By 2050, the BAU energy mix is still heavily reliant on fossil fuels (80% share) with some movement to electrification. In contrast, by 2050 the NZE energy mix alters radically as the consumption of fossil fuels drops by more than half relative to the baseline. This substantial change in the energy mix implies a substitution of renewable energy for fossil fuels. This is reflected in the growth in importance of electricity and hydrogen noting that most of the electricity is produced using wind and solar. It is also notable that the total energy use decreases in the NZE scenario and is 40% lower by 2050 compared to BAU. This implies a significant improvement in energy efficiency for the world economy.

5.2 Australian results

ATEM, having a more sophisticated representation of the Australian economy, is used to model the domestic impacts of the NZE scenario.

5.2.1 Emissions pathway

Australia's net emissions in 2020 were approximately 465 Mt CO_2e, made up of gross emissions of 529 Mt CO_2e and LULUCF of -64 Mt CO_2e. Figure 7 presents the net carbon emission pathways in the BAU and NZE scenarios over the 30-year forecast period. Total emissions more than halve by 2050 under the BAU scenario to 195 Mt CO_2e. This significant reduction is enabled by existing mitigation efforts as part of Australia's climate change policy. For example, as supported by government policy, the shift from coal-generated electricity to renewables is already happening driven by the closure of coal plants and the low cost of solar and wind electricity. The continuation of this trend is now regarded as a near certainty in expert circles (CCA, 2024). In contrast to the BAU scenario, the NZE scenario achieves NZE by 2040 after which the Australian economy progresses into a negative net emissions. This emissions trajectory is facilitated through more extensive policies, strategies, investments, industrial transformation, and technological advancements to accelerate decarbonisation. At the end of the forecast period, Australia's net emissions are 150% lower than the baseline, with a net residual of -123 Mt CO_2e.

Figure 7 also reports the carbon price pathway required to achieve NZE. A positive non-linear relationship is observed between the marginal cost and the degree of emissions abatement, i.e., the carbon price increases exponentially as the gap between the BAU and NZE emissions becomes larger. This implies that greater emissions abatement raises the marginal cost of abatement relative to the baseline. The real carbon price is about $700/t of CO_2e by the time the economy reaches net zero emissions from 2040 onwards. This carbon price flows through to each sector as a carbon tax imposed on businesses and individuals based on the amount of CO_2e emitted from the consumption of energy goods and other carbon-emitting activities.

The transition to NZE is achieved by a combination of decarbonisation efforts by industries and households. This is also complemented by negative emissions from DACCS and LULUCF.[5] Figure 8 shows the breakdown of emission sources under the NZE scenario. From 2020 to 2040, the largest contributor to decarbonisation is the reduction in industry emissions. From 2041 onwards, negative emissions become a larger component of total net emissions. In 2050, negative emissions contribute a residual of 240 Mt CO_2e, 70% of which is from LULUCF and the remaining 30% from DACCS. There is also an 85% emissions reduction from shifts in household consumption over the forecast period; these are primarily attributed to the use of energy in household transport and dwellings.

Total industry emissions fall significantly from 468 Mt CO_2e in 2020 to 205 Mt CO_2e by 2050 in the BAU and 110 Mt CO_2e in the NZE economy. The magnitude of emissions reduction varies greatly across sub-industries. The greatest reduction is seen in electricity generation (151 Mt of CO_2e abated) followed by mining (-86 Mt CO_2e), agriculture (-36 Mt CO_2e) and transport (-33 Mt CO_2e). These sectoral abatements are driven by increased electrification and reduced energy intensity together with the uptake of emissions-reducing technologies (e.g., material substitutions and process improvements). Appendix 3 provides further decomposition and explanation of the sectoral emissions.

[5] Our modelling incorporates several negative emissions technologies: (i) DACCS, (ii) BECCS, (iii) carbon plantings (LULUCF).

5.2.2 Transformation in the energy system

The power sector accounts for more than a third of Australia's total emissions, which is higher than any other sector of the economy. Given its substantial carbon footprint, the rapid decarbonisation of this sector is crucial to attaining NZE in Australia.

Power generation in Australia is currently dominated by coal- and gas-fired generation for grid power, and predominantly diesel generation in off-grid systems (see Figure 9). In 2020, electricity generation was around 255 terawatt-hours (TWh), more than half of which was coal-fired, followed in importance by natural gas (22%), non-hydro renewables (13%), hydro (7%), and bioenergy (<1%). In the NZE scenario there is a significant change in the electricity fuel mix as the economy transitions from non-renewable to renewable energy sources. This transition is rapidly underway driven by the retirement of aging coal plants, the rapid expansion of residential rooftop solar photovoltaic (PV) systems, and the large-scale deployment of wind and solar power generation. Notably, the share of non-renewable electricity generation is projected to decline sharply through the 2030s, driven by renewable energy targets and the scheduled closures of coal-fired power plants. In the medium-term, there is an increasing share of variable renewable energy (VRE) through onshore wind farms, followed by an accelerated deployment of utility-scale solar PV farms and battery energy storage (Verikios et al., 2024). The share of renewables in total power generation reaches 70% by 2030 and increases to more than 95% by 2040. As such, Figure 9 shows that the NZE pathway for electricity generation means emissions fall close to zero by 2050. From around 157 Mt CO_2e in 2020, emissions decline rapidly to around 30 Mt of CO_2e in 2030. Consistent with these changes, emission intensity falls significantly over this period from 0.60 Mt CO_2e per terawatt hour (TWh) in 2020 to around 0.06 in 2030 and almost nil by 2040. Emissions continue to fall at a decreasing rate reaching 10 Mt by 2035, 5 Mt by 2040 and close to nil in 2050.

Figure 10 presents the path of the energy mix in the BAU and NZE scenarios over the forecast period.[6] Initially, the Australian economy is very dependent on fossil fuels as an energy source. About 35% of total energy consumption in 2020 is from oil-derived fuels (e.g., petroleum). This is followed in importance by coal (22%), gas (21%) and electricity (20%). The energy mix is projected to change in both scenarios. Under BAU conditions, the share of oil-derived fuels declines slightly to 32% in 2050 while the share of electricity doubles to 42% as renewable energy is substituted for coal-fired power. Under the NZE scenario, there is a more rapid change in the energy mix with coal plants being phased out by 2035. Electricity

[6] Figure 10 only refers to domestic energy demand, i.e., it does not include exports.

becomes the major source of energy in 2050, contributing 70% to total energy consumption. The share of oil-based fuels declines by more than half by 2050. There is also a decline in the share of gas in total energy consumption from 21% in 2020 to 7% in 2050.

Figure 11 further decomposes the changes in the energy mix across six broad sectors: agriculture, mining, transportation, manufacturing, services and households.[7] As mentioned earlier, pricing emissions means higher consumer prices especially for energy goods where the carbon tax is directly levied. The relative prices of energy commodities influence the energy mix across sectors as industries economise by substituting cheaper energy sources for expensive ones. In the initial year (2020), the largest energy user is the household sector followed by manufacturing, mining, transport, services and agriculture. The initial energy mix of most sectors is dominated by oil-derived fuels such as petroleum and diesel. These fuels are used mainly in private vehicles (by the household sector), heavy vehicles and machinery (by the mining and agriculture sectors), and buses, trucks and boats (by the transport sector). Gas, however, is mainly used by the manufacturing sector for heating especially in forging iron, steel and aluminium products. In general, the share of fossil fuels declines over time in both the BAU and NZE scenarios and is offset by an increase in the use of electricity with a much stronger switch to electricity under the NZE pathway.

