Climateworks CENTRE

Climateworks Centre decarbonisation scenarios 2023

AusTIMES Modelling Assumptions and Methodology

TECHNICAL REPORT

NOVEMBER 2023

ACKNOWLEDGEMENT OF COUNTRY

We acknowledge and pay respect to the Traditional Owners and Elders – past and present – of the lands and waters of the people of the Kulin nation on which the Climateworks Centre office is located, and all of the Elders of lands across which Climateworks operates nationally. We acknowledge that sovereignty was never ceded. We extend our respect to all Traditional Custodians and Elders of the lands and waters where Climateworks operates. More information.

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ABOUT US

Climateworks Centre bridges the gap between research and climate action. We are climate transition specialists, working in Australia, Southeast Asia and the Pacific with decision-makers who have the power to reduce emissions at scale. Climateworks develops evidence-based solutions to accelerate emissions reduction in line with the global 1.5°C temperature goal and shared climate safety.

Co-founded by philanthropy and Monash University, Climateworks is an independent not-for-profit working within the Monash Sustainable Development Institute. To learn more about this work, visit www.climateworkscentre.org.

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Introduction

Since its foundation in 2009, Climateworks Centre has played an important role in defining decarbonisation pathways backed by credible analysis and modelling. Decarbonisation pathways help decision-makers in government and business to understand expectations on how their emissions reduction ambition should contribute to global climate agreements, and to plan ahead for the transitions in the shift to net zero emissions. The 'AusTIMES model' is used for this analysis. Climateworks co-developed and co-manages the AusTIMES model with CSIRO, to provide a long-term least-cost view of decarbonisation transitions that underpin much of the advice Climateworks provides to its stakeholders. Climateworks' primary application for AusTIMES is to model scenarios that can be used to advise decision-makers regarding actions and enablers for the transition to net zero emissions.

This technical report summarises the assumptions and methodology behind the Climateworks Centre decarbonisation scenarios 2023, published in November 2023. The report is intended to communicate at a high level the implementation of AusTIMES to model scenarios and the inputs and assumptions underpinning those scenarios.

Prior to this November 2023 release, Climateworks published its 2020 report, *Decarbonisation Futures: Solutions, actions and benchmarks for a net zero emissions Australia*. *Decarbonisation Futures'* whole-of-economy decarbonisation scenarios provided an evidence base for how Australia can decarbonise in support of Paris Agreement climate goals. That is, to limit global temperature rise to well under 2 degrees Celsius above pre-industrial levels, pursuing efforts to limit the temperature increase to 1.5 degrees above pre-industrial levels. These scenarios showed Australia can achieve net zero emissions before 2050 through accelerated deployment of mature and demonstrated zero-emissions technologies, and the rapid development and commercialisation of emerging zero-emissions technologies in harder to abate sectors. *Decarbonisation Futures* reported the economy-wide 2030, 2035 and 2050 emissions reductions modelled under Paris-aligned scenarios, as well as sector-specific metrics such as renewable energy build-out, electric vehicle uptake and carbon forestry.

In the years since Climateworks published *Decarbonisation Futures*, global momentum towards committing to the 1.5°C temperature limit has increased. The science regarding the risks of exceeding 1.5°C is now more certain. It has thus been communicated and accepted more broadly, drawing on advice from authorities including the Intergovernmental Panel on Climate Change (IPCC 2022). Governments and investors are acknowledging the climate-related risks presented to their constituents and shareholders. Through programs like the Climateworks-convened Australian Industry Energy Transitions Initiative, industry is increasingly calling for greater coordinated action to keep global temperature rise below 1.5°C.

Modelling future scenarios is inherently uncertain, and the technology and policy context has also shifted significantly since Climateworks published *Decarbonisation Futures*. Global events like the COVID-19 pandemic and the invasion of Ukraine have triggered social and economic shifts that could not have been anticipated when Climateworks last modelled its AusTIMES decarbonisation scenarios. Further, there has been increased investment in hydrogen technology, and greater acceptance and understanding of its role in decarbonising hard-to-abate sectors. Three more years of data on electric vehicle uptake, population growth, sequestration potential and other factors that may impact decarbonisation have adjusted and provided greater clarity and confidence about likely future trends. Australia also elected a new government in 2022, and this has shifted the climate policy and regulatory context across the nation.

While it would not be possible to account for all of these factors in a single scenario modelling exercise, Climateworks is now able to present an updated view on future emissions pathways, based on what we know today. This report summarises the key assumptions and methodology behind

Climateworks' AusTIMES modelling: Insights from latest modelling outputs are available at the Climateworks website.

Scenario design and modelling is a dynamic process that evolves over time, and Climateworks welcomes contributions of up-to-date data or research questions to consider for our future work. To provide feedback, please get in touch via info@climateworkscentre.org

Defining the scenarios

In this report, Climateworks defines two scenarios for decarbonising Australia's economy in line with the Paris Agreement. These scenarios provide a powerful tool for building our understanding of potential pathways the country could adopt, and the implications that costs, economic activity and different technology constraints or supports might have through the lens of those future pathways.

Defining the scope (what's being considered, and not considered?), purpose (what's it for?) and narratives (what does it describe?) of scenarios is a critical step in the scenario modelling process, as this has a significant impact on findings and how scenarios can be applied in different contexts. If it were possible to model an infinite number of scenarios using every tool available for modelling, we could theoretically answer any "what if" question about the transition.

