DECARBONISATION FUTURES

Solutions, actions and benchmarks for a net zero emissions Australia

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ClimateWorks AUSTRALIA

DECARBONISATION FUTURES

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CSIRO Energy is working to ensure economic competitiveness and energy security while enabling the transition to a lower-emissions energy future. It is pioneering energy technologies that create value for industry and households and provide the knowledge to guide us towards a smart, secure energy future. CSIRO Energy develops pathways to achieve an enduring legacy from energy resources and the social cohesion to tackle the environmental consequences of the options chosen.

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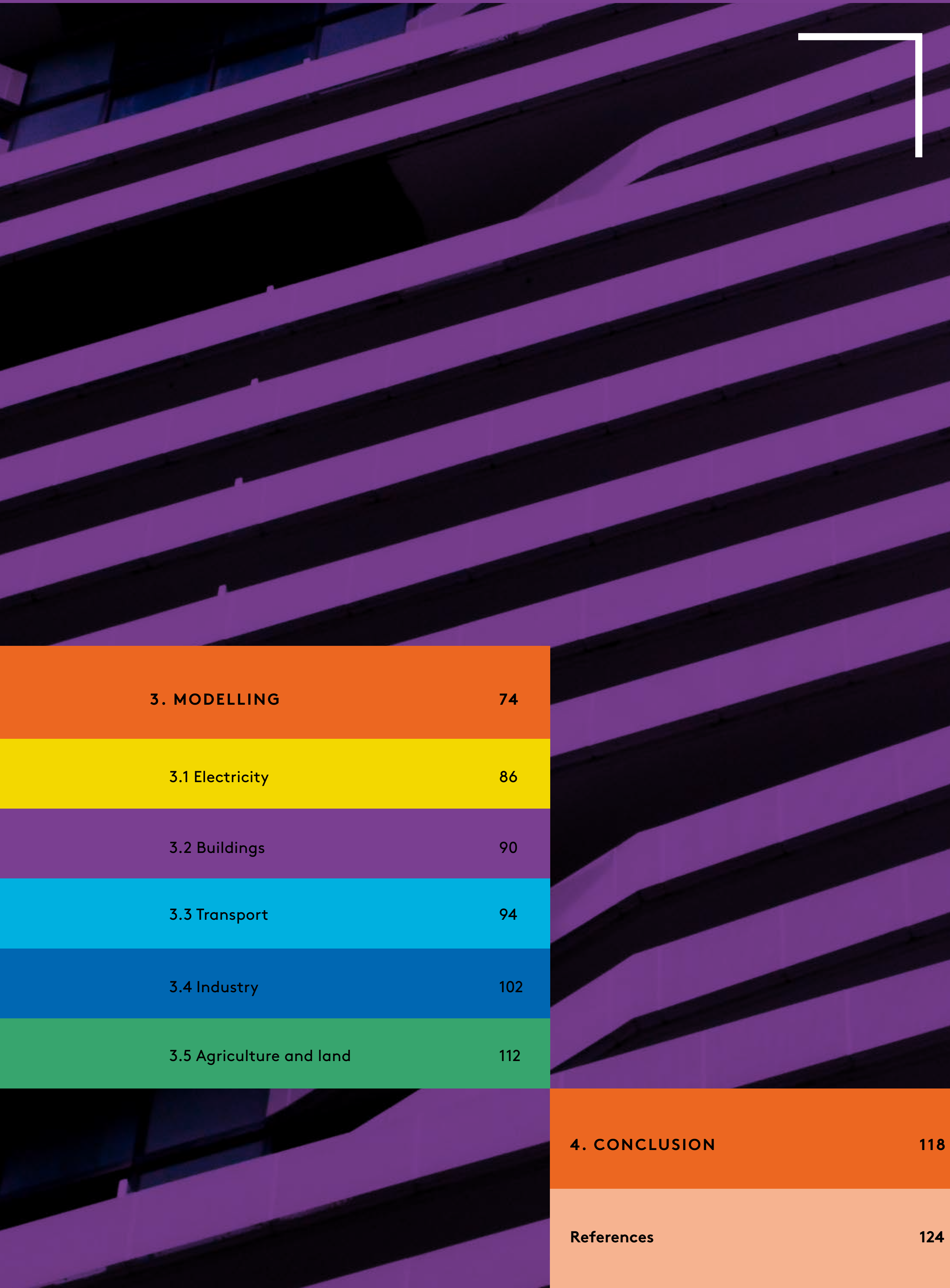

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Executive summary

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* provides a guide for Australian government and business decision-makers on priority technologies, deployment pathways and benchmarks for achieving net zero emissions.**

Decarbonisation Futures shows Australia can still play its part in meeting the Paris Climate Agreement goal of limiting global temperature rise to well below 2 degrees Celsius and as close as possible to 1.5 degrees. This report identifies the priority technologies and actions for achieving net zero emissions across all sectors of the Australian economy.

Its analysis shows how Australia can reduce emissions in line with the Paris climate goals by:

- **Immediately accelerating the deployment of mature and demonstrated zero-emissions or best available technologies**
- **Rapidly developing and commercialising emerging zero-emissions technologies in harder to abate sectors.**

Summary of key zero-emissions solutions and supporting actions, by sector and maturity

Maturity	Solutions	Action	Supporting actions
DEMONSTRATED + MATURE SOLUTIONS	100% renewables, storage (incl. batteries), demand management Deep energy efficiency, electrification Electric and fuel-cell vehicles for light road transport Energy efficiency, circular economy, proven electrification, bioenergy and bio-feedstocks, industrial CCS Sustainable agriculture practices, plant-based substitutes, fertiliser management, carbon forestry	ACCELERATE DEPLOYMENT	GOVERNMENT + Standards & targets + Taxes & incentives + Infrastructure investment + Stimulate private investment (such as with reverse auctions, co-investment or market design) + Information & access + Procurement BUSINESSES + Targets + Procurement + Products & services + Business models + Engagement & advocacy INDIVIDUALS + Consumption patterns + Investments
EMERGING SOLUTIONS	Biofuels, synfuels, electrification, ammonia or hydrogen for other transport Material substitution, high grade heat electrification, solar thermal, hydrogen Lab food, enteric fermentation treatments (such as livestock vaccines)	INVEST IN RD&D	GOVERNMENT + Direct investment + Incentivise private investment BUSINESSES + Direct investment → ACCELERATE DEPLOYMENT

Net zero emissions by 2050 or earlier is fast becoming the norm in support of the Paris climate goals to limit global temperature rise to 2 degrees Celsius and pursue efforts to restrain warming to 1.5 degrees.

Globally and in Australia, major corporations, investors and governments are already moving to align their strategies with the goal of net zero emissions.

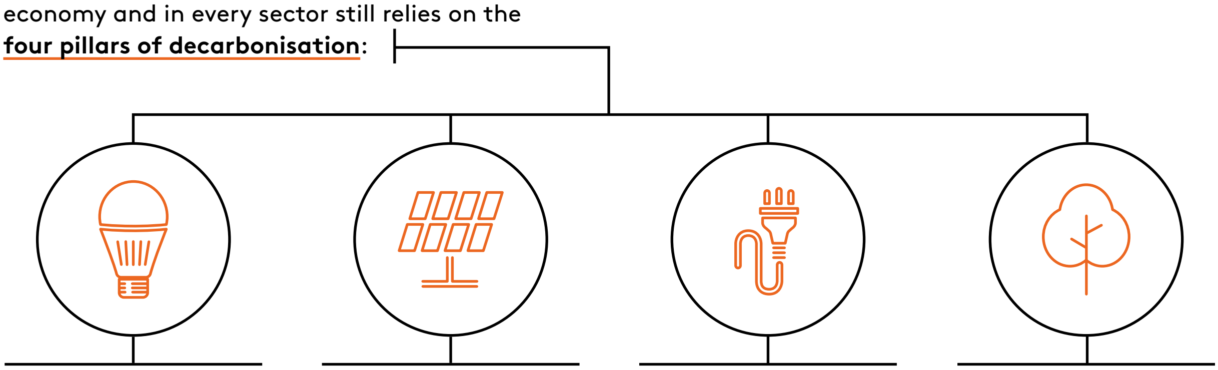
For example, in September 2019, an international group of institutional investors – representing some US$4 trillion in assets under management – came together as the Net-Zero Asset Owner Alliance. Collectively, these investors declared that they would transition their portfolios by 2050.

Some of Australia's largest businesses are committing to achieve net zero emissions by or before 2050, including software company Atlassian, property companies Dexus and Mirvac, resources company Rio Tinto and Qantas airlines.

All Australian states and territories are now aiming to achieve the same by or before 2050. In addition, Australian capital cities and local governments are increasingly setting net zero emissions targets for their communities.

Progress in the past five years has closed the technical gap – making achieving zero emissions possible in many sectors.

Achieving net zero emissions across the economy and in every sector still relies on the <u>**four pillars of decarbonisation**</u>:



Energy waste reduction, including through energy productivity and a shift away from energy-intensive products and services

100% renewable electricity

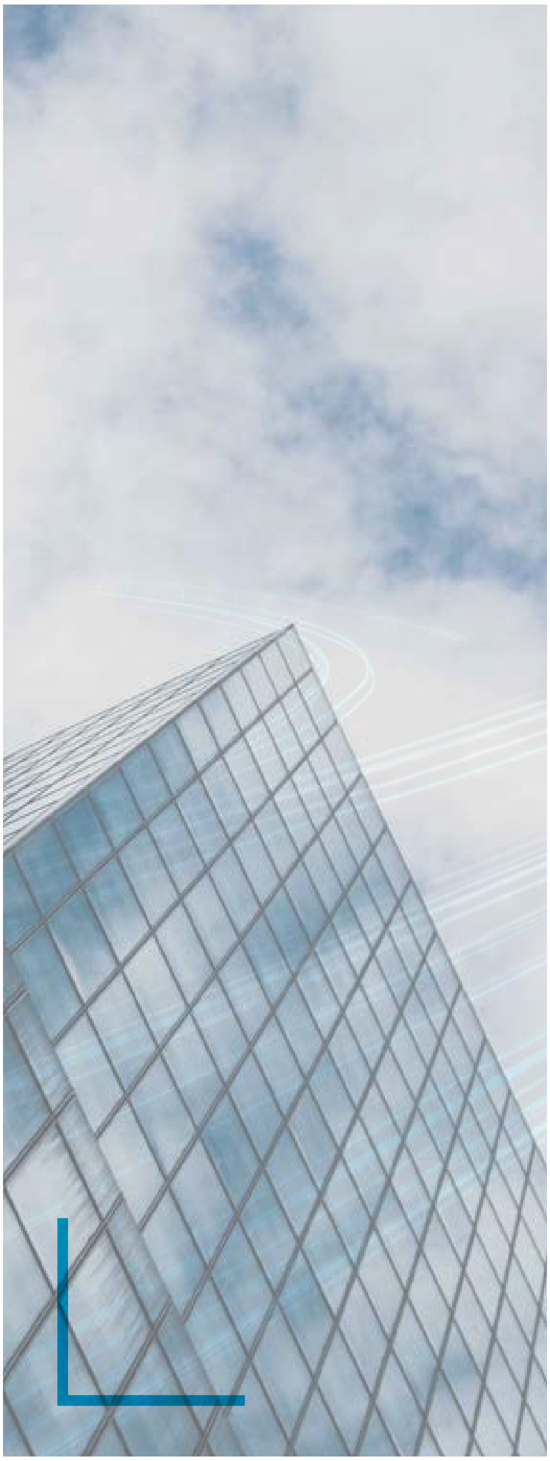
Electrification and a shift away from fossil fuels to zero- or near-zero emissions alternatives

Non-energy emissions reductions and offsetting of residual emissions

Mature technologies capable of achieving zero emissions already exist in many sectors. In the five years since ClimateWorks Australia released its previous comparable research (*Pathways to Deep Decarbonisation in 2050*) many technical obstacles have been overcome.

This report, *Decarbonisation Futures,* outlines progress – in some instances, remarkable progress – made in the past five years towards zero-emissions technologies across major sectors of the economy: **electricity**, **buildings**, **transport**, **industry**, and **agriculture and land**.

In **electricity**, zero-emissions technologies are readily available although not yet deployed at sufficient scale. In particular, large and small-scale renewable electricity generation (supported by new storage capabilities and demand management measures) can fully decarbonise Australia's power supply. The increased uptake of new technologies worldwide has led to significant cost reductions, with new large-scale renewable electricity generation now less expensive than new fossil fuel generation, and battery costs per kilowatt hour 80% cheaper than in 2010.



Similarly, in the **building** sector, most of the solutions required to achieve zero emissions (for instance, deep energy efficiency and the electrification – with renewable energy – of power, heating and water services) are mature and commercially competitive or have been demonstrated at scale. Energy-efficient technologies continue to become cheaper and more effective. For example, LED lighting costs have declined 80% in the past five years and globally, some 60,000 'passive houses' (including a growing number in Australia) illustrate how heating requirements in homes can be drastically reduced by state-of-the art design and insulation. Consumer uptake has, however, not kept pace with the technology improvements.

In other sectors, accelerating deployment of mature technologies can be supplemented by emerging technologies to meet zero-emission targets. In **transport**, the extraordinary fall in battery costs (together with supportive government policies) means some 3 million electric vehicles are already being driven throughout the world. The electrification of passenger and freight transport (together with the optimisation of travel needs, mode-shift, and the transition to renewable electricity) demonstrates how the transport sector can be cost-effectively decarbonised.

Meanwhile, one- and two-person electric planes are beginning to enter the market, suggesting new possibilities for air travel. In longer-haul road, air and shipping, emerging technologies include second- and third-generation biofuels, renewable hydrogen and ammonia, and synfuels. Current commercial-scale demonstration projects in Australia involving renewable ammonia and hydrogen have the potential to develop into a large energy export market.

Within **industry**, however, readily available technologies for zero emissions remain scarce. In this sector, immediate emissions-reduction opportunities such as energy efficiency, electrification and renewable energy must be maximised. The use of emissions-intensive materials (for example, steel) can also be reduced through the application of 'circular economy' principles, and via a shift to zero- or near-zero carbon materials. In Brisbane, for example, the 10-storey office tower known as '25 King' showcases the structural capabilities of cross-laminated timber as a replacement for emissions-intensive steel and cement.

Electrification powered by renewable energy can decarbonise industrial processes such as material handling and heating. In mining, this technology is already mature. In food manufacturing, electric heat pumps are being demonstrated for low-grade heat. Technologies to fully decarbonise other sources of industrial emissions are emerging or being demonstrated. Hydrogen, for instance, shows potential for replacing coking coal in the steel manufacturing process and carbon capture and storage could facilitate a response to non-energy emissions such as fugitive methane in gas extraction.

In **agriculture**, mature technologies exist to reduce energy and water usage, with 80% of farms in the grain sector already using information communication technology to improve production efficiency. The reduction of non-energy emissions poses particular technological challenges. Cattle (beef and dairy) constitute the sector's largest source of emissions, and, while mature solutions exist for incremental improvements in cattle emissions, options for zero emissions remain at the emerging stage (with, for instance, vaccines to mitigate methane under testing in New Zealand). Meanwhile, technical improvements have made lab- and plant-based meat more feasible – with both generating interest from investors. Symptomatically, the share price of Beyond Meat grew more than 700% in the three months following its 2019 NASDAQ release.

Nature-based solutions such as **carbon forestry** will continue to play a role in Australia – although carbon forestry can only be a temporary solution on a pathway to zero emissions. In order to keep offsetting new emissions, new parcels of land need to be reforested, a process that cannot continue forever. Forestry is also vulnerable to bushfires, drought and heatwaves – many of which are being made worse by climate change.

Summary table of key emissions-reduction solutions by sector

	DEMONSTRATED + MATURE SOLUTIONS	EMERGING SOLUTIONS
ELECTRICITY	100% renewables, storage (including batteries), demand management	*There are sufficient demonstrated and mature solutions to decarbonise these sectors. However, emerging solutions could decrease costs and aid deployment at scale.*
BUILDINGS	Deep energy efficiency, electrification	
TRANSPORT	Electric and fuel-cell vehicles for light road transport	Biofuels, synfuels, electrification, ammonia or hydrogen for other transport
INDUSTRY	Energy efficiency, circular economy, proven electrification, bioenergy and bio-feedstocks, industrial CCS	Material substitution, high grade heat electrification, solar thermal, hydrogen
AGRICULTURE + LAND	Sustainable agriculture practices, plant-based substitutes, fertiliser management, carbon forestry	Lab food, enteric fermentation treatments (such as livestock vaccines)

All sectors play a part in the transition. *Decarbonisation Futures* scenarios show that Australia can still reduce emissions in line with limiting the temperature rise to 2 degrees – and if governments, businesses and individuals go 'all-in', a 1.5 degree limit could be within reach.

Decarbonisation Futures utilises the Aus-TIMES Model – an Australian adaptation of a techno-economic modelling framework developed by the International Energy Agency (IEA) and used in over 60 countries – to explore through 'scenario analysis' three possible low-emission futures:

+ The first scenario (**'2C Deploy'**) models emissions reductions compatible with a two degree global temperature limit, achieved primarily through direct government intervention with policies focused on regulating emissions and accelerating the deployment of demonstration and mature stage technologies
+ The second scenario (**'2C Innovate'**) shows how technology at the upper bounds of current expectations can facilitate the same outcome. In this model, emerging technologies create widespread change in emissions-intensive sectors – driven by supportive government and business action
+ The third scenario (**'1.5C All-in'**) models an emissions outcome compatible with limiting the global temperature rise to 1.5 degrees. It combines elements from the two earlier scenarios and assumes governments drive policies to limit emissions and facilitate technological innovations, with collaboration between policy-makers, businesses and individuals across all sectors.

All three scenarios in this study achieve net zero emissions by or before 2050, with the '1.5C All-in' scenario reaching net zero around 2035.

All three scenarios assume current economic conditions, and so do not include possible structural changes to the Australian economy (such as the emergence of large-scale hydrogen exports).

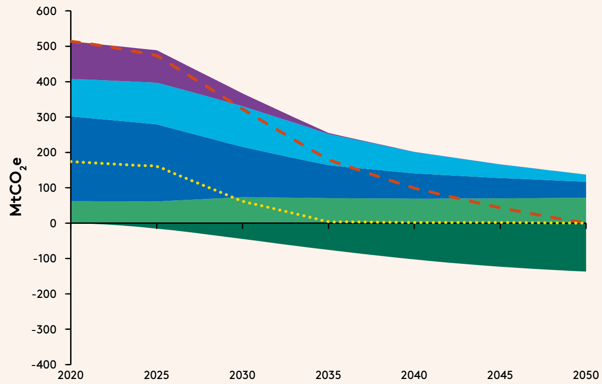
It should be noted that not all emerging zero-emissions technologies or options could be modelled (carbon forestry was used to compensate for residual emissions in the models). Some of these emerging technologies may prove of special significance to the industry sector, where global supply chains will continue to shift.

All three scenarios model transitions to zero-emissions technologies taking place as soon as is feasible, with best-available solutions implemented to reduce emissions where appropriate technology does not yet exist.

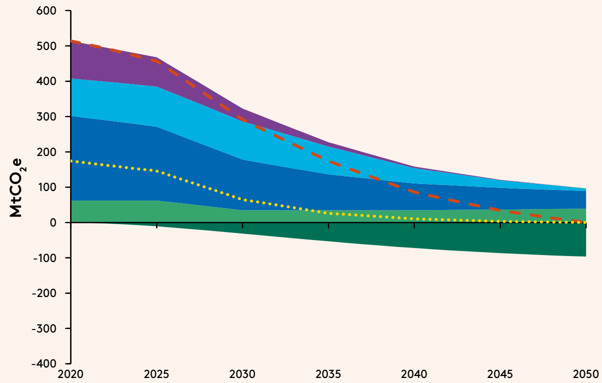
In all three scenarios, decarbonisation of electricity generation is a precondition for decarbonisation throughout other sectors. Electricity produced by renewable energy facilitates a shift away from fossil fuels in buildings, transport and other areas.

Australian emissions by sector and by scenario

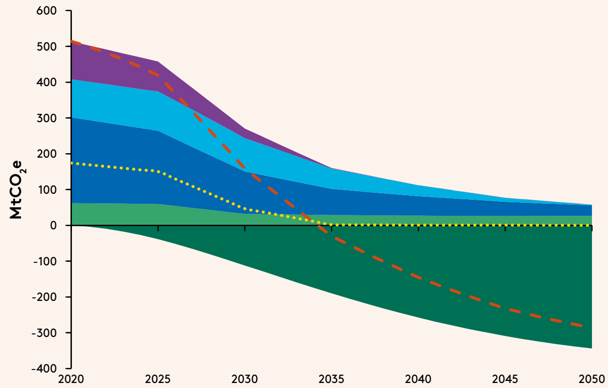
'2C Deploy'



'2C Innovate'



'1.5C All-in'



Buildings · Transport · Industry

Carbon forestry · Agriculture and land

Electricity generation · Net emissions

The stacked wedges above the x-axis in the figures show emissions (scope 1 and 2) for four major sectors of the Australian economy. The emissions trajectory of electricity generation is depicted as a separate yellow dotted line to avoid double counting, as electricity emissions have already been included in end-use sectors. The amount of sequestration required to offset emissions and remain within relevant carbon budgets (modelled here as carbon forestry) is also presented as a distinct sector with 'negative' emissions below the x-axis. Net annual emissions – calculated as residual sector emissions minus carbon forestry sequestration – are represented by the orange dashed line.

Across all scenarios, sectoral emissions trajectories reflect the maturity of zero-emissions technologies available to them. Buildings and electricity, which have access to mature zero-emissions technologies, achieve zero or near zero emissions around 2035. Transport, which has a mixture of mature and emerging zero-emissions technologies, achieves near-zero emissions by 2050. Industry and agriculture, at the other end, have significant residual emissions by 2050, which reflects the technical gap to zero-emissions technologies. The impact of a decarbonising electricity grid can be observed through those sectors that already derive a large proportion of their energy use from electricity (such as buildings and industry before 2035), and on those that are progressively switching from fossil fuels to electricity (such as transport and industry post-2035.)

Key differences between the scenarios include the amount of residual emissions by 2050, which are lowest in the '1.5C All-in' scenario, followed by the '2C Innovate' scenario. This reflects the accelerated efforts to develop and deploy zero-emissions technologies in hard-to-abate sectors. Other differences include the rate of retirement of fossil-fuel powered electricity generation assets (and therefore the rate of emissions reductions in the electricity sector), and the uptake of industrial carbon capture and storage, which are higher in the scenarios with the strongest policy action. Finally, the level of carbon forestry required to achieve the 1.5 degrees carbon budget is much higher than that required to achieve the 2 degrees carbon budget.

Aligning with the Paris climate goals requires technology uptake to be significantly accelerated compared to current trends. Widespread, rapid deployment of mature technologies can achieve much of what is needed this decade and can accelerate immediately, while substantial investment in research, development and commercialisation can close the gap to zero emissions across sectors.

All three scenarios in *Decarbonisation Futures* show significantly accelerated technology deployment and emissions reductions in the next decade compared to current trends, as is evident in the benchmarks across all sectors (see tables overpage).

For instance, government figures project a decline of national emissions by 16% on 2005 levels by 2030. In contrast, both the '2C Deploy' and '2C Innovate' scenarios benchmark a decrease of 48–53% while the '1.5C All-in' scenario arrives at 74%.

Likewise, government projections suggest Australia will generate 48% of electricity from renewables by 2030. The '2C Deploy' and '2C Innovate' scenarios put the figure at 74% and 70% respectively; the '1.5C All-in' scenario at 79%.

In transport, government projections state that, by 2030, around one in five new cars purchased will be electric. In contrast, that figure becomes one in two for '2C Deploy' and '2C Innovate' – and three in four for the '1.5C All-in' scenario.

These examples show the challenge ahead.

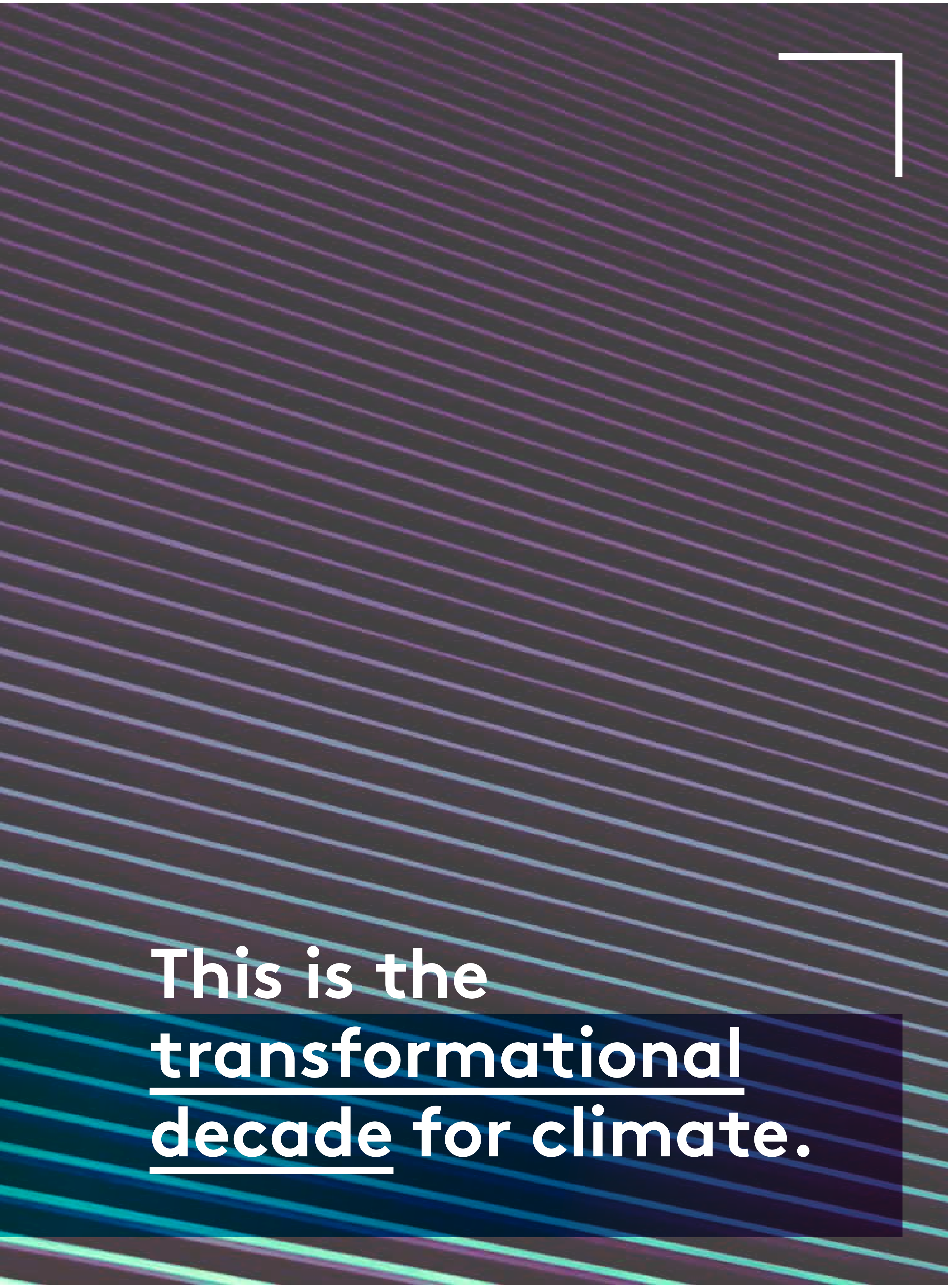
While the modelled benchmarks might seem ambitious, they are by no means impossible. The research highlights the progress being made – progress that now must be turbocharged, with governments, businesses and individuals mobilising to achieve faster change than under typical market conditions.

In short, action – the deployment of renewables, investment in research and development, construction of transition infrastructure, commercialisation of emerging technologies, and other measures discussed in the report – cannot wait until 2030 or 2050.

> Deploying mature and demonstrated solutions can achieve much of what is needed this decade and can accelerate immediately.

From 2030 to 2050, the implementation challenge shifts to zero-emissions solutions for long-haul transport, agriculture and industry, which need to be the focus of accelerated RD&D (research, development and demonstration) investment this decade.

This is the transformational decade for climate.



This is the transformational decade for climate.

Benchmarks of progress towards net zero emissions by 2050

EMISSIONS

BENCHMARK	2°C PATHWAYS		1.5°C PATHWAY	
	2030	CHANGE versus 2020	2030	CHANGE versus 2020
Net annual emissions	**291-322 $MtCO_2e$**	**37-43% decrease**[1]	**159 $MtCO_2e$**	**69% decrease**[2]
Electricity emissions	**62-65 $MtCO_2e$**	**63-64% decrease**	**46 $MtCO_2e$**	**73% decrease**
Buildings emissions	**36-37 $MtCO_2e$**	**63-64% decrease**	**27 $MtCO_2e$**	**73% decrease**
Total transport emissions	**108-115 $MtCO_2e$**	**2-9% increase**[3]	**93 $MtCO_2e$**	**12% decrease**
+ Road transport emissions	89-95 $MtCO_2e$	5-12% increase[4]	76 $MtCO_2e$	11% decrease
+ Other transport emissions	18.8-19.5 $MtCO_2e$	5-8% decrease	17 $MtCO_2e$	16% decrease
Total industry emissions	**141 $MtCO_2e$**	**40% decrease**	**120 $MtCO_2e$**	**49% decrease**
+ Extractive sectors emissions	67-71 $MtCO_2e$	36-39% decrease	56 $MtCO_2e$	49% decrease
+ Manufacturing and other sectors emissions	70-74 $MtCO_2e$	40-43% decrease	63 $MtCO_2e$	49% decrease
Agriculture and land emissions	**37-75 $MtCO_2e$**	**6-54% decrease**	**34 $MtCO_2e$**	**57% decrease**
+ Livestock emissions	19-53 $MtCO_2e$	5-66% decrease	18 $MtCO_2e$	69% decrease
+ Other agriculture emissions	18-22 $MtCO_2e$	7-24% decrease	16 $MtCO_2e$	31% decrease
+ Carbon forestry sequestration	31-45 $MtCO_2e$ sequestration		112 $MtCO_2e$ sequestration	

1 This represents a reduction of approximately 48-53% on 2005 emissions levels

2 This represents a reduction of approximately 74% on 2005 emissions levels

3 Emissions peak in 2025, and decline consistently afterwards

4 Emissions peak between 2025-2027 and decline consistently afterwards

TECHNOLOGY				
BENCHMARK	**2°C PATHWAYS**		**1.5°C PATHWAY**	
	2030	**CHANGE versus 2020**	**2030**	**CHANGE versus 2020**
Emissions intensity	220-252 tCO_2e/GWh	63-67% decrease	177 tCO_2e/GWh	74% decrease
Share of renewable electricity generation	70-74%	2020 = 25%	79%	2020 = 25%
Additional renewable capacity between 2020 and 2030		24-28 GW added		29 GW added
Additional storage capacity between 2020 and 2030		44-66 GWh added		56 GWh added
Rooftop solar electricity generation	22-26 TWh	85-116% increase	26 TWh	116% increase
Electric cars (battery electric vehicles and fuel cell electric vehicles)	50% of new car sales, 15% of total fleet	2020 = <1% of sales and total fleet	76% of new car sales, 28% of total fleet	2020 = <1% of sales and total fleet
Electric trucks (battery electric vehicles and fuel cell electric vehicles)	25-39% of new truck sales, 8-13% of total fleet	2020 = <1% of sales and total fleet	59% of new truck sales, 24% of total fleet	2020 = <1% of sales and total fleet
Volume of zero emissions fuels (bioenergy and hydrogen)	83-111 PJ	171-265% increase	134 PJ	338% increase
Share of electricity in energy used for steel production	16-20%	2020 = 11%	27%	2020 = 11%
% clinker in cement	45-75%	2020 = 75%	15%	2020 = 75%
Share of new large buildings built using timber	7%-20%	2020 = negligible	20%	2020 = negligible
Carbon forestry	~ 5 Mha plantings		~ 8 Mha plantings	

ENERGY

BENCHMARK	2°C PATHWAYS		1.5°C PATHWAY	
	2030	CHANGE versus 2020	2030	CHANGE versus 2020
Total final energy use		3-8% decrease		16% decrease
Share of electricity and zero-emissions fuels in final energy use	31-32%	2020 = 23%	35%	2020 = 23%
Share of electricity in total energy	24%	2020 = 20%	27%	2020 = 20%
Residential building energy intensity[5]		44-48% decrease (improvement)		49% decrease (improvement)
Commercial building energy intensity[6]		16-25% decrease (improvement)		28% decrease (improvement)
Share of electricity in residential buildings	76-78%	2020 = 49%	75%[7]	2020 = 49%
Share of electricity and zero-emissions fuels in transport energy	9-11%	2020 = 3%	16%	2020 = 3%
Share of electricity and zero-emissions fuels in road energy use	5-9%	2020 = 2%	17%	2020 = 2%
Fossil fuel use in non-road transport	226-233 PJ	5-8% decrease	203 PJ	17% decrease
Total energy use	1684-1785 PJ	4-10% decrease	1580 PJ	15% decrease
Share of electricity and zero-emissions fuels in total energy use	30-32%	2020 = 25%	33%	2020 = 25%

5 Represented as energy use per household

6 Represented as energy use per m^2 commercial building floor space

7 Higher rates of energy efficiency improvements lead to slightly lower levels of building electrification in the '1.5C All-in' scenario by 2030 relative to other scenarios

The transition will not happen in time without strong action by every level of government, businesses and individuals to support technology development, demonstration and deployment.

Decarbonisation Futures identifies three key 'drivers' that help develop and deploy solutions when and where they are required:

+ Policy
+ Businesses and individuals
+ Technology.

Policy made by governments can drive emissions reductions through legislation, regulation or incentives (for example, renewable energy targets, vehicle greenhouse gas emissions standards, direct procurement and investment in climate solutions). Governments can provide essential infrastructure to support the rollout of solutions (such as investments in electricity transmission, rail transport, and electric vehicle charging infrastructure), and reduce non-price barriers to their adoption (for example, by providing consumer information and requiring companies to disclose climate strategies and actions).

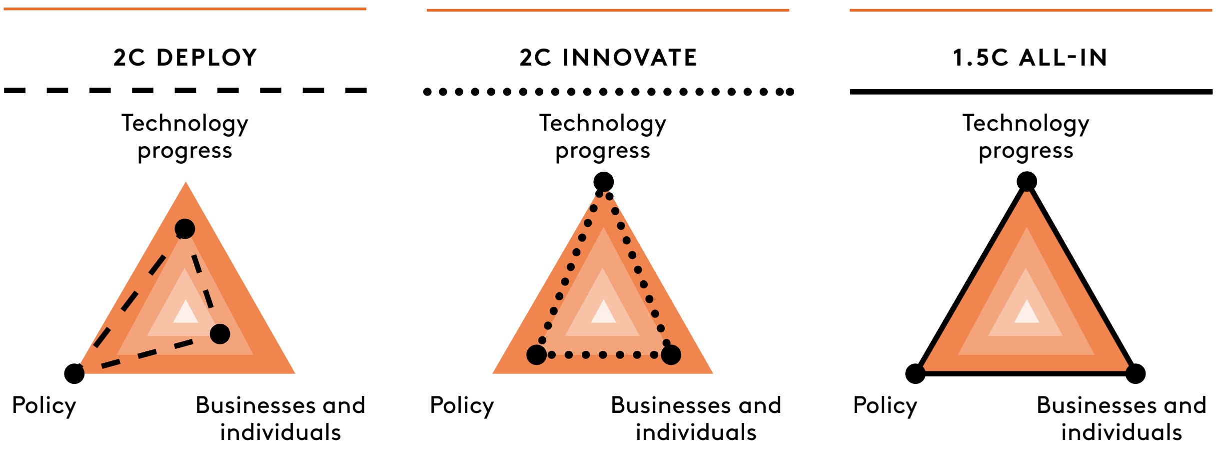
Businesses and individuals can significantly impact emissions reductions through their consumption, investment and advocacy. Businesses can move their operations away from high-emissions processes or inputs to zero-emissions alternatives, and transition their workforces to be developing low-emissions products and services. Individuals can demand carbon neutral products in almost every sector as well as investments (for example, ethical superannuation and banking products) thus providing a strong signal to peers, businesses and governments.

Technology research, development and innovation can help overcome inherent challenges, accelerate uptake of solutions and provide new ways of working, potentially benefiting multiple sectors. But this entails support, with **all three modelled scenarios requiring action by government, businesses and individuals.** In particular, the '1.5C All-in' scenario depends on all three drivers working together: everyone needs to go 'all-in' for the more ambitious goal to remain within reach.

Overview of the three scenarios modelled

These triangles represent the level of progress/ action taken towards net zero emissions for each driver, by scenario.

Settings closer to the inside of the triangle indicate less action, while outer settings indicate more/strong action.



Actions by government, business and individuals to achieve these pathways vary depending on technology maturity. For both demonstrated and mature technologies, actions to support deployment at scale are key. Indeed, in recent years, most cost reductions and performance improvements for new technologies have been gained through economies of scale, engineering and competitiveness.

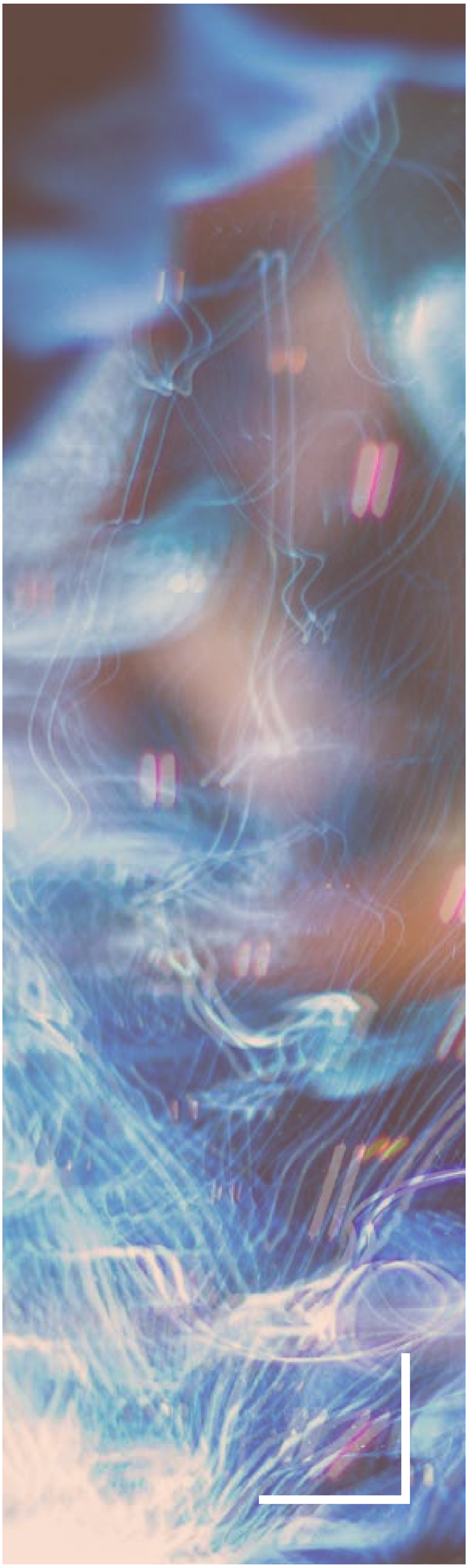
Overview of actions government, businesses and individuals can take to accelerate solution development and deployment

SOLUTION STATUS		ACTIONS		
		GOVERNMENT	BUSINESSES	INDIVIDUALS
MATURE	ACCELERATE DEPLOYMENT	+ Set standards and targets to accelerate the exit of old solutions and uptake of best-practice solutions + Tax emissions-intensive activities and products + Provide financial support and/or market structure amendments + Invest in supporting infrastructure + Improve information and accessibility	+ Set targets for operations and supply chains + Bring forward asset replacement investments with net-zero ready versions + Shift products and services towards low-carbon options + Create new business models to accelerate uptake + Policy advocacy + Investor engagement with companies	+ Shift in consumption towards low-carbon products and services + Shift in behaviour, for example transport preferences + Investment in energy-efficiency upgrades and solar PV + Shift in investments towards low-carbon options + Business and policy advocacy
DEMONSTRATION	ACCELERATE DEPLOYMENT	+ Provide incentives for early deployment + Early demand through government procurement + Invest in supporting infrastructure + Stimulate private investment (such as with reverse auctions, co-investment or market design)	+ Early demand, willing to pay price premium + Targeted procurement for demonstration and testing + Create consortium for risk sharing for earlier stage demonstrations	+ Early demand, willing to pay price premium + Community investment in low-carbon solutions
EMERGING	INVEST IN RD&D	+ Public investment in RD&D towards zero-emissions solutions + Incentives for private investment in RD&D + Place-based experimental deployment	+ Private investment in RD&D towards zero-emissions solutions + Create consortium for risk sharing for earlier stage demonstrations	

In short, Australia can reduce emissions in line with the Paris climate goals through the accelerated deployment of mature and demonstrated zero-emissions technologies in all sectors, and the rapid development and commercialisation of emerging zero-emissions technologies in sectors such as agriculture and industry that are harder to abate.

The *Decarbonisation Futures* report presents comprehensive information for decision-makers in government and business. It provides, across all sectors of the economy, technology pathways for achieving net zero emissions, guidance to formulate action plans and benchmarks to track their implementation.

An Australia ready for a decarbonised world requires ambition and focus from political and business leaders.



By setting targets immediately, decision-makers can focus attention on new solutions and prevent missed opportunities in technological investment.