So what are the sectoral drivers of these changes in the energy mix? The household sector is expected to have a strong uptake of renewable energy as driven by significant growth in the deployment of distributed rooftop solar PV systems, especially on residential buildings, followed by large-scale renewable generation (primarily onshore wind and solar PV). For road transport, an increase in the deployment of more efficient internal combustion engine vehicles (especially hybrids), and to some extent battery electric vehicles (BEV) will reduce the use of oil-derived fuels. There is also an uptake of hydrogen, mainly in road freight and shipping and, to some extent, in rail transport. For the mining sector, the increasing demand for batteries and electrification drives demand for processed minerals such as copper, nickel, lithium, cobalt and other rare earth metals. This switch in mining activity from coal-oil-gas to other mineral extraction leads to the substitution of electric or fuel cell drivetrains in heavy machinery and transportation for diesel engines. For the manufacturing sector, the change in energy mix is the result of a combination of autonomous energy efficiency improvements, and specific

[7] Note that transportation refers to the transport industry itself providing different modes of transport services such as road, shipping and aviation. This excludes the use of private vehicles for transport, which is accounted separately under household consumption.

technology adoption and process improvements.[8] For the service sector, electrification advancements reduce the use of oil-derived fuel especially those used in heavy vehicles and machinery by the construction services. There is also an option to blend hydrogen into the natural gas uptake by commercial buildings.

5.2.3 Macroeconomic effects

The abatement cost of decarbonising the Australian economy raises the cost of production in various sectors. This means that the direct effect of pricing emissions is a rise in the price of output. Figure 12 shows the inflationary effect of the carbon price as indicated by the significant increase in the CPI. Over the 30-year period, consumer price increase by 5.67% relative to baseline. The rise in consumer prices causes a fall in aggregate demand, which in turn, leads to a lower output growth for the whole economy: real GDP falls by 4.22% relative to baseline. With the reduction in economic activity, industries employ less labour and capital than they would have without the carbon tax. The changes in the demand for labour are reflected in changes in employment and the real wage rate: employment falls by 1.97% while there is a much larger fall in the real wage rate at 8.37%; this reflects the inelasticity of the labour supply.

Figure 12 also shows the effects on the expenditure-side components of GDP such as consumption, investment, exports and imports. The largest reduction is seen in real exports. This is expected as Australia's NZE pathway requires a significant reduction in output by the coal, oil and gas sectors, which are both emission intensive and export oriented. In 2020, these sectors contribute 23% to total exports. A high domestic carbon price raises production costs significantly for these and other emission intensive exports, and this leads to a fall in quantity demanded. Furthermore, a high global carbon price significantly reduces global demand for coal, oil and gas which also acts to reduce Australia's exports by these sectors. Thus, Australian exports fall by 14.83% by 2050.

The mining sector is an intensive user of capital inputs. As mining sector activity contracts due to higher production costs, rates of return on capital and thus investment fall. Figure 12 shows a 3.35% reduction in real investment by 2050. The lower wage rate, together with higher consumer prices, implies lower purchasing power of households. Overall, real consumption falls by 5.71% by 2050. Imported goods contribute a significant portion of

[8] Specific manufacturing industries with potential energy improvements include alumina (via mechanical vapour recompressions and hydrogen calcination), iron ore mining (via electrification in material handling and some fuel cell uptake in heavy trucking), liquified natural gas export (via compressor electrification and waste heat recovery), ammonia (via feedstock substitution of natural gas for hydrogen) and cement (via material substitution of Portland).

household consumption and investment inputs in Australia. Hence, with both consumption and investment falling, the demand for imports also falls (-12.93%).

5.2.4 Sectoral effects

To reiterate, implementing the NZE pathway for Australia is facilitated by a carbon price imposed on the amount of GHG gases emitted from the use of energy goods and other carbon-emitting activities. Hence, the first-round effect of the carbon price is to raise the price of fossil-fuel-based energy goods (i.e., coal, oil, gas and petroleum) relative to renewables (i.e., wind and solar). The price effect is presented in the first panel of Figure 13. The carbon price provides an incentive for producers to switch to the cheaper and cleaner energy source. This substitution effect is evident in the second panel of Figure 13 where the output of renewables increases relative to baseline while fossil-fuel-based energy declines. Overall, as indicated in Figure 14, there is an expansion in the economic activity of the electricity generation sector with its output increasing by 60% at the end of the forecast period. For non-energy sectors, the effect of higher fuel prices implies a higher cost of production, which would flow through to higher output prices. The largest average annual change in output prices is observed in manufacturing (+0.15% p.a.) which is an intensive user of fossil fuels. Its output contracts by 0.57% p.a. over the forecast period relative to baseline. The price of agricultural commodities also increases by 0.20% p.a., causing a reduction in output by 0.45% p.a. relative to baseline.

Unlike manufacturing and agriculture, the price of mining does not rise as much (0.02% p.a.) but its output contracts by 0.54% p.a. This implies that the effect on the mining sectors is supply-driven as many coal-fired plants are shut down when the energy system is transformed to favour more renewable sources. The transport sector also contracts by 0.11% p.a. relative to baseline. This change is smaller relative to other sectors as it excludes private transport used by households. Lastly, the output of the service sector does not fall by much as its energy and emission intensity are relatively low compared to other sectors.

6. Sensitivity analysis

This section investigates the sensitivity of the Australian results to three parameters in ATEM: (1) the speed with which NZE is achieved, (2) the cost of endogenous reductions in emissions intensities, and (3) climate-induced productivity loss.

The first sensitivity test evaluates the importance of the speed with which NZE is achieved. In the current scenario (referred to as benchmark), Australia reaches net zero in 2040. For the sensitivity test we adjust the net zero year by implementing two alternatives emission pathways: (i) a rapid decarbonisation pathway where NZE is achieved earlier (in 2035), and (ii) a delayed transition pathway where NZE is achieved later (in 2045). Simulation results in Figure 15 (Panel A) shows a positive relationship between economic disruption and the speed of NZE attainment. The economy has a higher adjustment cost when NZE is achieved earlier in 2035, i.e., real GDP falls by more (1.76 percentage points) relative to the benchmark. Similarly, the economic cost of decarbonisation is lower when NZE is delayed to 2045, i.e., real GDP falls by less (1.30 percentage points) relative to the benchmark.

The second sensitivity test evaluates the importance of the parameter γ (see equations (4) and (6)) – the cost of carbon-price-induced reductions in emission intensity. The benchmark value of this parameter is 0, which means that any carbon-price-induced reduction in a given emission intensity is costless. First we test the sensitivity of γ_j^O (output-based emissions) by setting its value to 10, which means that a 1% carbon-price-induced reduction in the emission-intensity of output leads to an output loss 0.1%. Next we test the sensitivity of γ_{iu}^F by setting its value to 10 for input-based emissions, which means that a 1% carbon-price-induced reduction in the emission-intensity of intermediate inputs reduces the efficiency of intermediate inputs by 0.1%. The results of these two sensitivity simulations are presented in Figure 15 (Panel B). Assuming a non-zero cost to carbon-price-induced reductions in output-based emissions leads to an additional fall in real GDP of 0.07 percentage points, which is only a marginal effect. Assuming a non-zero cost to carbon-price-induced reductions in input-based emissions leads to an additional fall in real GDP of 0.73 percentage points, which gives a coefficient of variation of 0.17. Thus, the cost of carbon-price-induced reductions in input-based emissions is significant whereas this is not the case for output-based emissions.

The last sensitivity test evaluates the effect of varying the parameter in the climate damage function (CDF) that governs the relationship between productivity losses and global temperature increases.[9] The value of this parameter is initially set to 2.35. We conduct a sequence of simulations where the value of this parameter is increased by 25% in each simulation run. Results in Figure 15 (Panel C) show the changes in real GDP are marginal across sensitivity runs. Real GDP only falls by an additional 0.01 percentage points for every 25% increase in the value of the CDF parameter.

[9] The climate damage function is adopted from the MERGE model. See Manned and Richels (2005) for a detailed exposition of this function.