For the Climateworks Centre decarbonisation scenarios 2023, Climateworks has limited the scope of modelling to two scenarios:

+ The *1.5°C scenario* aligns with limiting global warming to 1.5°C.
+ The *well-below-2°C scenario* aligns with limiting warming to 1.8°C.

These two scenarios represent the range of ambition defined in the Paris Agreement and relate to aligning the decarbonisation of Australia's economy with limiting global temperature rise compared to pre-industrial levels.

The scenarios do not predict the future of Australia's emissions based on current and expected trends, nor do they represent all the possible pathways for Australia's net zero transition. Climateworks has deliberately designed the scenarios for the specific purposes described below.

Climateworks' scenarios aim to set Paris Agreement-aligned benchmarks and expectations for Australia

The intention behind the Climateworks Centre decarbonisation scenarios 2023 is to address what aligning with the Paris Agreement will mean for decarbonising Australia's economy. A key way that scenarios can do this, is by providing benchmarks for the total level of climate ambition required for that alignment. This includes ambition on future emissions levels, levels of renewable generation, the uptake of alternative fuels and a net zero emissions target year. By comparing two scenarios, Climateworks provides insights into which areas of the economy accelerate decarbonisation efforts to reach 1.5°C, and which areas decarbonise rapidly, regardless of temperature outcome.

The scenarios draw on the latest available research and data sources and reflect current policies and targets. As such they provide a foundational set of data, including assumptions and quantitative outputs, which can be leveraged to explore more specific research questions.

They offer a cross-sectoral, whole-of-economy perspective which supports coordination of decarbonisation efforts. They optimise for the lowest cost across the Australian economy, making them a useful tool for prioritisation of decarbonisation efforts.

The scenarios also assume that global and Australian climate ambition steps up from current commitments. The main purpose of the scenarios is to explore alignment with the Paris Agreement, rather than achieving the Australian Government targets. As such, the effectiveness of using the scenarios to assess progress against current government targets may be limited. In the long run, Climateworks' scenarios provide a basis upon which specific research questions can be answered, particularly through sensitivity analysis of the scenarios. Sensitivity analyses interrogate the impact of changes to key inputs, for example reduced cost of a particular technology, changes to policy settings or increased demand for green exports.

The scenarios represent an assumed worldview, where action steps up immediately to align with the Paris Agreement

Both scenarios are grounded in a worldview which assumes immediate and sustained action, both globally and within Australia, to address climate change and align with the Paris Agreement. This includes a global shift away from reliance on fossil fuels, particularly in the 1.5°C scenario.

Decarbonisation efforts are taken across the whole of the Australian economy, with improvements in energy efficiency, uptake of low emissions energy sources and processes, reduction in non-energy emissions and investment in land sequestration solutions.

The scenarios focus on technology investment and uptake, with investment decisions determined by what will result in the lowest cost to the whole of the Australian economy, while meeting assumed growth in economic activity and energy demand, as well as meeting the carbon budget of Paris-aligned temperature outcomes. Technology costs and behavioural changes as well as economic and population growth continue evolving based on historical trends.

The scenarios align with the Paris Agreement by applying carbon budgets. These define a fair share of the total emissions Australia can emit between now and 2050, to have the best chance of limiting global temperature rise. Climateworks has used the method developed by Nicholls and Meinshausen (Nicholls and Meinshausen 2022) to calculate Australia's fair share of the global carbon budgets calculated in the IPCC Sixth Assessment Report (IPCC 2023).

Climateworks' scenarios are designed to align broadly with internationally-referenced global scenarios

Climateworks Centre decarbonisation scenarios 2023 are broadly aligned with well-established global decarbonisation scenarios that explore Paris-aligned futures. This is to enable comparison and compatibility of scenario outputs. However, Climateworks' scenarios are grounded in an Australian context, using predominantly Australia-specific data and assumptions on demand projections such as population growth, and sources such as the Australian Bureau of Statistics (ABS). Where practical, they also align with international scenarios. Narratives also differ between modelling exercises because scenarios are designed to answer different research questions and engage with different stakeholders.

The broad language used in describing the scenarios draws on equivalent 1.5°C and well-below-2°C scenarios:

+ International Energy Agency World Energy Outlook
+ Network for Greening the Financial System scenarios
+ Institute for Sustainable Futures - Achieving the Paris Agreement Goals
+ ClimateWorks Foundation scenarios (developed by the US-based ClimateWorks Foundation, as distinct from Climateworks Centre)

Carbon budgets for well under 2°C scenarios vary between these global scenarios. Carbon budgets used for 1.5°C scenarios generally align with a 50 per cent probability of limiting warming to 1.5°C. Climateworks has used a more stringent budget that aligns with a 67 per cent probability of limiting warming to 1.5°C. The higher probability reflects stronger scientific consensus that every increment of warming, particularly above 1.5°C, presents significantly greater risks of climate impacts and tipping points that may trigger further cascading risks.

Each of the global scenarios in the list above focus primarily on technological options for achieving Paris Agreement goals, which aligns with the approach taken in the Climateworks Centre decarbonisation scenarios 2023. Network for Greening the Financial System scenarios also explore the contribution of behavioural changes, as well as the physicals risks posed by climate change. The scenarios presented in this report do not take physical risks into account or provide insights on behavioural shifts, though this could be built into future iterations of the scenarios. Climateworks Centre decarbonisation scenarios 2023 are grounded in the Australian policy context and explore technology options with a focus on energy efficiency improvement, electrification and low emissions energy generation.