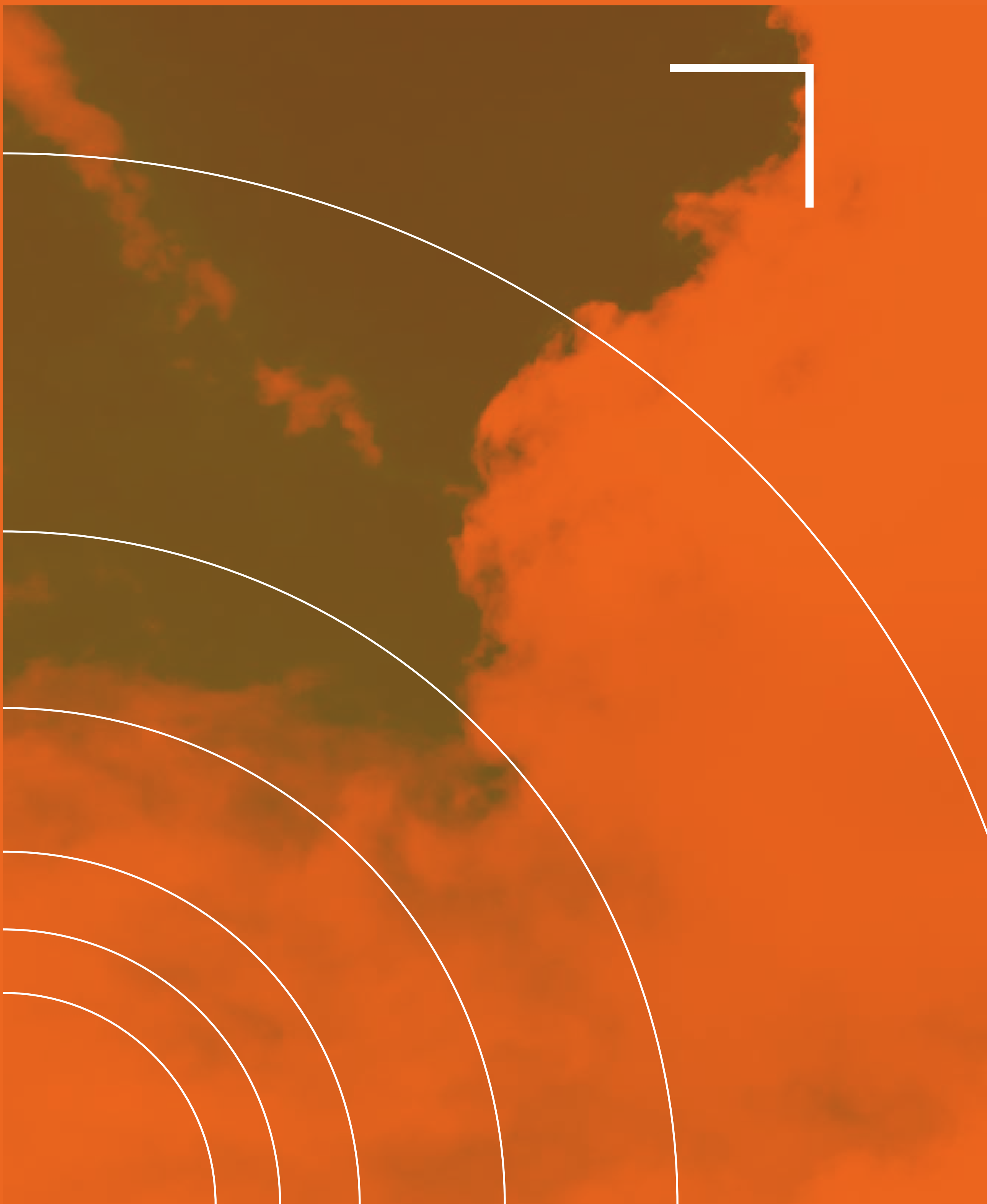
Data released by NASA and the American/ National Oceanic and Atmospheric Administration shows the past decade to be the hottest ever recorded on the planet.

The stark data from such agencies and others, show devastating impacts if the current rates of global warming continue.

Yet the modelling in *Decarbonisation Futures* establishes that multiple pathways to the Paris goals remain open. Australia can still achieve a zero-emission future – but only by taking action today.

INTRODUCTION

1



Net zero emissions by 2050 or earlier is fast becoming the norm in support of the Paris climate goals to limit global temperature rise to 2 degrees Celsius and pursue efforts to restrain warming to 1.5 degrees.

Under the Paris agreement, 180 countries agreed to limit global temperature rise this century to well below 2 degrees Celsius above pre-industrial levels, and to pursue efforts to limit temperature rise to 1.5 degrees Celsius (UNFCCC, 2015).

As the rise in global mean temperature is directly related to cumulative greenhouse gas emissions, global emissions must reach net zero to stabilise temperature rise. If there is to be any chance of keeping global warming below 1.5 degrees, global emissions need to reach net zero by around 2050 (IPCC, 2018). Globally and in Australia, major corporations, investors and governments are already moving to align their strategies with the goal of net zero emissions by mid-century or earlier.

By mid-2019, almost one-sixth of global GDP was covered by a net zero emissions target by or before 2050 (ECIU, 2019). In many cases, targets are backed by comprehensive policy measures. The United Kingdom (UK) has established policies, regulations and market measures to drive change in the electricity sector and end reliance on coal power – alongside a detailed zero-emissions transport strategy, legally binding emissions-reduction targets and an independent committee on climate change to advise the government on achieving its targets.

New Zealand has developed policy and legislation targeting electricity and transport (including incentives for electric vehicles). California and New York are actively pursuing 100% renewable electricity (by 2045 and 2040 respectively) and net zero emissions across the economy (by 2045 and 2050 respectively).

The European Commission has proposed a 'Green New Deal' policy agenda for the European Union (EU) 'to transform the EU into a fair and prosperous society, with a modern, resource-efficient and competitive economy where there are no net emissions of greenhouse gases in 2050 and where economic growth is decoupled from resource use' (European Commission, 2019). Norway, whose wealth is heavily linked to the extraction of oil, has adopted a target to reach net zero emissions by as early as 2030.

All eight Australian state and territory governments have committed to, or aspire to, net zero emissions by 2050 or sooner. These commitments and aspirations are summarised in Figure 1.1.

FIGURE 1.1: Australian national, state and territory commitments

NATIONAL TARGETS

2030: Emissions 26-28% below 2005 levels

2020: 33,000 GWh of renewable energy

NORTHERN TERRITORY

2050: Net zero emissions (aspirational)

2030: 50% renewable energy

QUEENSLAND

2050: Net zero emissions

2030: 50% renewable energy

NEW SOUTH WALES

2050: Net zero emissions

AUSTRALIAN CAPITAL TERRITORY

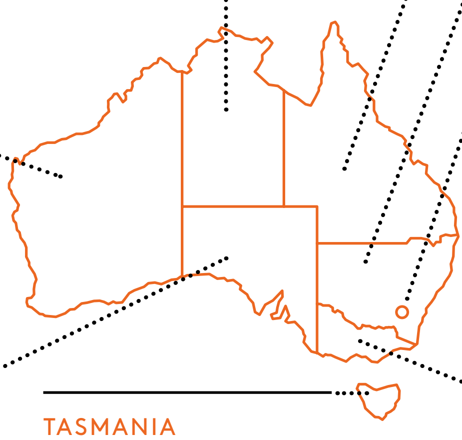
2045: Net zero emissions (legislated)

2020: 100% renewable energy

The ACT legislative assembly is also responsible for local government functions.

WESTERN AUSTRALIA

2050: Net zero emissions (aspirational)



SOUTH AUSTRALIA

2050: Net zero emissions

TASMANIA

2050: Net zero emissions (under review to before 2050)

2040: 200% renewable energy (to support a clean export industry)

VICTORIA

2050: Net zero emissions (legislated)

2030: 50% renewable energy

In addition, Australian capital cities and local governments are increasingly setting net zero emissions targets for their operational and community emissions. A recent analysis by ClimateWorks found that 37% of the local governments assessed – representing 21% of the Australian population – have a target, aspiration or have made emissions reduction commitments aligned with net zero emissions by or before 2050 for all, or the majority of, their community emissions (ClimateWorks Australia, 2020).

Large investors and businesses are also increasingly adopting net zero emissions targets by, or before, 2050. The Net-Zero Asset Owner Alliance, for instance, brings institutional investors from all over the world together in a pledge to transition portfolios – collectively representing some US$4 trillion in assets under management by 2050.

Around the world, companies in the highest emitting sectors – including Germany's largest steelmaker, ThyssenKrupp, and the world's fourth largest cement-making company Heidelberg Cement (which owns a 50% participation in Cement Australia) – are also starting to set net zero targets by 2050 (Geck, 2019). The world's second largest iron ore producer, Vale, has committed to net zero by 2050, with a pledge that includes emissions resulting from the sale of its products (scope 3 emissions). Spain's largest oil company, Repsol, has done the same (Geck, 2019).

The growing expectation around net zero commitments is likely to impact Australia's large industrial and mining companies in coming years.

Already, Australian businesses committed to net zero include large listed companies names like Atlassian, Dexus, Mirvac, Rio Tinto and Qantas. Many businesses are heading in the same direction, with 826 companies – including Westpac, Origin Energy, Woolworths and Telstra – now committed to developing, or have developed, a science-based target aligned with the Paris goals of keeping global warming well below 2 degrees Celsius.

Australia, and the world, has limited time to reach the net zero emissions required to stay within the Paris Climate Agreement goals.

The amount of greenhouse gases that can be emitted while keeping warming below a specific temperature goal is known as a 'carbon budget'. The carbon budget for 1.5 degrees Celsius of warming is necessarily smaller than that for 2 degrees Celsius. *Decarbonisation Futures* utilises a carbon budget approach to assess the compatibility of the scenarios analysed against the temperature outcomes.

Table 1.1 shows the global and Australian carbon budgets for different likelihoods of staying below 2 and 1.5 degrees (IPCC, 2018; GCP, 2019). The Australian carbon budgets are calculated from the global budgets using assumptions consistent with those developed by the Climate Change Authority (CCA, 2014). The calculation shows that if emissions are not reduced as fast as possible, the carbon budgets for 2 and 1.5 degrees will be consumed very rapidly.

A 1.5 degrees Celsius goal requires significant emissions reductions, in the order of halving global emissions every decade (Rockström *et al*, 2017).

These emissions reductions will need to occur alongside measures to remove emissions from the atmosphere through land uses such as forestry and negative emissions technologies, so that net zero emissions is reached globally by 2050.

Australia's total greenhouse gas emissions have increased over the past three years, although they peaked in 2018 (DoEE, 2017; Department of Industry, Science, Energy and Resources, 2019). This has been driven by many factors: growing production and exports of liquefied natural gas (LNG), but also population growth, rising household incomes and increased travel. According to 2019 emissions projections, Australia's emissions in 2030 will be 16% below 2005 levels (DoEE, 2019a) – well short of Australia's emissions reduction target of 26-28% below 2005 levels, and only achieving a 4% reduction below 2019 levels. The achievement of a trajectory compatible with the Paris goals calls for a step change in the pace of emissions reductions in Australia.

TABLE 1.1: Global and Australian carbon budgets for 2 and 1.5 degrees

CLIMATE GOAL	CARBON BUDGET, AS OF 01/01/2020	EQUIVALENT TO X YEARS AT CURRENT EMISSIONS LEVELS	REQUIRES NET ZERO BY
GLOBAL PERSPECTIVE			
2°C, 67% chance	1,086 $GtCO_2$	26 years	~2070
1.5°C, 50% chance	496 $GtCO_2$	12 years	~2050
1.5°C, 67% chance	336 $GtCO_2$	8 years	~2050
AUSTRALIAN PERSPECTIVE[8]			
2°C, 67% chance	11.1 $GtCO_2e$	21 years	~2050
1.5°C, 50% chance	4.1 $GtCO_2e$	7.6 years	~2035
1.5°C, 67% chance	2.1 $GtCO_2e$	4.0 years	~2035 (with overshoot)

8 Calculated using methodology from Meinshausen (2019) drawing on DoEE (2019b). Assumes Australia's share of 0.97%, in-line with CCA (2014).

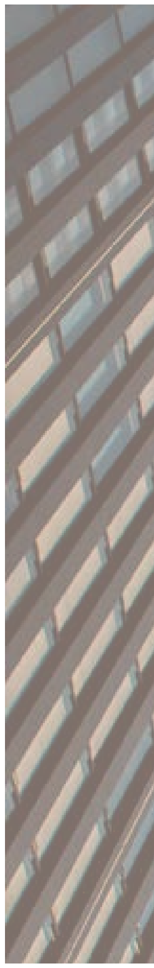
BOX 1.1: THE PARIS CLIMATE AGREEMENT AND THE IMPORTANCE OF TEMPERATURES WELL BELOW 2 DEGREES CELSIUS

Global temperatures have already risen approximately to 1 degree Celsius above pre-industrial levels (Allen *et al*, 2018). Data released by NASA and the American/National Oceanic and Atmospheric Administration shows the past decade to be the hottest ever recorded on the planet.

The human and environmental impacts of the current levels of warming observed in land and ocean temperatures since pre-industrial times are already being experienced, through, for instance, the increased frequency and magnitude of extreme weather. Australia's recent catastrophic fire season – a consequence of prolonged drought and intense heatwaves – provides one example of what the future might look like, with additional warming projected to increase impacts further (Climate Council, 2019).

Research into the relative economic benefits of climate targets shows that limiting of warming to 1.5 degrees Celsius will likely reduce the deleterious consequences for people, the planet and the economy – with estimated global benefits exceeding US$20 trillion under a 3% discount rate. People, the planet and the economy are all projected to suffer greatly with warming above 2 degrees Celsius (Burke *et al*, 2018). Other benefits include lessened global inequality and avoidance of more than 30% reductions in per capita output (Burke *et al*, 2018). Differences in the natural environment are expected to be significant under higher levels of warming, with, for example, 99% of reef-building corals lost under warming of 2 degrees or more (Hoegh-Guldberg *et al*, 2018) and a 20-40% decline in Murray Darling Basin river flows forecast if global average temperatures increase by 2 degrees (Foley, 2020; Chiew *et al*, 2008).

Decarbonisation Futures can help leaders in government and business leverage positive momentum, understand available solutions and accelerate their development and deployment.



While recent action in Australia and globally is not yet sufficient to reach net zero emissions before 2050, the momentum for emissions-reduction solutions provides a basis for further action – at the greater scale and speed required to align with a 1.5 degrees Celsius goal (WMO *et al*, 2019).

History has shown that rapid adoption of technology, policy and social innovations can result in change much faster than has been conservatively assumed. For example, the first mobile phone prototypes appeared in the 1970s. When asked by AT&T in the 1980s to predict the uptake of the new phones, the management company McKinsey & Company projected that less than 1% of the total population would own a mobile device by 2000 (The Economist, 1999). Mobile phone ownership in the United States is now estimated at 96% (Pew Research Center, 2019), reaching almost complete adoption in less than 40 years. The technology is continuing to cause rapid societal changes.

Examples of faster than expected progress in emissions reduction can be seen particularly in the uptake of renewable energy and storage, where the speed and scale of cost reductions has exceeded even the more optimistic projections. Globally, more solar power plants have been installed in five years than was projected to take place in 20 years (Liebreich, 2018). Similarly, the costs of battery packs for electric vehicles have fallen more, and years earlier, than expected. Recent progress includes cost reductions and performance improvements in electric vehicles and batteries. This means that larger vehicles such as buses and trucks are now being electrified in transport, while solar and wind power with energy storage dominate the pathway to zero emissions in electricity.

There is no single pathway to reduce emissions to net zero economy-wide. But as an alignment with net zero emissions by 2050 becomes the norm, financial regulators will increasingly expect companies and investors to consider climate risks and opportunities within their risk management frameworks (APRA, 2019).

Scenario testing can help ensure robust and resilient strategies, testing the impact of alternative futures on a company, an investment portfolio or a government policy. *Decarbonisation Futures* utilises the Aus-TIMES techno-economic modelling framework to empower decision-makers to make high-quality decisions towards a net zero goal, by detailing:

+ the maturity of solutions across different sectors of the economy
+ the drivers – policy, businesses and individuals, and technology – helping to develop and deploy solutions
+ ways to track progress, including benchmarks indicative of the changes needed this decade to remain aligned with the goal of limiting global warming to 2 and 1.5 degrees Celsius.

The modelling lays the groundwork for the next challenges: the accelerated deployment of mature and demonstrated technologies, and the rapid development and commercialisation of emerging zero-emissions technologies in harder to abate sectors.

It is worth noting that the report explores possible futures for the Australian economy based on its typical structure, and the modelling does not include the entry of new industries and global markets, such as green hydrogen.

The body of this document is divided into two main sections. Section 2 looks at each sector and characterises their emissions profile, as well as available solutions and the drivers that might contribute to their progress. In Section 3, the results of three illustrative scenarios are presented, alongside useful tracking benchmarks for 2030.

MOMENTUM

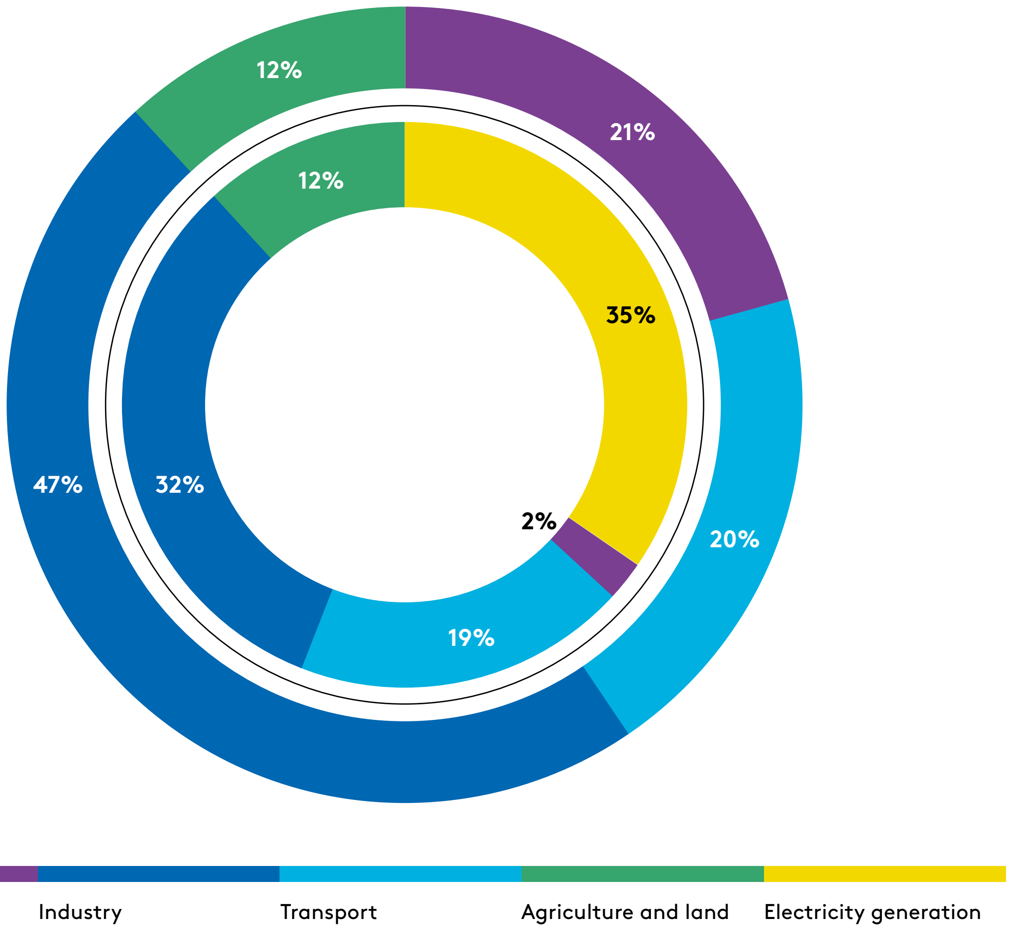
SECTION 02

The achievement of net zero emissions relies on four pillars of decarbonisation across all sectors of the economy.

Australia generates high levels of greenhouse gas emissions, with its economy ranking in the top 10 in the world for emissions per capita (IEA, 2019a). Australia's emissions are produced primarily by the electricity generation, industry and transport sectors, as shown in Figure 2.1. When electricity emissions in end-use sectors (rather than at generation) are counted, buildings and industry represent a much larger share.

Australia's emissions are mostly (79%) due to the burning of fossil fuels – coal, gas and oil. The remainder come from non-energy sources – namely industrial processes and product use, agriculture, waste and land use (DoEE, 2019e).

FIGURE 2.1: Australia's emissions shares by sector (2018). Inside circle: excluding end-use electricity (scope 1), outside circle: including end-use electricity (scope 1 & 2)



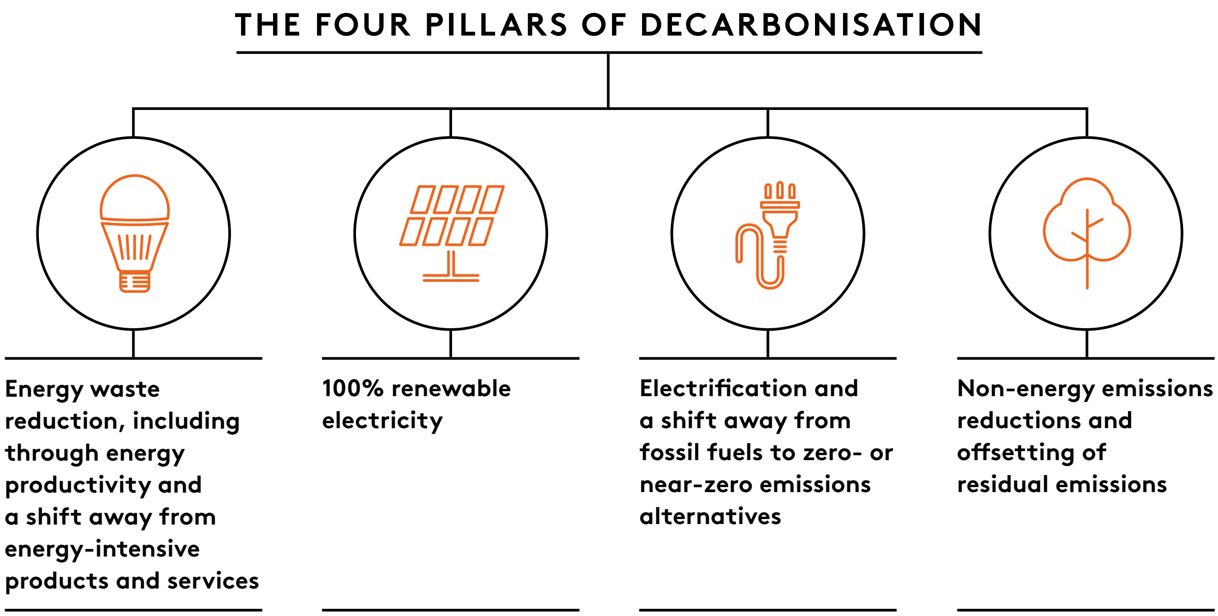
Source: ClimateWorks Australia analysis[9] using DoEE (2018b; 2019d).
Note: Numbers may not add up to one hundred due to rounding

9 Note: Exact emissions shares by subsector may differ slightly to those published in Australia's National Greenhouse Gas Inventory due to different emissions-accounting treatment and allocation.

In Australia, achieving net zero emissions across the economy and in every sector still relies on the four pillars of decarbonisation (Figure 2.2):

- Energy waste reduction, including through energy productivity and a shift away from energy-intensive products and services
- 100% renewable electricity
- Electrification and a shift away from fossil fuels to zero- or near-zero emissions alternatives
- Non-energy emissions reduction and offsetting of residual emissions.

FIGURE 2.2: The four pillars of decarbonisation



Source: ClimateWorks Australia (2014) *Pathways to Deep Decarbonisation in 2050*.

Much has changed in five years, with the technical gap closing to make zero emissions possible in all sectors.

Technical progress in decarbonisation has been rapid in recent years. Today, mature technologies capable of achieving zero emissions exist in many sectors. *Decarbonisation Futures* outlines progress made towards zero-emissions technologies across major sectors of the Australian economy – **electricity**, **buildings**, **transport**, **industry**, and **agriculture and land**.

TABLE 2.1: Summary table of key emissions-reduction solutions by sector

	DEMONSTRATED + MATURE SOLUTIONS	EMERGING SOLUTIONS
ELECTRICITY	100% renewables, storage (including batteries), demand management	*There are sufficient demonstrated and mature solutions to decarbonise these sectors. However, emerging solutions could decrease costs and aid deployment at scale.*
BUILDINGS	Deep energy efficiency, electrification	
TRANSPORT	Electric and fuel-cell vehicles for light road transport	Biofuels, synfuels, electrification, ammonia or hydrogen for other transport
INDUSTRY	Energy efficiency, circular economy, proven electrification, bioenergy and bio-feedstocks, industrial CCS	Material substitution, high grade heat electrification, solar thermal, hydrogen
AGRICULTURE + LAND	Sustainable agriculture practices, plant-based substitutes, fertiliser management, carbon forestry	Lab food, enteric fermentation treatments (such as livestock vaccines)

The following section explores the situation in each sector of the Australian economy, listing emissions sources, the factors contributing to their increase and the solutions that could help achieve zero emissions. For each sector, the solutions are summarised in table format and expanded on in text, along with examples. The 'readiness' of each solution is also presented, using three status designations:

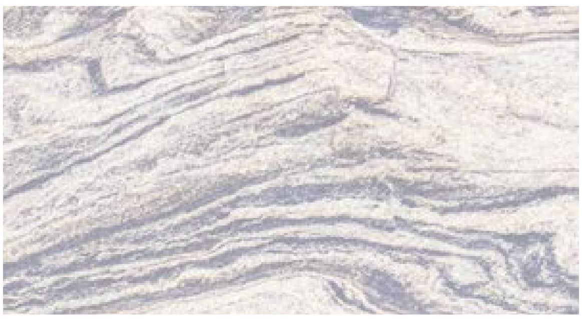
+ MATURE
These solutions have been proven, or are available 'off-the-shelf' for deployment. Their performance is comparable to existing solutions

+ DEMONSTRATION
These solutions are undergoing simulated or real-world demonstrations but may require further validation for new applications. More development is required to improve the price and/or performance compared to existing solutions

+ EMERGING
These solutions are yet to be deployed outside the research environment. They are still under development and testing to prove feasibility. Proof-of-concept is either underway or needed to demonstrate viability.

These designations are a simplified representation of technology maturity and integration readiness. They are intended to provide a high-level snapshot of the readiness of the solution for its abatement task – relative to other solutions within a sector, and in other sectors (Table 2.1).

Each sector must overcome unique challenges during the transition to net zero. In the buildings, electricity generation and light road transport sectors, many of the technologies required for full decarbonisation are available, and deployment and integration are the main challenges. In other sectors – particularly industry, transport, and agriculture and land – there is significant scope for technological solutions in hard-to-abate areas, as well as the scaling-up of currently available technologies.



The transition to net zero emissions in Australia will need backing from businesses and individuals and every level of government to support technology development, demonstration and deployment.

The growing momentum towards an increasing number of zero-emissions solutions in Australia is promising.

However, for Australia to be on a net zero trajectory (consistent with limiting global temperature rise to well below 2 degrees Celsius) the implementation of these solutions will need to scale up and accelerate. To achieve the required rate of implementation, many challenges must be overcome, including technological development, deployment and integration.

Technology progress, policy and business and individual actions have been identified as key drivers to help develop and diffuse the zero-emissions solutions discussed.

The extent to which each of these drivers is relevant to a sector or particular solution depends on how clear the path to zero emissions is currently thought to be. For example, where a sector is facing a deployment challenge, technological development is likely to be less important than supportive environmental policy or demands by businesses and individuals for existing technologies.

The investigation of the differences in the effect of each category of drivers is a key part of the *Decarbonisation Futures* analysis. The overall hypothesis is that a combination of technological, policy and business and individual drivers can overcome barriers to the development and uptake of solutions. For example, the uptake of 3D printing would likely grow if continued cost reductions are achieved (a technological driver, supported by public and private investment), and demand from businesses and individuals for products and services increases materially. Therefore, a scenario where technological and business/individual drivers are high, and where policy drivers are supporting progress, would see high levels of 3D printing. There could also be other paths to uptake of 3D printing.

Examples of how technology, policy, businesses and individuals can help address the challenges to achieving net zero:

TECHNOLOGY PROGRESS

Technological research, development and innovation can drive cost reductions through improvements such as production processes that enhance economies of scale and the use of more economical materials. Technological innovations and improvements can also support low-carbon technologies. This support can include overcoming inherent challenges (for example, batteries to store energy for variable renewables), providing a way to accelerate uptake or providing new ways of working (for example, sensors and automation in manufacturing). These supporting solutions may not have been developed solely to reduce emissions and could potentially benefit multiple sectors simultaneously.

POLICY

Policy can drive emissions reductions through legislation, regulation, standards or incentives to drive the rapid and widespread uptake of solutions (for example, renewable energy targets, vehicle greenhouse gas emissions standards, direct procurement, and investment in climate solutions). This provides essential infrastructure to support the rollout of solutions (for example, investments in electricity transmission, rail transport and electric vehicle charging infrastructure), addressing market failures and reducing non-price barriers to adoption (for example, consumer information). Policy can also provide support for communities and workers impacted by the transition to net zero emissions (for example, support for low-income households to access affordable electricity and transport, and just transition plans for communities and workers reliant on coal and gas power).

BUSINESSES AND INDIVIDUALS

Businesses and individuals can have a significant impact on emissions reductions through their consumption, investment and advocacy. Actions such as supply chain procurement rules for businesses are an example of shifting consumption. Businesses may move their operations away from high-emissions processes or commodities to low-emissions alternatives. For individuals, increasing demand for more sustainable products and investments (for example, ethical superannuation and banking products) provides a strong signal to businesses.

The involvement of businesses and individuals involvement in emissions-reduction leadership initiatives, campaigns or advocacy efforts can send a strong signal to peers and governments.

Table 2.2 illustrates how actions by government, businesses and individuals can help accelerate the development and implementation of solutions, depending on their current status.

Each sector must overcome unique challenges during the transition to net zero. In the building, electricity generation and road transport sectors, many of the technologies required for full decarbonisation are available, and deployment and integration are the main challenges.

In other sectors, particularly industry, transport, agriculture and land, there is significant scope for technological solutions in hard-to-abate areas, as well as the scaling-up of currently available technologies. The following sections discuss the most pressing challenges for each sector and the drivers that can help overcome them.

TABLE 2.2: Overview of actions that government, businesses and individuals can take to accelerate solution development and deployment

SOLUTION STATUS		ACTIONS		
		GOVERNMENT	BUSINESSES	INDIVIDUALS
MATURE	ACCELERATE DEPLOYMENT	+ Set standards and targets to accelerate the exit of old solutions and uptake of best-practice solutions + Tax emissions-intensive activities and products + Provide financial support and/or market structure amendments + Invest in supporting infrastructure + Improve information and accessibility	+ Set targets for operations and supply chains + Bring forward asset replacement investments with net-zero ready versions + Shift products and services towards low-carbon options + Create new business models to accelerate uptake + Policy advocacy + Investor engagement with companies	+ Shift in consumption towards low-carbon products and services + Shift in behaviour, for example transport preferences + Investment in energy-efficiency upgrades and solar PV + Shift in investments towards low-carbon options + Business and policy advocacy
DEMONSTRATION	ACCELERATE DEPLOYMENT	+ Provide incentives for early deployment + Early demand through government procurement + Invest in supporting infrastructure + Stimulate private investment (such as with reverse auctions, co-investment or market design)	+ Early demand, willing to pay price premium + Targeted procurement for demonstration and testing + Create consortium for risk sharing for earlier stage demonstrations	+ Early demand, willing to pay price premium + Community investment in low-carbon solutions
EMERGING	INVEST IN RD&D	+ Public investment in RD&D towards zero-emissions solutions + Incentives for private investment in RD&D + Place-based experimental deployment	+ Private investment in RD&D towards zero-emissions solutions + Create consortium for risk sharing for earlier stage demonstrations	

2.1 ELECTRICITY

Electricity generation is Australia's largest emissions source, affecting all downstream sectors of the economy.

Electricity generation is Australia's highest emitting sector, accounting for more than a third of the national total (DoEE, 2019f). Electricity also plays a significant enabling role in decarbonising other sectors, which utilise electricity for energy supply. Rapid decarbonisation of the electricity sector is essential for Australia to meet Paris Climate Agreement targets.

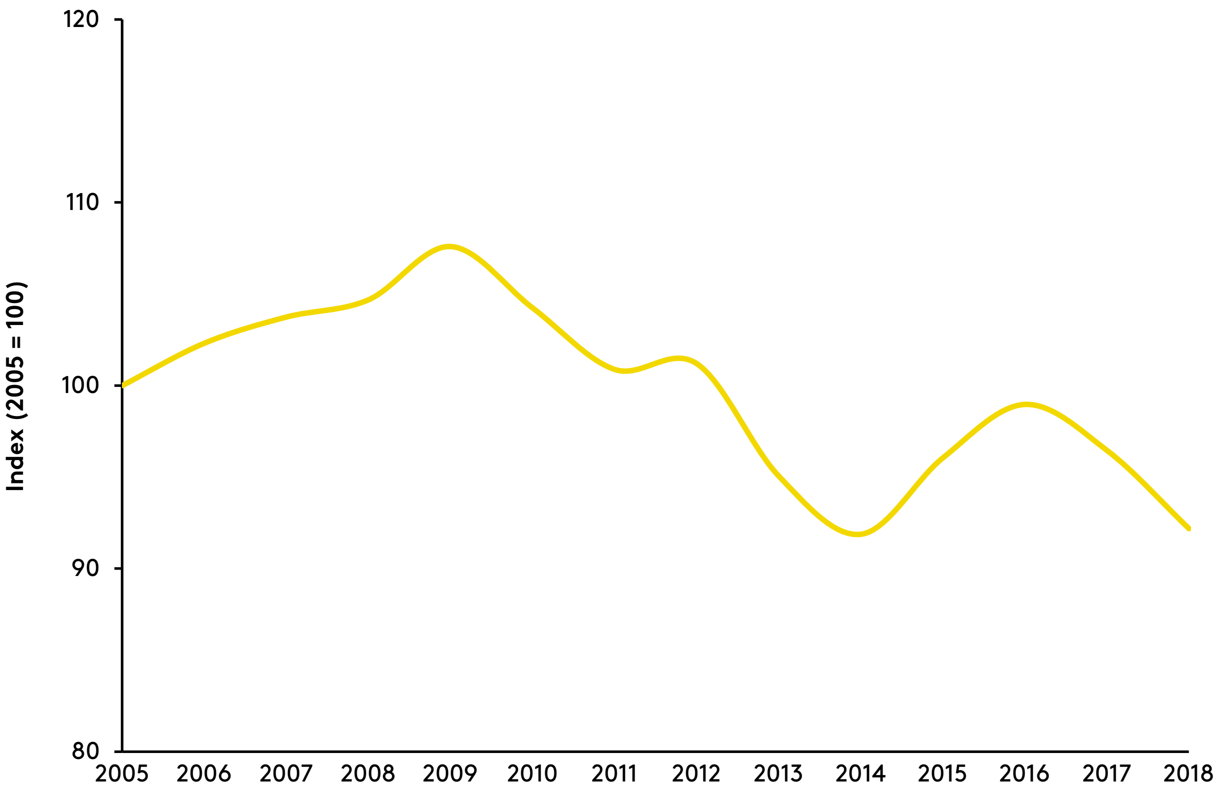
Most of the solutions required to achieve zero emissions in the electricity sector are mature and commercially competitive or have been demonstrated at scale. The key challenge for the sector is to achieve widespread adoption over a short period of time.

Electricity emissions have fluctuated over the past decade, as shown in Figure 2.3. Peaking in 2009, they declined over the five subsequent years. Several factors facilitated this decrease, including policies that supported renewable energy, a reduction in demand, and carbon pricing from mid-2012 to mid-2014. After 2014, emissions rose for two years before dropping again between 2017 and 2018.

The most recent fall in electricity emissions reflects the closure of coal power stations and increasing deployment of renewable sources. Wind and solar photovoltaics (solar PV) are now the cheapest sources of new electricity generation (Graham *et al*, 2018). The shift to renewable energy is likely to continue as existing high carbon sources are retired at end-of-life or sooner, depending on both financial and social drivers. The closure of the Hazelwood power station in Victoria in 2017 offers an example of these dynamics, with power station age, company strategy and difficult market conditions cited as reasons for the decision (Engie, 2016).

In 2018, global investment in renewable energy contributed 171 gigawatts of power, more than 60% of new installed capacity (IRENA, 2019). Solar PV (94 gigawatts) and wind (49 gigawatts) accounted for most of the new capacity.

FIGURE 2.3: Australia's annual electricity generation emissions trend (2005-2018)



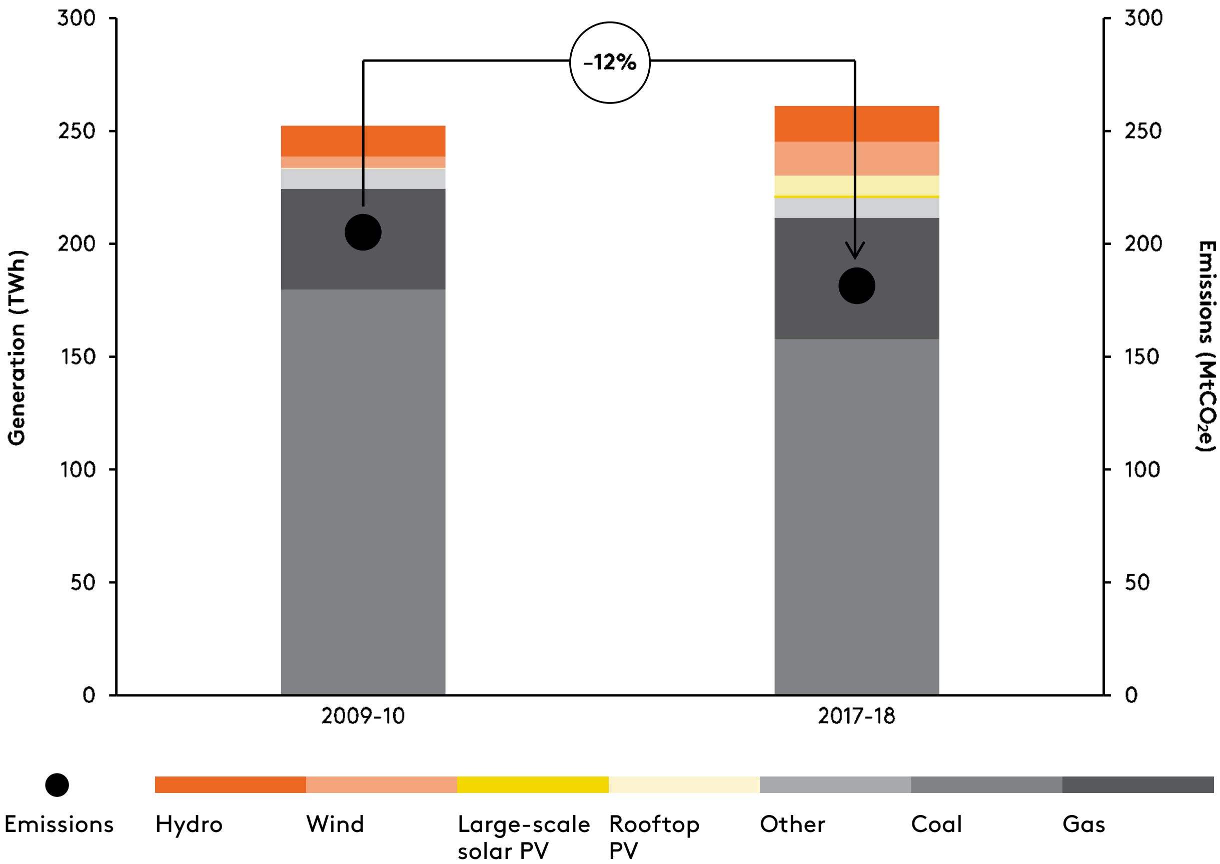
Source: ClimateWorks Australia analysis using DoEE (2018b; 2019d)

In Australia, coal-fired electricity generation fell to around 60% of total generation in 2018, down from 71% in 2010, while gas use has remained relatively consistent at around one-fifth of total generation (DoEE, 2019b) as shown in Figure 2.4 below. Australia's increased reliance on renewable energy has been driven by national and state renewable energy targets, renewable energy agencies (such as the Clean Energy Finance Corporation (CEFC) and the Australian Renewable Energy Agency), the retirement of coal power stations, uptake by business and individuals (particularly of solar PV), and substantial global cost reductions of new-build renewable energy. This is particularly the case for wind and solar PV, as well as energy storage technologies such as large-scale battery storage (Graham *et al*, 2018). Solar power generation, both small- and large-scale, has grown to nearly 4% of total generation, up from less than 1% earlier in the decade (DoEE, 2019b).

In the same time period, wind generation has more than doubled in capacity, now contributing just under 6% of total electricity to the grid.

Over the past decade, electricity demand has grown slightly. Much of this additional demand has successfully been met by renewable sources. This has had flow-on benefits, as new fossil fuel capacity has not been 'locked in' during this period. Ongoing energy-efficiency improvements and installations of 'behind-the-meter' solar PV – where consumers use electricity generated by rooftop solar in preference to drawing from the grid – will be likely to help decouple grid electricity demand from population and economic growth in some sectors of the economy. Increased production from electricity-intensive industries such as LNG production has, and could lead to further increases in demand for electricity. Widespread electrification in other sectors to replace fuels such as gas could also drive strong growth in electricity demand.

FIGURE 2.4: Electricity generation mix and emissions (2010 & 2018)



Source: DoEE (2019b; d)

Renewable energy has continued to gain momentum globally and in Australia – spurred by policy support and cost reductions. Renewable energy is a mature solution, well-positioned for widespread deployment.

In the electricity sector, zero-emissions technologies are mature. In particular, large- and small-scale renewable generation (supported for example by new storage capabilities) can fully decarbonise the power supply. The increased uptake of new technologies worldwide has led to significant cost reductions, with new large-scale renewable generation now less expensive than new fossil fuel generation, and battery costs per kilowatt hour 80% cheaper than in 2010 (Table 2.3).

Recent reports have suggested that Australia can transition to 100% renewable electricity generation (Blakers *et al*, 2017; Ueckerdt *et al*, 2019), while reducing costs across electricity networks (CSIRO & Energy Networks Australia, 2017). Australia can reach a 50% share of variable renewable energy (such as wind and solar) without needing significant energy storage capacity (Godfrey *et al*, 2017). Many countries (including Denmark, Uruguay, Ireland, Germany, Portugal, Spain, Greece and the UK) rely on a much greater proportion of variable renewable energy than Australia (IEA, 2017; REN21, 2019). Other than South Australia, all Australian states and territories currently have less than a 50% variable renewable share. Distributed generation – such as rooftop solar PV and large-scale renewable generation – can meet new demand and replace existing fossil fuel generation in a commercially competitive way.

As the proportion of energy and power delivered by variable renewables increases above 50%, storage and other system-balancing and stability technologies may need to be installed. Even accounting for the additional cost of such technologies, renewables remain the cheapest new source of electricity. Battery storage costs per kilowatt hour have dropped by more than 80% since 2010 and are continuing to decline (Climate Council, 2018).

There are also other energy storage options (such as pumped hydro) that are in varying stages of market and technological readiness.

While energy storage is one solution for balancing the variability of renewables, other approaches exist. These include the diversification of renewable energy sources, the extension of transmission networks, the overbuilding of renewable energy capacity, and the increased use of demand management.

Building more transmission infrastructure will provide access to more diverse renewable energy sources, allowing non-coincident[10] sources to be included in the generation mix. If renewable capacity is overbuilt relative to demand, surplus electricity can then be used to produce low-emissions fuels such as renewable hydrogen. Finally, demand management can be used to make demand more flexible, so that it can adapt to changes in supply.

Electric vehicles are expected to be a large future source of flexible electricity demand. As their charging times are adjustable, electric vehicles could be optimised to support grid reliability. Hydrogen electrolysers using renewable energy, if built at scale and grid-connected, could play a role as a flexible source of demand. Business models that engage behind-the-meter virtual power plants[11] to balance supply for the grid are also emerging. In addition, both network and market operators are investing in monitoring, forecasting and controlling behind-the-meter energy devices (Energy Networks Australia, 2018b). Finally, rule changes from the Australian Energy Market Operator (AEMO) require that retiring plants provide three years' notice of the date they will cease generation, so that replacement generation capacity can be developed in advance.