7. Conclusion

This study explores the economywide effects of a global and Australian net zero emissions (NZE) trajectory using an integrated CGE approach. The NZE scenario implements a global setting where coordinated action is taken to limit warming to 1.5°C. Within this global setting Australia reaches NZE in 2040 and then moves to negative net emissions by 2050. Two CGE models are applied in the analysis: the first is a global model (GTEM) that represents the regional trade and investment linkages in global economy and the second is an Australian model (ATEM) that has a very detailed representation of the Australian economy. These two models are integrated in a two-stage process. In the first stage, we run GTEM to simulate the economic effects of NZE at the global level and explore how the global macroeconomic effects influence the Australian economy through international investment and trade. In the second stage we apply the GTEM results for Australia as an input to ATEM. This linkage captures the interaction of the domestic economy with the world market. As ATEM has a more precise specification of the domestic economy, the second pass of our economic modelling generates detailed and fine-tuned results of the economic effects for Australia.

The results show that achieving NZE brings a negative shock to the economy as it requires substantive transformation of the Australian and global economy. The abatement cost of decarbonising the economy raises the cost of production thereby increasing consumer prices, which in turn leads to a reduction in total output and employment. The results show that global CPI is 0.18 percentage points higher per year under the NZE scenario relative to baseline. This causes the annual growth in global real GDP to fall by 0.17% and employment 0.10% relative to baseline. For Australia, the same pattern is observed for all economic indicators, but the magnitude of the effects is slightly different. Over the 30-year forecast period, the CPI in Australia is 5.67% higher (or 0.19% p.a.) in the NZE scenario relative to baseline. Real GDP is 3.95% lower (or 0.13% p.a.) and employment is 1.97% (or 0.06% p.a.) lower relative to baseline.

As a major commodity exporter Australia is highly exposed to global trade and the country's emissions-intensive exports are vulnerable to the energy transition pathway. Australia's transition to a low carbon economy is characterised by rapid electrification of economic activities. The energy mix of the economy is transformed from fossil- fuel-based to renewable-energy based. This transformation of the energy system impacts coal production, and to a lesser extent gas, as wind and solar energy generation increases. The changes in the energy mix vary greatly across sectors as do the scale of sectoral CO_2e abatement. Electricity decarbonisation is the largest source of industry abatement (41%) followed by mining, agriculture, transport, manufacturing and services. The emissions reduction of the industry sector is complemented with net negative emissions from land use and new technologies to support Australia's decarbonisation path.

Electricity generation expands by 1.45% per year on average over the entire forecast period. Nonetheless, the abatement cost of decarbonising the economy causes disruption in other industries. The disruption effects vary widely across sectors with an annual average output loss ranging from 0.05 to 0.60 percentage points. The potential divergent outcomes highlight substantive transition risks for manufacturing and mining sectors, which are intensive users of fossil fuels.

We tested the sensitivity of economic results to three parameters: (1) the timeframe of achieving the NZE target, (2) the cost of carbon-price induced emissions reduction, and (3) the size of the productivity loss due to temperature increases. The results are most sensitive to the first parameter, with the GDP loss higher by 42% more when the NZE target is achieved 5 years earlier.

There are several areas left unexplored in this work that may be important to the analysis. First, the analysis does not explore the range of transition risks under different socioeconomic pathways, different degrees of domestic and global decarbonisation, or consider an orderly pathway to NZE. These areas could possibly be important for accurately reflecting the transition risk to a low carbon economy. Second, our analysis focuses only on the economic transition whilst disregarding the economic effects of physical hazards (particularly acute risk) associated with climate change. Research suggests that both chronic and acute climate hazards will increase into the future, particularly to the agricultural and construction sectors. The inclusion of these risks will be an important area to focus on in future analysis.

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Tables

Table 1. Exogenous shocks imposed in the baseline scenario of GTEM and ATEM.

Variable	**GTEM**	**ATEM**
Macroeconomic forecast	Movements in regional population, regional labour supply, regional employment, world real GDP and global CPI. Regional debt-to-GDP ratios are stabilised by 2050.	International variables are extracted from GTEM and imposed as inputs in GTEM's baseline. These include foreign prices of exports and imports, real world GDP, world GDP deflator, global rates of return, investment price and capital stock. Australian economic forecast such as the growth in real GDP, labour supply, population and employment. Ratio of current account to GDP is stabilised by 2050 as well as the ratio of government budget to GDP.
CO2e emissions	Global pathway and selected regional emissions. Global CO2 emissions pathways for selected industries. Global and regional AFOLU CO2-eq emissions pathways.	Australia's total net emissions and across broad sectors. LULUCF emissions and negative emissions technology pathways.
Surface temperature per region	Global temperatures calculated using MAGICC and regional averages calibrated using CMIP5 climate model outputs.	Productivity impacts for Australia as calculated by the climate damage function in GTEM.
Electricity output and technology mix	Global and regional electricity output pathways. Global electricity technology mix pathway.	Australia's electricity technology mix
Fossil fuel output	Global coal, oil and gas output pathways from IEA Stated Policies scenario.	Australia's supply of coal, oil and gas
Energy efficiencies	Global energy efficiencies for households and selected industries.	Energy efficiencies for Australian households and selected industries.
Real carbon price	$10/t of CO2e in low-income regions and $20 in high-income regions	$20/t of CO2e

Table 2. Treatment of key variables for modelling the NZE scenario

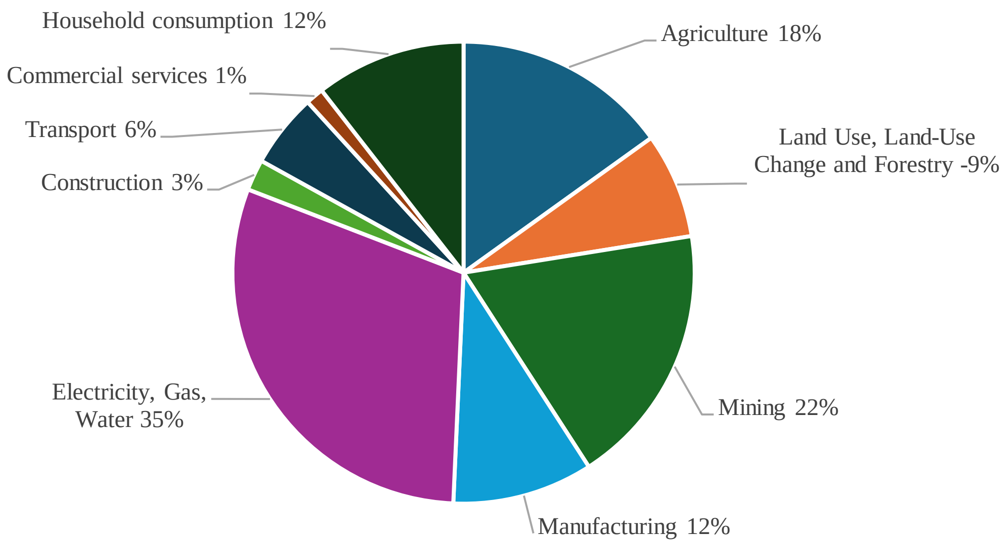
Variable	GTEM	ATEM
Macroeconomic forecasts	Movements in regional population and regional debt-to-GDP ratios match the CSP scenario.	Movements in global prices for Australian exports and imports are consistent with GTEM.
Carbon price	Endogenously responds to emissions targets	Same treatment as GTEM.
Emissions	Consistent with IMP_Ren scenario carbon budget in the *IPCC sixth Assessment Report*.	Consistent with DISER's GHG emissions forecast for Australia.
Electricity output and technology mix	Global electricity output and technology mix pathway from NZE scenario in IEA 2021 report.	Australia's electricity output and technology mix pathway from AusTIMES.
Fossil fuel output	Global coal and gas output pathways from IEA NZE scenario.	Australian fuel demands for coal, oil, petroleum and gas.
Energy efficiency	1.5% annual energy efficiency improvement for households and firms. Extra 0.5% annual energy efficiency improvement for iron and steel, non-ferrous metals, and all transport sectors. Extra 0.5%-1% annual efficiency improvement in use of fossil fuels.	Same assumption as GTEM.