Climateworks assumes in both scenarios that policy and technology ambition strengthen immediately. This aligns with the approach taken by each of the global 1.5°C scenarios listed above. However, some of these allow for delay in action in well under 2°C scenarios, in particular the Institute for Sustainable Futures' 2°C scenario.

Modelling methodology

Our model provides a cross-sectoral, technology-specific perspective on emissions trajectories

AusTIMES models how the whole of the Australian economy could decarbonise in a way that reflects the lowest overall cost between now and 2050. Climateworks and CSIRO have been developing the model since 2018, based on the globally-recognised TIMES model from the International Energy Agency (IEA) Energy Technology Systems Analysis Program (ETSAP).

The advantages of using AusTIMES to produce decarbonisation scenarios include:

+ Emissions reduction pathways based on minimising overall long-term costs, which can inform long-term target-setting and policy decisions.
+ The model captures interactions and trade-offs between different sectors of the economy, under a national decarbonisation objective.
+ The approach offers guidance on potential uptake and phase-out of particular technologies, including timings.

Climateworks and CSIRO define model inputs based on up-to date research, data sources and current policy settings

Climateworks and CSIRO have adapted the globally-recognised TIMES model to suit the Australian economy, by providing AusTIMES with three main inputs:

+ Assumptions on how energy demand will change over time.
+ Assumptions on how the costs of different options for reducing emissions will change over time.
+ Constraints which implement, for example, annual emissions caps, renewable energy targets or the phasing out of emissions intensive technologies.

Based on these inputs, AusTIMES produces what we often refer to as an ‘emissions pathway’, which includes:

+ Changes in emissions from the whole economy, over time.
+ Changes in emissions from each sector of the economy, over time.
+ The types of decarbonisation solutions which are implemented in the scenario, the scale of their implementation and when they are implemented.

AusTIMES mathematically models the Australian economy to solve for the least cost pathway to decarbonisation

AusTIMES uses a 'partial equilibrium model' to represent the Australian economy. The objective of the model is to minimise total operational and investment costs for the Australian economy, (described as the 'system'), over the modelling period. The model also ensures that Australia's energy needs are met while adhering to specific constraints, including emissions targets. In mathematical terms, the model finds the emissions pathway that minimises net present value (NPV) according to the following equation:

$$NPV = \sum_{r=1}^{R} \sum_{REFYR}^{2060} \frac{ANNCOST_{r,y}}{(1+d)^{(y-REFYR)}}$$

NPV	net present value of the total costs
$ANNCOST$	total annual cost incorporating investment, operation and trade (where relevant)
d	general discount rate. A discount rate of 7 per cent per annum is applied, in line with The Office of Impact Analysis recommendations
$REFYR$	reference year for discounting
y	set of years for which there are costs
r, R	regions represented in the model (for example, regions of the electricity grid)

Emissions targets can be implemented in the model using two types of constraint:

+ A carbon budget is specified: This limits Australia's total domestic emissions between now and 2050. (see Key assumptions section for more detail).
+ National emissions reductions targets are implemented, ensuring that in key years, emissions levels meet current ambition levels as a minimum.

As well as investing in technologies to reduce emissions, the model is able to invest in carbon dioxide removal solutions. This is predominantly through the use of land sequestration, but also includes direct air capture and carbon capture and storage (CCS).

THE SCOPE OF AUSTIMES MODELLING OF THE AUSTRALIAN ECONOMY:

Covers all states and territories: ACT, NSW, NT, QLD, SA, TAS, VIC and WA

Models the economy in increments from 2021 to 2050 (every two years in Climateworks Centre decarbonisation scenarios 2023)

Represents annual operations of the supply-side of the electricity sector:

+ Models 16 load blocks – these represent demand variations resulting from changes to seasons and time of day.
+ Includes all of Australia's major electricity grids. Off-grid modelling is limited to particular zones in Western Australia.

- Models existing generators including lifetime and retirement plans
- Covers 31 generation and storage technologies for possible deployment
- Accounts for availability of renewable resources, including solar and wind
- Models distributed generation and storage, for example rooftop solar

Segments Australia's economy into five end-use sectors:

- agriculture (7 subsectors)
- industry (43 subsectors across mining, manufacturing and 'other')
- buildings (14 building types across residential and non-residential)
- road transport (10 vehicle types)
- non-road transport (rail, sea and aviation).

Includes all major fuel types and energy feedstocks across end-use sectors, including coal, diesel, biomethane, renewable energy and hydrogen.

Key assumptions

The scenarios translate Paris Agreement goals into specific emissions limits for Australia using carbon budgets

Global temperature rise is closely linked to the total concentration of greenhouse gases in the atmosphere. Climate scientists use the term ‘carbon budget’ to refer to the maximum cumulative amount of greenhouse gases that can be emitted over a period of time before the concentration of these gases in the atmosphere exceeds a level that results in a specified rise in global temperature.