10 If the system can access renewable energy sources which increase and decrease production at different times to when existing renewables generate, this smooths aggregate variable renewable electricity supply.

11 A virtual power plant refers to the aggregation, management and control of distributed energy resources such as rooftop solar and batteries to deliver services to households and communities, in a similar manner to a conventional power plant.

Australia is, however, unlikely to achieve the pace of transition required to reduce emissions through market forces alone, and will require policy and market intervention or pressure from businesses and individuals to retire existing generation, as well as investment in transmission infrastructure and a flexible grid. An additional challenge in the transition away from existing generation sources is ensuring a 'just transition'[12] for regions heavily reliant on these industries (ACTU, 2016).

BOX 2.1: MANAGING SECURITY OF A RENEWABLE GRID

In addition to balancing supply and demand, the electricity system requires additional services to manage the grid. Services including inertia, frequency control and voltage control ensure the electricity grid can quickly recover from unexpected events. These are largely supplied by existing fossil fuel and hydroelectric generation, as well as by transmission lines. As fossil fuel generation retires, however, new approaches have become available.

For example, synchronous condensers, historically used for industrial power load management, are gaining favour for their ability to regulate grid voltage by absorbing and generating reactive power. ElectraNet, the main transmission supplier for South Australia, recently selected synchronous condensers in preference to contracting existing generation, a decision approved by the Australian Energy Regulator.

In addition to traditional sources of grid stability, wind, solar and battery storage facilities with smart inverter technology can also be modified to provide regulation, voltage support and frequency response services to support grid reliability and security (California ISO, 2016).

TABLE 2.3: Summary table of strategies and key solutions for electricity supply emissions reductions

STRATEGY	KEY TECHNOLOGIES	STATUS	MOMENTUM
PRODUCE AND STORE ZERO-EMISSIONS ELECTRICITY			
Meet new demand and replace existing fossil fuel electricity generation with renewables to achieve a zero-emissions electricity grid	Distributed generation (e.g. rooftop solar PV)	Mature	Distributed rooftop solar PV is now cost effective for many households with sufficient roof space. In recent years, rooftop solar PV generation has increased by around 20% annually to form over 3% of total electricity supply[13]. The rise of small generation aggregators is unlocking even greater potential for rooftop PV penetration in our grid[14].
	Grid-connected renewables (e.g. solar, wind)	Mature	The capital costs of large-scale renewable generation in Australia have now fallen below costs for new-build fossil fuel generation[15], making it a more commercially viable solution for new generation.

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12 Refers to a framework developed by labour unions and environmental justice groups to help secure the rights and livelihoods of workers affected by transitions away from polluting industries (Climate Justice Alliance, 2018).

13 Clean Energy Regulator (2018)

14 AEMO (2020)

15 Graham *et al* (2018)

Integrate high levels of renewables	Pumped hydro energy storage (PHES) technology	Mature	Pumped hydro energy storage has been used in Australia since the 1970s – including schemes at Talbingo, Shoalhaven and Wivenhoe. Additional opportunities are increasingly being identified across Australia: Hydro Tasmania is investigating three high-potential sites under the Battery of the Nation initiative[16]; work has begun on the Snowy 2.0 pumped hydro project; and the Australian Renewable Energy Agency (ARENA) recently committed funding to fast-track development of the first pumped hydro plant in South Australia[17].
	Battery storage (large-and small-scale)	Mature	Battery costs per kilowatt hour have dropped by more than 80% since 2010, and could more than halve by 2026[18]. Initiatives such as AEMO's National Electricity Market Virtual Power Plant Demonstrations Program aim to increase the impact of local battery storage on electricity grids[19]. Additionally, large utility-scale batteries are already operating in Australia, such as the Neoen and Tesla Hornsdale Power Reserve in South Australia – the world's largest battery[20]. Others are currently under testing or construction[21].
	Demand response and commercial models for valuing storage	Demonstration	The Australian Energy Market Commission is currently considering a rule change to better integrate demand-side participation in the National Electricity Market. This would create a more favourable market environment to incentivise large energy producers to shift their demand response[22]. As Australia's electric vehicle fleet grows, opportunities for 'vehicle-to-grid' storage and demand response mechanisms are also set to increase[23].
	Renewable hydrogen	Emerging	One work stream of the Council of Australian Governments Energy Council's Hydrogen Working Group focuses on hydrogen to support electricity systems. The group plans to investigate hydrogen's potential to help balance electrical supply and demand[24]. ARENA has also awarded $22.1 million in funding for hydrogen research and development[25], while also directly supporting numerous demonstration projects[26].

16 Hydro Tasmania (2019)

17 ARENA (2019a)

18 IEA (2018a)

19 AEMO (2018)

20 Neoen (2019)

21 ARENA (2019b)

22 Public Interest Advocacy Centre, Total Environment Centre and The Australia Institute (2018)

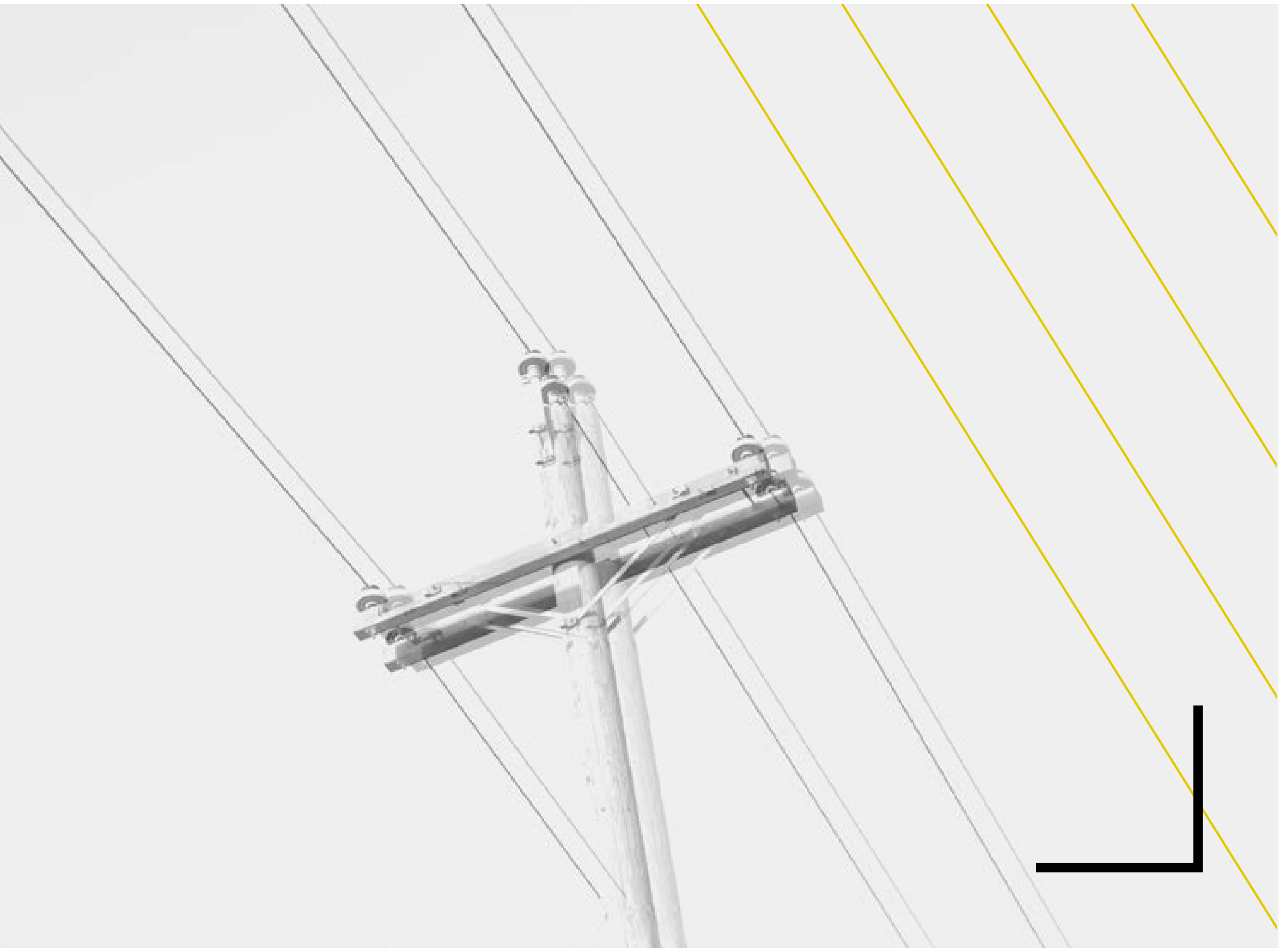
23 ARENA (2019c)

24 Australian Government Chief Scientist (2018)

25 ARENA (2018)

26 ARENA (2019d), ARENA (2019e)

Integrate high levels of renewables	Microgrids	Demonstration	Victoria's Microgrid Demonstration Initiative has supported seven demonstration projects around the state[27]. Notably, Monash University is demonstrating the potential economic opportunities for microgrid operators in a large-scale trial that also aims to inform state policy to address existing barriers to microgrid implementation[28].
	Inertia-control technology	Demonstration	Synchronous condensers are an established technology – previously used for industrial power load management. The technology is now seeing a comeback for grid-stability applications[29]. Development of renewable inertia-providing generation is also scaling up, with major players such as GE and Mitsubishi currently working on large-scale hydrogen-powered turbines[30].



27 DELWP (2019)

28 Monash University (2019)

29 Modern Power Systems (2019)

30 Patel (2019)

2.2 BUILDINGS

Residential and commercial buildings comprise around one-fifth of Australia's emissions, yet the sector can achieve zero emissions by pairing energy efficiency and electrification with renewable electricity.

Residential and commercial buildings, including their electricity emissions, comprise around one-fifth of Australia's emissions[31] (ClimateWorks Australia, 2018b). As buildings are used for living and working, they consume significant energy to power lighting, appliances, hot water and space heating and cooling.

Commercial buildings derive nearly 80% of their energy from electricity, with the rest coming from gas. Residential buildings use electricity for nearly half of their energy needs, gas for one-third, and biomass – such as firewood – for most of the remainder. Given the high rate of electricity use, future emissions for the buildings sector are likely to be determined by the speed and extent to which the electricity grid is supplied by low- or zero-carbon sources.

Over the past decade, an increase in Australia's building stock, driven by population and economic growth, has resulted in higher energy use in both residential and commercial buildings. The energy mix has remained similar during this time, with electricity the primary source. Emissions reductions in the electricity sector have had a flow-on effect for buildings – building emissions have roughly plateaued despite increased demand, as shown in Figure 2.5.

FIGURE 2.5: Australia's annual buildings emissions trend (2005-2018)

Source: ClimateWorks Australia analysis using DoEE (2018b; 2019d)

The technology required for a zero-emissions building sector – deep energy efficiency and electrification powered by renewables – is already available. The key challenge for the sector is to achieve widespread deployment.

Most of the solutions required to achieve zero emissions in the building sector (for instance, deep energy efficiency and the electrification, powered by renewables, of heating and water services) are mature and commercially competitive or have been demonstrated at scale. Energy-efficient technologies continue to become cheaper and more effective. For example, the cost of LED lighting has declined 80% over the past five years; and internationally, some 60,000 'passive houses' (including a growing number in Australia) illustrate how heating requirements in homes can be drastically reduced by state-of-the-art design and insulation (Table 2.4). The key challenge for the sector is to achieve widespread deployment over a short period of time.

Reducing energy use is critical. This can be achieved through the construction of buildings with low energy requirements for lighting, heating and cooling. Commercially competitive and widespread measures exist, including insulation, draught-sealing, electrochromic windows and passive house standards. The supply of buildings with the most efficient appliances, such as LED lighting, is key to reducing energy use. The optimisation of equipment through technologies like smart systems and lighting controls will also reduce building energy demand. Further investment in research and development to improve the cost-competitiveness or ease-of-use of commercially-mature solutions (perhaps integrated with smart systems) could facilitate such deployments.

Both residential and commercial buildings can shift reliance on gas to electricity, with many electrical appliances now more energy efficient and cost effective than their gas counterparts. Retrofit options are available for existing buildings, while advances in technology mean new buildings can be constructed with electricity as the sole power source. For instance, electric heat pumps – such as split system air conditioning – can replace gas heating and deliver a five- to seven-fold improvement in the energy efficiency of space heating (ASBEC, 2016). When coupled with smart technologies, these appliances can increase the energy efficiency of buildings and reduce peak demand.

Increasing deployment of energy-efficient electric technologies is providing opportunities for both current and new buildings to become 100% electrified. This will allow the sector to be fully powered by renewable energy. With sufficient deployment of energy-efficient electrical solutions, the building sector could reach zero emissions by 2040.

As well as reducing building emissions, energy-efficiency measures can deliver significant cost savings. A recent study from the Australian Sustainable Built Environment Council (ASBEC, 2016) estimates that an energy reduction of 50% is achievable across the entire building sector, at little to no additional net cost – as the long-term cost savings delivered by energy-efficiency measures generally exceed the capital investment required.

Buildings can also produce and store their own zero-emissions electricity. Rooftop solar PV is an economically viable source of energy for many Australian consumers, with more than two million homes and businesses in Australia installing rooftop solar (Clean Energy Regulator, 2018). On-site solar generation also has wider economic benefits, since it diverts demand from the centralised grid. This reduces the need for new energy generation infrastructure and grid network costs, such as those associated with transmission and distribution. Increased distributed generation could, however, also increase some system costs through initial connection or ongoing maintenance (Essential Services Commission, 2017), highlighting the need for forward planning to manage this transition.

Through renewable power options such as the use of on-site solar, buildings also have the potential to generate more energy than they demand and export the remainder back into the grid. This is a unique opportunity for building sector assets to move beyond zero emissions to achieve net negative emissions.

In June 2019, national, state and territory building ministers agreed to strengthen the National Construction Code in 2022 to provide stronger minimum energy provisions and a trajectory to zero energy and carbon buildings.

A net zero energy and carbon building is one that is highly energy efficient and fully powered from on-site and/or off-site renewable energy sources.

BOX 2.2: MULTIPLE BENEFITS OF ZERO-EMISSIONS BUILDING PRINCIPLES

The reduction of energy use, replacement of fossil fuels, and production and storage of zero-emissions renewable electricity has enabled the construction of homes that produce low or zero emissions.

In 2010, the first Australian net zero emissions home was completed in Laurimar, Victoria. The home leverages demand-response mechanisms, on-site renewable energy generation, and a home energy-management system. The carbon emissions generated during construction, including materials, have been calculated and offset.

Another example is the Innovation House in Townsville, which uses passive building design for natural heating and cooling. The windows are designed to allow winter sun to penetrate and warm the home in cooler months, while shading excludes direct summer sun and openings capture cooling breezes.

The roof and walls use light colours to reflect heat, and the dwelling is optimised for solar PV, which allows the home to generate sufficient electricity for its needs.

In the past decade, government and industry have applied a range of design, technology and materials solutions to make net zero housing available to more consumers. For example, adoption has been encouraged by Climate-KIC's Fairwater Living Lab, which collects evidence on how houses perform in a real-world context.

To further encourage widespread adoption of net zero home principles, Sustainability Victoria is leading a pilot program to construct and market net zero homes in partnership with property developers. The program will introduce better quality homes – with lower energy bills and reduced emissions – into the market. This may act as a catalyst in the building sector, encouraging the creation of an endorsement scheme for net zero homes for builders and consumers alike.

Current and emerging building technologies can also support emissions reductions in other sectors such as electricity supply. For example, buildings can support the transition to a renewable-powered electricity grid by using buildings to provide demand response. Demand response aggregates equipment that uses electricity, collates energy needs, and distributes power as required.

TABLE 2.4: Summary table of strategies and key solutions for buildings emissions reductions

STRATEGY	KEY SOLUTIONS	STATUS	EXAMPLES OF MOMENTUM
REDUCE ENERGY USE			
Construct buildings with the lowest possible lighting, heating and cooling energy requirements	Insulation, draught-sealing	Mature	While building insulation is a well-established, cost-effective solution, recent technological advances continue to improve performance, reduce costs and lower the environmental footprint of products[32].
	Homes built to passive house standard, electrochromic windows	Demonstration	The number of certified passive house buildings has grown to more than 60,000 globally. There are currently less than 100 in Australia, but this number is expected to increase in line with global trends[33]. The global market for electrochromic windows is expanding. Currently worth US$1.5 billion, projections estimate the market will reach US$5-10 million by 2025[34].
Ensure that the most efficient equipment is installed in buildings	LED lighting, HVAC[35], solar hot water, appliances and other equipment	Mature	LED lights are already more energy efficient and cost effective than conventional lighting[36]. Costs have declined 80% in the past five years[37], while efficiency and output are expected to improve by 3-5% per year[38]. HVAC technology efficiency has been steadily improving[39]. For instance, the average efficiency for residential air conditioning units in Australia increased by 74% between 2001 and 2015[40].

32 Rubio (2019)

33 Clarke and Marlow (2019)

34 Grand View Research (2018)

35 Heating, ventilation and air-conditioning

36 Viribright (2019)

37 Navigant Consulting (2017)

38 Ramirez (2019)

39 Abergel *et al* (2019)

40 DoEE (2018c)

Optimise the usage of building equipment	Total building optimisation, smart systems, demand response, lighting controls	Demonstration	Investment in smart home systems has been surging in recent years, with annual growth forecast at more than 10% in coming years[41]. Demand-response solutions are rapidly emerging alongside other technological developments and disruptions such as microgrids, standalone power systems, peer-to-peer trading and electric vehicles[42]
SWITCH FROM FOSSIL FUELS TO LOW OR ZERO EMISSIONS ALTERNATIVES			
Switch remaining power requirements to electricity	Heat pumps for residential applications	Mature	Global sales of heat pumps rose by nearly 10% between 2017 and 2018, doubling the previous year's growth rate. China, Japan and the US account for most installations, although Europe's market is also expanding quickly[43]
	Heat pumps for commercial applications	Demonstration	
	Induction cooking	Mature	Induction cooking appliances are now more than twice as efficient as gas stovetops in transferring energy to food[44], and their cost-competitiveness and model availability have continued to improve
PRODUCE AND STORE ZERO-EMISSIONS ELECTRICITY			
Maximise the potential for buildings to produce electricity onsite	Rooftop solar PV	Mature	In recent years, small scale solar PV generation has increased by around 20% annually to form over 3% of total electricity supply[45]. There are now more than two million homes and businesses with rooftop PV installations[46]
	Building integrated PV	Emerging	The global market for building integrated PV products is expected to grow strongly in the near term, driven by a range of considerations such as flexibility, cost, aesthetics and emissions[47]. For example, Onyx Solar develops photovoltaic glass for use in building facades, canopies and floors[48], while Tesla has recently announced the official launch of its Solar Roof V3[49]
Support high penetration of renewables in the grid through demand response: see examples above in 'Optimise usage of building equipment'			

41 Ali and Yusuf (2018), Ablondi (2018)

42 Energy Networks Australia (2018a)

43 Abergel (2019)

44 Sweeney *et al* (2014)

45 DoEE (2019b)

46 Clean Energy Regulator (2018)

47 Markets and Reports (2016)

48 Onyx Solar (2017)

49 EnergySage (2019)

2.3 TRANSPORT

Transport is a significant emitter, and transport demand is expected to grow alongside the population and the economy. Most transport emissions come from passenger and freight road transport.

The transport sector is one of Australia's largest and fastest growing sources of emissions. Transport has seen the most significant growth in recent decades, increasing more than 60% since 1990 to account for around one-fifth of total emissions in 2019 (DoEE, 2019f). Since 2005, emissions have increased by more than 20% (Figure 2.6). Demand for all forms of transport is expected to rise in the future, as population and economic activity grow.

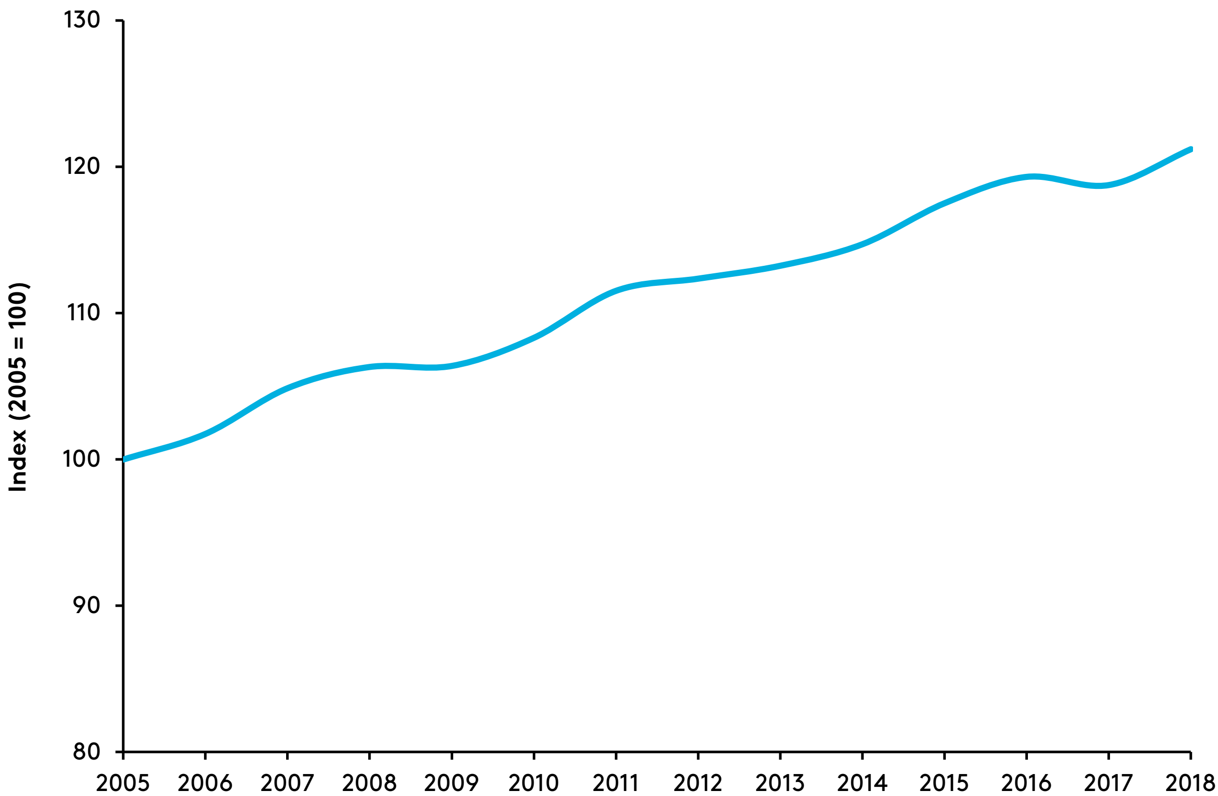
The vast majority of transport sector emissions come from road vehicles, with passenger vehicles (mostly cars) and freight vehicles accounting for 43% and 38% respectively (Figure 2.7).

Australia currently has one of the most energy- and emissions-intensive road vehicle fleets in the world. Australia's average emissions intensity for passenger vehicles is 45% higher than Europe (NTC, 2019). Australia is one of only a small number of Organization for Economic Cooperation and Development (OECD) countries without vehicle greenhouse gas emissions standards (CCA, 2014).

Recent increases in road transport emissions have been driven by a strong increase in freight activity and diesel passenger vehicle sales. In the six years to 2019, petrol consumption dropped 4.7% while diesel consumption rose by 19.8% (DoEE, 2019f).

Domestic aviation is the most significant source of non-road transport emissions, comprising around 10% of total transport emissions. Rail freight and shipping are responsible for a smaller share, while international aviation and shipping is not included in Australia's total emissions (see Box 2.3 below). While non-road transport emissions are much lower than road vehicle emissions, anticipated growth in demand for non-road transport and fewer proven alternatives means future non-road emissions are likely to grow.

FIGURE 2.6: Australia's annual transport emissions trend (2005-2018)

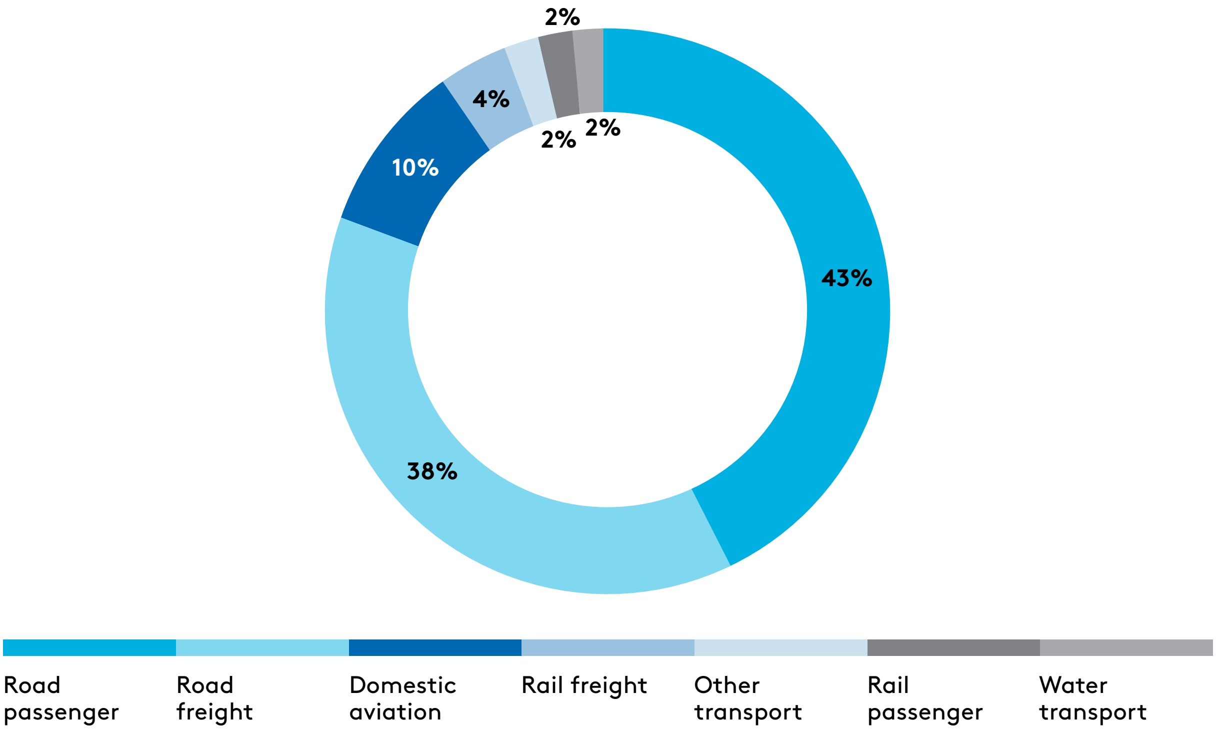


Source: ClimateWorks Australia analysis using DoEE (2018b; 2019d)

Recent developments in non-road transport have focused on improving energy efficiency. Design and operation improvements have not, however, prevented increases in emissions for the sector, since most non-road transport modes remain heavily tied to emissions-intensive fuels such as turbine fuel in domestic aviation and diesel in long-distance rail. Studies have also shown that high-altitude aircraft have a more harmful climate impact due to atmospheric effects from non-CO_2 emissions, which in some cases is far greater than the effect of CO_2 emissions (Timperley, 2017).

Given these numerous challenges, the discovery of low- or zero-emissions solutions for aviation and shipping will become increasingly critical as other parts of the economy reduce emissions towards zero.

FIGURE 2.7: Australia's transport emissions shares by subsector (2018)



Source: ClimateWorks Australia analysis[50] using DoEE (2018b; 2019d). Note: Numbers may not add up due to rounding

BOX 2.3: HOW IS INTERNATIONAL AVIATION MANAGED?

The United Nations Framework Convention on Climate Change (UNFCCC) dictates that for the purposes of emissions accounting, domestic aviation be counted as part of country targets, while international aviation is managed by the International Civil Aviation Organization (ICAO). Member states of ICAO, including Australia, are committed to an annual improvement in fuel efficiency of 2% until 2050. To strive for carbon-neutral growth for international aviation from 2020, on the way to an ultimately carbon-free industry. Primary avenues for reaching these goals in the Australian context are (Department of Infrastructure, 2019):

- Improvements in flight routes and air traffic sequencing
- The introduction of new, more efficient aircraft
- Managing airport emissions contributions, for example, such as initiating green commercial developments.

50 Note: Exact emissions shares by subsector may differ slightly from those published in Australia's National Greenhouse Gas Inventory due to different emissions accounting treatment and allocation.

Electric vehicles, combined with renewable electricity, can now be deployed at scale to achieve zero emissions for light road transport.

Electric vehicles are the most significant and promising technology for reducing road transport emissions. When combined with renewable electricity supply, electric vehicles offer the prospect of zero emissions for road transport.

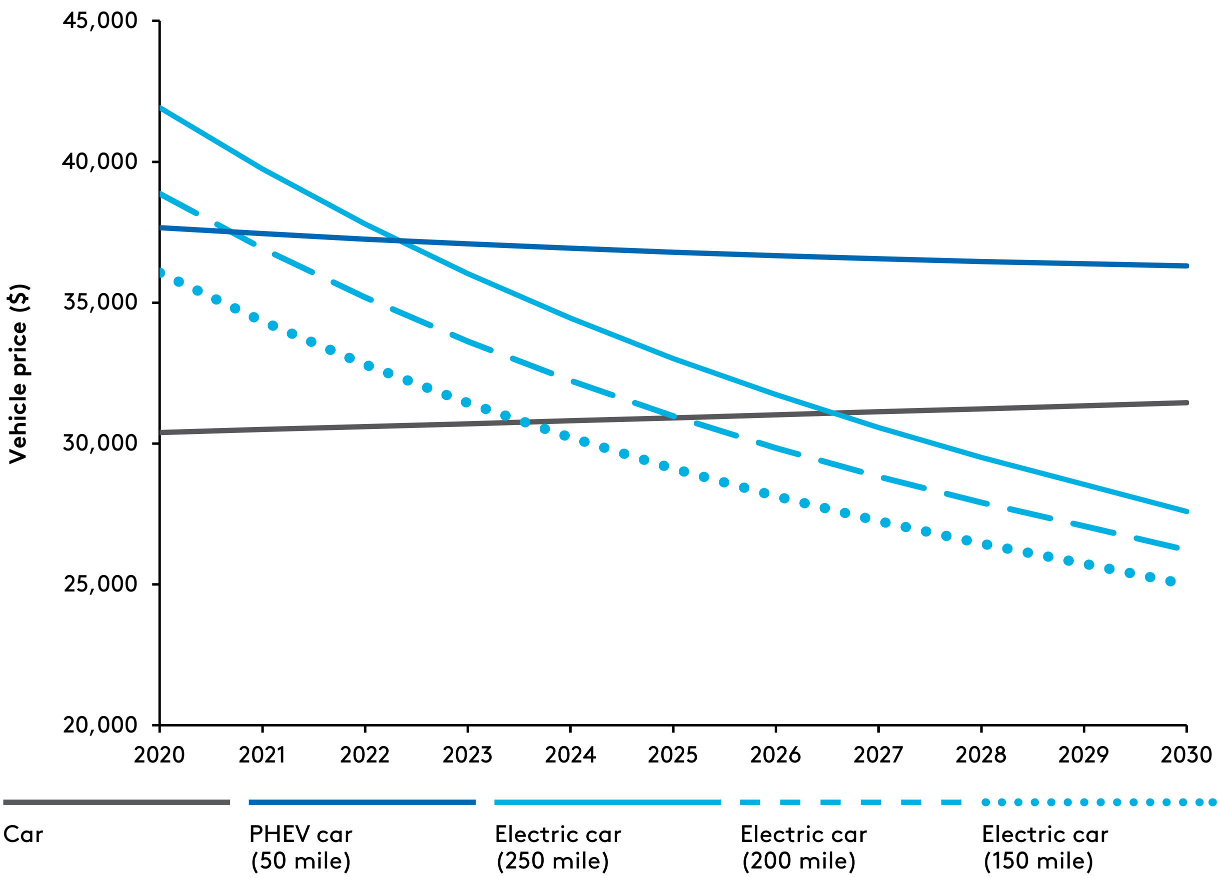
Key elements of Australia's transport system – particularly passenger rail services – are already electric. Currently, the prospects for further electrification are most promising in light passenger vehicles such as cars and motorcycles.

Scaled-up global production of electric vehicles, combined with the declining cost of batteries, has reduced manufacturing costs. This has led to improved affordability and increased uptake of electric vehicles in many countries, with, for example, electric vehicles comprising 46% of new cars sold in Norway in 2018 (IEA, 2019d).

Globally, there are now more than 3 million electric vehicles on the road (IEA, 2018a). Progress in the Australian market has been, however, considerably slower, with less than 3,000 electric vehicles sold in 2018 (Electric Vehicle Council, 2019). Globally there were 460,000 electric buses operating in 2018, a 25% increase on 2017 numbers, with 99% operating in China (IEA, 2019d).

Within the next decade, electric vehicles are expected to become cost-competitive with, or cheaper than, conventional vehicles (Figure 2.8). This may significantly shift buying patterns for new vehicles (ICCT, 2019). The favourable outlook for electric vehicle battery cost and performance implies that a greater share of heavier vehicles will be electrified.

FIGURE 2.8: Projected initial purchase price of conventional and electric cars (2020-2030)



Source: ICCT (2019)

Electric vehicles using grid electricity are already less emissions-intensive than conventional vehicles, in all states but Victoria (ClimateWorks Australia, 2018a). They require, nevertheless, significant deployment and uptake to reach their potential and reduce a significant portion of transport emissions. Policy action can assist the transition, encouraging rapid uptake through investment, incentives, regulation, and infrastructure (such as constructing charging stations to enable electric vehicle uptake). This is being demonstrated around the world, with some countries already seeing strong deployment (IEA, 2019d). Availability and cost are important factors for rapid adoption. If lower-cost models of electric vehicles do not become locally available in the near future, Australia risks another generation of vehicles being locked into high-emissions internal combustion systems.

For electric vehicles to deliver full emissions reductions, they need to be powered by additional renewable electricity. This means recharging stations powered by on-site or purchased renewable electricity. As supply to the grid becomes more sustainable, electric vehicles will be able to use grid electricity and still deliver significant emissions reductions.

Reduction of vehicle demand and the overall kilometres travelled will support the emissions reductions achieved by electrifying road transport. Over the past two decades, growth in rail passenger travel has outpaced growth in road travel as individuals switch from private to public transport in urban centres (Bureau of Infrastructure, 2018). Similarly, investment in public transport infrastructure and services, new business models and shifts toward teleconferencing and away from business travel can reduce overall road transport activity.

There is significant uncertainty regarding the impact emerging transport technologies (such as automation) will have on overall transport use. Adoption rates and flow-on effects across transport systems are hard to predict. For example, if managed poorly, autonomous vehicles may lead to a reduction in public transport usage, increasing rather than reducing overall road congestion. As autonomous vehicles are likely to be electric, however, any potential increased usage will have a limited emissions impact so long as the vehicles are powered by additional renewable electricity.

BOX 2.4: AUTONOMOUS VEHICLES INCREASE SAFETY AT MINING SITES

For heavy road transport, a combination of emerging and mature technologies is likely to support the transition to zero-emissions transport.

Sandvik Group, a Swedish engineering firm, specialises in machinery and materials for the mining and construction industries. Over 20 years ago, the company developed autonomous trucks and loaders for use on mine sites.

As every mining site is unique, the machinery uses a combination of tools for navigation. A route is manually 'taught' to the loader, with an operator driving it through the required path initially, allowing it to collect data. Sensors use lasers to scan the walls of the site, developing a pattern that the machine can follow later.

This allows the machinery to adapt to any setting. Specifically developed algorithms, gyroscopes and angle sensors enable the machines to navigate effectively deep underground, out of range of GPS networks. Effective functionality in these circumstances means that human hours spent underground – often the most dangerous part of mining – can be kept to a minimum. The latest models from Sandvik can load, transport and empty materials completely unattended. As of 2018, Sandvik autonomous vehicles had clocked over 2 million hours without incident.

Larger players including Komatsu, Caterpillar and Hitachi are also exploring the role of autonomous vehicles for the mining sector, with Komatsu and Caterpillar launching a range of autonomous trucks, and Hitachi investing in research and development.

For heavy road transport, short-term efforts can focus on improving energy efficiency and increasing the use of biofuels, while technology progresses for zero-emissions solutions.

Technological development of electric and hydrogen small vehicles, and reduced battery prices, have stimulated interest from the heavy road transport subsector. Rapid growth of the electric vehicle industry is likely to reduce upfront costs for electric trucks and buses to below those of internal combustion engines, although further technological development and demonstration will be needed to stimulate uptake. Adoption of electrification for heavy and long-haul freight will also be determined by the deployment of fast-charging infrastructure or widespread uptake of autonomous driving. Hydrogen has also shown potential as a possible alternative fuel for freight (ETC, 2018) – and if produced using new renewable electricity, it can be a zero-emissions fuel.

Some 'drop-in'[51] biofuels can be used by existing freight vehicles as a replacement for diesel and other high-emissions fuels. They are a good temporary measure, as electrification and hydrogen solutions require new vehicles to be introduced to the market, and as such are dependent on the retirement of existing vehicle stock. Improved fuel efficiency of conventional vehicles also has a key role to play in the short term to curtail emissions growth while zero-emissions technologies are further developed.

Investment in RD&D will be required to progress zero-emissions technologies in non-road transport, likely to rely on electrification for short-haul, as well as biofuels, synfuels, ammonia and hydrogen for long-haul transport.

The shift from fossil fuels to bioenergy, synfuels, renewable hydrogen and ammonia will substantially reduce emissions in non-road transport. There are, however, uncertainties as to whether these zero-emissions fuels can be delivered cost-effectively at the scale required.

Electrification is also an option, especially for short-haul travel. While electric aviation is not modelled in *Decarbonisation Futures*, it appears likely that it will make some contribution to emissions reductions in air transport, at least in regional transport segments. Prototype aircraft are able to take nine passengers up to 1000 kilometres, with an electricity storage of 900 kilowatt hours (Eviation, 2018).

Optimising flight routes can deliver further reductions, particularly in non-CO_2 emissions (Timperley, 2017).

In shipping, liquid biofuels and electrification have the potential to reduce emissions. Electric ferries are already in operation to varying degrees in countries such as Norway, where the Hordaland county administration has committed €140 million to purchase a fleet of 20 all-electric ferries (Maritime impact, 2018). As Australia has mostly small watercraft, it is unlikely that ammonia and hydrogen will play a significant role as fuels, as they are more suited to heavy transport. Table 2.5 provides a summary of strategies and key solutions for transport emissions reductions.

51 Refers to chemically-identical substitutes for conventional fuels that do not require engine modification

BOX 2.5: AUSTRALIAN AIRLINE TRIALS SUSTAINABLE JET FUEL

Virgin Australia has run a sustainable aviation fuel trial at Brisbane Airport – making it one of a small number of airports in the world to be capable of deploying sustainable aviation fuel. Virgin Australia partnered with the Queensland government, US-based biofuel producer Gevo, Inc., Brisbane Airport Corporation, DB Schenker and Caltex to test the supply-chain readiness of these fuels in the Australian market.

The trial saw four isotainers of sustainable aviation fuel imported from the US to Queensland, where it was blended, certified as Jet A-1 fuel, transported to Brisbane Airport and used to fuel aircraft operating in and out of this port. During the trial, aircraft operating from Brisbane Airport flew over 1 million kilometres, and more than 700 domestic and international flights were supplied with sustainable fuel. The trial provided valuable insights into the logistics of supplying sustainable aviation fuel within current airport infrastructure.

Sustainable aviation fuel represents a significant opportunity to reduce aviation emissions in the medium term. This trial paves the way for the longer-term supply of sustainable aviation fuel to all airlines flying into Brisbane's international and domestic airports.

BOX 2.6: ELECTRIC SHORT-HAUL FLIGHTS REDUCE AIRCRAFT EMISSIONS

Electric and hybrid passenger aircraft are being trialled around the world (The Atlantic, 2019). Hybrid aircraft are targeting middle-distance flights of up to 1500 kilometres, using a mixture of conventional and electric power sources. Multiple companies are planning to launch hybrid aircraft for passenger transport in 2021. All-electric passenger aircraft are emerging, with Electro. Aero, an Australian company, operating the world's first commercial electric aircraft flight in 2018 (Electro.Aero, 2019). Israeli firm Eviation also launched a craft in July 2019 capable of carrying nine passengers 1000 kilometres. The aircraft is slated for public release in 2022.

Electric and hybrid aircraft are also being researched heavily by larger organisations, including Boeing, Airbus and Raytheon. The electric aircraft market is estimated to reach over US$22 billion in value by 2035. The successful transition of the industry to electric propulsion is reliant on improving battery storage capability.

Lithium-ion batteries have replaced traditional lead-acid batteries in laptops, phones and electric cars. But, for aircraft, advances are needed to improve energy storage to meet space and weight constraints. This is the primary barrier to the introduction of all-electric aircraft.

To address this challenge, Massachusetts Institute of Technology is exploring lithium-ion polymer, liquid-based batteries that hold double the energy of lithium-ion options of comparable size and weight.

Electric or hybrid aircraft also offer additional benefits. The Taurus G4, developed by Slovenian aircraft manufacturer Pipistrel, requires less runway length for take-off than its fuel-powered equivalent. Electric planes are also near silent, which allows them to fly and land closer to dwellings – an increase in flexibility that could improve aircraft flight paths. Large-scale improvements to flight path efficiency could also significantly reduce fuel consumption for the industry.

TABLE 2.5: Summary table of strategies and key solutions for transport emissions reductions

STRATEGY	KEY TECHNOLOGIES	STATUS	MOMENTUM
REDUCE ENERGY USE			
Reduce the demand for energy-intensive transport services	Mode shift	Mature	Over the period 2000-01 to 2015-16, rail passenger kilometres in Australia grew at twice the annual rate of road passenger kilometres (2.4% compared to 1.1%)[52].
	Business models and practices	Demonstration	New business models are emerging to decrease the demand for travel. For instance, retail giant Amazon's use of in-house logistics (often automated) and the location of warehouses close to demand centres, allows them to save substantially on transport costs (and embodied emissions)[53].
	Autonomous vehicles in passenger and freight transport	Emerging	While autonomous vehicles are not yet commonplace, large investments are being made into the technology globally[54]. GM's autonomous division Cruise Automation is now worth over US$19 billion[55], with investors valuing Uber's equivalent division at US$7.25 billion[56].
Improve the efficiency of road and non-road transportation	Vehicle design improvements, route optimisation, and improved fleet maintenance	Mature	The benefits of 'eco-driving' principles for road freight are gaining research attention[57], with companies like DHL including eco-driving in their emissions reduction strategies[58]. Freight load and route optimisation software is also becoming more mainstream, with demonstrated emissions reductions across several case studies[59]. Generally, global car fuel efficiency has improved by over 18% since 2005[60], and aviation fuel efficiency has recently improved at a rate of 2.9% per annum[61]. Recent studies have shown that airlines' climate impact can be reduced by up to 10% through route optimisation measures that only add cost increases of 1%[62].