Table 3. Key macroeconomic performance on the global level in both scenario

	2020-2030	2031-2040	2041-2050	2020-2050
Real GDP (average annual percentage change)				
BAU	2.47	2.05	2.50	**2.35**
NZE	2.43	1.97	2.11	**2.18**
Real GDP per capita (average annual percentage change)				
BAU	1.49	1.26	1.88	**1.54**
NZE	1.45	1.18	1.49	**1.37**
Consumer price index (average annual percentage change)				
BAU	2.57	1.91	2.59	**2.36**
NZE	2.62	1.99	2.99	**2.54**
Employment (average annual percentage change)				
BAU	0.79	0.60	0.62	**0.67**
NZE	0.72	0.56	0.38	**0.56**
Capital (average annual percentage change)				
BAU	3.92	3.51	3.07	**3.51**
NZE	3.89	3.47	2.78	**3.40**

Figures

Figure 1. Sectoral distribution of Australia's GHG emissions, 2020



Source of basic data: Australia's National Greenhouse Accounts, DCCEEW

Figure 2. IAM framework for the economic analysis of climate change

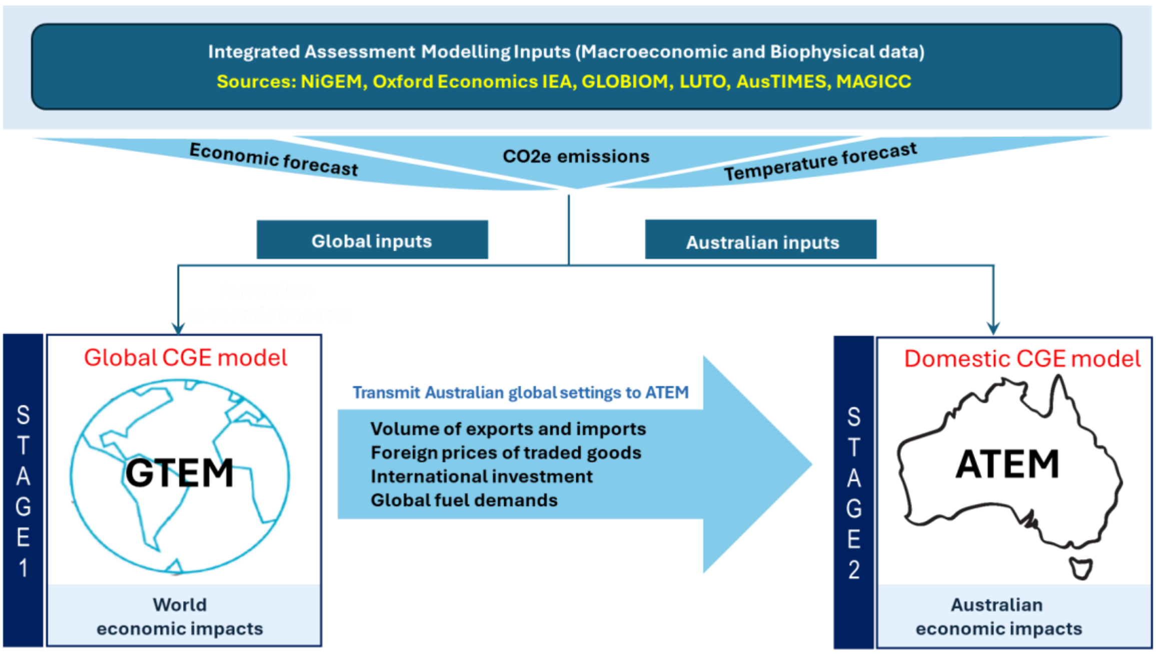
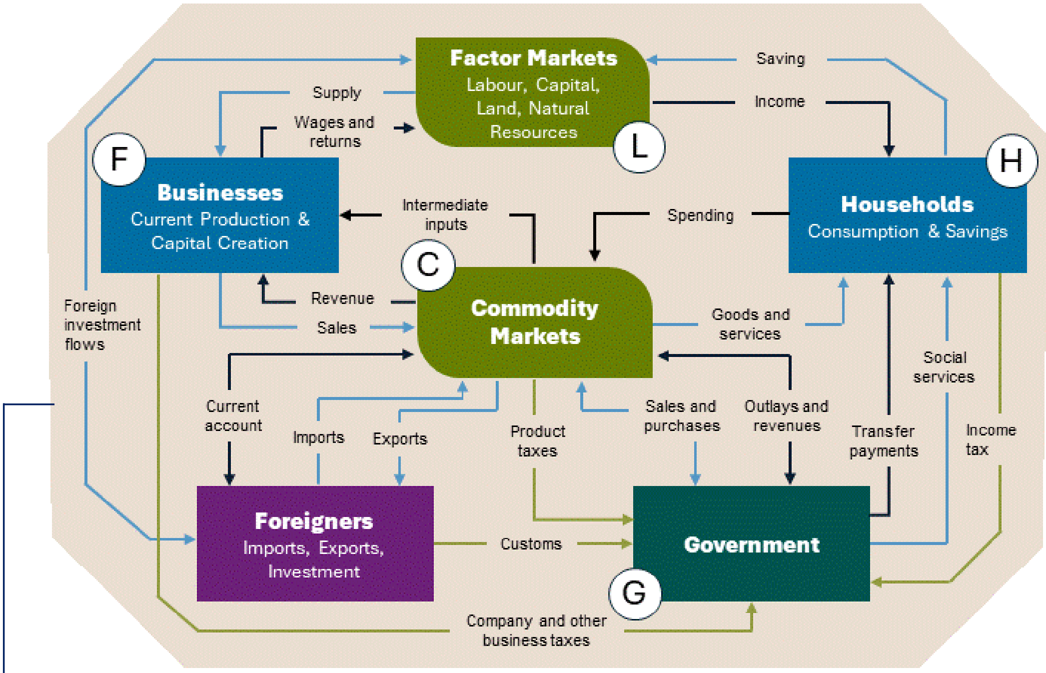