Due to the complexity of the planet’s climate system, it is impossible to accurately predict the average global surface temperature rise resulting from a particular amount of emissions. To account for this, temperature rises are represented using percentiles. This communicates the probability that the planet’s temperature will remain below a particular temperature rise, given a specific amount of cumulative carbon emissions. For example, if globally 850 $GtCO_2$ are emitted, there is an estimated 33 per cent chance global temperature rise will remain below 1.6°C, 50 per cent chance of below 1.7°C and 67 per cent chance of below 1.8°C. This is illustrated in Table 1 below taken from the IPCC (2023).

Table 1: IPCC estimate of remaining carbon budgets and uncertainties (IPCC 2023)

Global surface temperature change since 1850-1900 (°C)	Estimated remaining carbon budgets from 2020. Expressed in terms of percentiles of the relationship between temperature rise and carbon emissions ($GtCO_2$)				
	17th	33rd	50th	67th	83rd
1.5	900	650	500	400	300
1.6	1200	850	650	550	400
1.7	1450	1050	850	700	550
1.8	1750	1250	1000	850	650

IPCC global budgets have been scaled to the Australian context using a methodology that is consistent with the Nicholls and Meinshausen approach (Nicholls and Meinshausen 2022). This assumes Australia’s fair share, based on a modified contraction and convergence approach, is 0.97 per cent of remaining global carbon budgets. This approach proposes that to reach global emissions reductions targets, countries’ per-capita emissions should converge over time, with all countries eventually having similar emissions per person.

This approach includes a number of adjustments, to account for:

- Historical emissions that Australia has produced since the IPCC published its carbon budgets in 2020.
- Adjustments that consider greenhouse gas emissions other than carbon dioxide. The IPCC carbon budgets only account for carbon dioxide, and not other greenhouse gases such as methane.
- Using a pre-industrial baseline of temperature in 1750, rather than an early industrial baseline of 1850-1900 which is used for IPCC budgets.

TABLE 2: CUMULATIVE CARBON BUDGETS USED FOR THE CLIMATEWORKS SCENARIOS

Scenario	Temperature outcome and likelihood	Global budget (from 2020) – refer to Table 1	Australian budget (from 2021)
1.5°C	1.5°C at the 67th percentile	400 $GtCO_2$	3.02 $GtCO_2$-e
well-below-2°C	1.8°C at the 67th percentile	850 $GtCO_2$	7.65 $GtCO_2$-e

Annual emissions constraints are also applied to the model to ensure that emissions levels in 2030 (43 per cent below 2005 levels) and 2050 (net zero emissions) meet, as a minimum, the emissions reduction targets that have been set by the Australian Government.

Electricity sector assumptions draw on latest cost data, infrastructure plans and policy commitments

Electricity sector assumptions are based on up-to-date cost data and reflect current government commitments on the deployment and retirement of generation plant. Costs of generation and associated transmission infrastructure are aligned with the *Generation Cost (GenCost) 2023* report produced by the Australian Energy Market Operator (AEMO) and CSIRO (Graham et al. 2023). Climateworks' 1.5°C scenario aligns with the GenCost Global Net Zero Emissions 2050 scenario, while the well-below-2°C scenario aligns with the GenCost Global Net Zero Emissions Post 2050 scenario.

GenCost 2023 details the costs of energy generation for different technologies and fuel sources used for power generation, as well as costs for storage technologies. The GenCost report is produced annually based on extensive analysis of AEMO's electricity market data and informs AEMO's planning and investment decisions.

Examples of electricity and storage generation technologies included in AusTIMES, drawing on GenCost data, include:

- gas generation
- coal generation
- biomass generation
- solar generation
- onshore and offshore wind generation
- wave and tidal technologies

- geothermal generation
- hydrogen and diesel reciprocating engines
- small modular nuclear reactors
- pumped storage hydro with 12, 24 and 48 hours of storage
- battery storage with two, four and eight hours of storage.

The addition of renewable energy generation capacity is aligned with the Australian Government target of reaching an 82% share of renewable energy in the National Energy Market (NEM) by 2030. State level targets and policies for renewable energy and storage are also assumed to be reached at a minimum. These include the *New South Wales Energy Infrastructure Roadmap*, the *Updated Victorian Renewable Energy Target,* the *Victorian Energy Storage Target,* the *Victorian Offshore Wind Target*, the *Updated Queensland Renewable Energy Target,* the *Tasmanian Renewable Energy Target* and the Northern Territory *Roadmap to Renewables* report.

The availability of wind and solar resources is modelled using a capacity factor, which varies by renewable energy zone of the NEM (AEMO 2022). The maximum additional renewable generation capacity that can be deployed annually is constrained to limits applied at each renewable energy zone and aligned with the AEMO *Inputs and Scenarios Report* (AEMO 2023). Regional cost factors are also applied at the renewable energy zone level for solar and wind deployment, and for other technologies at the transmission zone level, aligned with the AEMO *Inputs and Scenarios Report* (AEMO 2023).

Incumbent and emerging alternative fuels are modelled to different levels of detail

Energy in Australia is not solely provided by the electricity sector. For example, transmission and distribution pipeline infrastructure delivers gas directly to many Australian homes and the transport sector relies predominantly on fossil fuels. Other fuels represented in AusTIMES are diesel, liquid petroleum gas, hydrogen and biomethane.

AusTIMES models these fuel sources as an energy source for end-use sectors that are described in the following sections of this report. It does not model in detail transmission and distribution infrastructure such as gas pipelines, however infrastructure costs are accounted for in fuel costs. This means that discrete investment costs related to the commissioning or retirement of gas infrastructure are not captured in the model, but rather averaged over multiple years.