52 Bureau of Infrastructure (2018)

53 Schreiber (2016)

54 Lutsey and Nicholas (2019)

55 Hawkins (2019)

56 Conger (2019)

57 Huang *et al* (2018)

58 Manibo (2015)

59 Li and Yu (2017)

60 IEA (2019b)

61 Scheffer (2019)

62 Grewe *et al* (2017)

SWITCH FROM FOSSIL FUELS TO LOW- OR ZERO-EMISSIONS ALTERNATIVES			
Electrify road transport (passenger and freight)	Battery-electric road vehicles (cars, motorcycles, and buses)	Demonstration	Technology advances and expansion of production are driving significant cost reductions for electric vehicles. The number of models available to consumers has increased steadily in recent years, and over 20 manufacturers have an electrification strategy. For example[63]: + Ford: 40 new electric vehicle models by 2022 + Toyota: 1 million electric vehicle sales by 2025 + Infiniti: All models electric by 2021 + Volvo: 50% of vehicle sales to be electric by 2025. Bloomberg New Energy Finance has projected that over 500 million electric cars will be sold cumulatively by 2040[64], and the IEA more than doubled its previous estimate of global electric vehicle sales[65].
	Hydrogen fuel cell and electric vehicles for heavy and long-haul road freight	Demonstration	Testing of hydrogen freight trucks is planned for long-distance routes in Canada[66]. Several manufacturers are leading the low-emissions freight movement, including Toyota and Kenworth with their jointly developed fuel cell electric heavy-duty trucks[67] launched in 2019. Manufacturer Nikola Motor specialises in the development of electric and fuel cell heavy freight vehicles, with three models currently available[68].
Pursue alternative fuel use in aviation, water transport and rail	Bioenergy	Demonstration	In the past few years, several airlines have successfully demonstrated 100% biofuel-powered flights, including Qantas[69], India's SpiceJet[70] and Finland's Finnair[71]. Five biofuel blends have been approved by the ICAO, and one is commercially available at a small number of locations worldwide including Brisbane airport[72].

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63 IEA(2019c)

64 BNEF(2019)

65 ClimateWorks Australia (2018a)

66 Tabak (2019)

67 Toyota Newsroom (2019)

68 Nikola Motor Company (2019)

69 Qantas News Room (2018)

70 The Economic Times (2018)

71 Biofuels International (2019)

72 Le Feuvre (2019)

Pursue alternative fuel use in aviation, water transport and rail (cont.)	Renewable hydrogen	Emerging	Several companies are investigating the use of hydrogen in aviation. ZeroAvia and Alaka'i have produced prototype hydrogen-powered small aircraft[73 74], and NASA recently committed US$6 million to developing more advanced hydrogen-electric hybrid technology for aircraft[75].
	Renewable ammonia	Emerging	Ammonia has attracted attention as a key low-carbon fuel in shipping, given the relative ease of retrofitting existing shipping fleets[76]. It is already being investigated by major companies including Maersk[77].
	Electricity (rail freight)	Demonstration	Electric locomotives are readily available, but require electrified rail lines. Hybrid-electric[78] and hydrogen-powered trains that avoid the need for electrified lines are under development, being demonstrated in Germany[79] and the UK[80], with feasibility studies showing promise for multiple applications across Europe[81].
	Electricity (other short-haul applications)	Emerging	One- and two-person electric plane designs are already on the market in very limited numbers[82], and 2019 saw other small aircraft pass several key testing milestones[83]. Airbus plans to start test flights of their electric 100-seater E-Fan X planes in 2020[84](Biofuels International, 2019) and the ICAO is monitoring developments as they work towards creating new standards for electric aircraft[85]. Electric ferries are also gaining momentum, with the record-breaking 60-metre electric ferry, Ellen, completing its maiden journey in Denmark in 2019[86], and a Norwegian local authority recently committing to purchase a fleet of 20 all-electric ferries[87].

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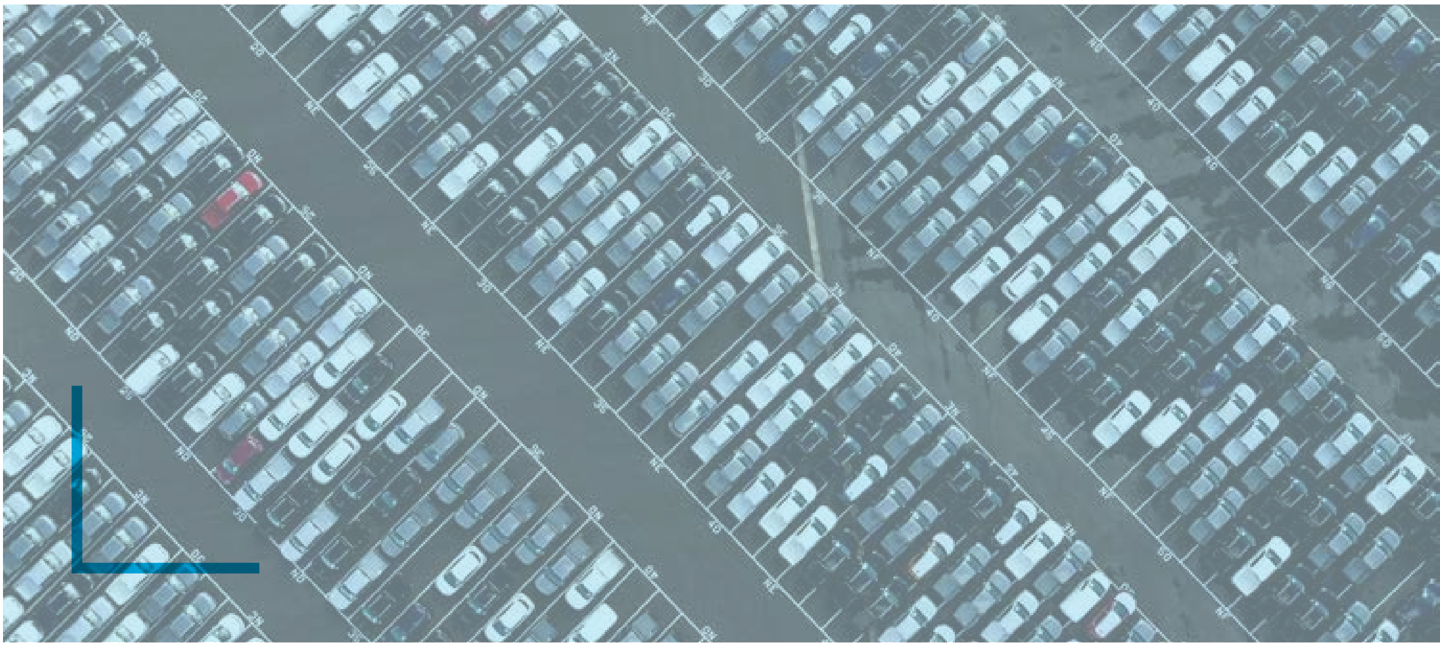
73 ZeroAvia (2017)
74 Alaka'i Technologies (2019)
75 NASA (2019)
76 ETC (2018)
77 Wienberg (2019)
78 Noon (2018)
79 France-Prese (2018)
80 Parkinson (2019)
81 Ruf *et al* (2019)
82 ICAO Secretariat (2019)
83 Deutsche Welle (2019)
84 Airbus (2018)
85 International Civil Aviation Organization (2019)
86 Lambert (2019)
87 Maritime impact (2018)

Establish alternative fuel supply	Bioenergy (first generation)	Mature	Biofuel-blended fuels are available in most jurisdictions, mainly as the result of biofuel mandates. There is limited scope for significant scale-up given the environmental trade-offs associated with production from current sources.
	Bioenergy (second and third generation)	Emerging	Future supply of biofuels is emerging from feedstocks with no significant impact on agricultural production. In Australia, Licella's Advanced Drop-In Fuels project[88] and Northern Oil's Advanced Biofuels Laboratory[89] are working on the production of biocrude and subsequent refinement into usable fuels respectively.
	Renewable hydrogen	Emerging	The Australian government has a working group to develop a national hydrogen strategy for completion by the end of 2019[90], and the Asian Renewable Energy Hub project includes up to 15 gigawatts of renewable generation in the Pilbara, Western Australia. This will be largely dedicated to the large-scale production of green hydrogen products[91].
	Renewable ammonia	Emerging	A commercial-scale ammonia plant with a production capacity of 50 tonnes per day and an electrolyser capacity of 30 megawatts is being built in Port Lincoln, South Australia. It is powered by renewables[92].



88 Licella (2019)

89 Southern Oil (2019)

90 Department of Industry (2019a)

91 Asian Renewable Energy Hub (2019)

92 Government of South Australia (2019)

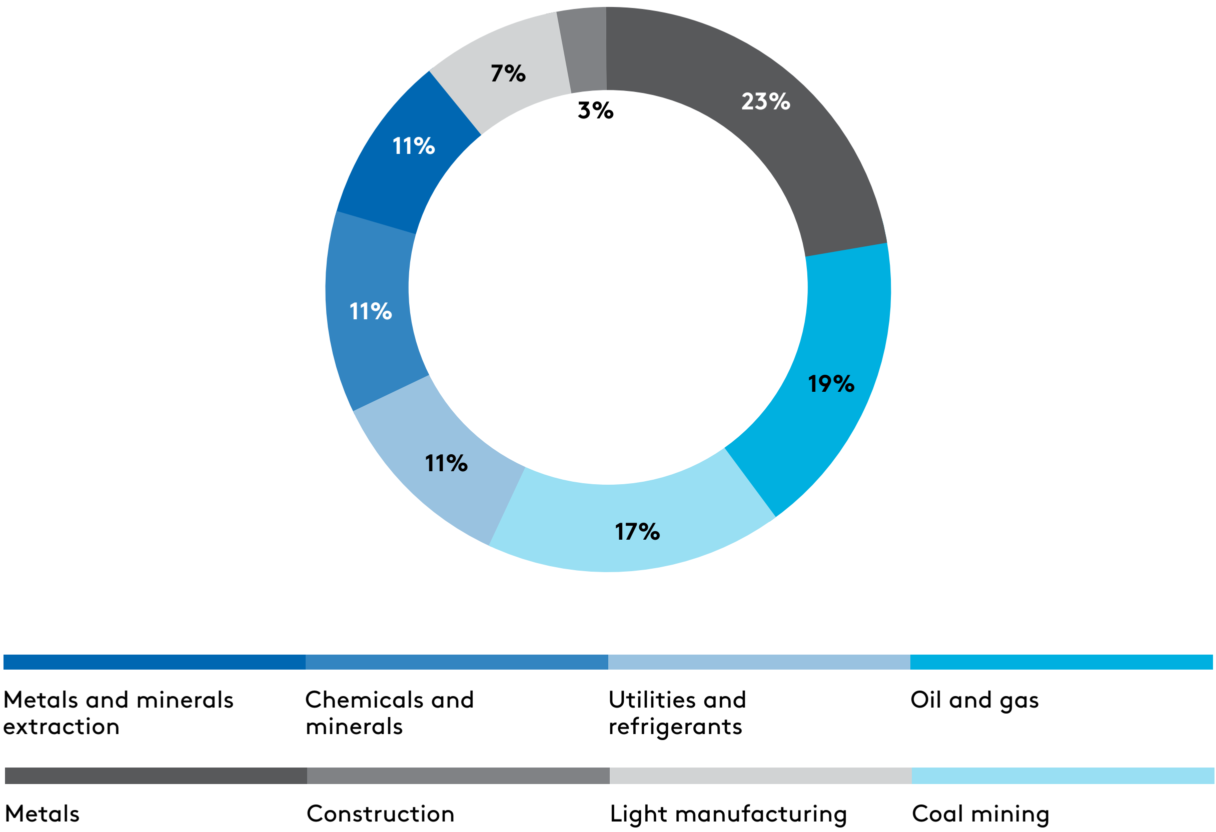
2.4 INDUSTRY

Industry produces nearly half of Australia's emissions, with a significant proportion from non-energy sources.

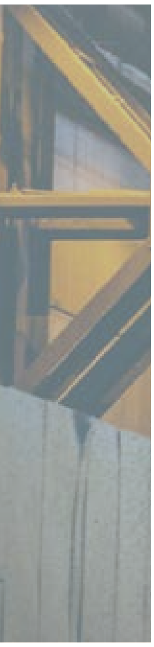
The industry sector includes mining, manufacturing and construction operations. It is currently responsible for over 40% of Australia's annual emissions when electricity use is included (ClimateWorks Australia, 2018b).

The largest industrial sectors by emissions are metals manufacturing, chemicals, coal mining, gas extraction and LNG production (Figure 2.9). Most industrial emissions result from electricity or direct fuel consumption to power process heating, material handling, and compression equipment in oil and gas operations, as well as electric motors, pumping and ventilation systems, fans and blowers, and compressed air systems (Campey *et al*, 2017). Electricity emissions are a significant component in many industry subsectors, such as aluminium and light manufacturing, so are heavily influenced by the emissions intensity of the grid.

FIGURE 2.9: Australia's industry emissions shares by subsector (2018)

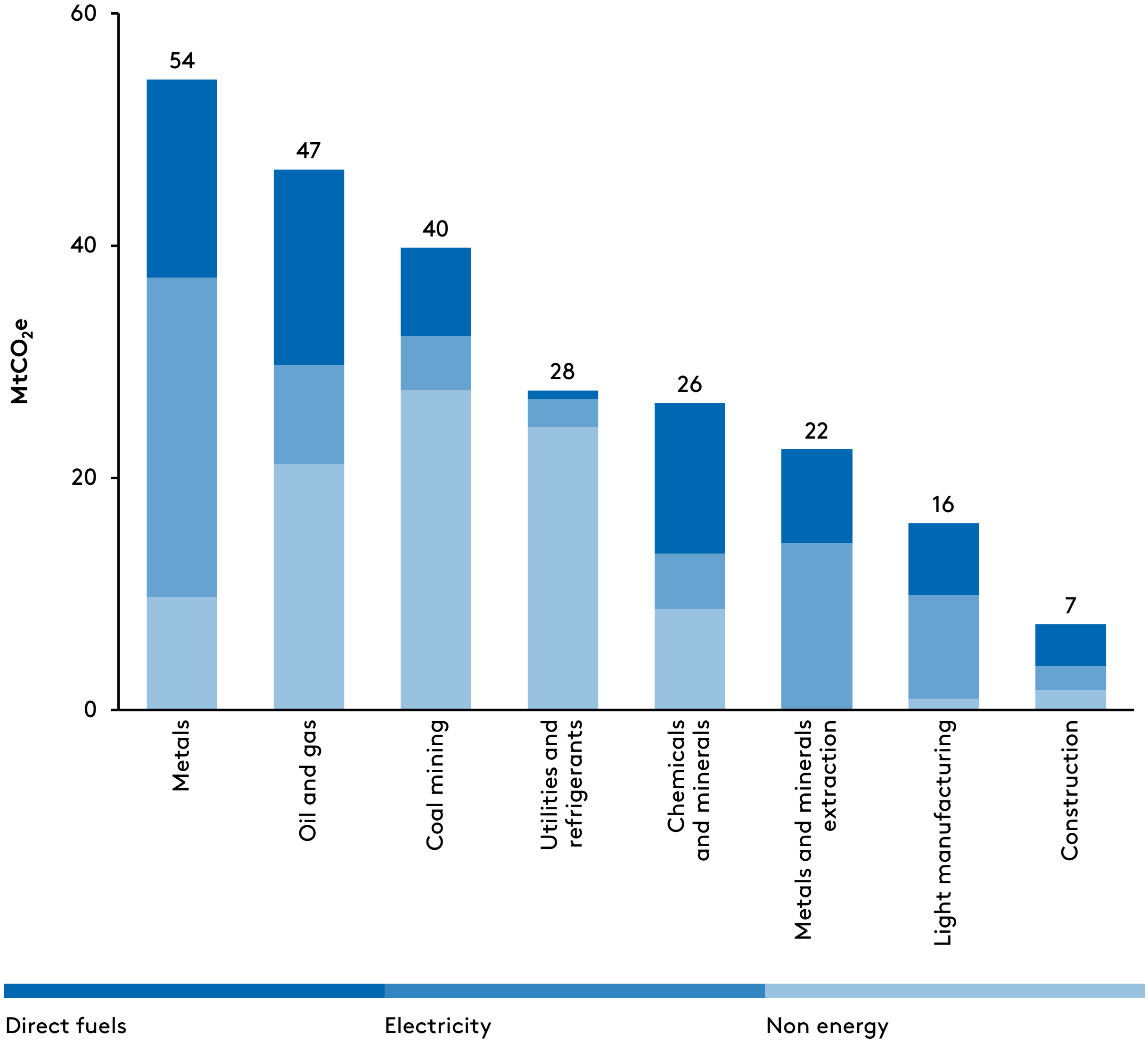


Source: ClimateWorks Australia analysis[93] using DoEE (2018b; 2019d). Note: Numbers may not add up due to rounding



93 Note: Exact emissions shares by subsector may differ slightly to those published in Australia's National Greenhouse Gas Inventory due to different emissions accounting treatment and allocation.

FIGURE 2.10: Industry emissions by subsector and emissions type (2018)



Source: ClimateWorks Australia analysis[94] using DoEE (2018b; 2019d)

Just under half of all emissions in industry are from non-energy sources. This differs from other sectors such as buildings and transport, where emissions are entirely the result of direct fuel and electricity consumption. Some of the most significant sources of non-energy emissions for industry are fugitive emissions[95] from mining, and process emissions[96] during the manufacturing of heavy metals and materials (Figure 2.10).

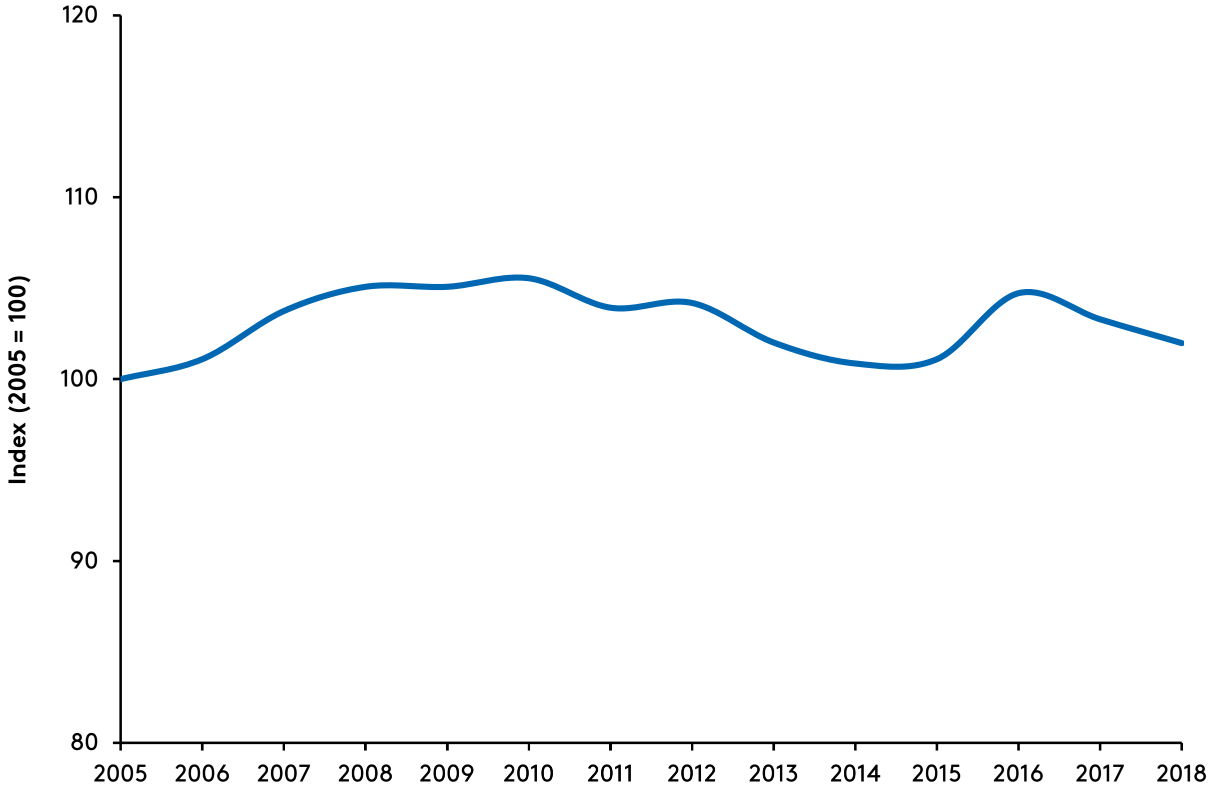
While process emissions are generally directly proportional to production activity, fugitive emissions can be more difficult to track and abate. This is because they may be the result of leaks or other unintended releases of gas from industrial operations, often within large transmission and distribution systems.

94 Note: Exact emissions shares by subsector may differ slightly to those published in Australia's National Greenhouse Gas Inventory due to different emissions accounting treatment and allocation.

95 Emissions from the extraction, production, flaring, processing and distribution of fossil fuels (DoEE, 2019e).

96 Emissions generated during the conversion of raw materials into industrial products such as iron and steel, cement and fertilisers. This also includes the production and use of synthetic gases in refrigeration and air-conditioning (DoEE, 2019e; CCA 2016).

FIGURE 2.11: Australia's annual industry emissions trend (2005-2018)

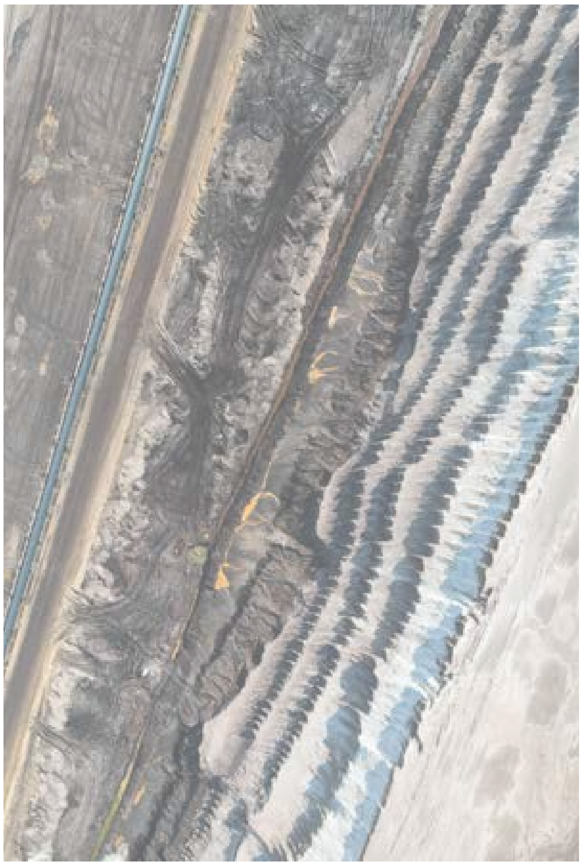


Source: ClimateWorks Australia analysis using DoEE (2018b; 2019d)

In the past decade, emissions from industry have fluctuated but increased overall (Figure 2.11). This is because the growth in industrial activity has outpaced reductions in emissions intensity of industrial processes (ClimateWorks Australia, 2018b), leading to increased energy and non-energy emissions (DoEE, 2018a). This has been partially offset by a shift to less emissions-intensive energy – with gas use growing strongly as coal use declines.

This shift has been driven by increased production of LNG and decreased demand for coking coal in primary iron and steel production. Non-energy emissions intensity has also shown promising improvements (ClimateWorks Australia, 2018b), but without further improvements in energy and emissions intensity, sector production growth will continue to drive increases in overall emissions.

The diversity of production processes and high proportion of non-energy emissions makes industry one of the most challenging sectors of the economy to decarbonise. Current emissions trajectories show that significant improvement is required, which will involve a wider range of solutions than in other sectors.



The technological and commercial readiness of industry emissions-reduction opportunities varies greatly by subsector, but there are opportunities to improve energy efficiency across the sector.

Emissions from industry result from a diverse variety of processes and require a range of solutions. Broadly, solutions fall into the following categories: reducing energy use of emissions-intensive materials; shifting from fossil fuels to low- or zero-emissions alternatives; and implementing targeted solutions for reducing non-energy emissions. Some solutions, such as measures of energy efficiency, are mature and ready to implement.

Across most industrial subsectors, strong energy-efficiency improvements can be achieved for equipment such as electric motors and fluid or material handling systems. Behaviour change and process redesign can also enhance process productivity.

For example, the use of more efficient, high-pressure grinding rolls in the crushing and grinding processes of mining can unlock direct energy savings, and indirect savings through avoiding energy use to transport materials (CEEC, 2019a). Many of these energy-efficiency solutions are mature, with successful examples of implementation. There has been recent momentum, however, around additional productivity solutions including automation and artificial intelligence (Industry 4.0[97]). Some of the more established applications include the use of automated vehicles in mining and the deployment of artificial intelligence for process optimisation.

Transitioning demand towards materials with lower emissions intensity and implementing circular economy principles can reduce industry's reliance on emissions-intensive processes.

Material efficiency, substitution and recycling allow industries to meet demand for products without relying on energy- or emissions-intensive primary processing. For example, high levels of recovery and recycling – a very mature process – could reduce or eliminate the need to mine virgin metals (Denis-Ryan *et al*, 2016). Recent examples have showcased the potential for multi-storey timber buildings ('Australia's tallest engineered timber office building opens', 2018) to replace steel and concrete structures, which would reduce emissions from steel and cement production.

There is also a growing role for emerging technologies such as 3D printing in manufacturing processes, with some manufacturers using 3D printing to produce jet engine parts (Kover, 2019). Overall, the reduction of demand for emissions-intensive materials could reduce global industrial emissions by about 40% in the highest-emitting sectors (ETC, 2018).

97 Industry 4.0 (or the Fourth Industrial Revolution) refers to current transformations in industry that are expected to deliver improvements in productivity and flexibility through increased adoption of automation, artificial intelligence and other data-driven technologies (Department of Industry, Innovation and Science, 2018).

BOX 2.7: POTENTIAL BENEFITS OF CIRCULAR ECONOMY PRINCIPLES

A circular economy aims to eliminate waste and to keep resources in a continually flowing loop, using products and materials multiple times through reuse and recycling. It seeks to close industrial loops, turning outputs from one manufacturer into inputs for another. This reduces the need to manufacture or mine raw materials. Circular economy principles aim to maximise value at each point in a product's life and can be applied to a range of sectors. Close the Loop is a Melbourne-based initiative providing the world's largest take-back scheme for ink and toner cartridges. The materials are reused to create an asphalt alternative, moving recycled materials into industrial supply chains. With the announcement of e-waste being banned from landfill in Victoria, recovery and reuse of valuable materials common to the industrial sector is being encouraged.

A circular economy is a shift from the current predominantly linear approach, where products are created and used for a single purpose, and then thrown away. New South Wales recently launched 'NSW Circular', an innovation network focused on reducing landfill and recycling resources. Victoria released a circular economy policy in 2020.

Circular economy principles were officially adopted by China in 2002, and legislated as a national endeavour. An example of effective change from legislative support is the proliferation of scavenger and decomposer companies, which profit from turning waste into reusable organic matter, plastic and metals. The Chinese government supports these types of companies through preferential industrial recruitment and financial policies, such as land subsidies and tax incentives.

Wider use of electrical machinery will reduce industry emissions as the electricity grid decarbonises.

Opportunities for electrification are particularly prevalent for material handling of commodities and process heating activities. One example of a well-established electrical process is the electric arc furnace in steelmaking (Commonwealth of Australia, 2017), which heats charged material using an electric arc. Momentum is building behind several other solutions, including electrified mining equipment and heat pumps for industrial heating. There are also opportunities for industry to further develop technologies such as electric compression turbines for LNG liquefaction.

BOX 2.8: 3D PRINTING TECHNOLOGY INCREASES MANUFACTURING ENERGY EFFICIENCY

3D printing, also known as additive manufacturing, builds three-dimensional objects from computer-aided design (CAD) models, successively adding to the product layer by layer. This removes the need for the moulds or casts used in traditional manufacturing. Potential energy savings from 3D printing have been predicted to reach 5-27% of current costs for the global manufacturing industry by 2050.

Titomic, an Australian company, has collaborated with CSIRO to develop technology for large-scale metal 3D printing, and has used it to create ultra-lightweight titanium parts. Using only the material needed to create the part, the process is more efficient and cost-effective than traditional methods.

In 2019, Titomic developed the world's largest 3D-printed drone, with a 1.8 metre diameter. Additive manufacturing creates a lighter and higher performing drone, as added complexity in the model does not necessarily require additional weight (Carlota, 2019). A proprietary cold-gas spraying process developed by Titomic allows for unusual combinations of metals to create strong structures, without the need for energy-intensive melting processes.

Many of the above actions can also lead to reductions in non-energy emissions for the sector. Further targeted solutions to reduce process and fugitive emissions could be developed and deployed.

For instance, metallurgical coal can be substituted with bio-coke in steelmaking, or renewable hydrogen can be used to produce direct-reduced iron to supplement electric arc furnace steel production. Emission-reducing catalysts are also available for the chemical-manufacturing industry, and geopolymer cements can act as a low-emissions alternative to traditional cement. Improved operational practices around venting and flaring can be implemented to manage fugitive emissions in oil and gas production. Opportunities exist to capture methane from landfill and waste-processing facilities, producing heat and electricity in the process.

Transitioning to natural refrigerants will also offer significant emissions-reduction opportunities.

Technologies that require more development include the substitution of carbon anodes with inert anodes in aluminium production, and ventilation air methane oxidation[98] in coal mining. Finally, capture and storage of carbon can be used where specific solutions do not completely eliminate emissions. This technology is particularly suitable for processes where CO_2 emissions are separated from other outputs in the production process, such as LNG or chemical production. Table 2.6 provides a summary of strategies and key solutions for industry emissions reductions.

Australia is well placed to be a key player in a global low-carbon industry.

Changes to the competitive landscape during global decarbonisation are likely to favour Australia, a nation with abundant renewable energy resources such as solar and wind, as well as the land and rooftop space to harness these resources (CSIRO, 2019). A shift to low-carbon supply chains will require substantial global production of new electricity and other low-carbon industry inputs such as hydrogen, ammonia and synthetic fuels, which may present new export opportunities for Australia. The potential size and benefits of these emerging markets, particularly hydrogen, have been explored in multiple recent studies (ACIL Allen Consulting for ARENA, 2018; Bruce *et al*, 2018; Garnaut, 2019; Ueckerdt *et al*, 2019).

There are substantial uncertainties about the degree to which Australian industry can capture the opportunities associated with a global transition to net zero emissions. Understanding these factors will require the formation of new alliances of parties interested in planning for the transition, across and between industrial supply chains that do not currently exist.

98 Refers to the capture and use of methane gas during the mining of coal deposits, rather than allowing it to be released into the atmosphere.

BOX 2.9: HYDROGEN A VIABLE ALTERNATIVE FOR COMBUSTION-FUEL APPLICATIONS

Some industrial applications that require combustible fuel – such as blast-furnace steel production – can be difficult to address through direct electrification. Hydrogen can fulfil this need, as it provides high-grade heat and can be made with renewable energy. Both gas and coal can produce hydrogen, but through an intensive extraction processes. Renewable hydrogen is generated through electrolysis – running currents from wind and solar through water to split it into hydrogen and oxygen. As wind, solar and electrolysis machinery declines in cost, renewable hydrogen is expected to become cost-effective compared to hydrogen from fossil fuel sources (Staffell *et al*, 2019).

South Australia recently announced its goal to have a 100% renewable hydrogen economy. New projects have been greenlighted for funding. One example is the Crystal Brook Energy Park, which is projected to generate 125 megawatts of wind power, 150 megawatts of solar PV, 400 megawatt hours of battery storage, and 50 megawatts of hydrogen (up to 25,000 kilograms per day).

While Australia has ample opportunity to leverage its natural assets and increase hydrogen use, a barrier for worldwide adoption is the cost of transportation. Countries with the largest markets – such as Japan, South Korea, China and Singapore – have fewer natural resources to generate hydrogen themselves and are likely to rely on imports.

TABLE 2.6: Summary table of strategies and key solutions for industry emissions reductions

STRATEGY	KEY TECHNOLOGIES	STATUS	MOMENTUM
REDUCE ENERGY USE			
Improve the efficiency of extracting and producing materials	Behaviour change, process design and controls, and equipment improvements	Mature	The Coalition for Energy Efficient Comminution has successfully propagated more efficient crushing and grinding practices in Australia and worldwide. For example, they partnered with Newmont to improve crusher throughput by 25% at the Boddington mine in Western Australia[99]. A range of other solutions are available for different stages of the mining process, ranging from novel drilling processes to more efficient trucks and high-pressure grinding technology[100].
	Artificial intelligence and automation	Demonstration	Although Industry 4.0[101] is not yet widespread, some subsectors of Australian industry are benefitting from this approach. For example, driverless trucks have been operating in Australian mines for over a decade, moving more than 1 billion tonnes of material during that time[102].

99 CEEC (2019b)

100 Awuah-Offei (2018)

101 See footnote 97

102 Rio Tinto (2018)

Transition demand towards materials with lower energy intensity, and implement circular economy principles	Metal recycling	Mature	Australia currently recovers 90% of its metals for recycling[103], including 4.9 million tonnes of steel per year[104]. Much of this scrap is exported, but there are significant opportunities for Australia to build a circular economy by using scrap for domestic production[105]. Globally, demand for recycled metals is predicted to grow by between US$64 and $85 billion by 2025[106].
	Plastic recycling	Mature	Australia's plastic recovery rates have significant room for improvement, with just 11.8% of plastic waste recycled in 2016-17[107]. In 2018, federal and state environment ministers agreed to increase Australia's plastic recycling capacity, and endorsed a target of 100% recyclable plastic packaging by 2025[108].
	Timber buildings (residential)	Mature	In recent years, public buildings such as Melbourne's Library at The Dock[109] and Brisbane's 10-storey 25 King office tower[110] have showcased the structural capabilities of cross-laminated timber. Australia's high-strength timber construction capacity is ramping up, with Hyne Timber currently building a new glue-laminated timber plant in Queensland[111].
	Timber buildings (low- to medium-rise)	Demonstration	
	Timber buildings (high-rise)	Emerging	
	3D printing	Demonstration	The market for 3D printers has more than doubled in the past five years[112], and this trend is expected to continue. The software to run and manage 3D printing workflows is improving, and investment and development of materials is on the rise[113].

103 Picken *et al* (2018)

104 Australian Steel Stewardship Forum (2019)

105 Golev and Corder (2016)

106 Global Market Insights (2019)

107 O'Farrell (2018)

108 Seventh Meeting of Environment Ministers (2018)

109 City of Melbourne (2018)

110 'Australia's tallest engineered timber office building opens' (2018)

111 Hyne Timber (2019)

112 Statista (2019)

113 Jackson (2019)

SWITCH FROM FOSSIL FUELS TO LOW- OR ZERO-EMISSIONS ALTERNATIVES			
Electrify the extraction, processing and transportation of energy and mineral commodities	Electrification of mines (conveyors)	Mature	A growing number of mining operators are reaping the benefits of electric equipment. Rio Tinto's new Silvergrass mine in Western Australia includes a nine-kilometre-long ore conveyor system[114], and BHP has rolled out electric Land Cruisers at the Olympic Dam site in South Australia[115].
	Electrification of mines (vehicles)	Demonstration	Electric mining technology is improving. In 2019, Caterpillar launched the R1700 XE electric loader in response to demand from global underground mine operators for cleaner, more efficient machinery[116]. Anglo American and Engie have announced a partnership to develop a hydrogen-powered mining haul truck[117].
	Electric compressing turbines for LNG liquefaction	Emerging	Electric compressing turbines for LNG liquefaction are rapidly improving – current all-electric liquefaction systems can be 40% more efficient than gas-driven systems, with half the operating expenditure[118]. In 2018, GE tested a record-breaking 80 megawatt induction motor for the LNG industry, which can reach efficiencies of up to 98%, and could replace groups of smaller gas turbine motors[119].
Electrify manufacturing processes	Industrial heat pumps	Demonstration	While relatively new to the global market[120], industrial heat pumps are gaining traction as a viable and efficient alternative to gas for many low- and medium-heat applications[121]. Case studies from the food industry have highlighted the benefits this technology offers to businesses[122].
	Electric arc furnace in iron and steel production	Mature	Over 25% of Australia's steel is produced from scrap using electric arc furnace processes. These facilities operate at a capacity utilisation rate of 97% –98% higher than the global average[123]. Combined with a high scrap-recovery rate, this positions Australia well to increase the share of electric arc furnace steelmaking in our supply chains.

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114 International Mining (2017)

115 Stringer (2018)

116 Australian Mining (2019)

117 Engie (2019)

118 ABB Group (2006)

119 LNG World News (2018)

120 IEA (2014)

121 ARENA (2015)

122 Jutsen, Pears and Hutton (2017)

123 Commonwealth of Australia (2017)

Switch from fossil fuels to renewable sources for industrial heat	Bioenergy, solar thermal	Demonstration	A recent catalogue of bioenergy activities in Australia found over 57 active industrial bioenergy plants with over 22 additional projects at the feasibility stage or under construction[124]. Examples include an integrated waste-to-biogas system which produces heat and electricity at the RichGro site at Jandakot WA, and a grape-marc-fuelled biomass boiler at an Australian Tartaric Products facility in Victoria[125]. Due primarily to high technology costs, solar thermal energy generation in Australia is currently in the early stages of development, with one large-scale plant used to preheat feedwater for the Liddell coal-fired power station in NSW. If future technology costs continue to fall, solar thermal could play a key role in providing dispatchable energy supply to Australian industrial sectors[126].
	Geothermal, hydrogen	Emerging	Geothermal energy could be suitable for low-heat requirements in industry, and is currently most commonly used in food dehydration[127]. Currently, there are no major demonstrations of using hydrogen to generate industrial heat, although opportunities may emerge to compete with gas, particularly in certain industrial clusters or near hydrogen pipelines[128].
REDUCE NON-ENERGY EMISSIONS			
Transition demand towards materials with lower process emissions, and implement circular economy principles	Geopolymer cement	Demonstration	The consumer demand for low carbon products[129] and practical advantages to traditional concrete, have led some analysts to predict rapid growth in the geopolymer cement market[130]. Geopolymer cement is key to decarbonising the cement industry, and has been used for paving at Brisbane's West Wellcamp Airport[131] and precast panels at the Melton Library in Victoria[132]
	Metal recycling, timber buildings (reducing demand for iron and steel): As above		

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124 KPMG (2018)

125 ARENA (2019f)

126 Clean Energy Council (2018)

127 EIA (2019)

128 IEA (2019c)

129 Van Deventer et al (2012)

130 BCC Research (2018)

131 Wagners (2011)

132 Aurora Construction Materials (2014)

Switch to low-emissions alternatives in iron and steel production	Bio-coke	Emerging	CSIRO and key industry stakeholders in Australia are becoming established as global leaders in the research and development of bio-coke, already demonstrating that large percentages of bio-coke can be used in steelmaking without substantial process redesign[133].
	Direct-reduced iron (using hydrogen)	Demonstration	Global production of direct-reduced, iron-based steel increased by 130% between 2000 and 2018, including a jump from 87 megatonnes per year in 2017 to 100 megatonnes per year in 2018[134]. By 2030, the hydrogen demand from direct-reduced iron processes could more than double compared to current levels[135].
Reduce emissions intensity in the production of other materials and products	Catalysts for chemicals	Demonstration	Catalytic emissions-reduction technology is becoming increasingly accessible to businesses. For example, IPL have reduced the nitrous oxide intensity of nitric acid production by 35% between 2015-2018 using catalyst technology[136]. Orica has also implemented successful trials of similar technology at the Kooragang Island plant, with a view to investing in the technology across other assets[137].
	Inert anodes for aluminium	Emerging	Momentum is growing to develop inert-anode technology to a commercially viable level. Research and development is currently focused on the selection of ideal inert-anode materials from a range of options, and the most effective design of reduction cells[138].
	Ventilation air methane oxidation in coal mining	Demonstration	BHP Billiton pioneered ventilation air methane oxidation in Australia with the WestVAMP project[139]. Other operators have since started trialling this innovative technique, including Centennial Coal's Mandalong Coal Mine[140]. Progress is also being made globally. Gaohe coal mine in Shanxi, China recently implemented the world's largest ventilation air methane oxidation system, designed to avoid 1.4 $MtCO_2e$ of emissions per year[141].
Capture and store remaining carbon	Carbon capture and storage (CCS)	Demonstration	In 2019, the world's largest CO_2 injection project started operating at the Gorgon gas processing plant in Western Australia. This CCS project aims to reduce the Gorgon project's overall emissions by 40%, by capturing and storing up to 4 $MtCO_2e$ per year[142].