Figure 3. Integrated assessment CGE modelling framework

A. Theoretical structure of ATEM and GTEM



B. Interaction between ATEM and GTEM

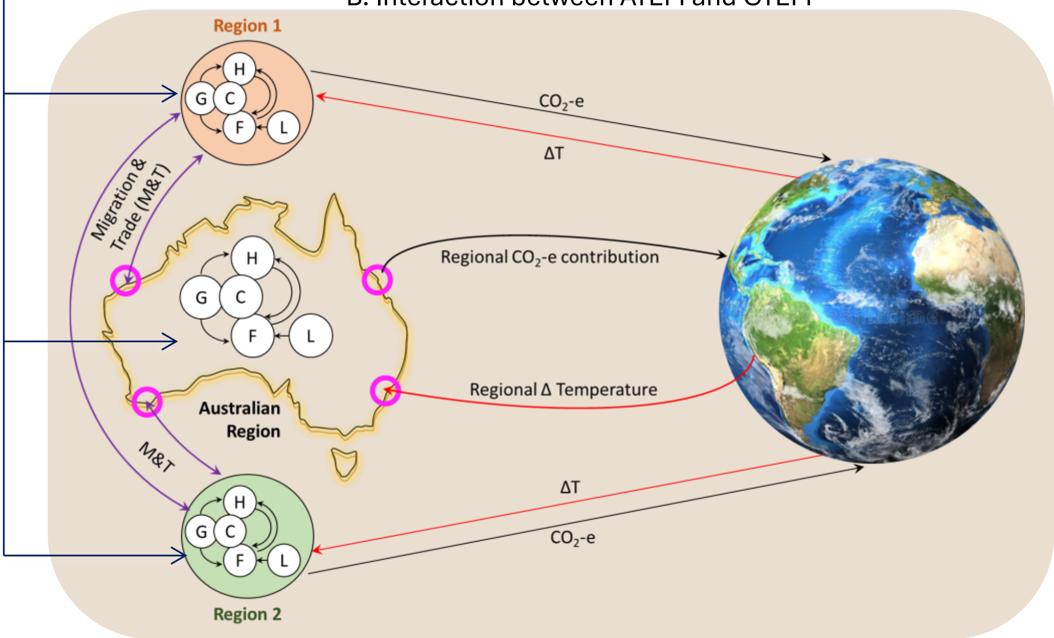


Figure 4. Global net emissions pathway and carbon price

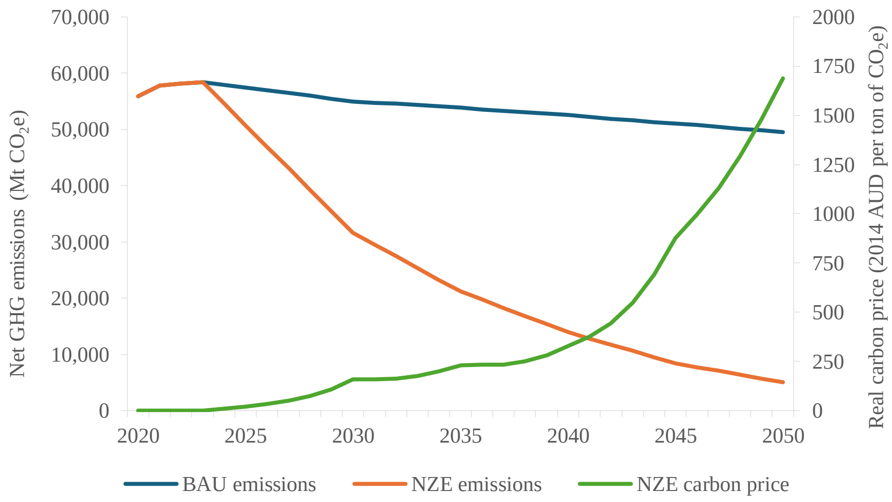


Figure 5. Macroeconomic results across broad global regions

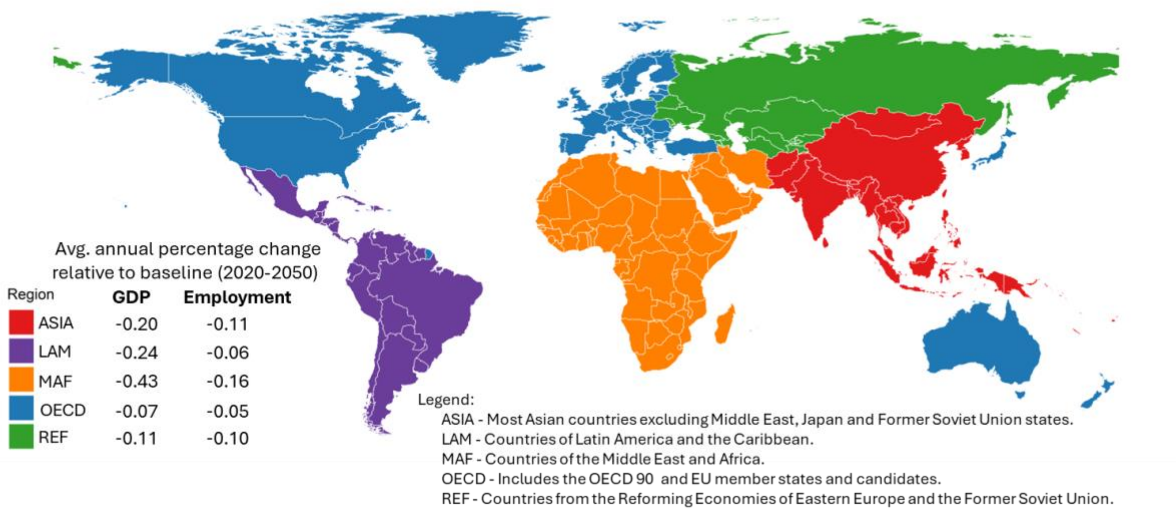


Figure 6. Global energy mix ('000 PJ) in the BAU and NZE scenarios

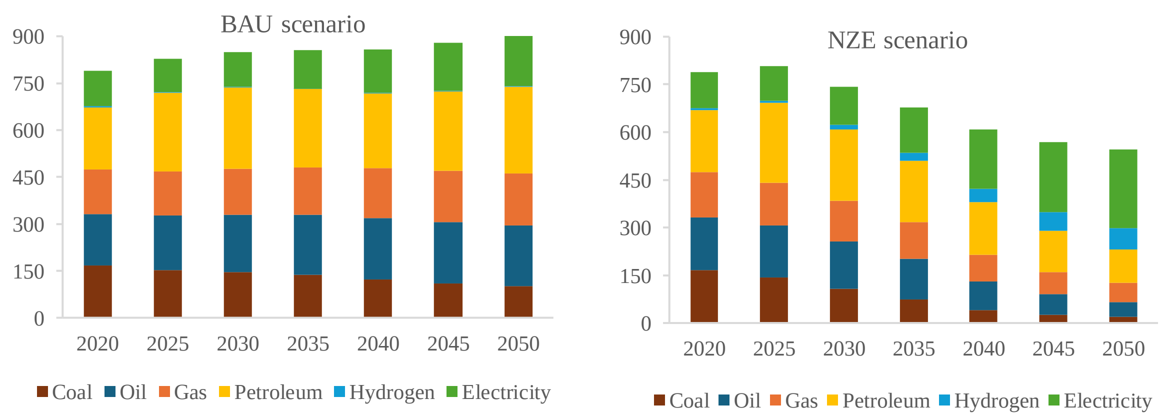


Figure 7. Net emissions and real carbon price, Australia