The use of both hydrogen and biomethane as a decarbonisation option is available to a number of the end-use sectors detailed in the following sections of this report. Five hydrogen production pathways are modelled, as detailed in the *Pathways to industrial decarbonisation* report (Climateworks Centre and Climate-KIC Australia 2023). Biomethane production is modelled using two pathways in line with the AEMO *Inputs and Scenarios Report* (AEMO 2023):

- anaerobic digester using municipal or animal waste as feedstock
- gasification and methanation of plant and tree residue.

Fuel cost settings for Queensland, New South Wales, Victoria, South Australia, Tasmania and the Australian Capital Territory are aligned to Lewis Grey Advisory gas price projections (Lewis Grey Advisory 2020). Gas price projections for Western Australia and Northern Territory were sourced from Rystad Energy.

A range of decarbonisation technologies are available to decarbonise end-use sectors

End-use sector decarbonisation technologies are modelled through energy efficiency improvements, electrification and specific technologies where data is available

Decarbonisation in end-use sectors is primarily modelled through improvements to energy efficiency and electrification. Energy efficiency improvements result in less energy, and therefore lower emissions required, to meet the same level of demand. Electrification reduces emissions by replacing emissions-intensive fuels with electricity, which, as renewable energy displaces fossil fuel generation in the electricity grid, will represent a lower-emissions energy source.

AusTIMES also accounts for the increased energy efficiency of electrical equipment compared to gas, diesel or petrol equipment it replaces. For example, it is assumed that hot water heat pumps in commercial and non-residential buildings can deliver the same amount of hot water using one-fifth of the energy used by an equivalent gas boiler. When comparing induction cooktops to gas stoves, this ratio is assumed to be around one-quarter; when comparing heat pumps with gas heating for households, the ratio is assumed to be one-fifth.

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

+ **Autonomous:** This only applies to energy efficiency. All end-use sectors experience a business-as-usual energy efficiency improvement at no cost which is known as autonomous energy efficiency. Rates of autonomous energy efficiency improvements vary by sector and by technology. These are informed by long-term energy efficiency trends such as improvements that have been observed in space conditioning energy efficiency over time. It is also worth noting that in some cases, energy efficiency diminishes over time. For example, some mining subsectors become more energy intensive as mines expand.
+ **Endogenous:** This applies to both energy efficiency and electrification. These are costed options which are implemented if economically attractive, based on a combination of capital costs, fuel costs and equipment lifetime, and are subject to uptake limits. The final uptake of endogenous efficiency is determined by the model and is not a pre-defined input. Endogenous efficiency largely represents technologies that are commercially available today, for example, LED lighting and heat pump hot water systems in the buildings sector. If cost effective, endogenous energy efficiency is taken up in addition to autonomous efficiency. Any electrification taken up by the model is done so endogenously.
+ **Exogenous:** This applies to energy efficiency and other technology changes where cost data is limited. External inputs determine the amount of emissions reduction from these technology changes. Inputs align with the scenario narratives based on extensive research previously conducted for the *Decarbonisation Futures* report (ClimateWorks Australia 2020). The scenarios only rely on exogenous decarbonisation in particular industry subsectors as noted in the following sections.

Agriculture

SCOPE

AusTIMES models agriculture in seven subsectors: Agricultural services and fishing, dairy, grains, sheep and cattle, forestry and logging, other agriculture, and other animals. The subsectors are aligned with Australian and New Zealand Standard Industrial Classification (ANZSIC) sectors which also inform the activities included in each subsector.

Emissions in the agriculture sector come from both energy and non-energy sources. Examples of energy source emissions include agricultural machinery and transport. An example of non-energy source emissions is the application of nitrogen fertilisers. Energy emissions are modelled on a subsector by subsector basis, whereas non-energy emissions are modelled on a subsector by subsector and state by state basis.

ACTIVITY LEVEL

Baseline energy demand projections for the agriculture sector are based on *Australian National Outlook 2019* (Brinsmead et al. 2019). Projections incorporate changes in domestic demand and international demand which drive changes in agricultural exports.

Baseline non-energy emissions are directly related to activity energy demand projections and use a sector and state specific non-energy emissions intensity which changes over time, based on the *Pathways to Deep Decarbonisation in 2050* report (ClimateWorks Australia 2014).

OPTIONS FOR DECARBONISATION

Each subsector has different non-energy emissions sources. As such, options for decarbonisation differ between the subsectors, as shown in table 3. Decarbonisation technologies are characterised by two main parameters:

+ A marginal abatement cost defines the cost of emissions avoided by the technology. Costs range from 60-150 $/tCO_2e$ in 2030 and 20-290 $/tCO_2e$ in 2050.
+ A mitigation efficiency parameter defines the technology's feasible adoption rate. This depends on the technology but generally increases over time. Adoption rates range from 3 to 31 per cent in 2030, and 4 to 51 per cent in 2050.

These assumptions have been developed through Climateworks research and are informed by studies from organisations such as Meat & Livestock Australia, Net Zero Australia, DPIRD (WA), USDA, DPI, SugarResearch Australia and GrainGrowers, as well as other academic studies.