133 Mathieson *et al* (2015)

134 Midrex (2018)

135 IEA (2019c)

136 Incitec Pivot Limited (2019)

137 ORICA (2018)

138 Sai Krishna *et al* (2018)

139 Hall (2007)

140 Centennial Coal (2014)

141 Dürr Systems Inc (2015)

142 Chevron (2013)

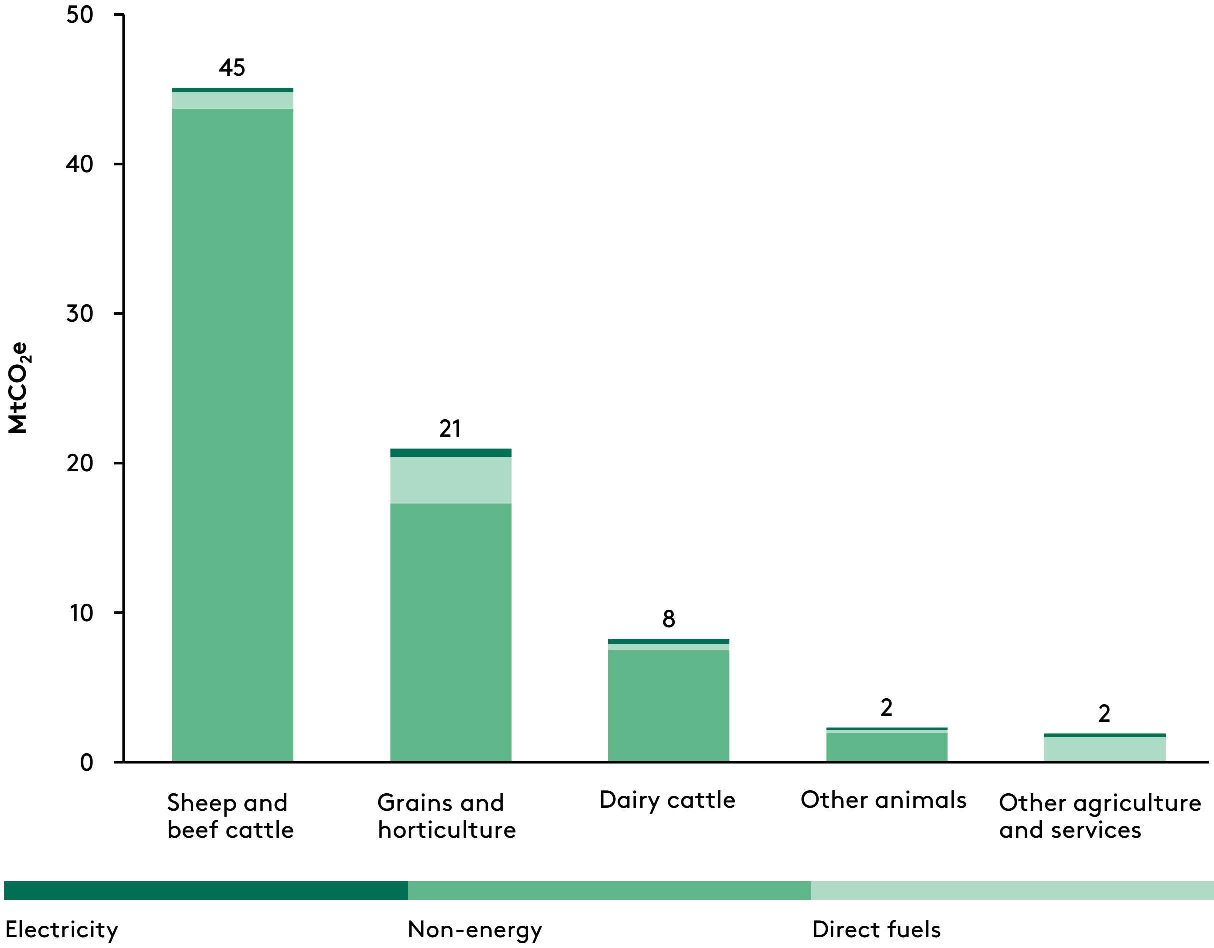
2.5 AGRICULTURE AND LAND

The majority of agriculture and land emissions come from livestock, which means non-energy emissions solutions are key for this sector, as shown in Table 2.7 at the end of this section.

The agriculture and land sector includes beef and dairy cattle, other animal stock such as sheep and lambs, grain production, horticulture and other agricultural services. The majority of emissions from this sector come from non-energy sources, such as methane from livestock, with a marginal contribution from direct fuels and electricity use (Figure 2.12).

Emissions also come from land use, land use change and forestry (LULUCF) – in essence, the transformation of the natural landscape by human activity. This makes agriculture and land different to other sectors in Australia's economy, as energy efficiency and fuel switching will have a less significant impact than innovations that directly address non-energy emissions reductions. For this reason, agriculture and land emissions are likely to contribute an increasing proportion of Australia's residual emissions as other sectors reduce emissions. Currently, emissions from agriculture and land account for around 15% of Australia's total emissions, or around 12% when accounting for LULUCF (DoEE, 2018b; DoEE, 2019f).

FIGURE 2.12: Agriculture emissions by subsector and emissions type (2018)



Source: ClimateWorks Australia analysis[143] using DoEE (2018b; 2019d)

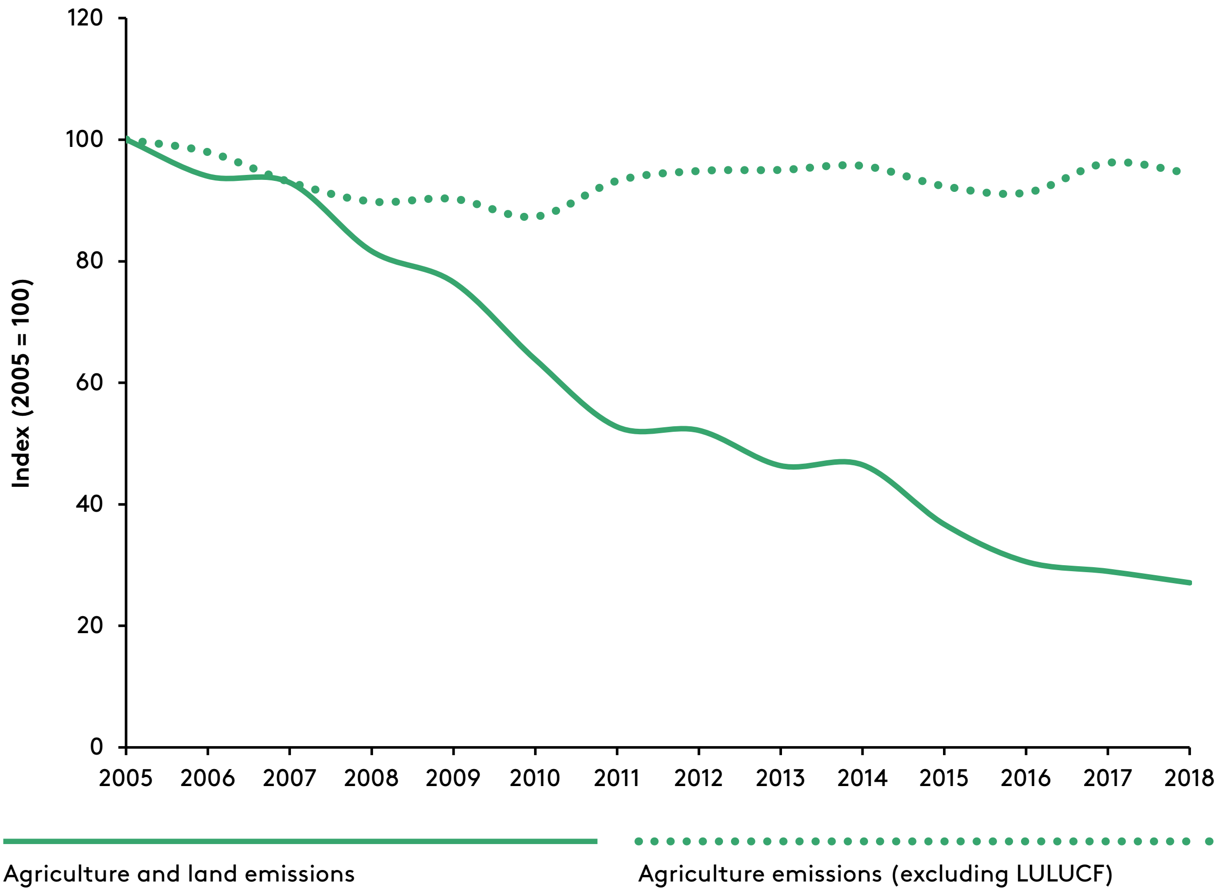
143 Note: Exact emissions shares by subsector may differ slightly to those published in Australia's National Greenhouse Gas Inventory due to different emissions accounting treatment and allocation.

In recent years, average non-energy emissions intensity across the agriculture and land sector has decreased rapidly. This is primarily due to strong reductions in LULUCF emissions, mostly driven by reduced rates of deforestation. Livestock emissions have fluctuated with animal numbers, with emissions per head of livestock remaining relatively constant.

As a result, emissions from agricultural subsectors (excluding LULUCF) have seen little change since 2005 (Figure 2.13). In the past year, agricultural emissions decreased significantly – by 5.9% – due to impacts of drought across much of the country, as well as floods in Queensland (DoEE, 2019f). The impact of the 2019-20 Australian bushfires on domestic emissions accounts are yet to be formally assessed.

Current Federal Government emissions projections anticipate, however, an increase in agricultural emissions to 2030 due to a return to average levels of production to meet growing global and domestic demand.

FIGURE 2.13: Australia's annual agriculture and land emissions trend (2005-2018)



Source: DoEE, 2019d

Sustainable agricultural practices can be implemented today to reduce emissions, while more investment in RD&D will be required to develop solutions for zero-emissions meat and dairy products.

Reducing non-energy emissions, particularly from livestock for meat and dairy production, will have the greatest impact on overall agricultural emissions. However, other subsectors (like grains and cropping) can also reduce emissions through improved practices and the implementation of known, viable solutions. Furthermore, solutions such as precision agriculture and efficient irrigation can help reduce emissions and energy use and improve productivity.

Livestock's most significant emission is methane. Enteric fermentation – the digestive process by which carbohydrates are broken down for absorption – causes high levels of methane emissions from ruminant animals such as cattle and sheep. Emissions from enteric fermentation can be combated with vaccinations, feed supplements and genetic improvements (selecting livestock based on the genetic trait of lower methane emissions). This suite of solutions could almost eliminate methane from livestock digestive processes, but depends on further research, development and commercial demonstration. In particular, for extensive production, new delivery mechanisms are needed to get feed and vaccine products to animals. Emerging technologies such as drones could potentially address these issues.

An alternative solution involves a shift from cattle farming to the laboratory production of meat. Significant advances have been made in this domain (Linnane, 2019), but cost reductions are needed to make laboratory production a viable option. Emissions from agriculture can also be reduced through decreasing the demand for emissions-intensive products such as beef and dairy. Increased awareness of the environmental impacts of diet could influence eating habits. In other sources of red meat, such as kangaroos, enteric fermentation is up to 80% lower per kilogram than beef. Poultry and pork also offer lower-emissions meat alternatives, and other sources of protein are emerging, such as insects or plant-based meat alternatives.

BOX 2.10: THE CHANGING NATURE OF LIVESTOCK EMISSIONS

The digestive process of livestock generates large amounts of methane. Methane traps up to 25 times more heat in the atmosphere than CO_2. The New Zealand Agricultural Greenhouse Gas Research Centre is currently developing a prototype vaccine that aims to reduce methane emissions from both cattle and sheep by 20%. Rumen, the first part of a cow's stomach, hosts a huge number of microbes. Approximately 3% of these are methane-producing methanogens. Once the vaccine is ingested, the animal's immune system attacks these methanogens.

Livestock emissions can also be reduced by using chemical inhibitors that make methanogens inactive. European advances have identified potential inhibitors, but they are based on entirely dry diets (grains). Research specific to Australia and New Zealand context is required, as livestock here is raised primarily in pastures (wet diet). New Zealand researchers are attempting to isolate the chemicals that will work best for animals raised in pastures or on a mixed wet and dry diet.

Some of the variation in the methane output of livestock is due to their genetic makeup. In the United Kingdom, selective breeding programs have been in place for over two decades, successfully reducing the environmental footprint of milk and meat production by 20%. The reduction of methane production could be added as a goal of these programs. Another option involves changing the diet of animals. The amount of methane produced by cows has a correlation to the amount of fibre in their diet. Adding legumes, linseed and soy can reduce methane production. Pilot programs have also introduced seaweed to cattle diets to reduce methane production (Koreis, 2019).

Unlike anti-methanogenic treatments for cattle, emissions-reduction solutions for the grain and cropping subsector do not require extensive research and development. For example, emissions from grain and cropping can be reduced through improved systems for the management and storage of fertilisers, such as composting and pelletising manure instead of storing it in stockpiles.

Covering fertiliser that must be stockpiled can also reduce emissions. Other tools show significant potential, including sorbers[144], waste stabilisation ponds, and deep litter systems. For chemical fertilisers, nitrification inhibitors that reduce nitrogen loss in soil could reduce emissions by 60% (Department of Agriculture and Water Resources, 2017).

BOX 2.11: EXISTING TECHNOLOGY LEVERAGED FOR THE FOOD AND LAND USE SECTOR

Precision agriculture uses technological advances to increase crop yields, while preserving resources. Data from GPS systems, sensor arrays on harvesters, satellite imagery and drones are combined for highly accurate measurements of crop yields, terrain features, organic matter content, moisture, nitrogen, chlorophyll and pH levels. This allows farmers to optimise their use of resources such as water, fertiliser and pesticides.

Precision agriculture first emerged in the United States in the 1980s, and is gaining traction around the world, due to good returns on investment costs and large-scale environmental benefits that could secure a long-term sustainable food supply.

Another benefit is that GPS-enabled management devices reduce the requirement for physical monitoring using machinery, which means less fuel is required on farms. This reduces transport emissions and fuel run-off that can pollute waterways.

Several emerging technologies are showing early promise in further advancing precision farming, including agricultural robots. Self-steering tractors are being developed to identify ripe fruits based on their shape and size, and to pick them without damage. Drones are adding detail to satellite imagery, allowing harvest yields to be predicted based on the level of field biomass.

Nature-based solutions such as carbon forestry will continue to play a role in Australia – although this can only be a temporary solution on a pathway to zero emissions.

Carbon forestry involves the planting of trees to sequester CO_2, as living trees absorb more CO_2 than they release. Carbon forestry is an important aspect of Australia's transition to net zero emissions. Forestry is, however, vulnerable to bushfires, drought, and heatwaves – many of which are being made worse by climate change – which can trigger the release of stored carbon back into the atmosphere.

Forestry can provide an alternative source of income for farmers. One example of a compensation scheme is the Qantas offset program, which pays farmers directly for delivering carbon credits.

In some cases carbon forestry can deliver greater economic returns than using certain land for agriculture. Farmers can use carbon forestry to diversify their holdings, protecting themselves against losses from under-performing crops or livestock.

Yet solutions such as carbon forestry require that emissions reductions are valued sufficiently to make the labour-intensive activity of planting cost-effective for farmers. Sequestration also requires long lead times, given the preparation needed before planting and the time required for trees to start sequestering optimum amounts of carbon.

144 Insoluble materials that bind to nitrogen in fertiliser to allow it to gradually release.

Carbon forestry requires significant areas of land. In addition to reduced land area for food and fibre production, trade-offs for the scale of planting required include increased water use and potential negative effects on biodiversity if carbon-focused planting is restricted to limited tree species. Carbon forestry needs to be well managed to ensure benefits are maximised, by, for instance, the inclusion of carbon forestry within a mosaic of different land-use practices to balance trade-offs (CSIRO, 2019).

A further challenge is that carbon forestry provides a short-term fix for emissions abatement. Reforesting can only be carried out once, since carbon must remain locked in the land for the long term. In order to keep offsetting new emissions, new parcels of land need to be reforested, a process that cannot continue forever. Achieving net zero emissions in the long term will require full decarbonisation with no offsetting: carbon forestry may delay the need for full decarbonisation, but it does not remove it. Due to the short-term nature of abatement and trade-offs of carbon forestry, the potential to decarbonise as much of the energy and industry sectors as possible without relying on offsets should be investigated.

In addition to dedicated carbon forestry, there may also be other carbon sequestration solutions such as the combination of trees and pasture, soil sequestration, or 'blue carbon' stored in coastal and marine ecosystems (The Blue Carbon Initiative, 2016). While these and other sequestration methods could play a role in achieving net zero emissions, only carbon forestry has been included in the scope of *Decarbonisation Futures* modelling.

TABLE 2.7: Summary table of strategies and key solutions for agriculture and land emissions reductions

STRATEGY	KEY TECHNOLOGIES	STATUS	MOMENTUM
REDUCE ENERGY USE			
Improve on-farm efficiency	Sustainable agriculture practices and energy-efficient equipment	Mature	Due to attractive financing options provided by the Clean Energy Finance Corporation (CEFC) in partnership with major banks[145], many farms have benefited from energy and cost savings from more efficient equipment such as variable-speed drives in irrigation systems[146]. For example, the Mareeba Banana Farm in Queensland reduced its energy costs by 45% by switching to variable-speed drives[147].
	Precision agriculture and automation	Mature	Precision agriculture and automation techniques are gaining traction in Australia, as integrated systems for linking spatial data with on-farm autonomous equipment and variable-rate technology becomes more widely available[148]. Over 95% of Australian farmers have access to information and communications technology (ICT) equipment, which can help increase productivity. For example, 80% of farms in the grain sector use ICT to more efficiently operate equipment and manage production[149].

145 National Australia Bank (2017), Commonwealth Bank of Australia (2017)

146 CEFC (2019)

147 Ergon Energy (2014)

148 Robertson *et al* (2007)

149 Dufty and Jackson (2018)

SWITCH FROM FOSSIL FUELS TO LOW- OR ZERO-EMISSIONS ALTERNATIVES			
Switch energy sources for on-farm machinery and transportation to low-carbon electricity	Electric machinery	Demonstration	Electric tractors are available from John Deere[150] and Fendt[151]. Farmers in the US and UK have led global uptake of this equipment, which has benefits including lower running costs, increased safety and greater torque[152].
	On-site renewables and power purchase agreements	Mature	Australian agricultural businesses are proactively installing on-site solar PV and making use of power purchase agreements to decarbonise their electrical operations. Examples include the Nine Mile Fresh apple processing facility, Swan Hill abattoir and MC Herd abattoir[153].
REDUCE NON-ENERGY EMISSIONS			
Reduce demand for emissions-intensive agricultural products	Product substitutes: plant-based	Mature	The global market for plant-based meat substitutes is booming. Share prices of the company Beyond Meat grew over 700% in the three months following their 2019 NASDAQ release, and Barclays suggest that, in a decade's time, meat alternatives could be worth 10% of the current total value of the US market for meat products[154]. Technologies for plant-based substitutes are improving at a similar rate to actual meat products.
	Product substitutes: laboratory-grown meat	Emerging	While it is still an emerging technology, the cultured-meat industry has seen rapid technological developments in recent years, accompanied by significant interest from investors[155]. In Australia, several start-ups are now working towards making cultured meat a commercially competitive product for Australian consumers[156].

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150 White (2016)

151 Fendt (2017)

152 National Farmers Union (2019)

153 Australian Financial Review (2019)

154 Linnane (2019)

155 Ackland (2019), Purdy (2019)

156 McCarthy (2019)

Reduce or eliminate non-energy emissions from livestock	Incremental improvements in breeding, feeding and pasture practices; and manure management	Mature	Product trials are underway for CSIRO's 'Future Feed' livestock feed supplement that boosts productivity while reducing methane emissions[157]. The product has already attracted $2 million in investment. Australia is also developing approaches for improving manure-management practices to avoid nitrous oxide and methane emissions via the National Agricultural Manure Management program[158].
	Step-change improvements to practices	Demonstration	
	Anti-methane vaccines	Emerging	Vaccines to mitigate methane emissions from cows are already in the testing phase in New Zealand[159]. These vaccines could be commercially available for Australian farmers as early as 2028[160] (see Box 2.10).
Reduce non-energy emissions from grains and horticulture	Precision-agriculture and fertiliser management	Mature	Precision-agriculture practices are proving their potential to reduce not only energy use, but broader emissions on Australian farms through methods such as yield mapping, selective harvesting and variable rate application of fertilisers[161] (see Box 2.11). Australia is leading global research in enhanced-efficiency fertilisers and fertiliser additives that inhibit nitrous-oxide emissions[162].
Sequester CO_2	Dedicated large-scale carbon forestry	Mature	Opportunities in carbon forestry are growing, with organisations such as Carbon Farmers of Australia empowering landholders to participate in carbon markets[163]. In Tasmania, a Carbon Plantations Kit is available for landholders to assess the benefits of carbon forestry on their land, and several farmers are successfully earning an income from carbon credits[164].

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157 CSIRO (2016a)

158 CSIRO (2016b)

159 Bell (2015)

160 Meat and Livestock Australia and CSIRO (2019)

161 Bramley and Trengove (2013)

162 The University of Melbourne (2015), Primary Industries Climate Challenges Centre (2018)

163 Carbon Farmers of Australia (2019)

164 AK Consulting, Livingston Natural Resources Services, CSIRO Sustainable Agriculture Flagship, Private Forests Tasmania and Rural Development Services (2016)

Sequester CO_2 (cont.)	Soil carbon sequestration	Emerging	Soil carbon sequestration is a newly emerging solution, and an area where Australia could become a global leader. The world's first soil carbon credits were recently granted to Gippsland farmer Niels Olsen[165], and soil carbon specialist Agriprove has encouraged further participation by offering a cash prize to the next farmer to match Olsen's volume of sequestration[166].
	Silvopasture (a combination of trees and pasture)	Demonstration	Australia is already setting a global example in silvopasture, with over 200,000 hectares of farmland managed as intensive silvopasture with a combination of trees and pasture[167]. The benefits of silvopasture are attracting increasing attention from Australian landholders. For example, silvopasture played a key role in restoring Talaheni, a formerly over-grazed and unproductive 250 hectare property in Yass[168].

165 Corporate Carbon (2019)

166 AgriProve (2019)

167 Cuartas Cardona (2014)

168 Bank Australia (2019)

MODELLING

SECTION 03

Decarbonisation Futures uses scenarios to explore a range of possible low-emissions futures for Australia.

Due to the inherent uncertainty and complexity of the emissions-reduction challenge, it is impossible to accurately forecast the future. However, it is useful to employ a range of scenarios to test the impact of alternative futures on a company, an investment portfolio or a government strategy. Scenario testing can help ensure that strategies are robust and resilient.

Historically, only a few widely used modelling exercises have incorporated the substantial potential of future low-carbon innovations. Modelling generally makes conservative assumptions about transitions to low-emissions pathways, and assesses the future as a continuation of past trends rather than examining the potential for innovation. Recent experience has shown that innovation can result in change much faster than conservative assumptions suggest (Centre for Policy Development and ClimateWorks Australia, 2018).

It is, however, difficult to assess in advance which innovations will be rapidly adopted and which will not progress as fast as expected. This complexity is compounded by the fact that action on emissions reduction is a global issue, with diverse interactions between economic, social, technological and environmental systems.

Like any tool, modelling and scenarios should be used with knowledge of their strengths, weaknesses and limitations. All models are stylised, imperfect representations of the world. It is unlikely that any single emissions path will occur exactly as described in the scenarios modelled. These factors do not necessarily diminish the usefulness of modelling and scenarios, particularly when the process of exploring the important and interrelated aspects of such a highly uncertain and complex space is valuable.

BOX 3.1: *DECARBONISATION FUTURES* SCENARIO FRAMEWORK

ClimateWorks Australia has developed a scenario framework that can help identify climate-scenario drivers and develop narratives that incorporate scenario drivers, relevant for the whole economy.

This framework can be adapted and refined based on the organisation's business. It is not aimed at providing an exhaustive list of drivers, but rather indicates the wide range of drivers to be considered in the scenario-development process. This type of scenario framework has been used in the development of the scenarios in the *Decarbonisation Futures* project.

More information on ClimateWorks Australia's approach to scenario development is available in *Climate Horizons* (Centre for Policy Development and ClimateWorks Australia, 2018).

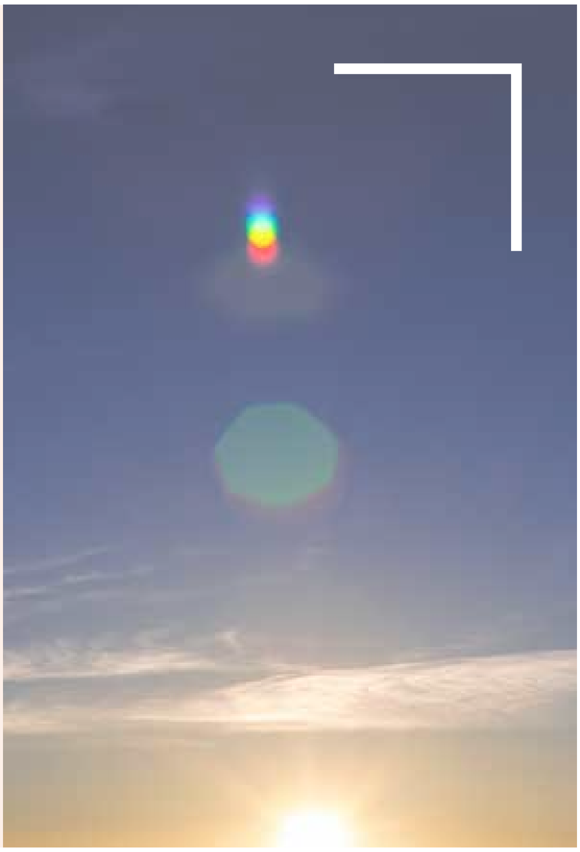
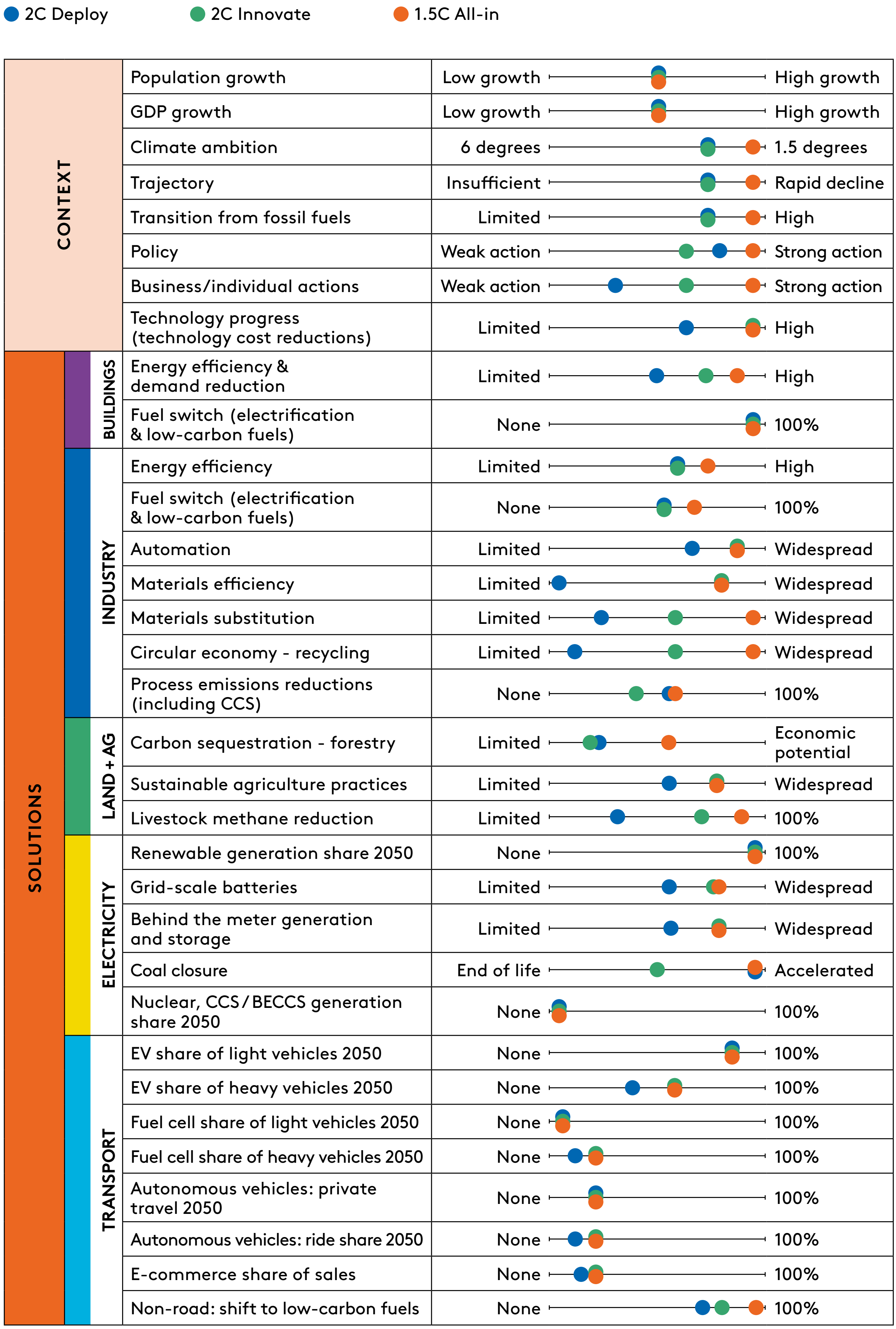


FIGURE 3.1: Illustrative scenario framework representation of *Decarbonisation Futures'* three scenarios



In this report, we explore three illustrative scenarios by which Australia might reach net zero emissions. The scenarios were developed as a result of stakeholder input and internal analysis of specific uncertainties around how the end goal could be reached. Since the research focused on pathways within Australia, the scenarios share some consistent contextual assumptions, such as population growth and global action towards abatement goals.

Key amongst the findings from the scenario development process is that a pathway exists for Australia that is compatible with limiting global temperature rise to 1.5 degrees Celsius, and there is potential for strong technological advances and action by businesses and individuals to influence emissions reductions. A prioritisation of solutions based on uncertainty and importance was undertaken alongside an investigation of key issues in order to focus the research effort.

The scenario-development process and analysis was informed by an extensive literature review on decarbonisation solutions, which included expert peer review. The findings of this process are summarised in Section 2. A mapping exercise was also undertaken to identify the drivers of uptake for each decarbonisation solution. This included an assessment of the challenges and potential enablers for each solution. More details about the modelling tools, scenarios, solutions and driver mapping are discussed in the *Decarbonisation Futures: Technical Report*.

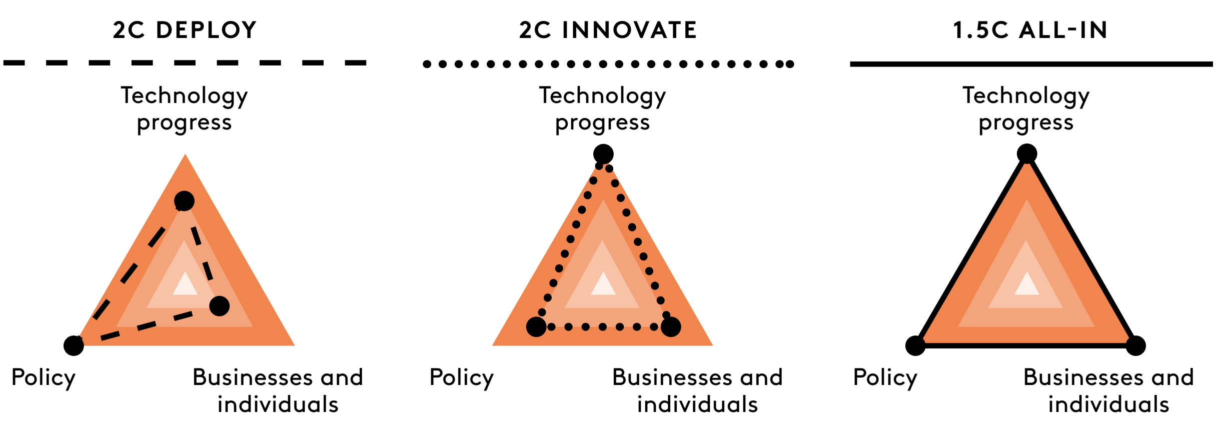
The chosen scenarios illustrate what Paris-aligned transitions could look like for Australia under a different set of technological, societal and policy drivers (Figures 3.1 and 3.2). Three scenarios are described in *Decarbonisation Futures*:

+ The first scenario (**'2C Deploy'**) models emissions reductions compatible with a 2-degree-Celsius global temperature limit, achieved primarily through direct government intervention focused on accelerating and regulating the deployment of demonstration- and mature-stage technologies
+ The second scenario (**'2C Innovate'**) shows how technology at the upper bounds of current expectations can facilitate the same outcome as the previous scenario. In this model, emerging technologies create widespread change in emissions-intensive sectors, driven by supportive government and business action
+ The third scenario (**'1.5C All-in'**) models an emissions outcome compatible with limiting the global temperature rise to 1.5 degrees Celsius. It combines elements from the two earlier scenarios, and assumes that governments will drive policies to limit emissions and facilitate technological innovations, with collaboration between policy-makers, businesses and individuals across all sectors.

FIGURE 3.2: Driver 'triangle' framework for the modelled scenarios

These triangles represent the level of progress/ action taken towards net zero emissions for each driver, by scenario.

Settings closer to the inside of the triangle indicate less action, while outer settings indicate more/strong action.



The scenario narratives are summarised in Table 3.1.

TABLE 3.1: Scenario narratives

'2C DEPLOY'	This scenario models emissions reductions compatible with a 2-degree-Celsius global temperature shift (>66% probability of staying below 2 degrees), achieved through direct government intervention via policies designed to accelerate and regulate the deployment of demonstration- and mature-stage technologies. It assumes no major technological breakthroughs, major structural changes to the economy, or substantial lifestyle shifts by the public. It does not model particular policies but calculates outcomes stemming from carbon pricing or legislative equivalents, in an economy embracing energy efficiencies, carbon capture and storage, a rapid shift to renewables, and other measures.
'2C INNOVATE'	This scenario also models emissions reductions compatible with a 2-degree-Celsius global temperature shift (>66% probability of staying below 2 degrees). It assumes technology at the upper bounds of current expectations, with emerging technologies creating widespread change in emissions-intensive sectors. It models the encouragement of new technologies by decision-makers, through increased investment into research and development by the public and private sectors. It assumes the facilitation of innovation by businesses and individuals (including new business models), as well as significant policy intervention in particular sectors.
'1.5C ALL-IN'	As its name suggests, the third scenario models an emissions outcome compatible with a limiting global temperature rise to 1.5 degrees Celsius. This scenario stays within the 50% probability of the 1.5 degrees Celsius carbon budget for Australia (achieving net zero by 2035), and then overcompensates with net-negative emissions through to 2050 to improve the chances of achieving this goal. This substantially more ambitious target requires the combination of elements from the earlier scenarios, with governments driving policies to limit emissions and facilitate technological innovations. It assumes action across all sectors, with collaboration between policy-makers, businesses and individuals, and technology providers.

BOX 3.2: LIMITS TO THE SCOPE OF *DECARBONISATION FUTURES*

While *Decarbonisation Futures* has taken a broad and deep approach to the scope of research and modelling, there are certain topics that have not been covered quantitatively. These include, but are not limited to:

+ The potential macroeconomic opportunities and structural effects of the transition on Australia's economy. For example, the emergence of a renewable hydrogen export market, or downstream processing[169] of low-carbon-compatible products such as lithium or green steel
+ Adopting zero-emissions fuels such as hydrogen for use in industry or international shipping (hydrogen was included as an option for road transport where data existed), ammonia as an energy carrier, or renewable synthetic fuels
+ Electrification of aviation and shipping
+ Negative emissions solutions beyond dedicated carbon forestry, such as bioenergy with CCS, direct air capture, soil carbon, blue carbon, biochar and agroforestry.

Where emerging zero-emissions technologies or options could be modelled, carbon forestry was used to compensate for residual emissions in the model.

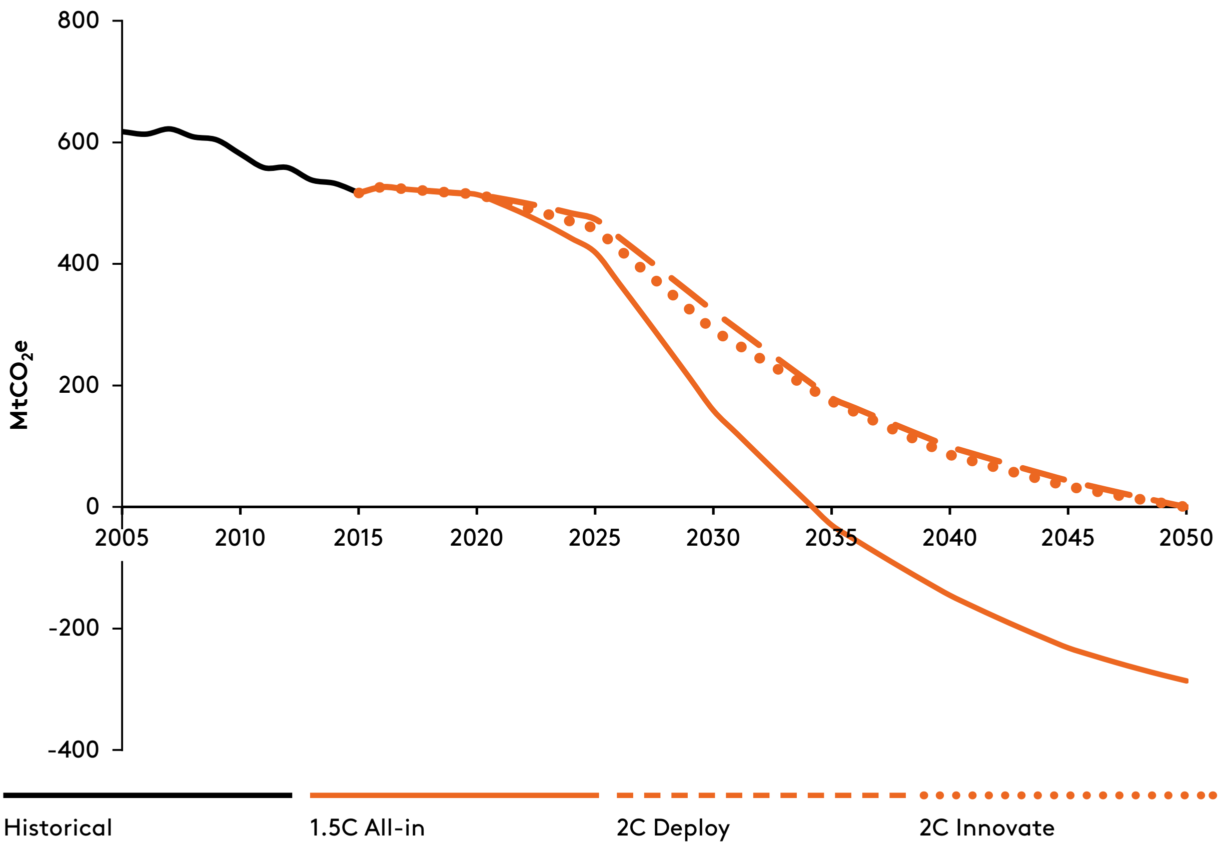
ClimateWorks is currently undertaking two multi-year programs of work – Land Use Futures and the Australian Industry Energy Transitions Initiative – that will explore many of these issues in greater detail.

169 While Australia has an abundance of valuable minerals, most of these are exported for processing, with significant economic value added overseas; for example, less than 1% of iron ore extracted in Australia is converted to steel domestically (Lord, 2019).

The scenarios show that Australia can still reduce emissions in line with limiting temperature rise to 2 degrees – and if governments, businesses and individuals go 'all-in', a 1.5-degree limit could be within reach. All sectors play a part in the transition.

All *Decarbonisation Futures* abatement scenarios are compatible with the Paris climate objective of keeping global warming well below 2 degrees Celsius[173]. All three scenarios in this study achieve net zero emissions by or before 2050, with the '1.5C All-in' scenario reaching net zero emissions around 2035. Each of the scenarios includes reductions across all sectors of the economy, with variations in magnitude between scenarios (Figure 3.3).

FIGURE 3.3: Overall annual net emissions in the modelled scenarios (2005-2050)



173 The scenarios' cumulative emissions are compatible with the global 1.5- and 2-degree carbon budgets, discussed in Section 1.

TABLE 3.2: Benchmarks of progress towards net zero emissions by 2050

BENCHMARK	2C PATHWAYS		1.5C PATHWAY	
	2030	CHANGE versus 2020	2030	CHANGE versus 2020
OVERALL OF ECONOMY BENCHMARKS				
Net annual emissions	291-322 $MtCO_2e$	37-43% decrease[170]	159 $MtCO_2e$	69% decrease[171]
Total final energy use		3-8% decrease		16% decrease
Share of electricity and zero-emissions fuels in final energy use	31-32%	2020 = 23%	35%	2020 = 23%
SECTORAL EMISSIONS BENCHMARKS				
Electricity emissions	62-65 $MtCO_2e$	63-64% decrease	46 $MtCO_2e$	73% decrease
Building emissions	36-37 $MtCO_2e$	63-64% decrease	27 $MtCO_2e$	73% decrease
Transport emissions	108-115 $MtCO_2e$	2-9% increase[172]	93 $MtCO_2e$	12% decrease
Industry emissions	141 $MtCO_2e$	40% decrease	120 $MtCO_2e$	49% decrease
Agriculture and land emissions	37-75 $MtCO_2e$	6-54% decrease	34 $MtCO_2e$	57% decrease

170 This represents a reduction of approximately 48-53% on 2005 emissions levels.

171 This represents a reduction of approximately 74% on 2005 emissions levels.

172 Emissions peak in 2025, and decline consistently afterwards.

All three scenarios in *Decarbonisation Futures* show significantly accelerated technology deployment and emissions reductions in the next decade compared to current trends, as is evident in the benchmarks across all sectors.

Government figures project a decline of national emissions by 16% on 2005 levels by 2030. In contrast, both the '2C Deploy' and '2C Innovate' scenarios benchmark a decrease of 48–53% while the '1.5C All-in' scenario puts the figure at 74%.

Likewise, government projections suggest Australia will generate 48% of electricity from renewables by 2030. The '2C Deploy' and '2C Innovate' scenarios put the figure at 74% and 70% respectively; the '1.5C All-in' scenario at 79%.

In transport, government projections state that, by 2030, around one in five new cars purchased will be electric. In contrast, that figure becomes one in two for '2C Deploy' and '2C Innovate' – and three in four for the '1.5C All-in' scenario.

These examples show the challenge ahead.

Although the modelled benchmarks might seem ambitious, they are by no means impossible. The research highlights the progress being made – progress that must now be turbocharged, with governments, businesses and individuals mobilising to achieve faster change than under typical market conditions.

In short, action – the deployment of renewables; investment in research and development; the construction of transition infrastructure; the commercialisation of emerging technologies; and the other measures discussed in this report – cannot wait until 2030 or 2050.

Deploying mature and demonstrated solutions can achieve much of what is needed this decade and can accelerate immediately. From 2030 to 2050, the implementation challenge shifts to zero-emissions solutions for long-haul transport, agriculture and industry, which need to be the focus of accelerated RD&D investment this decade.

There are some consistent trends across scenarios, which reflect the areas where technologies are most mature (Figure 3.4). For example:

+ Energy efficiency improves across all sectors and strong, early emissions reductions are largely enabled by the decarbonisation of electricity generation
+ Between 2035 and 2040, electricity emissions are near-zero, as renewables approach 100% of generation. In all scenarios, decarbonisation of electricity generation is a precondition for decarbonisation throughout other sectors. Electricity produced by renewable energy facilitates a shift away from fossil fuels in buildings, transport and other areas
+ After an initial increase, transport emissions also decline substantially by 2050, due largely to the electrification of road vehicles as well as uptake of other low-carbon fuels
+ Similarly, buildings achieve significant emissions reductions through energy-efficiency improvements, low-carbon electricity and electrification
+ Industry and agriculture, at the other end, have significant residual emissions by 2050, which reflects the technological gap to zero emissions technologies.

All scenarios model transitions to zero-emissions technologies taking place as soon as feasible, with best-available solutions implemented to reduce emissions where appropriate technology does not yet exist. Solutions for decarbonising the agriculture and industry sectors are the least mature, and show the most variation between scenarios. Due to residual emissions, particularly in agriculture and industry, all scenarios rely materially on carbon forestry to remain within the Australian carbon budget (see Box 3.2 for limitations of modelling).

The stacked wedges above the x-axis in Figure 3.4 show emissions (scope 1 and 2) for four major sectors of the Australian economy. The emissions trajectory of electricity generation is depicted as a separate yellow dotted line to avoid double counting, as electricity emissions have already been included in end-use sectors. Presenting results in this way highlights the impact of a decarbonising electricity grid on those sectors that already derive a large proportion of their energy use from electricity such as buildings and industry.