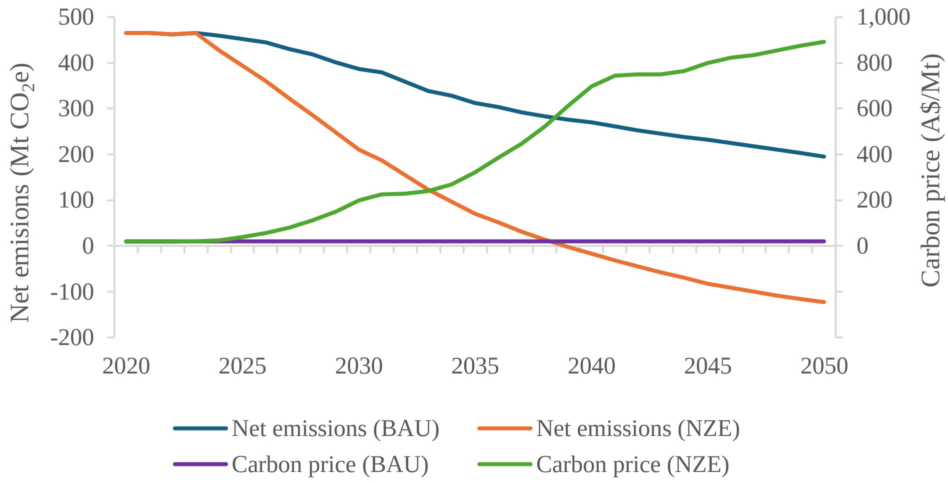


Figure 8. NZE by source (Mt CO_2e), Australia

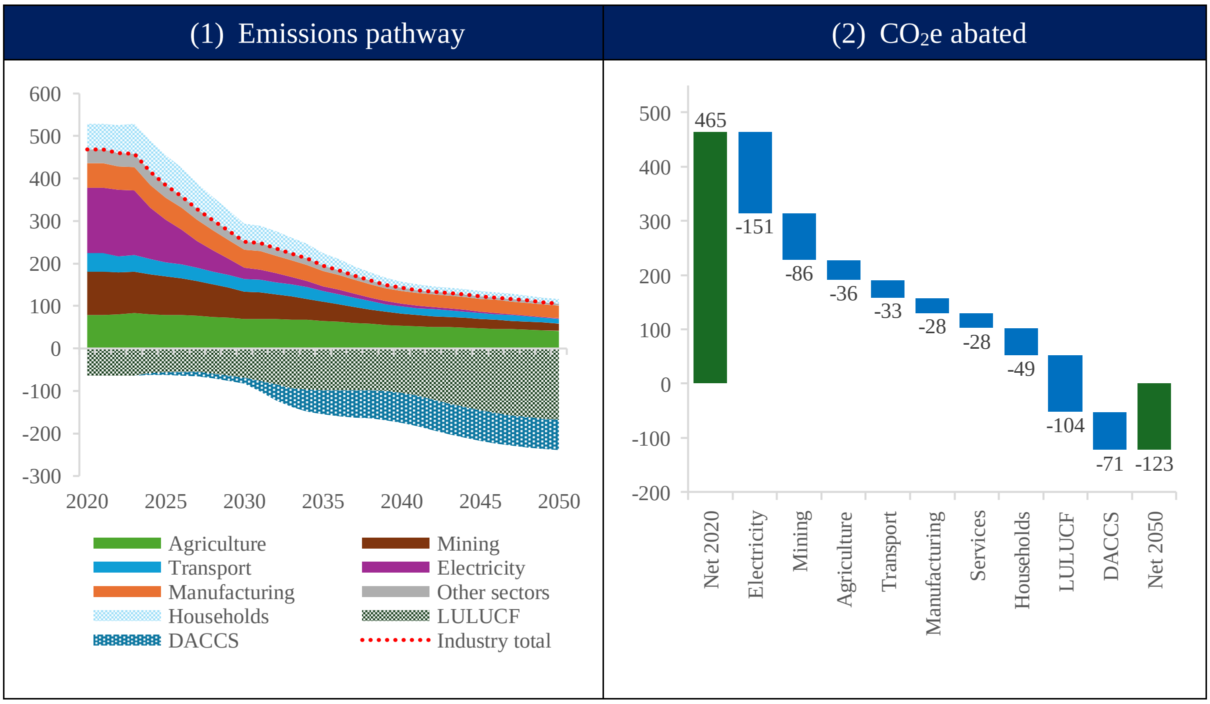


Figure 9. Australian electricity generation output and emissions, NZE scenario

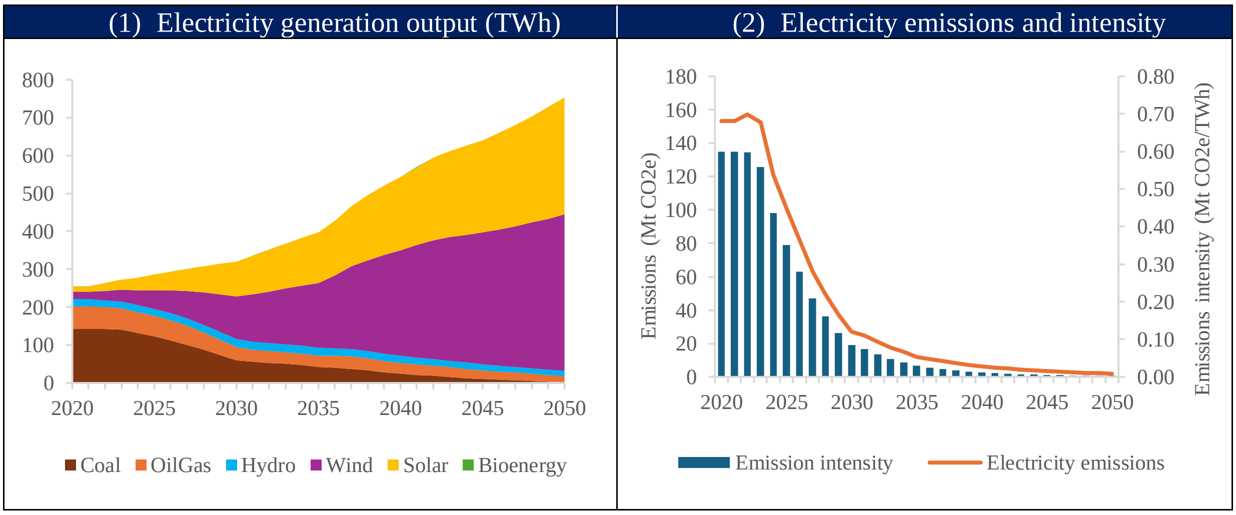


Figure 10. Australian energy mix (domestic demand) (PJ)

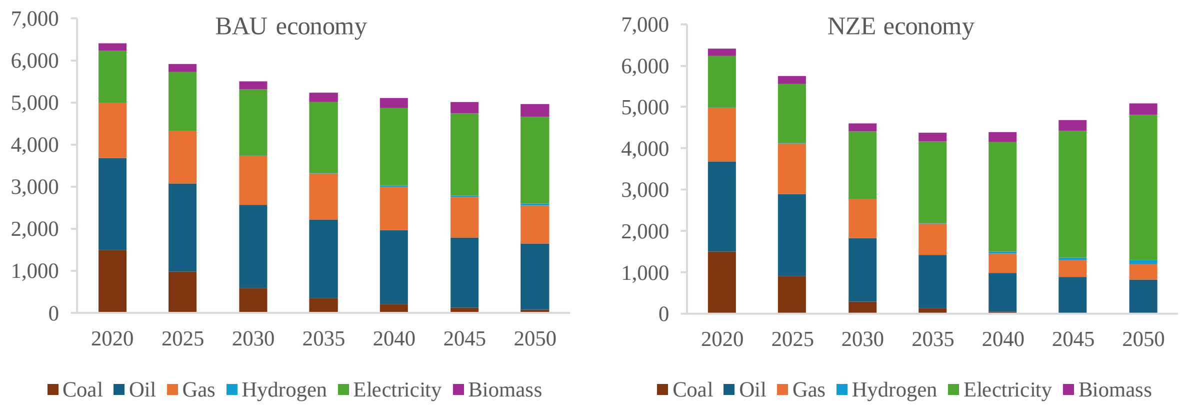


Figure 11. Australian energy mix by sector (domestic demand) (PJ)

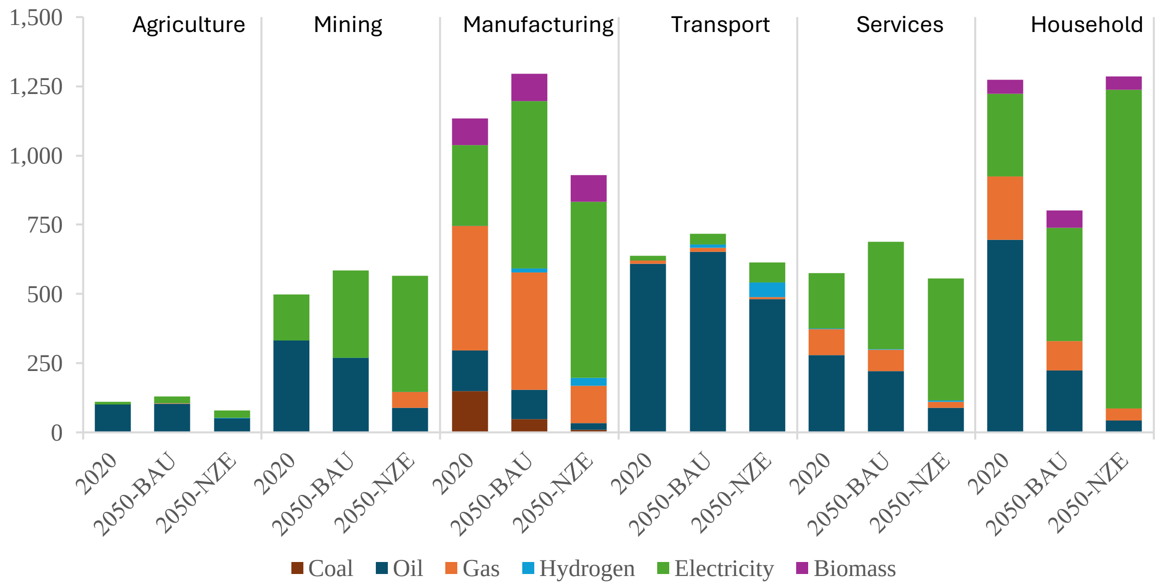


Figure 12. Macroeconomic results, Australia (cumulative % change relative to baseline in 2050)