TABLE 3: KEY NON-ENERGY EMISSIONS DECARBONISATION SOLUTIONS FOR THE AGRICULTURE SECTOR

Option for decarbonisation	Description of technology	Relevant subsectors
Feed additives: *Asparagopsis Taxiformis* and *3-Nitrooxypropanol*	Additives to livestock feeds that result in a reduction in methane emissions from livestock.	dairy, sheep and cattle
Digital agriculture/smart farming	Optimisation of processes using sensors and data analytics. Reducing fertiliser use and on-farm waste results in lower emissions.	dairy, sheep and cattle, grain, other agriculture
Slow and controlled release fertilisers, Nitrification inhibitors	Mitigating the risk of over-application of fertiliser, which results in increased nitrous oxide emissions.	grain, other agriculture

The energy efficiency of equipment and processes in the agriculture sector is assumed to improve autonomously at a rate of 0.4 per cent annually. Endogenous energy efficiency improvements are categorised as process improvements, small equipment upgrades and major equipment upgrades. Major equipment upgrades are more costly but have a lifetime of 20 years compared to 10 years for process improvements and small equipment upgrades.

Annualised energy efficiency upgrade costs vary annually and by fuel type. Upgrade costs are around 30 $/GJ for process improvements, 80 $/GJ for small equipment upgrades and 200 $/GJ for major equipment upgrades. Penetration limits for upgrades are 6 per cent in 2030 and 22.4 per cent in 2050.

Electrification in the agriculture sector is modelled using a generic category which models all services in the sector. This assumes a cost of $135 to displace 1 GJ of incumbent fuel use. Maximum limits are applied to the level of electrification in each agricultural subsector. These limits gradually increase annually, with no limit applied from 2030 onwards.

Industry

SCOPE

AusTIMES models industry using 43 subsectors. These can be broadly grouped into manufacturing, resources/mining and other industrial subsectors. Subsectors are aligned with ANZSIC sectors which also inform the activities included in each subsector.

The level of detail with which subsectors are modelled varies. The Australian Industry Energy Transitions Initiative (ETI) used AusTIMES to explore the decarbonisation of five key industrial and resources supply chains in Australia: iron and steel, aluminium, other metals (copper, nickel, zinc and lithium), chemicals (ammonia, fertilisers and commercial explosives) and liquified natural gas (Climateworks Centre and Climate-KIC Australia 2023). These subsectors are modelled in greater detail than other industry and resources subsectors.

ACTIVITY LEVEL

Baseline projections for energy demand for Australian Industry ETI subsectors is aligned with activity levels defined in *Pathways to industrial decarbonisation* (Climateworks Centre and Climate-KIC Australia 2023). The 1.5°C scenario is aligned with the Australian Industry ETI Coordinated action scenario and the well-below-2°C scenario is aligned with the Australian Industry ETI Industry-led scenario.

Export demand for coal and gas are aligned with IEA World Energy Outlook scenarios. The 1.5°C scenario is aligned with the IEA Net Zero by 2050 scenario, where export demand for gas decreases by an average of 2.4 per cent annually and demand for coal decreases by 7 per cent annually. The well-below-2°C scenario is aligned with the IEA Announced Pledges scenario, where export demand decreases by 0.8 per cent on average annually for gas and 3.6 per cent annually for coal.

Energy demand assumptions for all other industry and resources subsectors are the same in both scenarios and are based on the Australian National Outlook 2019 (Brinsmead et al. 2019)

All subsectors not directly involved in the production of fossil fuels are assumed to experience growth to 2050. Metal ore mining, including iron, lithium, zinc and copper experience the most significant growth, with demand increasing by 3.2 to 3.3 times by 2050.

OPTIONS FOR DECARBONISATION

Technology options for the decarbonisation of subsectors included in Australian Industry ETI supply chains are detailed in the *Pathways to industrial decarbonisation* report (Climateworks Centre and Climate-KIC Australia 2023). Example technologies include:

- battery electric trucks across multiple mining and manufacturing subsectors
- hydrogen or biomethane direct reduced iron and electric arc furnaces in the iron and steel subsector
- post combustion CCS in multiple subsectors

- biodiesel haulage in mining subsectors
- options of hydrogen, electric and biomass boilers for multiple subsectors.

Mining subsectors experience an autonomous reduction in energy efficiency of 0.1 per cent per year. Energy efficiency of non-mining subsectors improves by between 0.2 and 2 per cent annually at no cost.

Endogenous energy efficiency upgrades are categorised into process improvement and equipment upgrades. Equipment upgrades can be small or major – the latter requires a larger investment cost but offers a longer lifetime.

Annualised energy efficiency upgrade costs vary annually and by fuel type. Upgrade costs are around 22 $/GJ for process improvements, 65 $/GJ for small equipment upgrades and 150 $/GJ for major equipment upgrades. Penetration limits range between 6 and 31 per cent across industry subsectors.

Electrification upgrades are also modelled endogenously and, for non-Australian Industry ETI subsectors, apply to generic equipment types, including haulage, boilers, furnaces and compressors. The majority of subsectors can be fully electrified; however, limits are applied to some subsectors including petroleum refineries, due to technological constraints. Electrification costs depend on equipment type and range from $7 to $261 per GJ of incumbent fuel displaced.

A number of technological solutions which result in reduction in demand are exogenously defined as inputs to the model. These include materials substitution, process improvements, 3D printing, artificial intelligence and geopolymer cement.