It also demonstrates the value of increasing electrification of other processes throughout the economy as they increasingly reap the benefits of low- or zero-emissions electricity (see for example transport and industry post-2035).

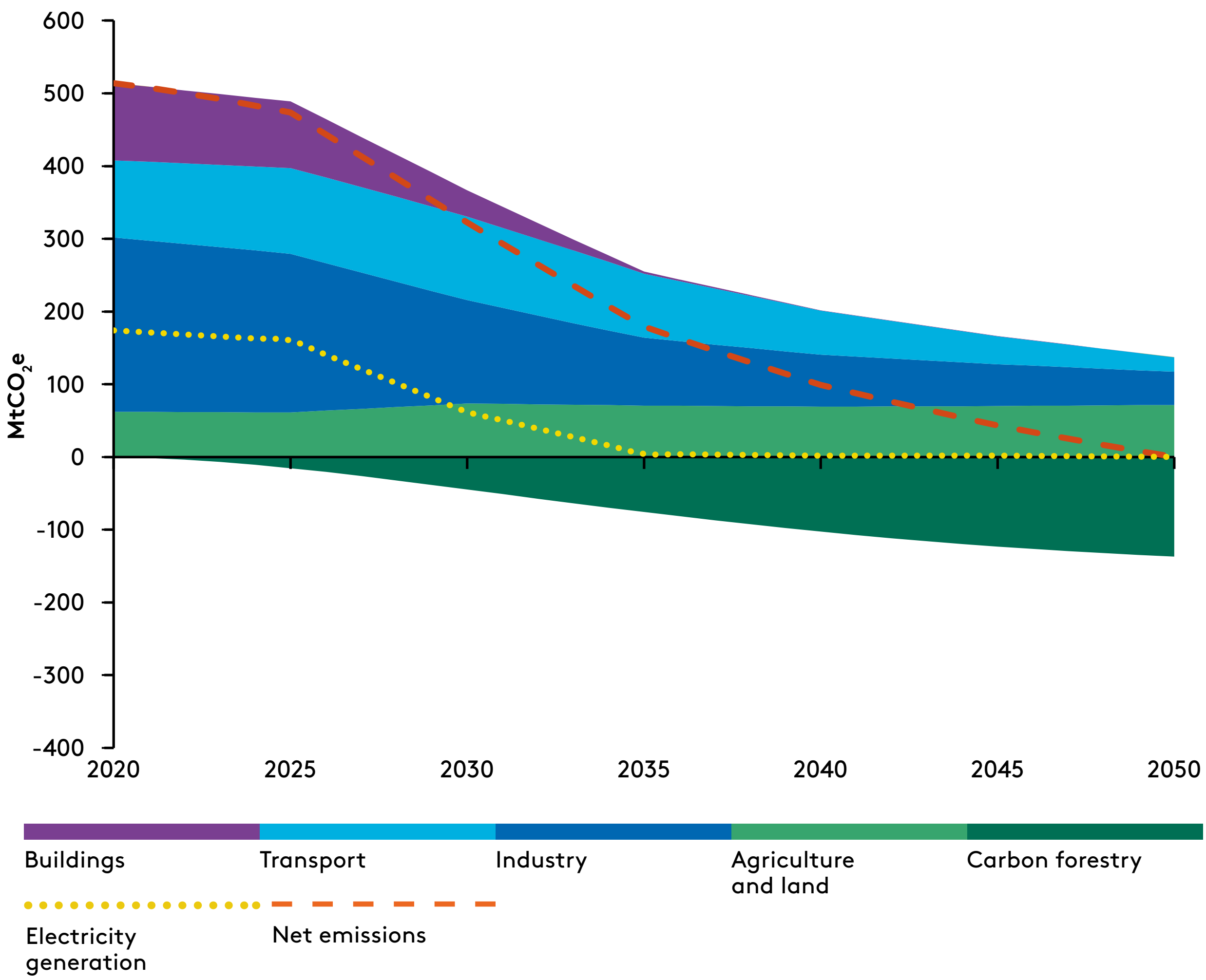
The amount of sequestration required to offset emissions and remain within relevant carbon budgets (modelled here as carbon forestry) is also presented as a distinct sector with 'negative' emissions below the x-axis. Net annual emissions – calculated as residual sector emissions minus carbon forestry sequestration – are represented by the orange dashed line.

'2C DEPLOY'

In the '2C Deploy' scenario, emissions reduce considerably over time in most sectors. Decarbonisation of electricity generation unlocks emissions reductions in end-use sectors, particularly industry and buildings. As electric vehicles (using decarbonised electricity) become significant in road segments post-2035, transport sees strong emissions reductions. Agriculture emissions grow slightly, reflecting the additional technological development required to compensate for expected growth in demand for emissions-intensive products for which low-emissions solutions are not widely available at present. Australia reaches net zero emissions by 2050.

FIGURE 3.4: Australian emissions by sector and by scenario

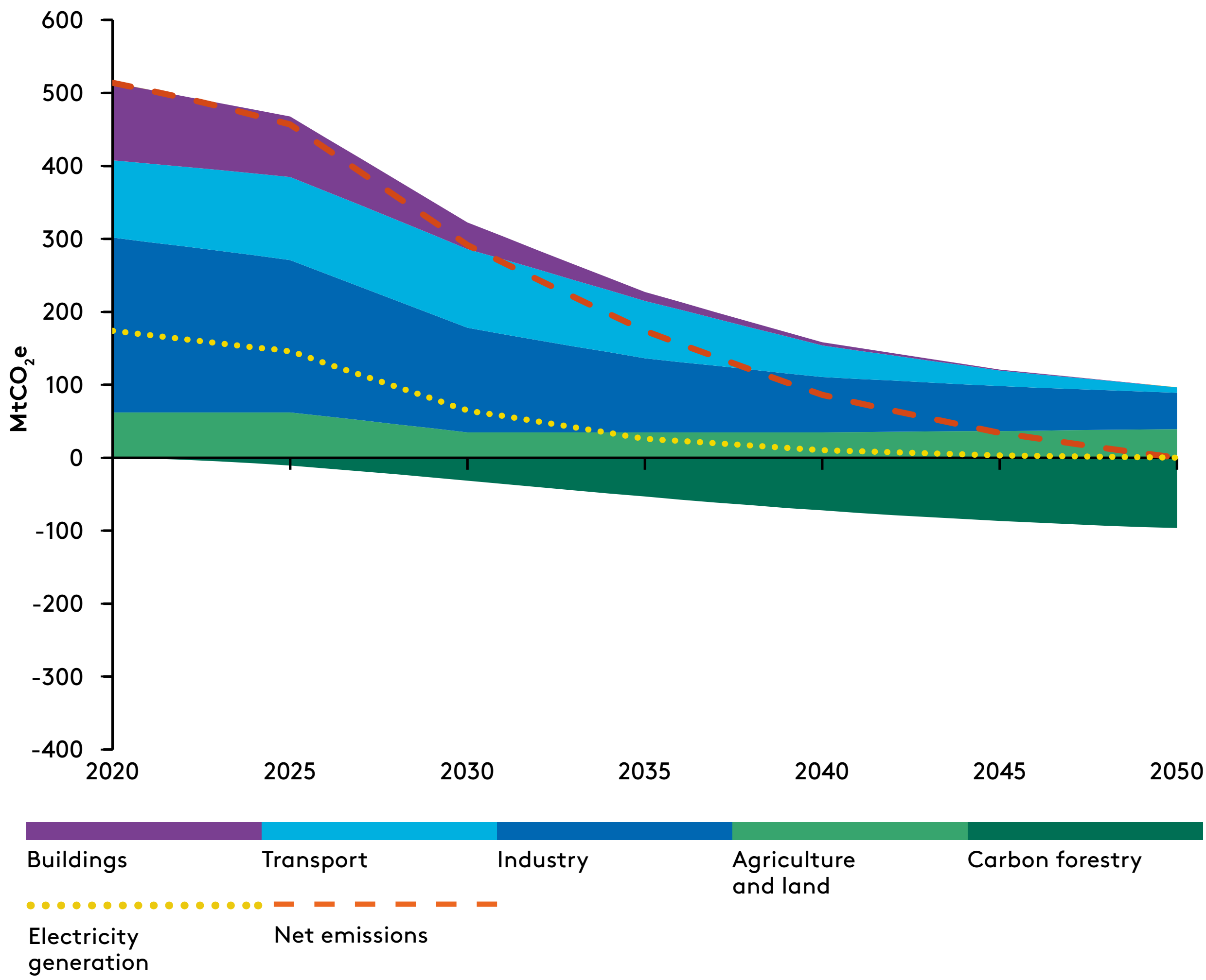
'2C Deploy'



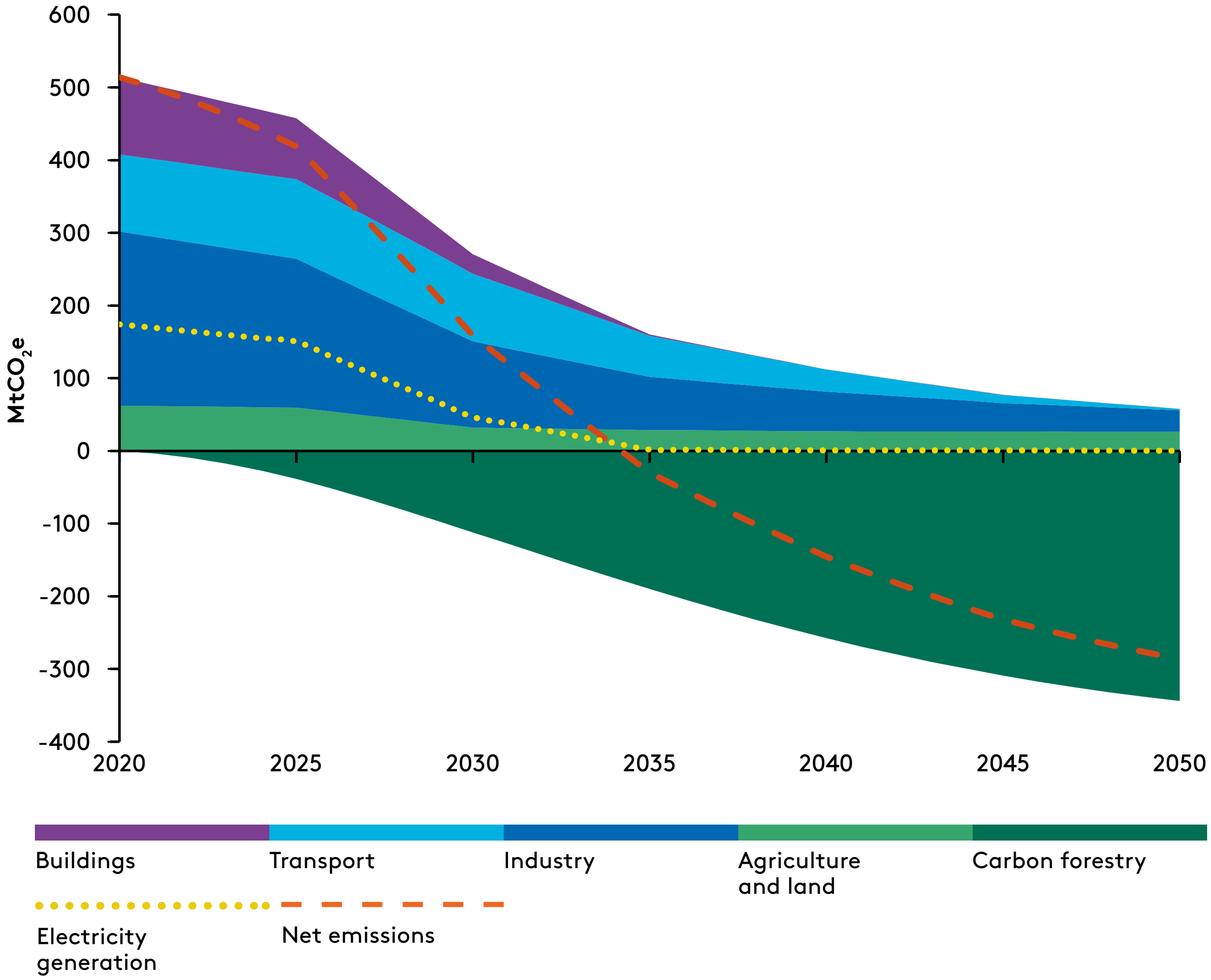
'2C INNOVATE'

The '2C Innovate' scenario sees emissions reduce across all sectors. While electricity generation also undergoes a significant transition, this is moderated relative to other scenarios due to relatively less policy action driving the exit of existing fossil fuel generation. Despite this, electricity generation still approaches near-complete decarbonisation between 2040 and 2045. This relatively slower transition results in higher emissions in buildings and industry in the medium term. Transport emissions benefit from similarly high levels of road transport electrification, while additional opportunities for fuel switching, particularly in non-road transport, unlock further abatement relative to '2C Deploy'. Other emerging technologies and solutions assumed in this scenario further reduce energy demand and emissions, particularly for industry and agriculture. In industry, some of these benefits are offset by lower levels of carbon capture and sequestration relative to other scenarios, due to a lower policy incentive for this technology. Australia reaches net zero by 2050, requiring fewer negative emissions compared to '2C Deploy' due to greater levels of abatement across the economy.

'2C Innovate'

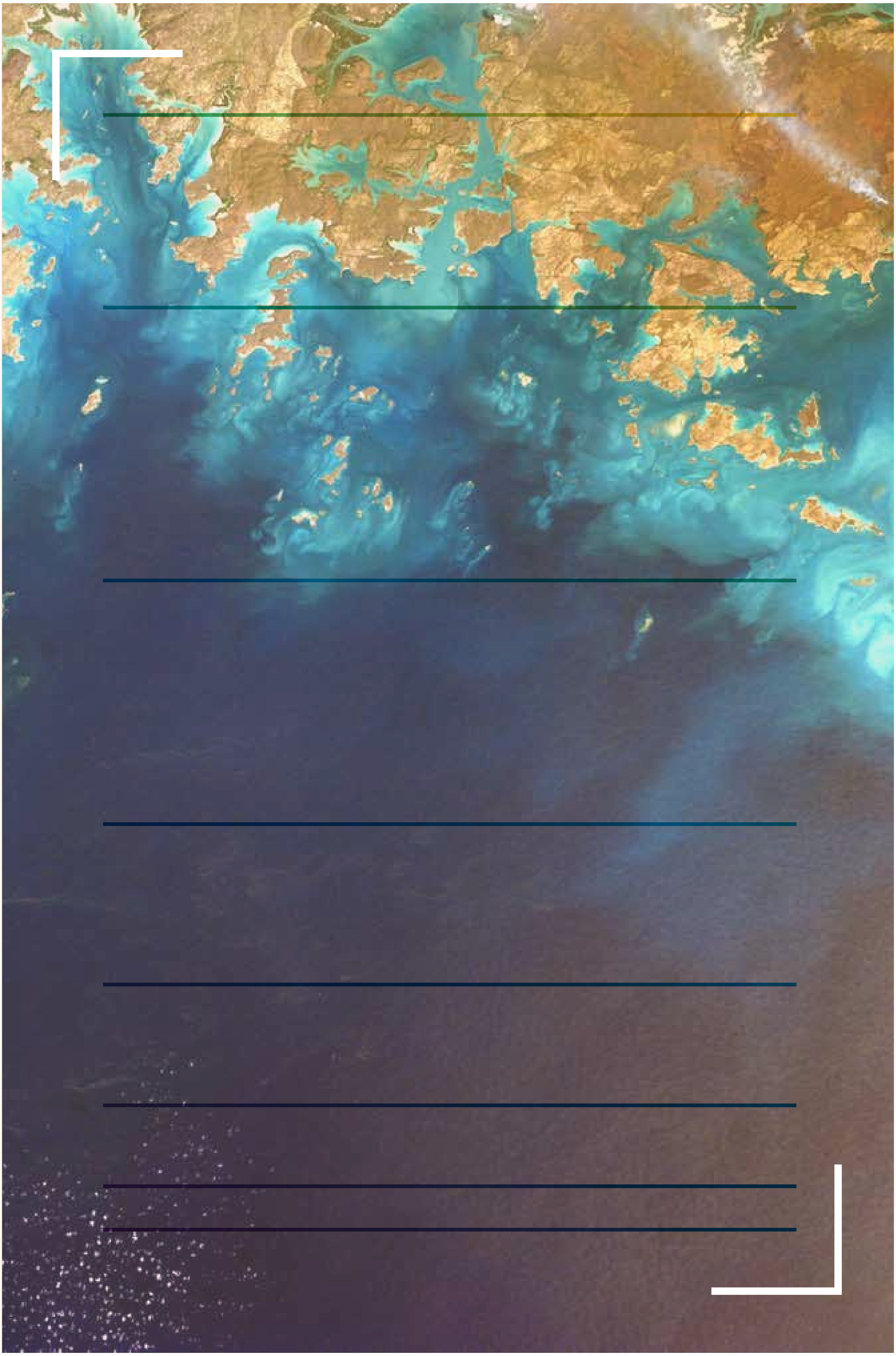


'1.5C All-in'



'1.5C ALL-IN'

In the '1.5C All-in' scenario, emissions reduce rapidly in all sectors and negative emissions ramp up significantly. The emerging technologies and stronger policy action assumed in this scenario further reduces energy demand and emissions across all sectors. This is particularly evident for industry and agriculture. Industry energy use and emissions are further reduced compared to the 2 degrees scenarios, drawing on increased efficiencies and process emissions-reduction solutions. Australian energy commodities are also affected by reduced global demand under this temperature goal. The widespread use of solutions to reduce or avoid livestock emissions greatly reduces emissions in the agriculture sector. Rapid decarbonisation of electricity generation and high levels of electrification drives buildings emissions towards zero between 2035 and 2040. An accelerated transition to electric vehicles reduces transport emissions in the medium term. Further fuel switching to zero-emissions energy sources (such as biofuels), greatly reduces emissions, particularly in non-road transport. This scenario presents the lowest total residual emissions in 2050 thanks to the combined efforts on accelerated technology development and deployment. Assisted by considerable carbon sequestration, Australia reaches net zero emissions around 2035, and substantial negative emissions continue after this time to meet the 1.5 degrees carbon budget for Australia.



3.1. ELECTRICITY

TABLE 3.3: Benchmarks of progress towards net zero emissions by 2050, electricity

BENCHMARK	2C PATHWAYS		1.5C PATHWAY	
	2030	CHANGE versus 2020	2030	CHANGE versus 2020
TECHNOLOGY BENCHMARKS				
Share of renewable electricity generation	70-74%	2020 = 25%	79%	2020 = 25%
Additional renewable capacity between 2020 and 2030		24-28 GW added		29 GW added
Additional storage capacity between 2020 and 2030		44-66 GWh added		56 GWh added
ENERGY BENCHMARKS				
Share of electricity in total energy	24%	2020 = 20%	27%	2020 = 20%
EMISSIONS BENCHMARKS				
Annual emissions	62-65 MtCO_2e	63-64% decrease	46 MtCO_2e	73% decrease
Emissions intensity	220-252 tCO_2e/GWh	63-67% decrease	177 tCO_2e/GWh	74% decrease

All scenarios reach about 75% renewable electricity generation by 2030, and 100% by 2050.

The electricity sector rapidly shifts to 100% renewable energy and reaches zero emissions by 2050 across in all scenarios (despite significant increases in overall electricity supply). The transition is fastest in '1.5C All-in' (Table 3.3). In every scenario, all new power generation assets are renewable, even in the absence of a strong policy driver, reflecting the cost competitiveness of new renewable energy compared with new fossil fuel generation.

On an economic basis alone, renewables are the preferred source of new generation, and come to dominate the generation mix by 2030. By that date, renewable electricity is the dominant source of electricity generation (73 – 79% of electricity generated) (Figure 3.5). This means that the major factor influencing the speed of the transition to renewable electricity is the rate at which coal generation (and then gas) exits the system. Additional policy drivers for coal and gas closure are needed to unlock faster decarbonisation in the sector. The '2C Innovate' results reflect a scenario with relatively low policy action, particularly in driving the exit of existing fossil fuel generation. As a result, the scenario involves a slower transition in the sector, with coal generation (and therefore associated emissions) extended by around 10 years relative to '2C Deploy' and '1.5C All-in' (Figure 3.6).

FIGURE 3.5: Electricity generation mix in the modelled scenarios (2020, 2030 & 2050)

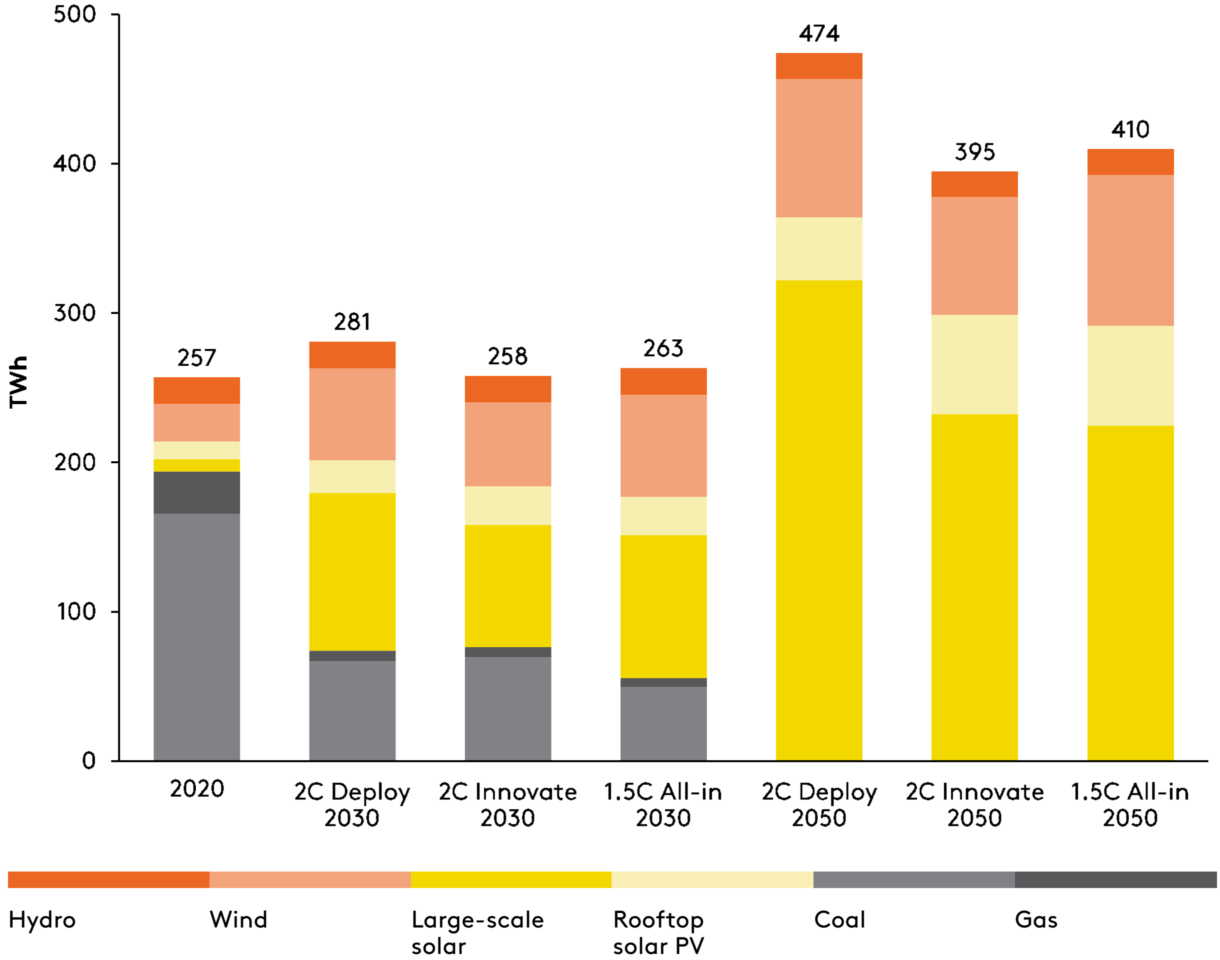


FIGURE 3.6: Electricity emissions intensity in the modelled scenarios (2020-2050)

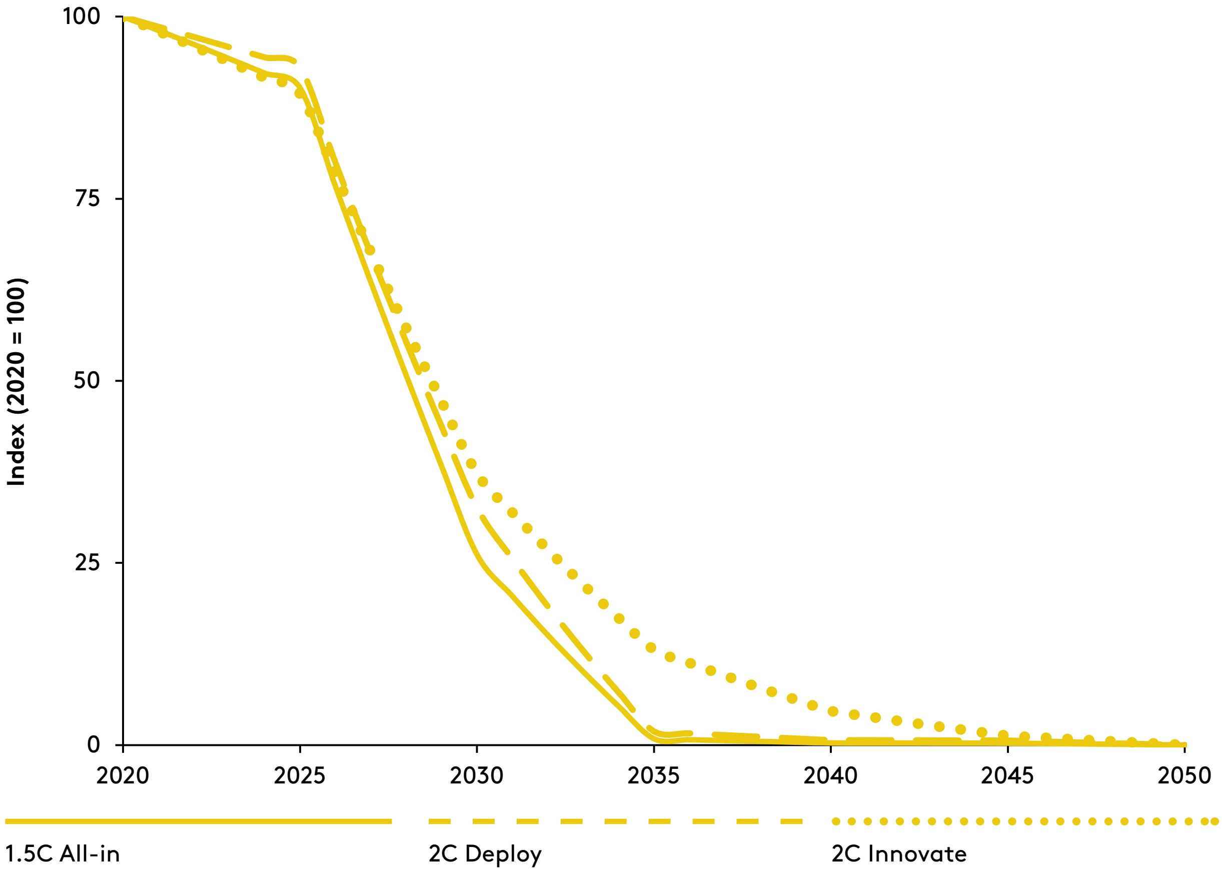
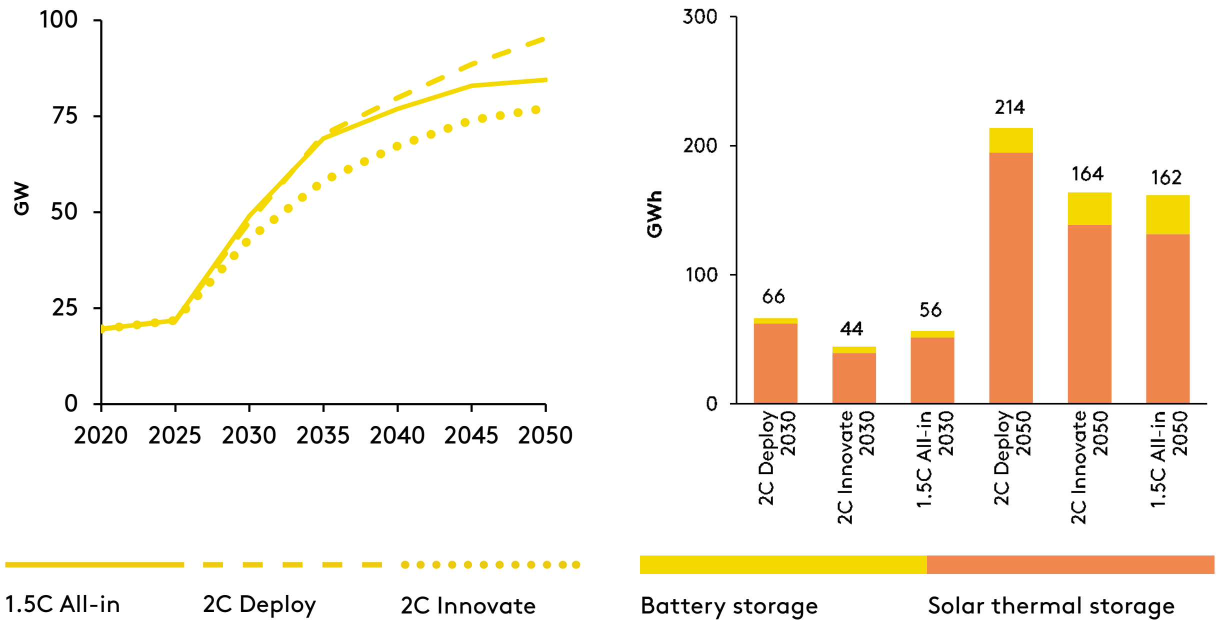


FIGURE 3.7: Cumulative renewable electricity build, 2020-2050 (left), and storage capacity by type (right) in the modelled scenarios, 2030 & 2050



In all scenarios, the transition to higher proportions of renewable electricity is managed via energy storage (Figure 3.7, right) and flexible demand (such as responsive electric-vehicle charging in later years in particular). Market-dispatch and power-system modelling are beyond the scope of this study.

Decarbonisation Futures presents a generation-mix composed of a significant share of solar thermal generation (with storage). However, this is highly sensitive to assumptions around future technology costs. Other studies suggest different mixes of renewable generation types (e.g. less solar thermal and more solar PV, pumped hydro and batteries).

Consistently, though, decarbonisation analyses have found that Australia moves to 100% renewables, enabled by increases in storage capacity and other integration measures. This study also excludes modelling of potential new export industries built on Australia's large renewable resources, such as green steel, green aluminium or hydrogen.

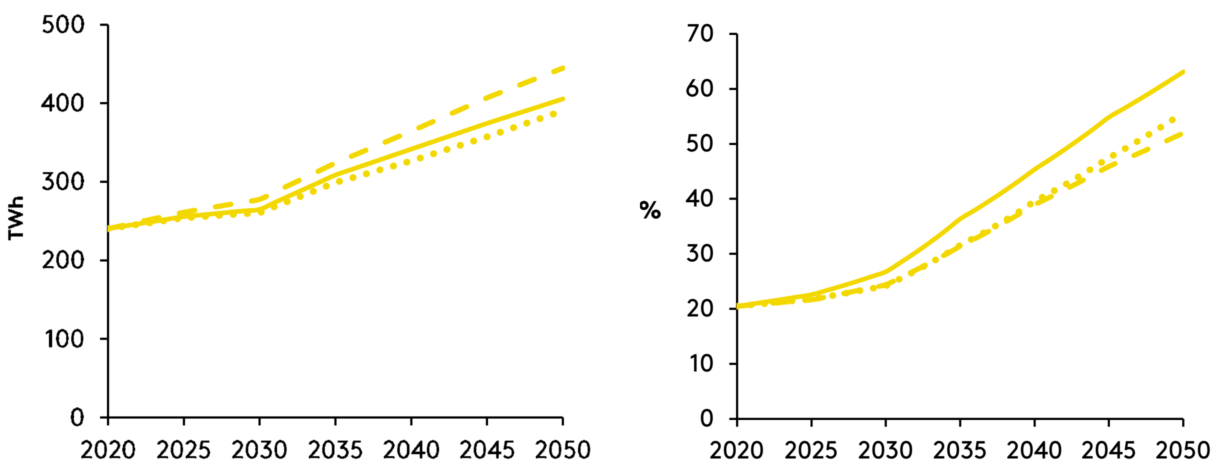
Recent research has shown that these new industries could help reduce the overall system costs of managing a renewable grid (Ueckerdt *et al*, 2019). This might be achieved by building more renewable generation assets than needed to meet domestic demand, and then using the surplus electricity to produce valuable goods.

Increased reliance on electricity across other sectors forms a major component of Australia's transition towards net zero emissions.

Electrification of end-use sectors (those directly used by consumers, such as buildings, transport, industry) via renewable electricity offers one of the most promising ways to reduce emissions across the economy. Future electricity demand will be driven by counterbalancing factors – particularly the uptake of energy efficiency, rate of electrification, and growth of new low-carbon export industries.

In all scenarios, electricity use grows significantly relative to 2020. In the '2C Deploy' scenario, electricity demand is higher than the other *Decarbonisation Futures* scenarios in absolute terms, but it is the lowest as a proportion of overall energy use (Figure 3.8). This reflects the lower rates of energy efficiency in this scenario, as a result of more conservative assumptions about technological improvements. In the '1.5C All-in' scenario, electricity accounts for more than 60% of overall energy use, as a result of stronger technology and policy settings that increase energy efficiency and electrification. The effect of energy efficiency on electricity demand is evident when comparing the '2C Deploy' and '2C Innovate' scenarios. Despite very similar rates of electrification, total electricity demand is less in '2C Innovate' due to technological advances driving energy efficiency.

FIGURE 3.8: Overall electricity demand (left) and as a proportion of final energy use (right) in the modelled scenarios (2020-2050)



1.5C All-in

2C Deploy

2C Innovate

3.2. BUILDINGS

TABLE 3.4: Benchmarks of progress towards net zero emissions by 2050, buildings

BENCHMARK	2C PATHWAYS		1.5C PATHWAY	
	2030	CHANGE versus 2020	2030	CHANGE versus 2020
TECHNOLOGY BENCHMARKS				
Rooftop solar electricity generation	22-26 TWh	85-116% increase	26 TWh	116% increase
ENERGY BENCHMARKS				
Residential building energy intensity[174]		44-48% decrease (improvement)		49% decrease (improvement)
Commercial building energy intensity[175]		16-25% decrease (improvement)		28% decrease (improvement)
Share of electricity in residential buildings	76-78%	2020 = 49%	75%[176]	2020 = 49%
EMISSIONS BENCHMARKS				
Annual emissions	36-37 $MtCO_2e$	63-64% decrease	27 $MtCO_2e$	73% decrease

174 Represented as energy use per household

175 Represented as energy use per square metre of commercial building floor space

176 Higher rates of energy-efficiency improvements lead to slightly lower levels of building electrification in the '1.5C All-in' scenario by 2030, relative to other scenarios

Zero-emissions buildings combine energy efficiency with renewable electricity.

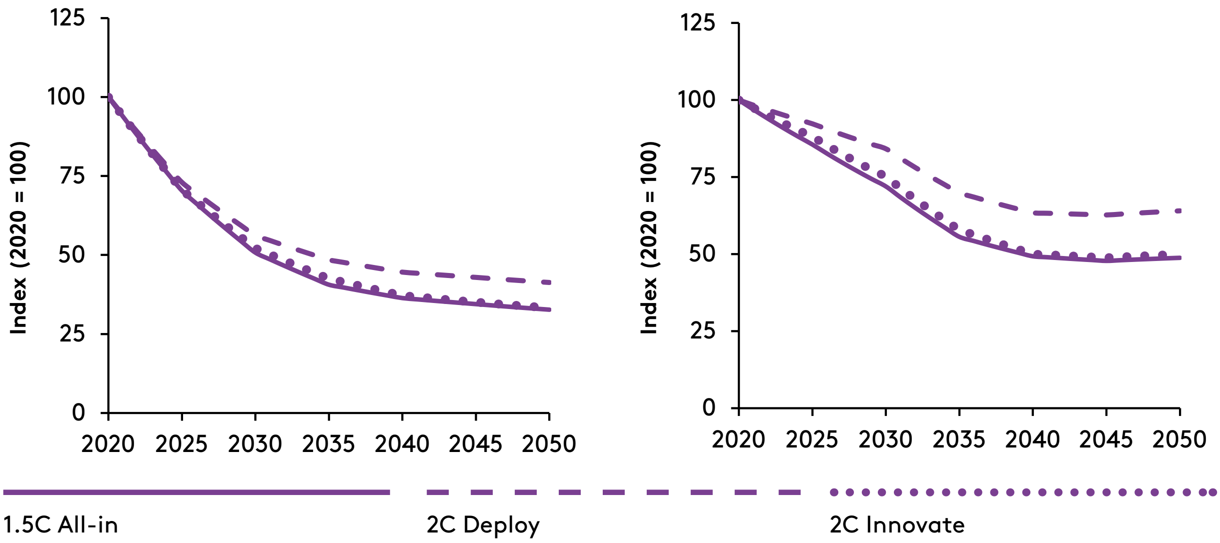
In all scenarios, residential and commercial buildings approach full electrification by 2040 (Table 3.4).

In residential buildings, energy efficiency improvements and electrification drive lower energy intensity[177] for all scenarios in 2050 relative to 2020 (Figure 3.9, left). This is most significant in '2C Innovate' and '1.5C All-in', where energy intensity decreases by more than 60% relative to 2020, highlighting the significant role that technological innovation and societal demand can play in unlocking energy-efficiency improvements.

In commercial buildings, reductions in building energy intensity[178] are less pronounced than in the residential sector, although trends across scenarios are fairly consistent (Figure 3.9, right).

In addition to achieving emissions reductions, energy-efficient technologies reduce energy costs, and enhance comfort and productivity for building occupants.