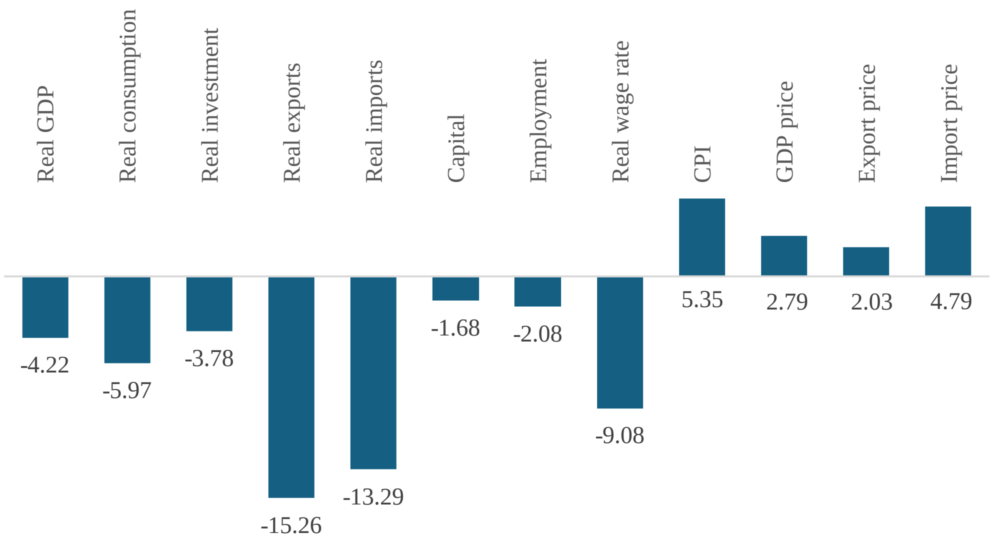


Figure 13. Sectoral output effects in the energy sector, Australia (% change relative to baseline)

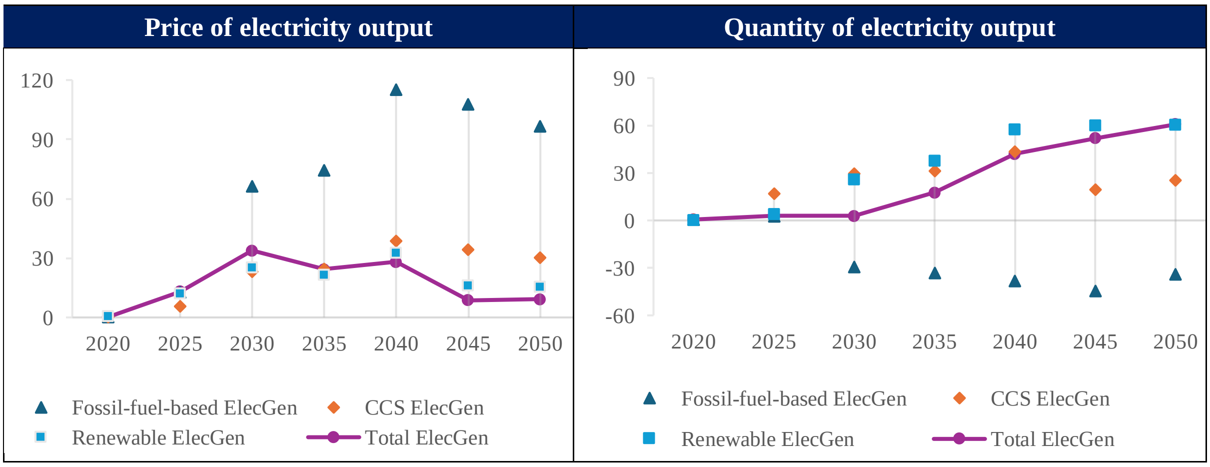


Figure 14. Average annual percentage changes in sectoral output relative to baseline, Australia

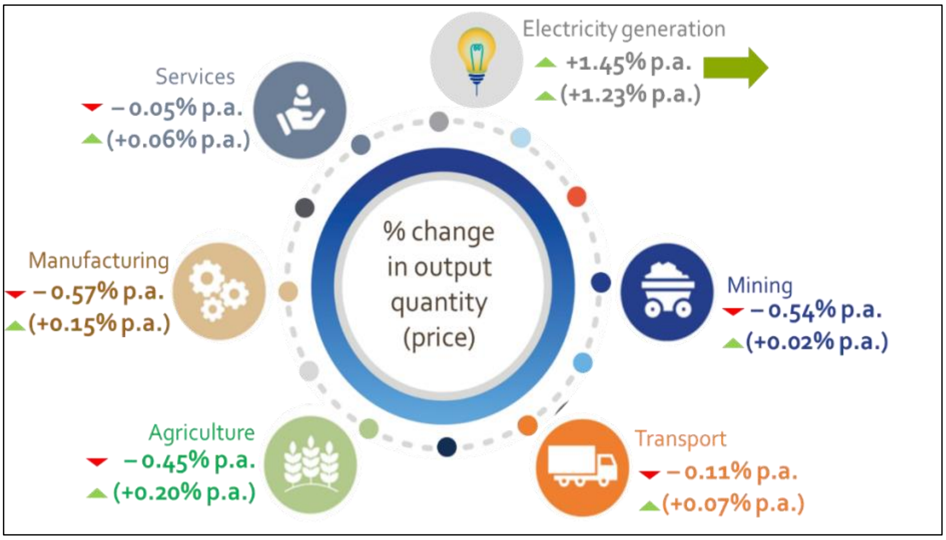


Figure 15. Sensitivity tests

Appendix 1. Regional and sectoral aggregations

Table A1. GTEM sectoral and regional aggregation

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

Table A2. ATEM sectoral aggregation

No.	Sector	No.	Sector
1	Sheep, Grains, Beef and Dairy Cattle	34	Electricity Generation from solar
2	Poultry and Other Livestock	35	Electricity Generation from Nuclear
3	Other Agriculture	36	Electricity Generation from Coal with CCS
4	Aquaculture	37	Electricity Generation from Coal with CCS
5	Forestry and Logging	38	Electricity Generation from Gas with CCS
6	Fishing, hunting and trapping	39	Electricity Generation from Bioenergy with CCS
7	Coal	40	Electricity Generation National Market
8	Crude oil (incl condensate)	41	Electricity Transmission and Distribution
9	Gas	42	Gas Supply
10	Iron Ore Mining	43	Water Supply, Sewerage and Drainage Services
11	Other Mining	44	Residential Building Construction
12	Food Manufacturing	45	Non-Residential Building Construction
13	Beverage Manufacturing	46	Other Construction Services
14	Textile, Cloth and Footwear	47	Wholesale and Retail Trade
15	Wood Product Manufacturing	48	Accommodation, Food and Beverage Services
16	Paper & Paper Products: includes printing and reproduction of recorded media	49	Road transport
17	Petroleum & Coke: manufacture of coke and refined petroleum products	50	Rail Transport
18	Hydrogen proton exchange membrane (PEM) “Green” Product Manufacturing	51	Water, Pipeline and Other Transport
19	Hydrogen steam methane reforming (SMR) Gas Product Manufacturing	52	Air Transport
20	Hydrogen SMR with carbon capture & storage (SMR-CCS) “Blue” Product	53	Transport Support services and storage
21	Basic Chemical Manufacturing	54	Information media and Telecommunication Services
22	Rubber and plastics products	55	Finance
23	Other non-metallic mineral products	56	Insurance, Superannuation Funds, and Other Auxiliary Finance
24	Iron & Steel: basic production and casting	57	Rental and Hiring Services (except Real Estate)
25	Other Metal products	58	Ownership of Dwellings
26	Transport Equipment manufacturing	59	Professional, Scientific and Technical Services
27	Electrical Equipment Manufacturing	60	Administrative Services
28	Other Manufacturing	61	Public Administration and Defence Services
29	Electricity Generation from coal	62	Education and Training
30	Electricity Generation from oil	63	Health Care Services and Social Assistance Services
31	Electricity Generation from gas	64	Arts and Recreation Services
32	Electricity Generation from hydro	65	Other Services
33	Electricity Generation from wind		