The model can also choose to invest in CCS to reduce emissions from cement, chemical manufacturing, iron and steel and oil and gas mining subsectors. Further details can be found in the *Pathways to industrial decarbonisation* report (Climateworks Centre and Climate-KIC Australia 2023).

Commercial and non-residential buildings

SCOPE

This sector models emissions from public buildings and private buildings used for commercial purposes. Commercial and non-residential buildings are categorised into ten building types including offices, hotels and schools, each of which have different assumptions about energy demand. This categorisation is based on the *Commercial Building Energy Consumption Baseline Study* (Harrington 2022).

Energy demand is modelled using four services: space conditioning, water heating, appliances and lighting. Fuels available for use in commercial and non-residential buildings are electricity, gas, diesel, hydrogen and biomethane. Lighting can only be fuelled by electricity.

Energy demand is modelled on the basis of the total floor space of each building type, multiplied by the energy consumed per metre squared of that building type.

ACTIVITY LEVEL

Base year data and growth projections for the floor space of each building type in Australia is based on the *Commercial Building Energy Consumption Baseline Study* (Harrington 2022). Activity level assumptions for commercial land non-residential buildings are the same for both the 1.5°C and well-below-2°C scenarios. Total commercial and non-residential floor space is assumed to grow by 15 per cent in 2030 and 56 per cent in 2050 compared to 2021.

OPTIONS FOR DECARBONISATION

Commercial and non-residential buildings are decarbonised through upgrades to end use service technologies such as space conditioning and water heating. These upgrades deliver electrification or an energy efficiency benefit. This is modelled endogenously, with the cost of energy efficiency upgrades ranging from $67 to $237 for 1 GJ of energy saving. Electrification costs are approximately $190 per GJ of incumbent fuel displaced. The lifetime of an upgrade depends on end use service.

An autonomous energy efficiency improvement of 39 per cent by 2050 compared to 2021 is implemented for lighting, with a 4 to 5 per cent improvement assumed for all other services. The Australian Capital Territory *Switching from Gas policy* to phase out gas in commercial buildings is also incorporated into assumptions (ACT Government 2022).

Hydrogen and biomethane can also be used to decarbonise gas appliances through pipeline blending. Hydrogen blending is limited to a maximum of 10%, in line with research on safe blending limits in Australia (Clean Energy Transition 2019). Biomethane is chemically the same as natural gas, hence there is no limit applied to the level of biomethane blending.

Residential buildings

SCOPE

The residential buildings sector models energy used within Australian homes, and emissions from this energy use. Housing stock is categorised into three archetypes: Apartments, houses and townhouses. Each of these includes different assumptions about energy demand.

Energy demand is modelled using five services: space conditioning, cooking, water heating, appliances and lighting. The fuels available for use in residential buildings are electricity, gas, LPG, hydrogen, biomethane and wood, however not all fuels can be used by all services; for example, lighting can only be fuelled by electricity.

Energy demand is modelled on the basis of the total number of residential buildings, multiplied by energy consumed in the building of that archetype.

ACTIVITY LEVEL

Baseline residential building growth is based on ABS *Household and Family Projections – Series II*, which projects growth state by state for each archetype modelled in the core scenarios (ABS 2019). Activity level assumptions for residential buildings are the same for the 1.5°C and well-below-2°C scenarios. The total number of residential buildings in Australia is assumed to grow by 23 per cent by 2030 and 65 per cent by 2050 compared to 2021.

OPTIONS FOR DECARBONISATION

Residential buildings are decarbonised through upgrades to end use service technologies such as space conditioning and cooking. These upgrades are to deliver electrification or an energy efficiency benefit. This is modelled endogenously, with the cost of energy efficiency upgrades ranging from $36 to $90 per GJ of energy saving. Electrification costs range from $35 to $74 per GJ of incumbent fuel displaced. The lifetime of upgrades differs based on end use service.

Autonomous energy efficiency improvement of between 6 and 20 per cent is assumed by 2030 compared to 2021, with an improvement of 14 to 50 per cent by 2050 depending on service. State policies on the phase out of gas are incorporated into assumptions, this includes *Victoria's Gas Substitution Roadmap* (State Government of Victoria 2023) and the Australian Capital Territory's *Switching from Gas policy* (ACT Government 2022).

Hydrogen and biomethane can also be used to decarbonise gas appliances through pipeline blending. Hydrogen blending is limited to a maximum of 10%, in line with research on safe blending limits in Australia (Clean Energy Transition 2019). Biomethane is chemically the same as natural gas, hence there is no limit applied to the level of biomethane blending.

Transport

SCOPE

This sector includes all domestic transportation modes. International shipping and air travel are also included in the AusTIMES model, however emissions from these subsectors are not considered in the Climateworks Centre decarbonisation scenarios 2023. This is to align with the scope of Australia's National Greenhouse Accounts (DCCEEW 2023)

Transportation activities are categorised into road transport and non-road transport. Road transport is modelled using ten vehicle types each with appropriate fuel options: These include three classes of passenger vehicles, motorcycles, buses, various classes of commercial vehicle, cycling and walking. Non-road transport is categorised into three subsectors: rail, domestic shipping and domestic aviation.

Energy consumption in the transport sector is estimated by multiplying vehicle kilometres travelled by a fuel efficiency factor specific to the transport mode. For passenger transport, vehicle kilometres are estimated based on activity levels and average vehicle occupancy. For freight, vehicle kilometres are estimated based on activity levels and vehicle capacity.