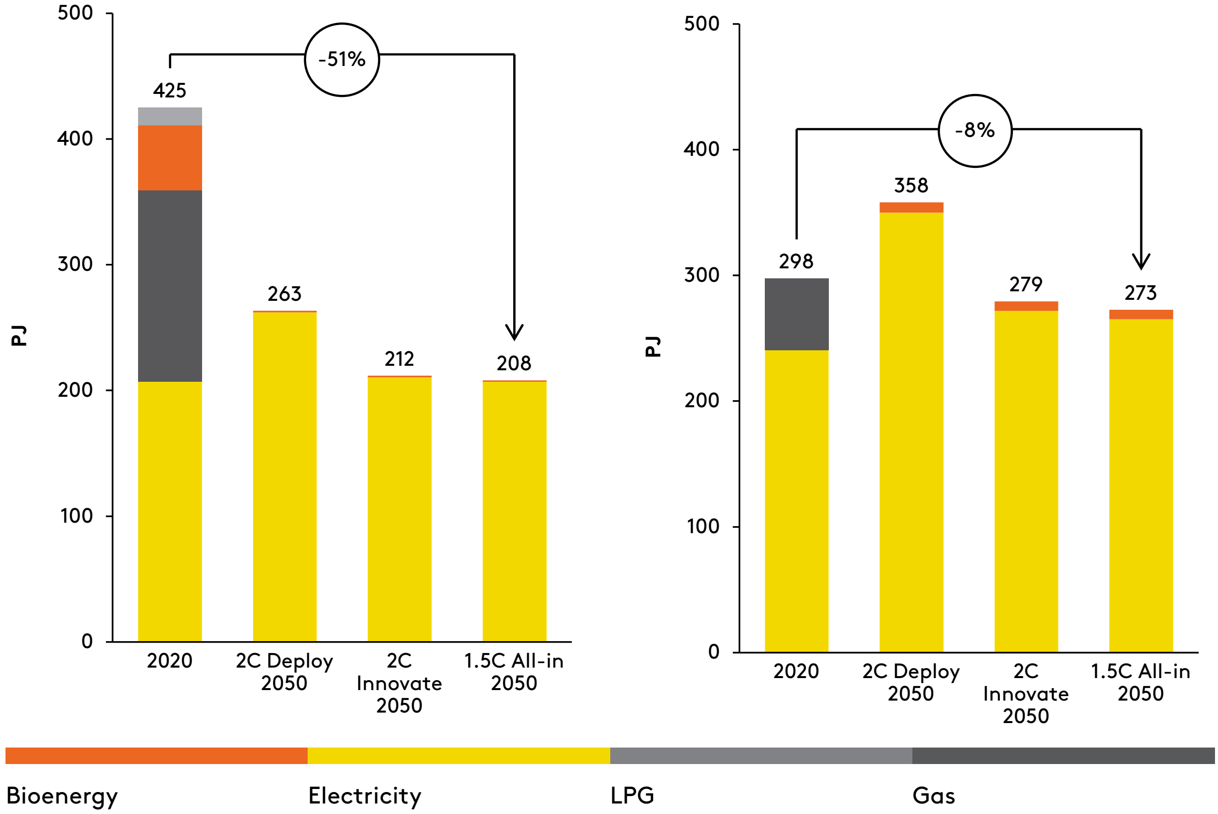
FIGURE 3.9: Residential (left) and commercial (right) buildings energy intensity in the modelled scenarios (2020-2050)

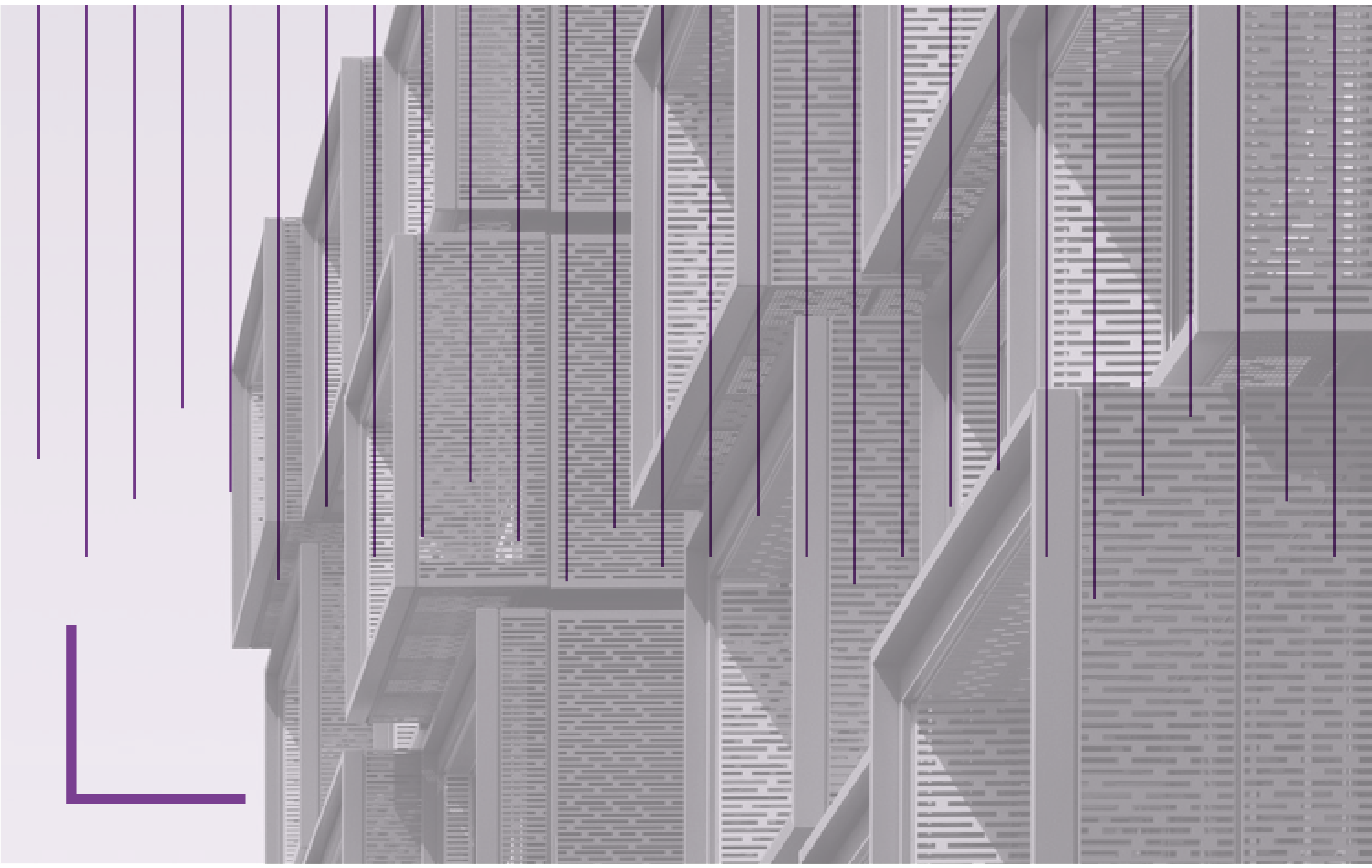


177 Calculated as energy use per household.

178 Calculated as energy use per square metre of commercial building floor space.

FIGURE 3.10: Residential (left) and commercial (right) buildings energy use in the modelled scenarios, by fuel type (2020-2050)





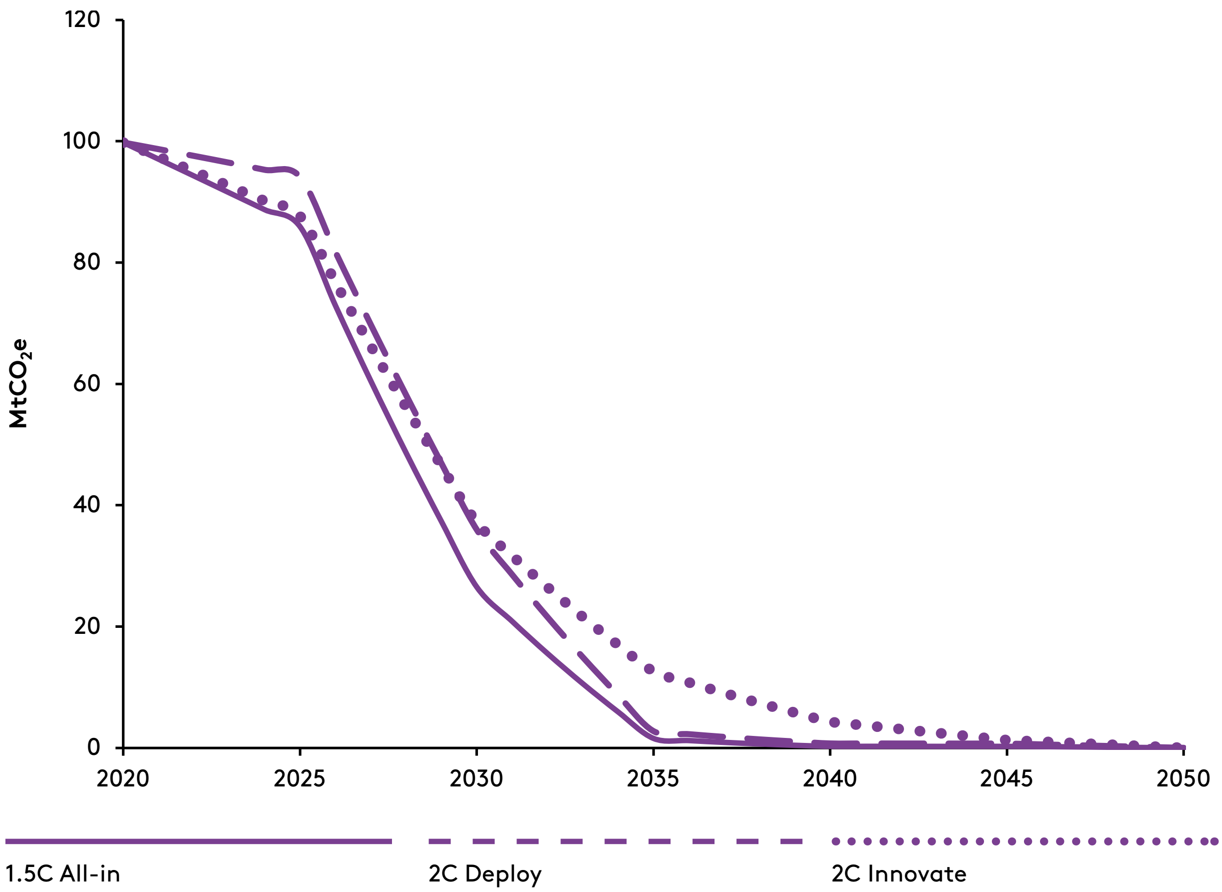
By 2050, residential energy use is lower in all scenarios relative to 2020, despite significant population growth during this period (Figure 3.10, left).

Although the energy intensity of commercial buildings in the '2C Deploy' scenario declines by nearly 30% relative to 2020, total energy use grows due to increases in total commercial floor space. Technological improvements drive higher rates of energy efficiency in '2C Innovate' and '1.5C All-in', leading to a slight decrease in overall energy use by 2050 in these scenarios (Figure 3.10).

In all scenarios, residential and commercial buildings approach full electrification by 2040. As buildings reach high rates of electrification, the costs of maintaining a gas-distribution network for an ever-shrinking number of end-users is likely to become prohibitive. This is a consideration that is worthy of further research. In most cases, electrification also delivers significant energy-efficiency benefits, as one unit of electricity can replace between two and seven units of gas, depending on the end service (ASBEC, 2016).

The emissions trajectory of the building sector is strongly linked to the transition to renewable electricity generation, as electricity is the primary source of building emissions. Across all scenarios, the building sector achieves emissions reductions of over 60% by 2030, and approaches zero emissions by 2040 in '2C Deploy' and '1.5C All-in', in line with the electricity generation emissions trajectory in those scenarios (Figure 3.11).

FIGURE 3.11: Overall buildings emissions in the modelled scenarios (2020-2050)



3.3. TRANSPORT

TABLE 3.5: Benchmarks of progress towards net zero emissions by 2050, transport

BENCHMARK	2C PATHWAYS		1.5C PATHWAY	
	2030	CHANGE versus 2020	2030	CHANGE versus 2020
TECHNOLOGY BENCHMARKS				
Electric cars (battery electric vehicles and fuel cell electric vehicles)	50% of new-car sales, 15% of total fleet	2020 = <1% of sales and total fleet	76% of new-car sales, 28% of total fleet	2020 = <1% of sales and total fleet
Electric trucks (battery electric vehicles and fuel cell electric vehicles)	25-39% of new-truck sales, 8-13% of total fleet	2020 = <1% of sales and total fleet	59% of new-truck sales, 24% of total fleet	2020 = <1% of sales and total fleet
Volume of zero-emissions fuels (bioenergy and hydrogen)	83-111 PJ	171-265% increase	134 PJ	338% increase
ENERGY BENCHMARKS				
Share of electricity and zero-emissions fuels in total transport energy use	9-11%	2020 = 3%	16%	2020 = 3%
Share of electricity and zero-emissions fuels in road passenger and freight energy use	5-9%	2020 = 2%	17%	2020 = 2%
Fossil fuel use in non-road transport	226-233 PJ	5-8% decrease	203 PJ	17% decrease
EMISSIONS BENCHMARKS				
Total transport emissions	108-115 $MtCO_2e$	2-9% increase[179]	93 $MtCO_2e$	12% decrease
+ Road transport emissions	89-95 $MtCO_2e$	5-12% increase[180]	76 $MtCO_2e$	11% decrease
+ Other transport emissions	18.8-19.5 $MtCO_2e$	5-8% decrease	17 $MtCO_2e$	16% decrease

179 Emissions peak in 2025, and decline consistently afterwards.

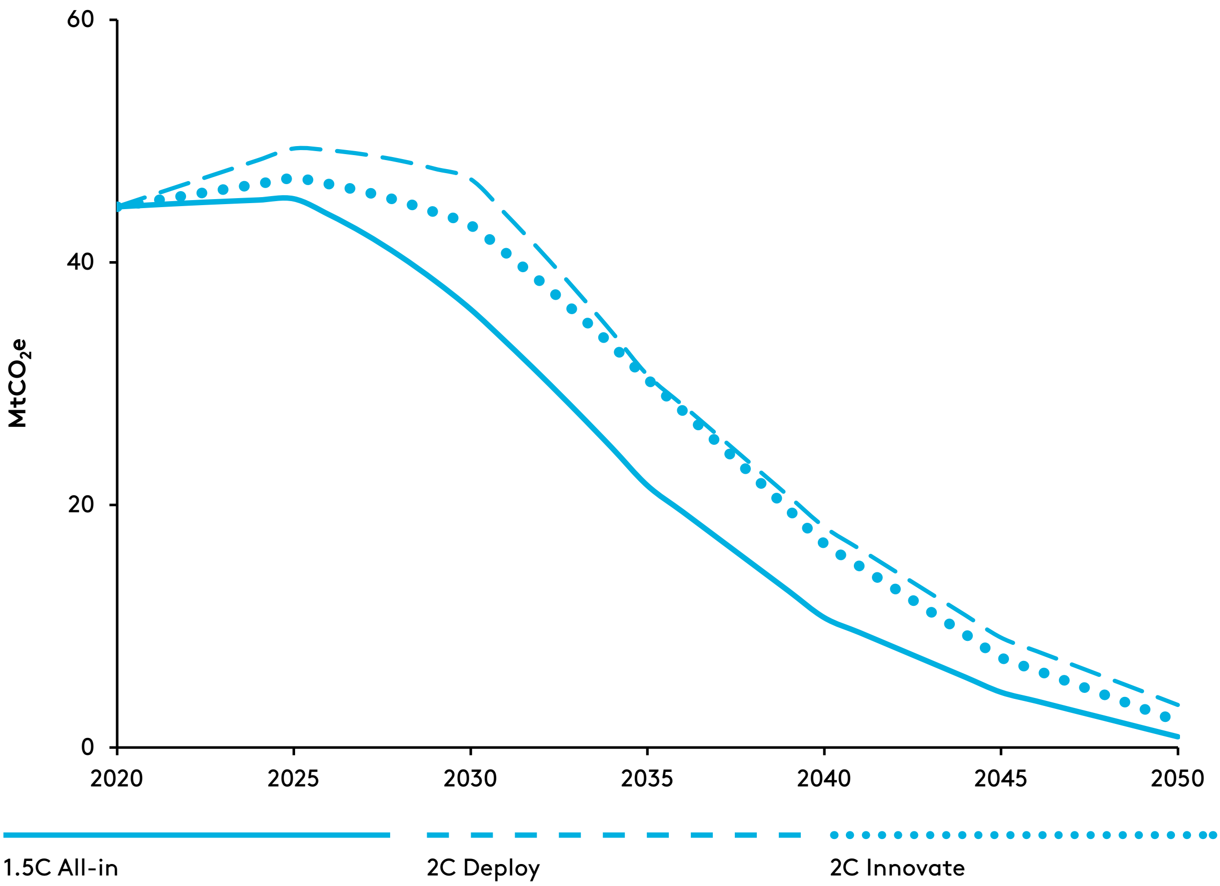
180 Emissions peak between 2025-2027, and decline consistently afterwards.

The high uptake of electric vehicles charged with renewable electricity has the potential has the potential to achieve close to zero emissions for road passenger transport.

With battery costs decreasing faster than expected, an increasing share of transport can be electrified by 2050 (Table 3.5). This trend facilitates a strong uptake of electric passenger vehicles in all scenarios with road passenger vehicle emissions approaching zero by 2050, as the electricity sector decarbonises (Figure 3.12). The most significant change for transport emissions occurs shortly after 2030.

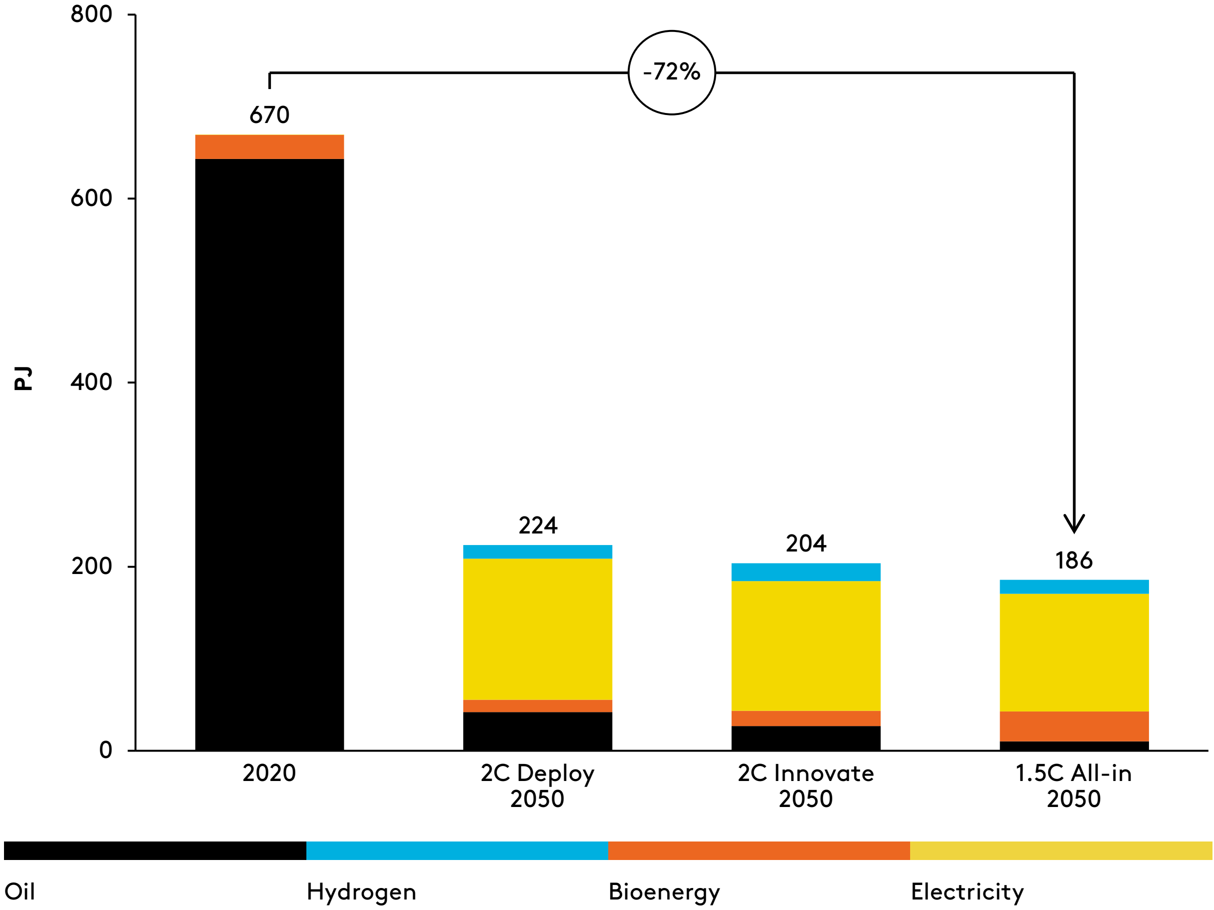
This reflects the delay between electric vehicles becoming cost-competitive (around 2025 – see Figure 2.8) and uptake in new-vehicle sales. The shift to electric vehicles is mainly fostered by their anticipated cost-competitiveness, but policy is important in expediting and supporting this transition.

FIGURE 3.12: Road passenger transport emissions in the modelled scenarios (2020-2050)



The strength of the expected uptake of electric vehicles for passenger transport is reflected by the similar trends observed across decarbonisation scenarios, where electricity dominates the fuel mix in 2050 (Figure 3.13). *Decarbonisation Futures'* analysis suggests that more than 90% of cars could be electrified by 2050 across all scenarios, with most switching to battery electric vehicles. It is also estimated that by 2050, up to 60% of Australia's truck fleet could switch to battery electric vehicles, with potentially more than 80% of the fleet switching to either hydrogen fuel cell electric vehicle or battery electric vehicles with strong technological improvements. Internal combustion engine vehicles persist in some medium- and large-passenger vehicle segments, but these account for less than 10% of the total light vehicle fleet in 2050.

FIGURE 3.13: Road passenger transport energy use in the modelled scenarios, by fuel type (2020 & 2050)



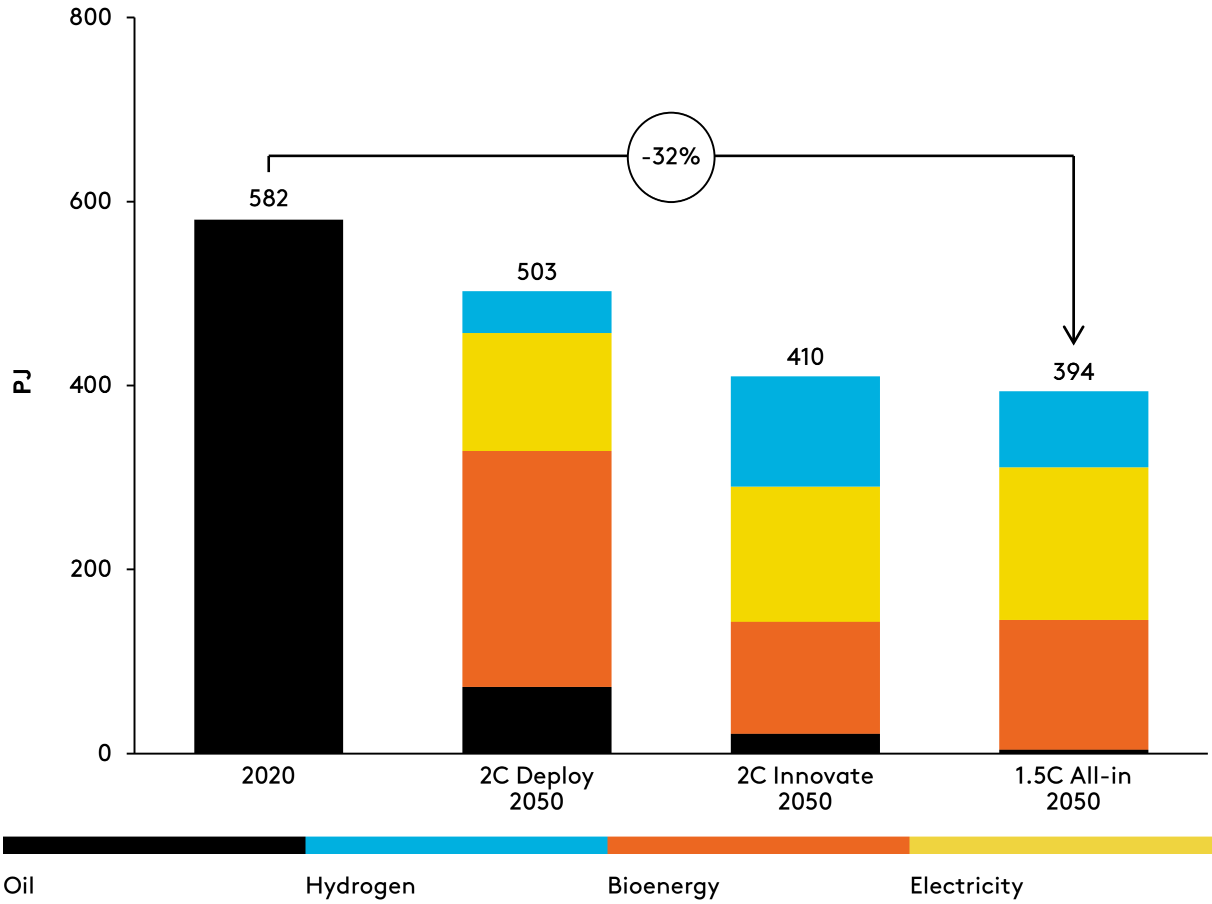
Technological developments and policy support could help road freight transport reach near-zero emissions in 2050 through shifts to renewable electricity, bioenergy and hydrogen.

In each of the scenarios, heavy road transport sees a reduction in energy use, a substantial shift to electricity, and a transition to zero-emissions fuel sources such as biofuels and renewable hydrogen (Figure 3.14). All scenarios see traditional fossil fuels such (as petrol and diesel) declining in road freight as renewable electricity and fuels dominate.

In the '2C Deploy' scenario, biofuels make up a larger share of the fuel mix for road freight relative to other scenarios.

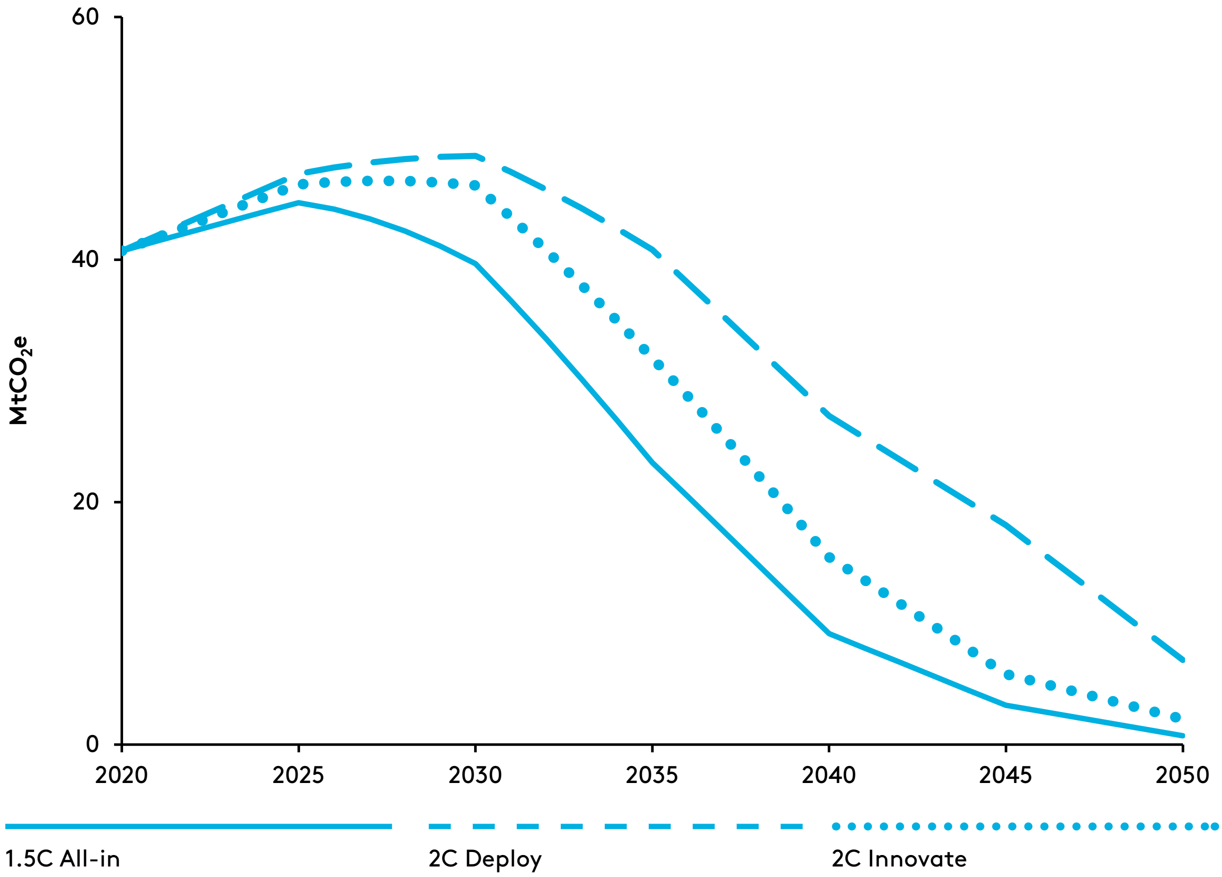
In the '2C Innovate' and '1.5C All-in' scenarios, road freight shows a more significant shift towards electricity and hydrogen, as technological improvements drive the cost of those options down compared to biofuels. In all scenarios there is a remaining portion of fuel use that is very hard to shift away from oil, particularly for certain high-volume, long-haul applications.

FIGURE 3.14: Road freight transport energy use in the modelled scenarios, by fuel type (2020 & 2050)



Emissions for the freight sector reduce in line with the volume of oil consumption. Road freight emissions reach near-zero by 2050 across all modelled scenarios (Figure 3.15) with the uptake of renewable electricity and fuel sources.

FIGURE 3.15: Road freight transport emissions in the modelled scenarios (2020-2050)



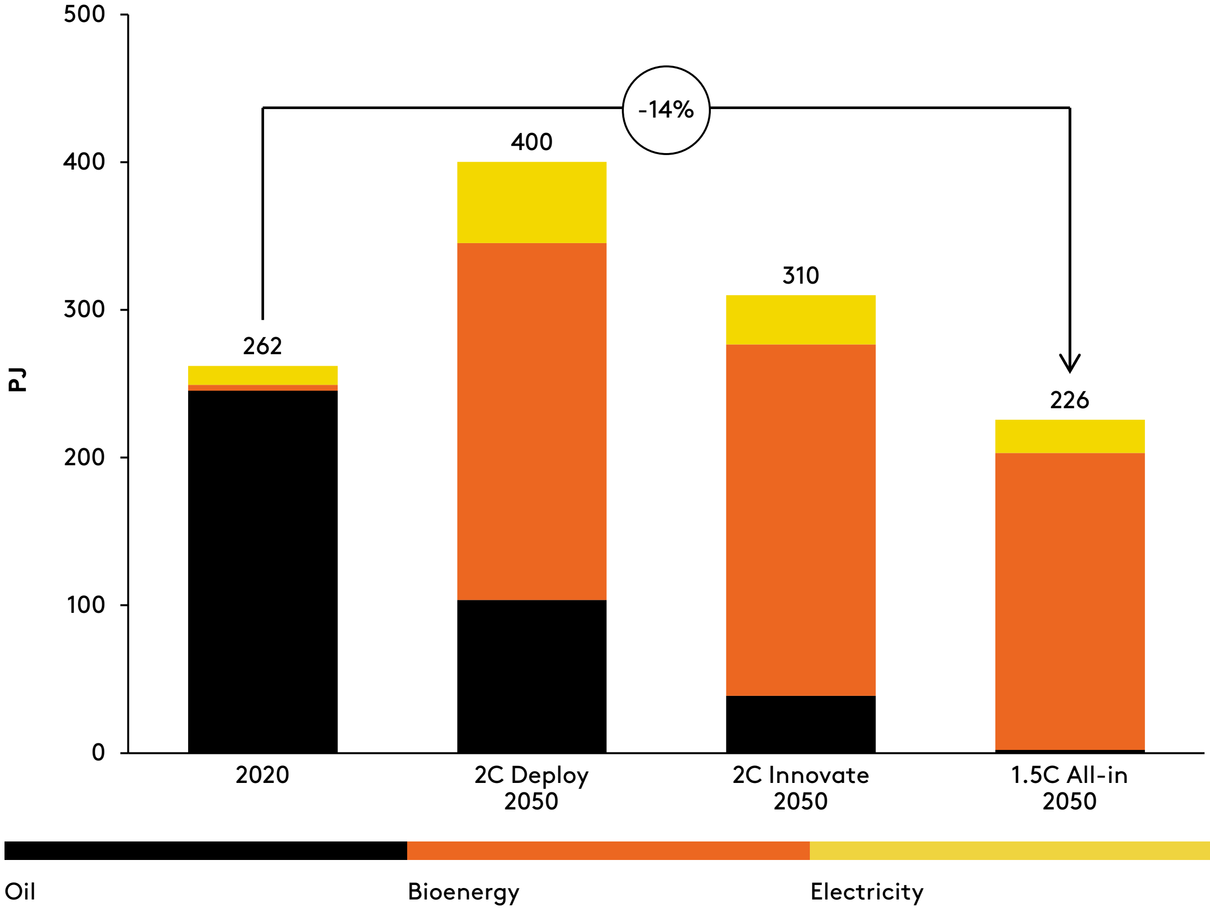
Energy-efficiency improvements, renewable-fuel cost reductions and demand shift can help significantly reduce emissions in aviation and shipping.

Demand for aviation, shipping, rail and other transport services is expected to increase with population and economic growth, making the task of reducing the energy and emissions intensities of these services vital to achieve zero-emissions transport.

The '1.5C All-in' scenario shows the significant effect that vehicle design and performance improvements, alongside reduced demand through shifting to more efficient transport modes such as public transport and rail freight, can have on fossil fuel use.

In '1.5C All-in', fuel use in non-road transport decreases by 2050 relative to current levels despite increased demand for non-road transport services (Figure 3.16). The importance of energy efficiency is reinforced when comparing the '2C Deploy' and '2C Innovate' scenarios, where, despite a broadly similar fuel mix in 2050, overall demand for energy is around 23% lower in '2C Innovate', driven by the assumed faster rates of technological improvements and cost reductions.

FIGURE 3.16: Non-road transport energy use in the modelled scenarios, by fuel type (2020 & 2050)

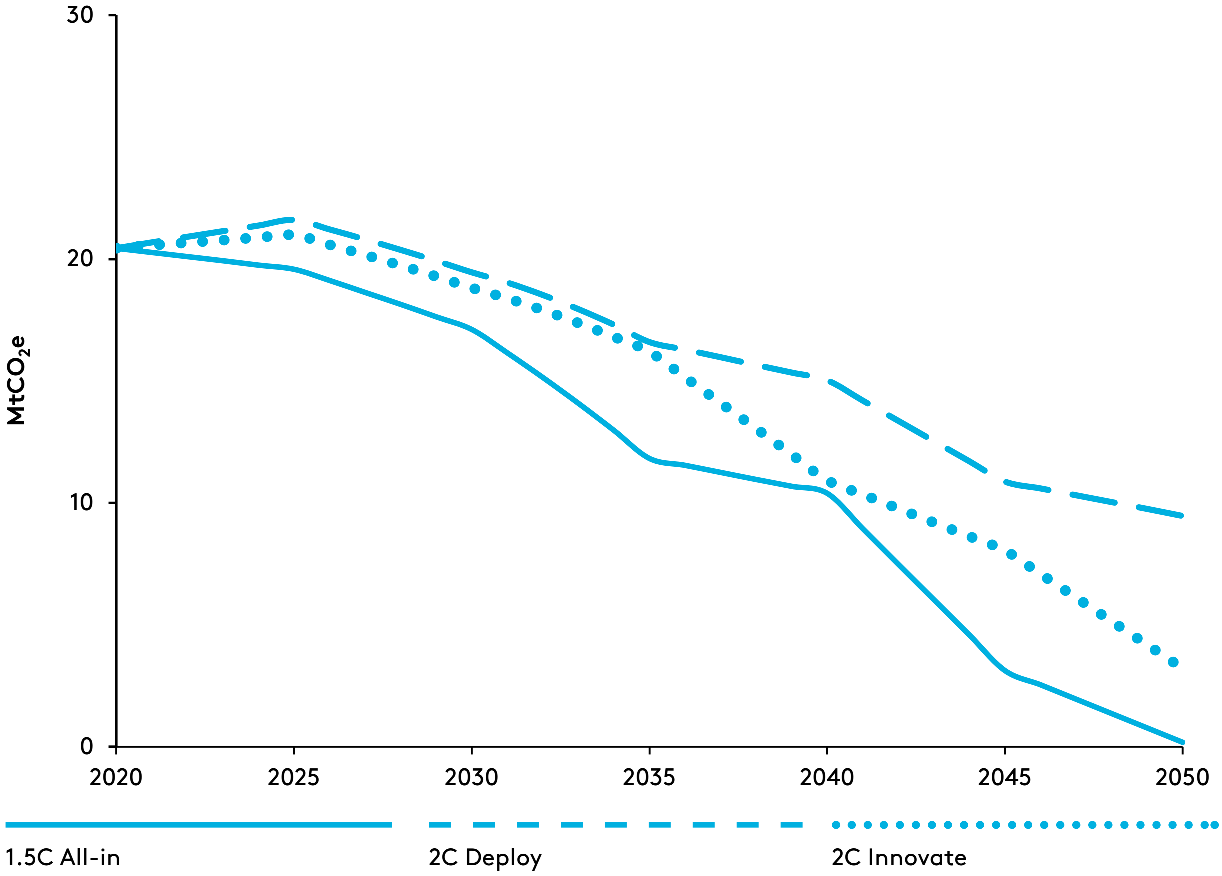


The use of zero-emissions fuels matters, particularly in domestic aviation (Box 3.3). Aviation currently accounts for more than half of all non-road transport energy use, and relies exclusively on oil products. In all modelled scenarios, domestic aviation makes a significant shift to biofuels. In the '1.5C All-in' scenario, biofuels almost completely displace oil products by 2050, due to strong policies that drive the cost competitiveness of zero-emissions fuels compared to oil-based fuels. In the '2C Deploy' and '2C Innovate' scenarios, some remaining oil use is modelled for domestic aviation, although this declines by more than 70% by 2050 on current levels. Biofuels are also the primary modelled solutions for domestic shipping and other transport services, replacing fossil fuels in all scenarios. Rail freight relies on a more even mix of biofuels and electricity by 2050, completely decarbonising in 2035, 2040 and 2045 in the '1.5C All-in', '2C Innovate' and '2C Deploy' scenarios respectively.

Electrification is also likely to play a role in other non-road segments. All scenarios see an increase in electricity use by 2050, led by a shift to electricity in rail freight. Due to a lack of available data on cost and performance, this modelling exercise excluded some emerging technology developments in the electrification of short-haul air and shipping, as well as the use of hydrogen and ammonia in shipping.

The combined impact of reduced demand for energy-intensive transport services, improved vehicle efficiency and zero-emissions fuels is demonstrated by the emissions trajectory of non-road transport in Figure 3.17.

FIGURE 3.17: Non-road transport emissions in the modelled scenarios (2020-2050)



BOX 3.3: MODELLING ZERO-EMISSIONS FUELS IN *DECARBONISATION FUTURES*

In sectors of the economy where electrification may be more technologically challenging, expensive or impractical, other zero-emissions fuels can be used in order to achieve emissions reductions. *Decarbonisation Futures'* modelling suggests the transport and industry sectors are likely to be the most challenging to fully electrify, and that these will be likely to rely on significant uptake of alternatives to displace fossil fuel sources.

Currently, bioenergy (such as liquid biofuels and solid biomass) are the most technologically mature and well-understood of these alternative energy sources. Given current land use trade-offs associated with production of first-generation sources, bioenergy is more likely to be produced using second- and third-generation feedstocks. While estimates of the potential quantity of biomass available in Australia by 2050 vary (ClimateWorks Australia, 2014), the levels of bioenergy consumption in this modelling are estimated to be compatible with recent biomass availability studies (Crawford *et al*, 2015).

Other solutions (such as synfuels, hydrogen and ammonia) are emerging, and could be significant. In most sectors, *Decarbonisation Futures'* modelling only considers fuel switching to electricity or bioenergy, due to issues of research scope, data availability, and uncertainties concerning future costs of those options (such as hydrogen use in industrial and commercial settings). Road transport – both passenger and freight – is an exception, where hydrogen is included in the modelling, due to greater data availability on technologies and costs of fuel cell vehicles.

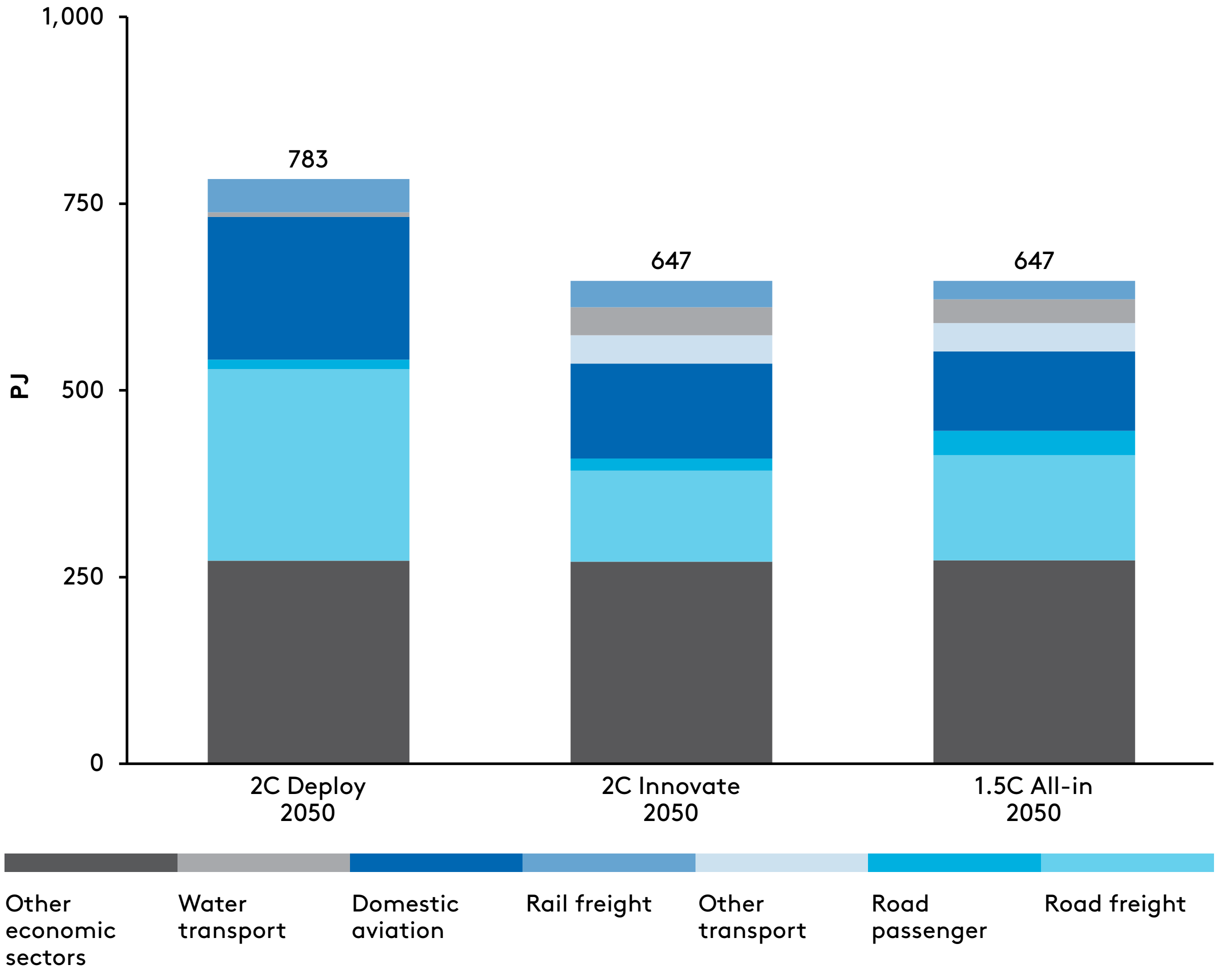
In reality, the future energy mix of industry and transport is likely to be a combination of these alternative fuels. In particular, enthusiasm for a hydrogen economy in Australia is growing significantly. Several studies have outlined the opportunity for a hydrogen export market (ACIL Allen Consulting for ARENA, 2018; Bruce *et al*, 2018; Garnaut, 2019; Ueckerdt *et al*, 2019), and a National Hydrogen Strategy was recently adopted by the Council of Australian Governments Energy Council (Commonwealth of Australia, National Hydrogen Strategy, 2019). As more research and data emerges, these developments will be incorporated in future modelling processes, such as the Australian Industry Energy Transitions Initiative (see Box 3.2).

This modelling should not, then, be interpreted as predicting one zero-emissions energy source over another. Rather, modelled bioenergy can be thought of as analogous to any future mix of zero-emissions fuels, with the magnitude of fuel use indicative of the research, development and deployment task required. Supplying the amount of bioenergy suggested by the *Decarbonisation Futures* modelling would be subject to numerous practical considerations.

TRANSPORT AS AN EXAMPLE:

In all scenarios, modelled bioenergy in transport accounts for more than half of the total use throughout the economy (Figure 3.18). This is primarily used in non-road sectors such as domestic aviation, and other transport, services and storage. In these sectors, electrification is not included in the modelling, but the technology and policy settings of the scenarios improve the prospects for zero-emissions fuels relative to fossil fuels, particularly oil. Road freight also accounts for a significant amount of bioenergy use, reflecting the challenges of fully electrifying trucks carrying heavy loads over long distances.

FIGURE 3.18: Bioenergy use in transport and other sectors in the modelled scenarios (2050)



3.4. INDUSTRY

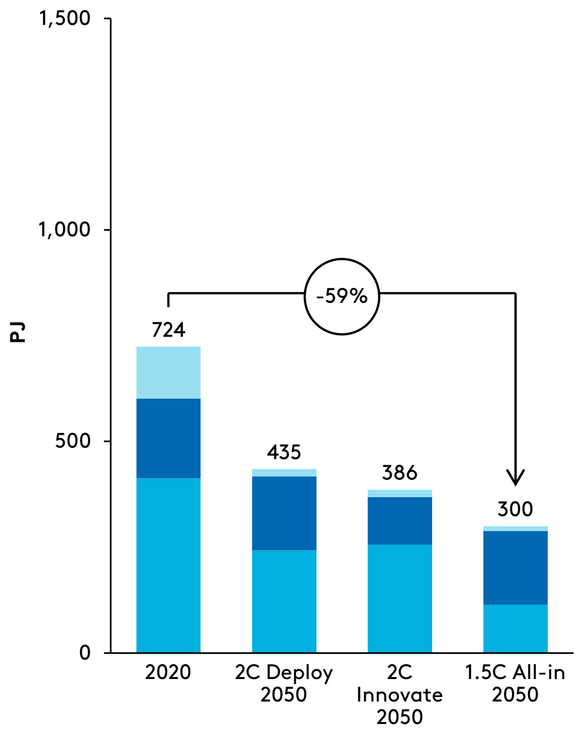
TABLE 3.6: Benchmarks of progress towards net zero emissions by 2050, industry

BENCHMARK	2C PATHWAYS		1.5C PATHWAY	
	2030	CHANGE versus 2020	2030	CHANGE versus 2020
TECHNOLOGY BENCHMARKS				
Share of electricity in energy used for steel production	16-20%	2020 = 11%	27%	2020 = 11%
% clinker in cement	45-75%	2020 = 75%	15%	2020 = 75%
Share of new large buildings built using timber	7-20%	2020 = negligible	20%	2020 = negligible
ENERGY BENCHMARKS				
Total energy use	1684-1785 PJ	4-10% decrease	1580 PJ	15% decrease
Share of electricity and zero-emissions fuels in total energy use	30-32%	2020 = 25%	33%	2020 = 25%
EMISSIONS BENCHMARKS				
Total industry emissions	141 $MtCO_2e$	40% decrease	120 $MtCO_2e$	49% decrease
+ Extractive sectors emissions	67-71 $MtCO_2e$	36-39% decrease	56 $MtCO_2e$	49% decrease
+ Manufacturing and other sectors emissions	70-74 $MtCO_2e$	40-43% decrease	63 $MtCO_2e$	49% decrease

Improvements in energy and material efficiency, combined with the uptake of other circular economy principles, drives significant energy use reductions in the industry sector.