Appendix 2. Modelling inputs

Table A3. Inputs applied for demographic and economic variables in the baseline (BAU) scenario

	2020-2030	2030-2040	2040-2050
Population* (average annual %-change)			
Global	0.97	0.78	0.61
Australia **	1.46	1.16	0.98
New Zealand	0.72	0.49	0.31
China	0.19	-0.10	-0.33
Japan	-0.45	-0.63	-0.69
South Korea	-0.01	-0.27	-0.61
Rest of Asia	0.89	0.56	0.28
Indonesia	0.92	0.63	0.38
India	0.88	0.58	0.28
Canada	0.80	0.63	0.49
USA	0.55	0.47	0.34
Mexico	0.91	0.61	0.35
South America	1.03	0.70	0.46
Brazil	0.54	0.23	-0.01
EU15	-0.02	-0.12	-0.24
EU12	-0.02	-0.12	-0.24
Rest of Europe	-0.34	-0.51	-0.63
Russia	-0.16	-0.30	-0.23
Middle East	1.69	1.31	1.07
Africa	2.61	2.32	2.01
Rest of World	0.96	0.75	0.58
Real GDP (average annual %-change)			
Global	2.43	2.07	2.52
Australia	2.61	1.96	2.13
New Zealand	2.30	1.95	2.38
China	4.84	2.88	2.95
Japan	0.67	-0.15	0.42
South Korea	2.28	2.27	2.68
Rest of Asia	3.75	3.31	3.35
Indonesia	3.80	3.07	3.10
India	4.99	5.06	4.54
Canada	1.69	1.60	2.05
USA	1.73	1.64	2.32
Mexico	1.54	1.60	2.30
South America	0.74	0.79	1.19
Brazil	2.06	1.92	2.48
EU15	1.27	0.93	1.62
EU12	1.26	0.87	1.60
Rest of Europe	2.18	1.89	2.38
Russia	1.67	1.05	1.45
Middle East	2.74	2.58	2.68
Africa	3.28	4.24	4.56
Rest of World	2.81	2.42	2.79
Consumer price index (average annual %-change)			
Global	2.57	1.91	2.59

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

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

Table A4. IEA targets (STEPS scenario from *IEA World Energy Outlook 2021*) applied in the baseline scenario

	2019	2020	2030	2040	2050
Non-AFOLU CO_2 emissions (Mt CO_2)					
Global	35,966	34,156	36,267	na	33,903
China	11,198	11,356	11,385	na	8,341
Japan	1,071	996	797	na	513
India	2,475	2,304	3,305	na	3,687
USA	4,826	4,303	3,969	na	2,936
Brazil	443	421	461	na	532
EU	2,744	2,485	1,957	na	1,208
Russia	1,691	1,612	1,727	na	1,619
Middle East	1,886	1,849	2,150	na	2,644
Africa	1,370	1,297	1,617	na	2,287
Electricity and heat sectors CO_2 emissions (Mt CO_2)					
Global	13,933	13,530	12,425	na	9,915
China	5,242	5,362	5,019	na	3,684
Japan	483	456	270	na	106
India	1,172	1,124	1,344	na	915
USA	1,682	1,501	1,053	na	607
Brazil	64	51	30	na	36
EU	811	715	388	na	196
Russia	791	762	785	na	706
Middle East	681	682	692	na	789
Africa	501	478	488	na	475
Other sectoral CO_2 emissions (Mt CO_2)					
Chemicals	1,182	1,160	1,382	1,456	1,428
Iron and steel	2,500	2,591	2,945	2,861	2,743
Road transport	6,043	5,419	6,391	6,311	6,194
Water transport	866	811	999	1,063	1,171
Air transport	1,027	606	1,242	1,463	1,631
Energy supply (EJ)					
Unabated coal	162.2	155.8	150.2	132.9	116.8
Oil	187.9	171.4	198.5	199.6	198.3
Unabated natural gas	141.4	138.7	155.9	168.0	174.0

Table A5. IEA energy targets (NZE scenario from *IEA World Energy Outlook 2021*) applied in the NZE scenario

	2020	2030	2040	2050
Energy supply (EJ)				
Coal (unabated + CCUS)	155.8	71.9	31.6	17.2
Oil	171.4	137.4	79.2	42.2
Natural gas (unabated + CCUS)	139.1	129.4	74.6	60.7
Hydrogen	0	21.4	49.2	69.7
Electricity generation (TWh)				
Global	26,762	37,316	56,553	71,164
Electricity technology mix (TWh)				
Coal	9,467	2,947	0	0
Oil	716	189	6	6
Natural gas	6,257	6,222	626	253
Wind	1,596	8,008	18,787	24,785
Solar	846	7174	17,911	24,855
Coal with CCS	1	289	966	663
Gas with CCS	0	170	694	669
Bioenergy with CCS	709	1,407	2,676	3,279
Hydrogen and ammonia	0	875	1,857	1,713
Carbon capture use and storage (Mt CO_2)				
Fossil fuels and processes	39	1,325	na	5,650
Direct air capture	0	70	na	630
Bioenergy	1	255	na	1,475

Appendix 3. Sectoral emissions

Figure A1 decomposes the NZE pathways across sub-sectors comparing the amount of emissions between the baseline and policy scenarios at the end of the simulation relative to the base year 2020 level. The agriculture sector includes various crops, poultry, livestock, fishing and forestry. Most of the reductions in agricultural gross emissions are the result of methane mitigation measures in Sheep, Cattle, and Dairy (e.g., feed additives, rumen modifiers, and vaccination against methanogenic archaea), and precision agriculture in Grains and Other Agriculture. In the mining sector, coal mining and gas extraction make up the bulk of emissions reductions as driven by the replacement of diesel engines with electric or fuel cell drivetrains, methane fugitives reducing methods and CCS technology. Moreover, the emissions from the transport sector are driven mostly by road transport electrification. There is also a significant drop in the emissions of the aviation sector due to the increasing uptake of bio-kerosene as a substitute for kerosene in existing turbine aircraft.

Furthermore, the large emissions reductions in the manufacturing sector are observed from metal product manufacturing through inert anode adoption in the aluminium industry, bio-coke material substitution in the iron and steel industry, and energy-reducing uptake mechanical vapor recompression in the Alumina industry. There is also a significant emissions reduction in the cement industry through CCS and material substitution. The chemicals industry also decarbonised through a combination of CCS uptake and catalyst process improvements. Lastly, the service sector includes commercial services such as retail, construction, hospitals, hotels, restaurants, offices, public buildings, and education facilities. The large reductions in emissions in this sector can be observed in the built environment (through lower combustion of fossil fuels in construction sites) and other commercial services (i.e., through higher energy efficiency buildings).

Figure A1. Emissions across industry subsectors (Mt CO_2e)