ACTIVITY LEVEL

Base year activity is estimated using data on passenger and freight travel from the *Bureau of Infrastructure and Transport Research Economics (*BITRE*) Yearbook 2022* (DITRDCA 2022). This is combined with vehicle travel and sales data from the ABS *Survey of Motor Vehicle Use* (ABS 2020). For passenger transport future activity assumptions are based on historic trends and ABS population data (ABS 2019). Freight uses AEMO projections of gross domestic product (BIS Oxford Economics 2022).

Activity levels are consistent across both 1.5°C and well-below-2°C scenarios. Road transport activity is assumed to grow by 22 per cent in 2030 and 54 per cent in 2050 compared to 2022 levels. Non-road transport activity grows by 37 per cent in 2030 and 81 per cent in 2050 compared to 2022 levels.

OPTIONS FOR DECARBONISATION

Decarbonisation of the transport sector is primarily driven by fuel switching. Road transportation can decarbonise using biofuels, hydrogen or through electrification. Non-road transport has similar options for decarbonisation but uptake is more delayed due to the slow stock turnover of trains, planes and ships.

The uptake of different types of biofuels is limited to particular vehicle types. For example, high ethanol blends are only available for use in new internal combustion or hybrid vehicles, whereas biodiesel blends can be used by existing internal combustion vehicles ('drop in' fuel). The use of hydrogen as a fuel requires new or upgraded hydrogen fuel cell vehicles. This option is available passenger and light commercial vehicles, buses and heavy road transport.

The adoption of alternative vehicles, including plug-in hybrid electric vehicles, battery electric vehicles and hydrogen fuel cell vehicles is based on modelling conducted by CSIRO as part of inputs to the AEMO *Inputs and Assumptions Report* (AEMO 2023).

Hydrogen is also available for use in the domestic shipping, aviation and rail subsectors, along with biofuels and synthetic fuels (kerosene and diesel). In these subsectors the cost of switching and upgrading vehicles is not modelled due to a lack of data.

Across all vehicle classes, the model assumes that potential constraints such as physical challenges in the roll-out of hydrogen refuelling infrastructure can be overcome.

Sequestration and other carbon dioxide removal options help the model reach net zero

Achieving net zero emissions in all scenarios requires the contributions of both economy-wide emissions reductions and carbon dioxide removal solutions. AusTIMES models the role of land-based sequestration, direct air capture and CCS. International offsetting is not modelled.

Land-based sequestration costs are informed by economic feasibility analysis produced by the Department of Industry, Science and Resources (DISER) (DISER 2022). This analysis presents projected sequestration supply across a range of supply prices, which is based on modelling conducted using the Land Use Trade-offs (LUTO) model (Bryan et al. 2023). Climateworks Centre decarbonisation scenarios 2023 use the 'conservative, high threshold' projections, presented on page 82 of the DISER report.

The LUTO modelling insights utilised by DISER account for lost optionality resulting from 'locking-in' land use, as well as insuring against physical risks to carbon forestry. This approach also assumes that future replanting is conducted when necessary to account for potential emissions sequestration deficits. The uptake of additional sequestration is limited to 7 $MtCO_2e$ per year until 2032 to align with historic sequestration levels. Beyond 2032, maximum additional sequestration increases to 15.8 $MtCO_2e$ per year to align with research on sequestration potential (Lenton et al. 2022).

Direct air capture is currently a novel technology undergoing testing, with limited volumes of carbon dioxide captured to date (IEA 2022). It is therefore treated as a speculative technology option, with decarbonisation potential in the long term. The scenarios assume that costs of direct air capture remain high at 1132 $/tCO_2e$ throughout the modelling period. This is based on the projected cost of the technology in 2025 (Fasihi et al. 2019).

A cap on the uptake of direct air capture is also implemented to reflect likely constraints in the build-out of this novel technology and corresponding infrastructure. Direct air capture is first introduced as an option in the model in 2031 with a maximum uptake rate of 0.25 $MtCO_2e$ removal per year, increasing to 5 $MtCO_2e$ per year from new plants by 2050.

CCS is modelled as an abatement technology for some industry subsectors such as alumina, iron and steel and chemicals production. It is also deployed for blue hydrogen production pathways. When deployed, CCS is assumed to operate at a capture rate of 27 to 90 per cent. Capital costs for CCS range from 81 to 140 $/tCO_2e$ in 2030 and 69 to 100 $/tCO_2e$ in 2050. Further details regarding CCS modelling in AusTIMES can be found in the *Pathways to industrial decarbonisation* report (Climateworks Centre and Climate-KIC Australia 2023).

Conclusion

This technical report outlines the assumptions and methodology used to produced Climateworks decarbonisation scenarios as of November 2023.

Climateworks is constantly updating assumptions and improving the modelling methodology to reflect the latest research and data. This includes aligning with the results of other sector specific modelling exercises, such as any updated results from the Land Use Trade Offs model (Bryan et al. 2023).

The design, development and modelling of scenarios is a dynamic process, and Climateworks will continually review and refresh our published scenarios over time. Climateworks welcomes feedback, inquiries and data requests, also welcoming suggestions for data sources that may be used to improve modelling.

For suggestions or access to more information we encourage you to reach out at info@climateworkscentre.org

Further reading:

https://climateworkscentre.org/scenarios2023

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