Table 3.6 and Figure 3.19 (below) show the changing energy profile of key industry sectors observed in the modelled scenarios, which are impacted by a range of solutions depending on assumptions about technology, policy and business and individuals. The overall trajectory of industry energy use throughout the modelled period is shown in Figure 3.20. In all scenarios, total energy use in industry declines – most significantly in the '2C Deploy' and '1.5C All-in' scenarios, where it is driven by reduced demand for fossil fuel commodities (see Box 3.4), combined with technological improvements such as automation, artificial intelligence, 3D printing and electrification. In the '2C Innovate' scenario, energy use is slightly lower than '1.5C All-in' for certain commodities. This is due to the inclusion of international impacts such as circular economy principles, and reduced demand for primary production of raw materials due to plastic and metal recycling (international impacts were not included in the '1.5C All-in' scenario).

FIGURE 3.19: Mining (left) and manufacturing and other industry (right) energy use in the modelled scenarios, by subsector (2020 & 2050)



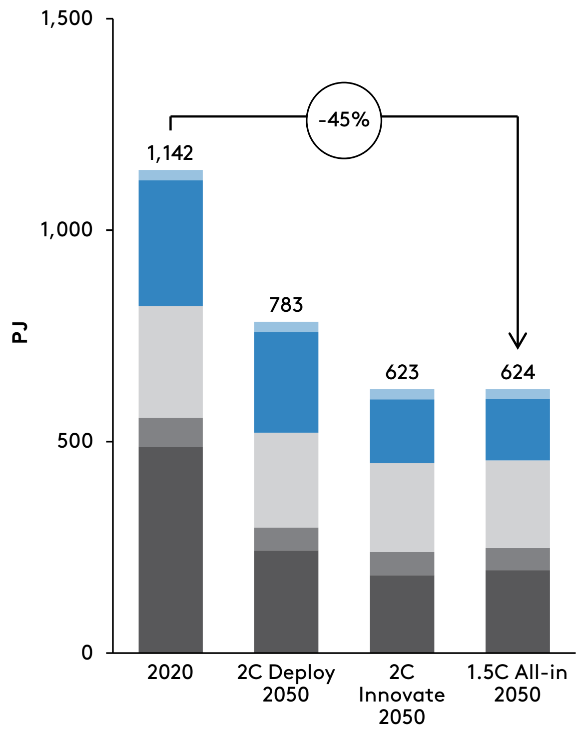
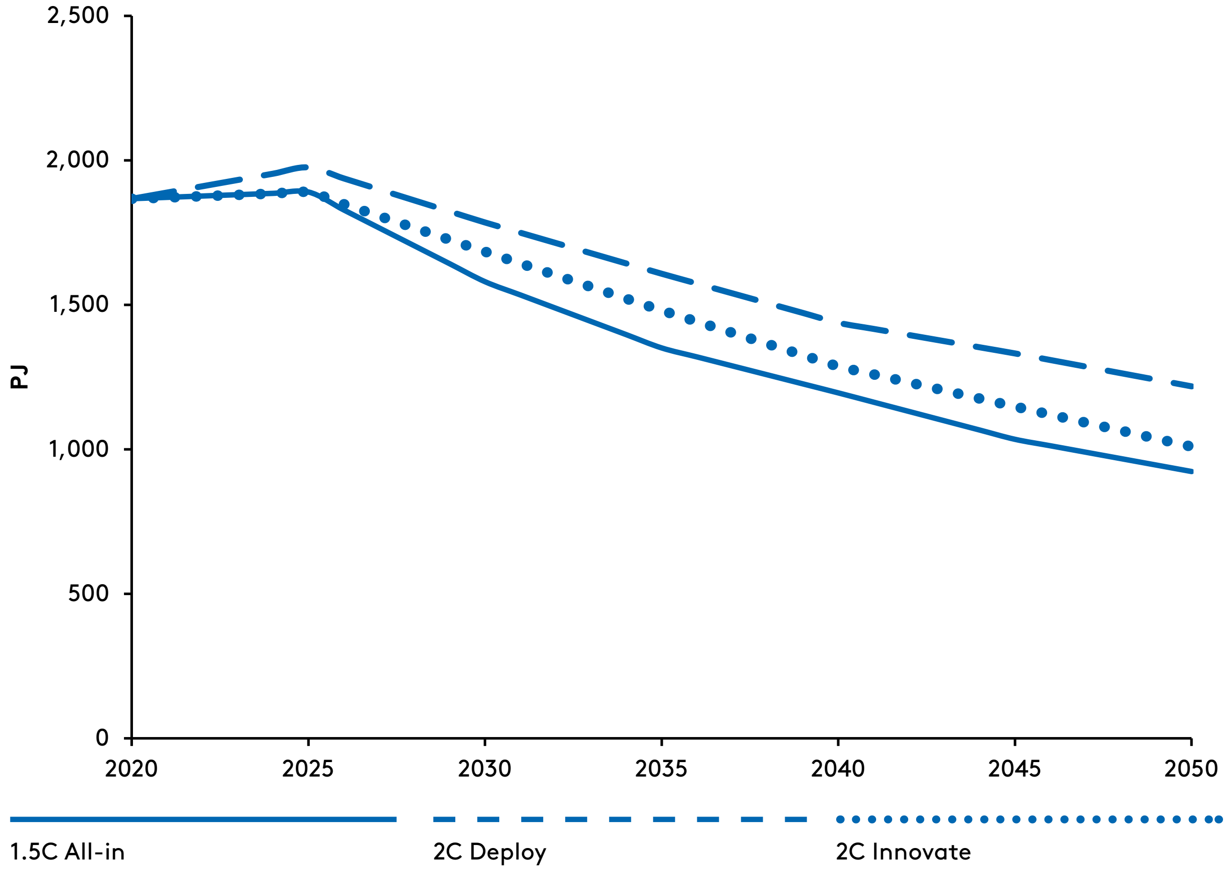


FIGURE 3.20: Industry energy use in the modelled scenarios (2020-2050)



BOX 3.4: TREATMENT OF ENERGY EXTRACTION INDUSTRIES IN *DECARBONISATION FUTURES* MODELLING

CURRENT CONTEXT AND FUTURE OUTLOOK OF AUSTRALIAN ENERGY COMMODITIES

The extractive resources sector, of which energy commodities are a large component, is economically significant in Australia. Most of Australia's energy commodities market consists of exporting fossil fuels in the form of thermal coal, metallurgical coal and LNG. Australia is the world's leading exporter of coal (IEA, 2019e) and LNG (EnergyQuest, 2020), with China, India, Japan, Korea and Taiwan the primary markets (Department of Industry, 2019b).

As Australia is a net exporter of energy (DoEE, 2019c), demand from highly competitive global markets will be a significant driver of future Australian production levels. It is commonly accepted that without dramatic improvements in the economics of CCS, any effort to significantly limit global warming will require the phasing-out of fossil fuels such as coal, gas and oil. A recent report from the Intergovernmental Panel on Climate Change (IPCC) estimated that for a 2-degree compatible pathway, global emissions from fossil fuels need to decline by around 2% per year, while a 1.5-degree compatible pathway would require emissions reductions of approximately 6% per year (Rogelj *et al*, 2018).

Within this context of necessary emissions reductions, the future demand for different fossil fuels will depend on many factors. One of these is the end-use of particular products, and how readily they can be reduced or replaced with other energy sources or production inputs. For example, renewable electricity generation is already cost-competitive with fossil fuels (see Section 2.2). Combined with falling costs of battery storage, this provides an alternative to the use of coal and gas in power generation globally. Thermal coal is also used for high-heat industrial applications such as cement production, while metallurgical coal is used in the manufacture of iron and steel. Gas has a range of applications throughout the economy, and is commonly used in residential, commercial and industrial heating and cooling. Gas and oil are also used as an input to produce many chemical products such as plastics and fertilisers. In these applications, oil and gas are more difficult to replace than in fuel combustion. Sections 2.3-2.5 outline the prospects for electricity and zero-emissions fuels to replace coal and gas for some or all of these energy and production inputs. Australia's major trading partners have also signalled that they are exploring other ways to meet their energy needs for various economic, health, environmental and energy security reasons (Drew, 2014).

Due to a lower emissions intensity than coal, gas is sometimes considered a potential 'transition fuel', suitable for bridging the gap left by reductions in more emissions-intensive fuels such as coal or oil (ETC, 2018). Recent studies have, however, questioned this assertion for a range of reasons (SEI, IISD, ODI, Climate Analytics, CICERO, and UNEP, 2019):

+ Methane-leakage emissions from natural gas systems, particularly unconventional gas, are not consistently measured and often significantly underestimated, and could counterbalance the reduced emissions at the combustion stage
+ Rapid advances in renewable energy and battery technologies and declining costs indicate there is little need for gas in electricity generation
+ Recent research found there is little or no room for new gas, coal or oil reserves to be developed under the Paris Climate Agreement. This is because production from existing and committed fossil fuel infrastructure already exceeds the carbon budget for 1.5 degrees Celsius (Tong *et al* 2019).

Regarding methane-leakage emissions, numerous studies conclude that the climate benefits of gas replacing coal are lost where fugitive emissions from all upstream operations exceed 3% of total production (Zavala-Araiza *et al*, 2015, Schandl *et al*, 2019). National emissions data suggests that this could be the case for several of Australia's gas fields, in particular if recent indications that industrial methane emissions have been underestimated by up to 40% (Hmiel *et al*, 2019) are confirmed.

TREATMENT OF ENERGY COMMODITIES IN *DECARBONISATION FUTURES* MODELLING

A globally-integrated economic modelling approach was beyond the scope of *Decarbonisation Futures*. Instead, assumptions were made regarding the prospects for fossil fuel extraction and trade in a global context compatible with 2 and 1.5 degrees Celsius of warming, based on the available literature. For the '2C Deploy' and '2C Innovate' scenarios, the IEA's Sustainable Development Scenario (IEA, 2018b) was considered the most appropriate analogue for global coal and gas demand, while for the '1.5C All-in' scenario, aggregated projections from 1.5-degree scenarios in the IPCC scenario database (Rogelj *et al*, 2018) were used. Some high-level assumptions were then made about the future demand for Australian production of energy commodities, based on current production levels and broad projections of demand from Australia's major trading partners (again drawing on the IEA's Sustainable Development Scenario (IEA, 2018b)).

This methodology bears similarities to that undertaken in a recent publication *The Production Gap* (SEI, IISD, ODI, Climate Analytics, CICERO, and UNEP, 2019), leading to broadly aligned results. For further information on the calculation approach, see the *Decarbonisation Futures: Technical report*.

Under these assumptions, Australian coal production declines by 61% between 2020 and 2050 in the '2C Deploy' and '2C Innovate' scenarios, and 74% in the '1.5C All-in' scenario. In all scenarios, metallurgical coal accounts for around three-quarters of residual coal production in 2050. These results reflect the retirement of all domestic coal-fired power generation, reductions in global thermal coal demand, and other solutions (such as metal recycling and electric arc furnace steelmaking removing a significant amount of demand for coking coal). This is evident in Figure 3.19, where energy use declines to near-zero for coal mining in all scenarios.

For gas mining and LNG production, global demand rises until around 2025, declining steadily thereafter across all scenarios. In the '2C Deploy' and '2C Innovate' scenarios, 2050 production levels are 4% lower than 2020, and 56% lower in the '1.5C All-in' scenario. As Australian gas mining and LNG production is largely driven by export markets, the considerable difference in a 1.5-degree compatible pathway is indicative of both a deeper and faster global transition away from fossil fuels, including gas.

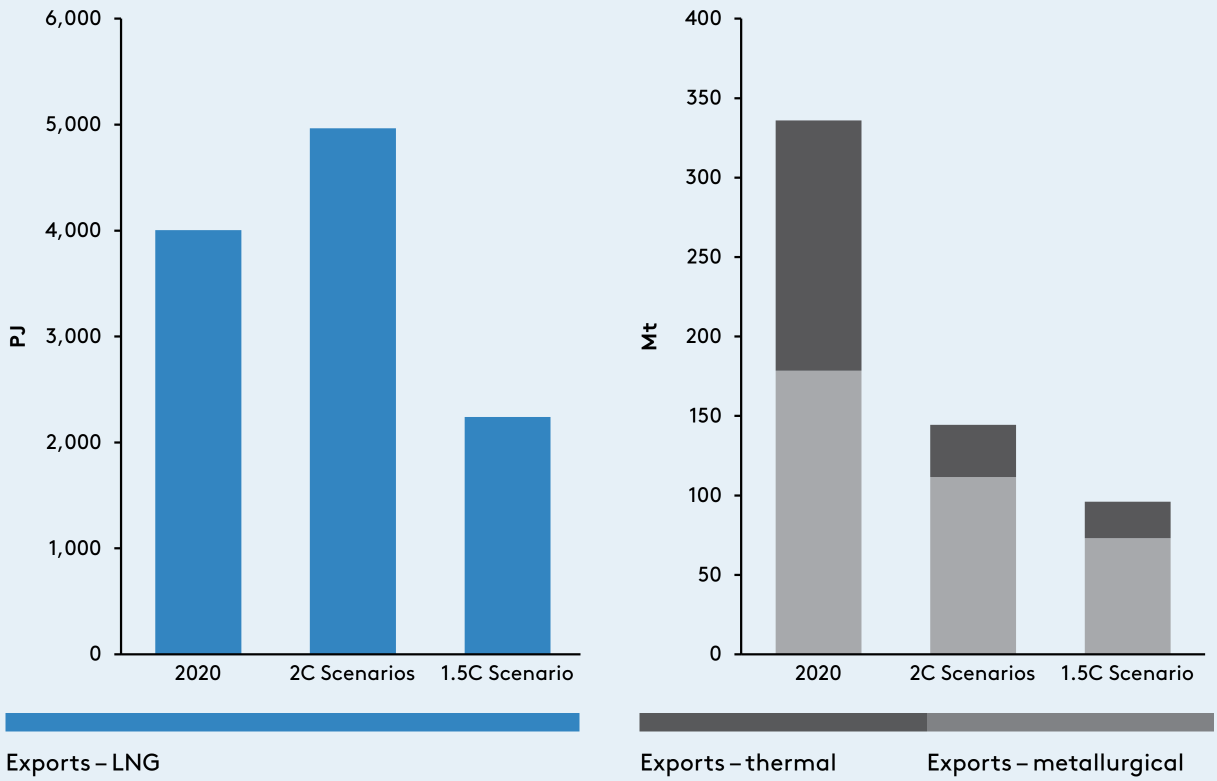
This decreased production (driven predominantly by global demand), combined with energy-efficiency improvements and liquefaction electrification (Section 2.5), leads to significant reductions in energy use for gas mining and LNG production (Figure 3.21).

Given Australia's current reliance on exporting fossil fuels, reduced global demand for fossil fuel commodities of the magnitude suggested by these figures would pose significant economic challenges for the Australian economy and require careful transition planning. As discussed in Box 3.2, the scope of modelling in *Decarbonisation Futures* is limited by resource and information constraints. As such, this report explores possible futures for the Australian economy based on its current structure, and does not include the entry of new industries and global markets in the modelling. For example, if a major renewable hydrogen export market was established in Australia, it could make use of the infrastructure, human capital and trade networks that might otherwise feel the impacts of declining fossil fuel production.

The National Hydrogen Strategy estimated that Australia is very well placed to capture a significant share of the future clean hydrogen market, thanks to its resources and experience (Commonwealth of Australia, National Hydrogen Strategy, 2019). It estimates that the contribution to GDP of this new energy export market could be between $11 and $26 billion per year by 2050. It could also generate over 17,000 new jobs.

Ross Garnaut also finds that if Australia takes appropriate measures to decarbonise its economy, it could become a 'global superpower in energy, low carbon industry and absorption of carbon in the landscape' (Morton, 2019).

FIGURE 3.21: Australian exports of gas (left) and coal (right) in the modelled scenarios



Electrification and fuel switching could help most industrial processes achieve zero emissions by 2050.

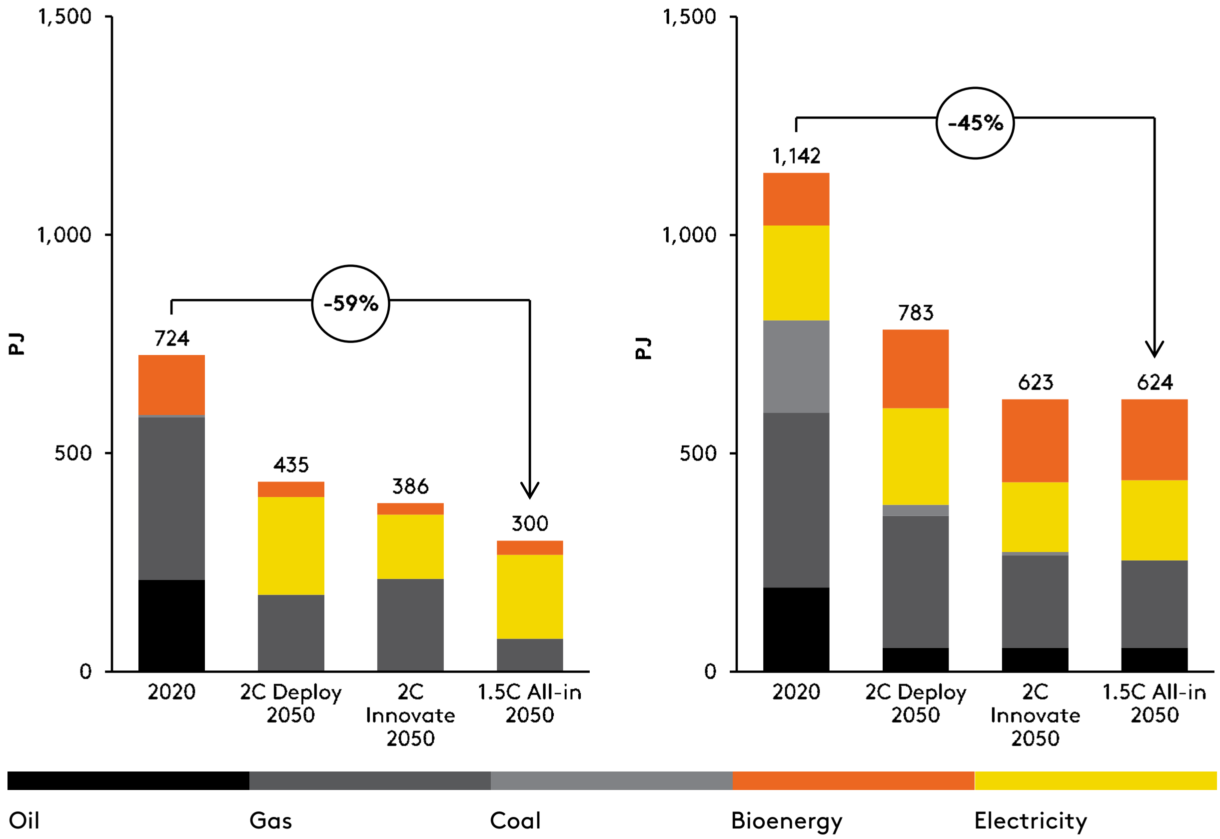
Figure 3.22 shows the changing fuel profile of industry in the modelled scenarios. Consistent across all scenarios is a significant reduction in total energy use, and a shift to higher proportions of low- or zero-emissions fuels in meeting this demand.

The proportion of electrical-energy use in industry rises strongly in all scenarios – increasing from around 19% of total energy use in 2020 to a 2050 level of 41% in the '1.5C All-in' scenario. Mineral extraction and processing accounts for the greatest proportion of industrial electricity use – particularly in the alumina and non-ferrous metal sectors – while electrification of LNG liquefaction also grows strongly. Other industrial sectors, such as iron and steel and light manufacturing, also see strong increases in electricity use, using technologies such as electric arc furnaces, electric boilers, induction and microwave heating. The combination of renewable electricity and full electrification offers the possibility of achieving zero emissions for subsectors such as aluminium and iron and steel.

Increases in the use of zero-emissions fuels such as bioenergy could deliver additional emissions reductions. Bioenergy is particularly well suited for high-heat applications that are close to a supply of cheap source material. Across the scenarios, modelled bioenergy use increases from approximately 6% of total energy use in 2020 to up to 24% of total energy use in the '1.5C All-in' scenario.

Despite significant shifts to electricity and bioenergy, considerable residual use of fossil fuels is evident across the scenarios. In mining, the majority of fossil fuel use and emissions in 2050 are due to continued production and exports of LNG. In manufacturing and other industrial sectors, emerging solutions such as the use of hydrogen in primary steel production and other high-heat industrial applications could be significant, but such technologies are not included in the modelling due to the lack of data on their potential cost and performance.

FIGURE 3.22: Mining (left) and manufacturing and other industry (right) energy use in the modelled scenarios, by fuel type (2020 & 2050)

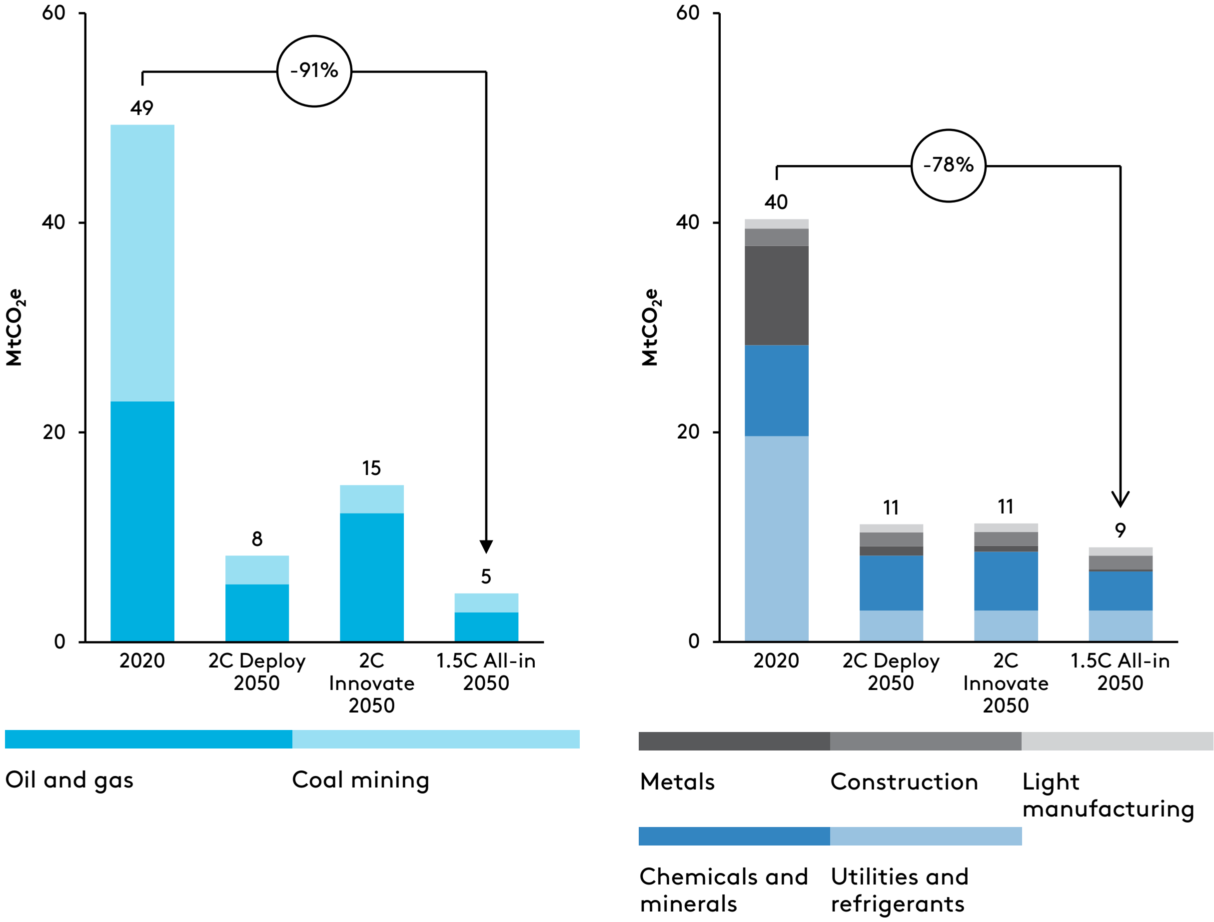


There is potential to significantly reduce non-energy emissions in key industrial sectors.

As non-energy emissions comprise such a large share of overall industry emissions, implementing solutions to address them is vital to achieving meaningful emissions reductions. Non-energy emissions decline significantly in all scenarios and industrial sectors. Fugitive emissions from mining see the largest decrease (Figure 3.23), heavily reliant on the use of CCS in oil and gas extraction, and ventilation air methane oxidation in coal mining. The impact of these technologies is greatest in the '2C Deploy' and '1.5C All-in' scenarios due to strong policy driving higher uptake of CCS (Figure 3.24).

Industrial process emissions are also reduced by more than 70% in all scenarios (Figure 3.23, right), with the largest impact in '1.5C All-in' due to the combination of strong technology and policy drivers. In particular, the use of catalysts in chemical production and inert anodes in aluminium production decreases process emissions in these sectors in all scenarios. In the '2C Innovate' and '1.5C All-in' scenarios, the use of geopolymer cement unlocks further non-energy emissions reductions.

FIGURE 3.23: Mining (left) and manufacturing and other industry (right) non-energy emissions in the modelled scenarios, by subsector (2020 & 2050)



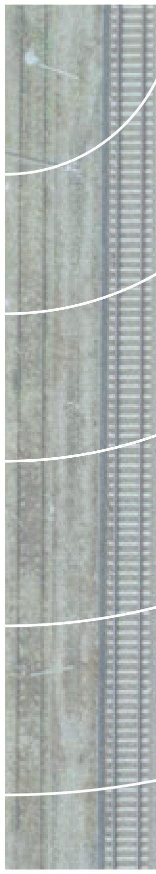
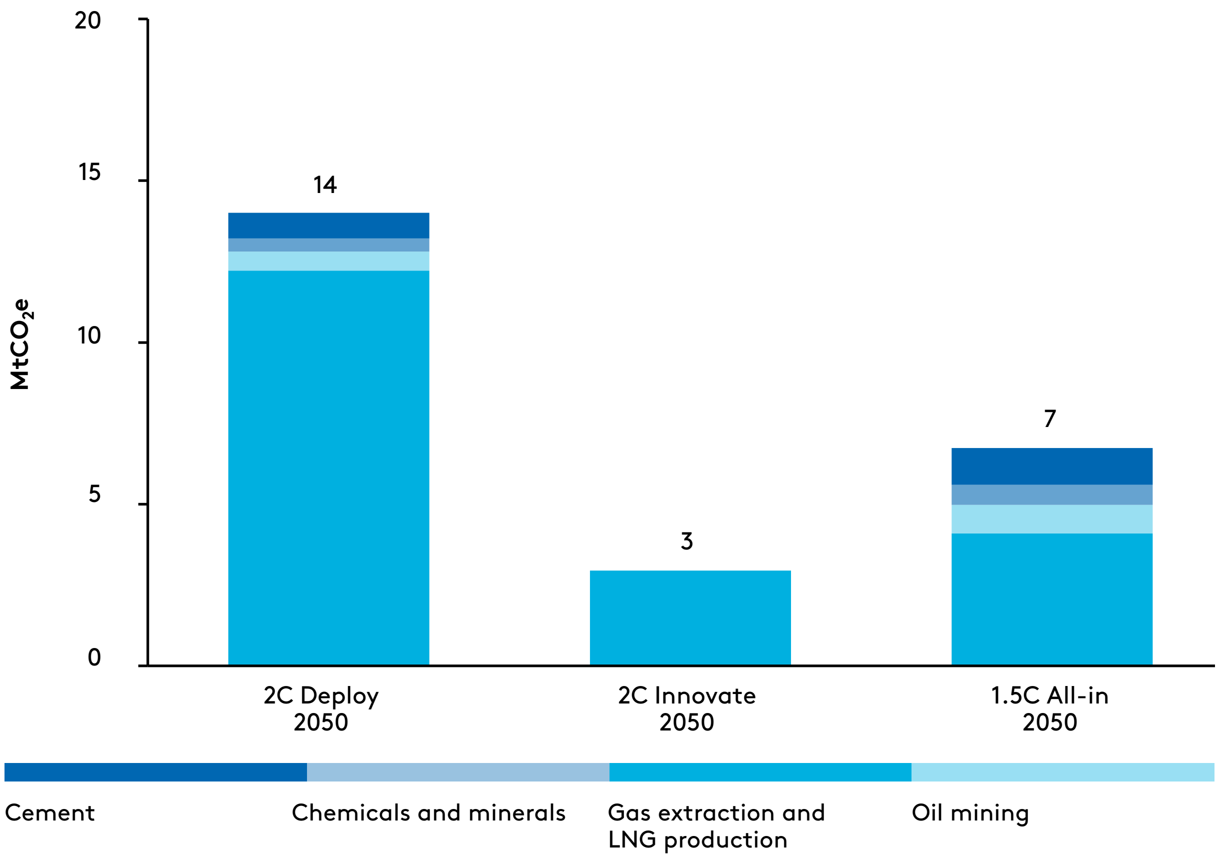
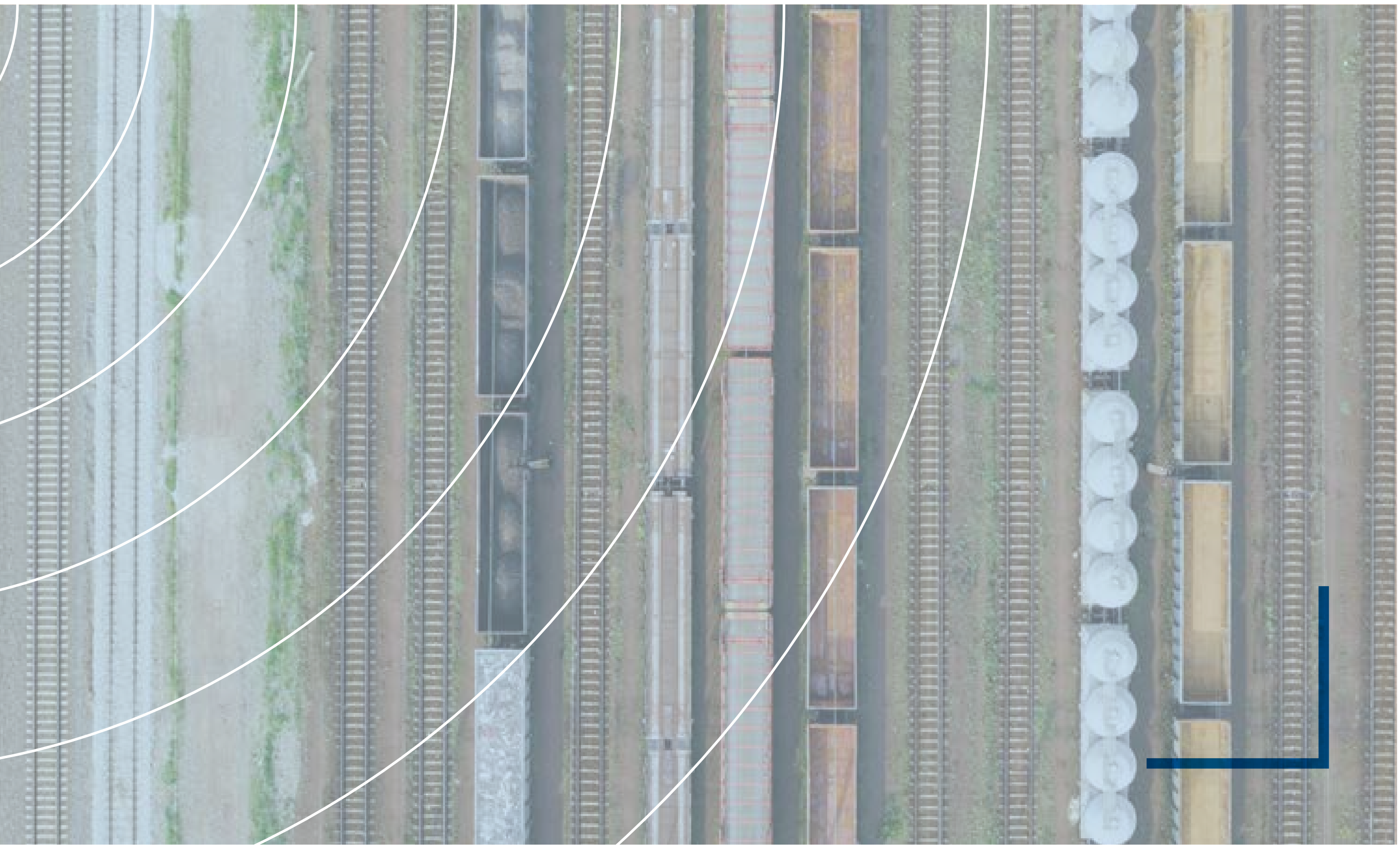


FIGURE 3.24: Industry carbon capture and storage in the modelled scenarios (2050)





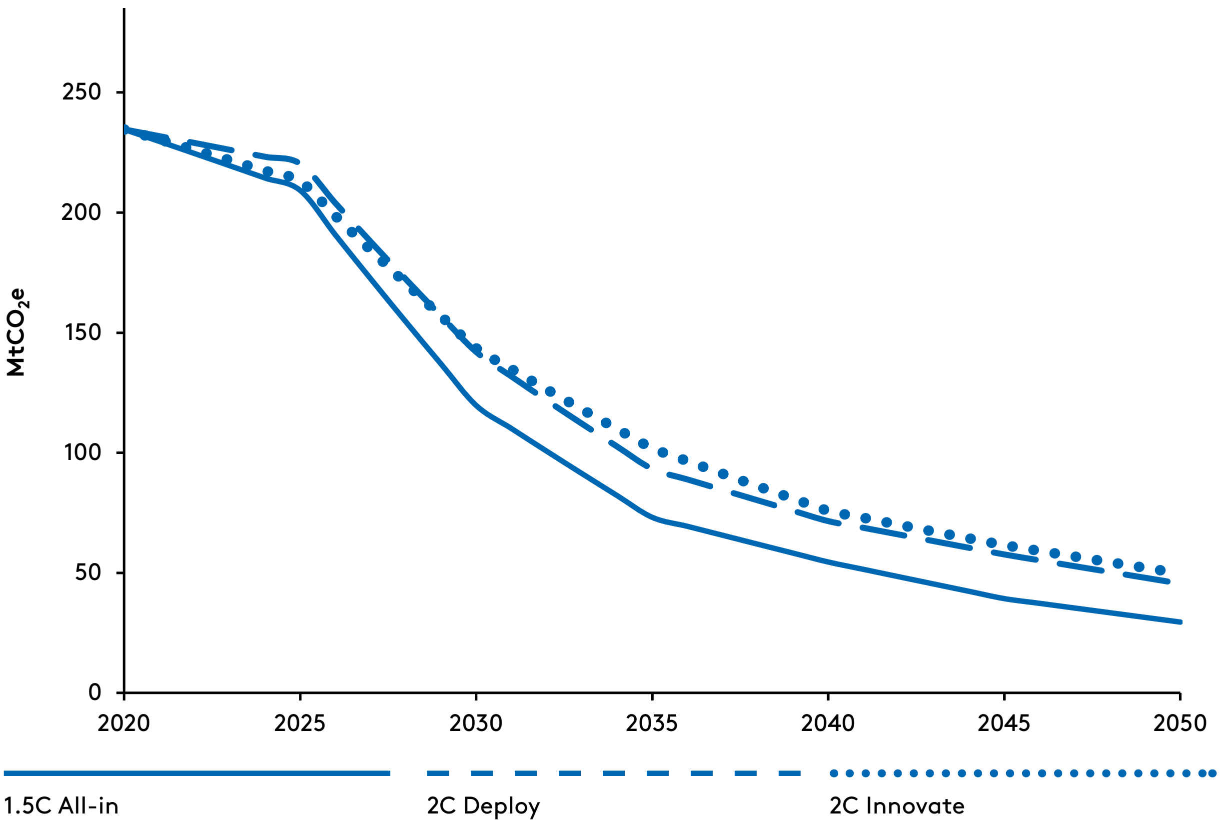
Substantial emissions reductions are achieved for industry in all scenarios, but significant challenges remain to achieve zero emissions by 2050.

Strong emissions reductions are achieved across all scenarios, and up to 87% by 2050 in the '1.5C All-in' scenario (Figure 3.25). The '2C Innovate' scenario sees the least emissions reductions (79% by 2050), mostly due to the relatively lower levels of CCS in oil and gas extraction discussed above. The '1.5C All-in' scenario sees the strongest emissions reductions, driven by improvements in electrification, energy efficiency and CCS, and material efficiency, recycling and substitution. It is worth noting, however, that there is significant uncertainty around the cost and competitiveness of these different technology options.

While results vary at the subsector level (Figure 3.26), chemicals and continued LNG production and exports present challenges to reaching zero emissions in all scenarios. This is due largely due to the difficulty of eliminating non-energy emissions in these sectors, particularly with lower levels of CCS in the '2C Innovate' scenario.

Subsectors which can be electrified can achieve very strong emissions intensity reductions – for example, iron and steel, or metals and minerals extraction. This reinforces the importance of renewable electricity in unlocking the decarbonisation of end-user sectors such as industry.

FIGURE 3.25: Industry emissions in the modelled scenarios (2020-2050)



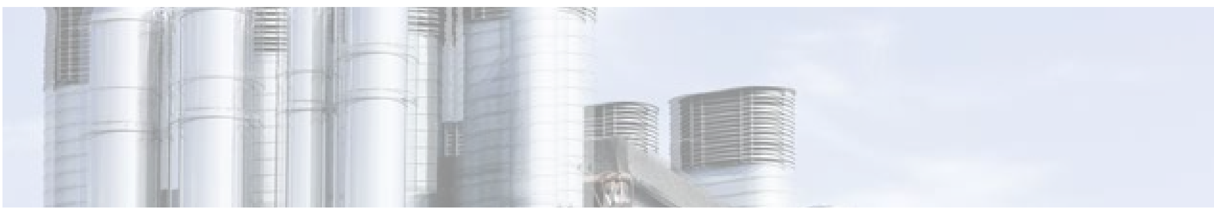
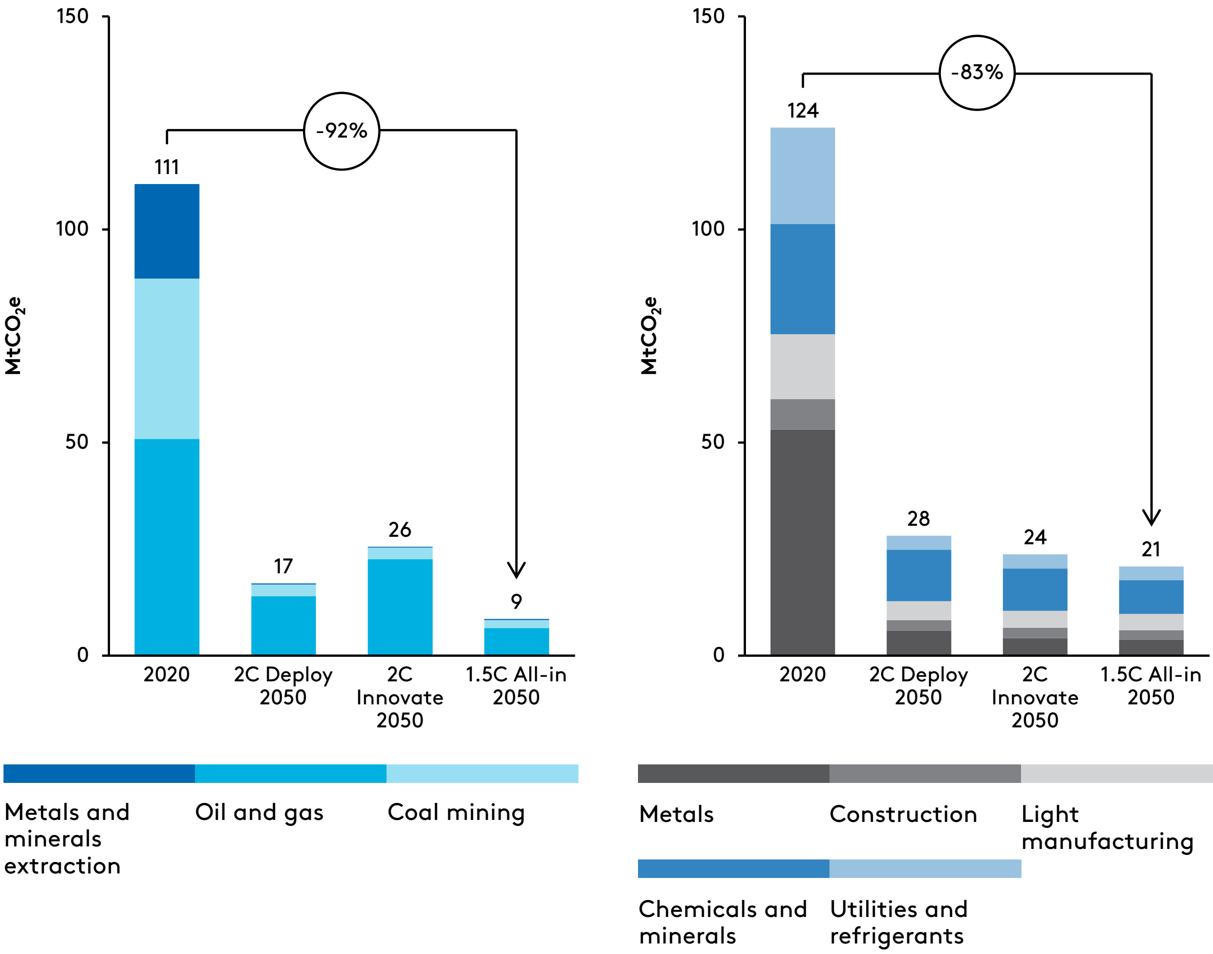
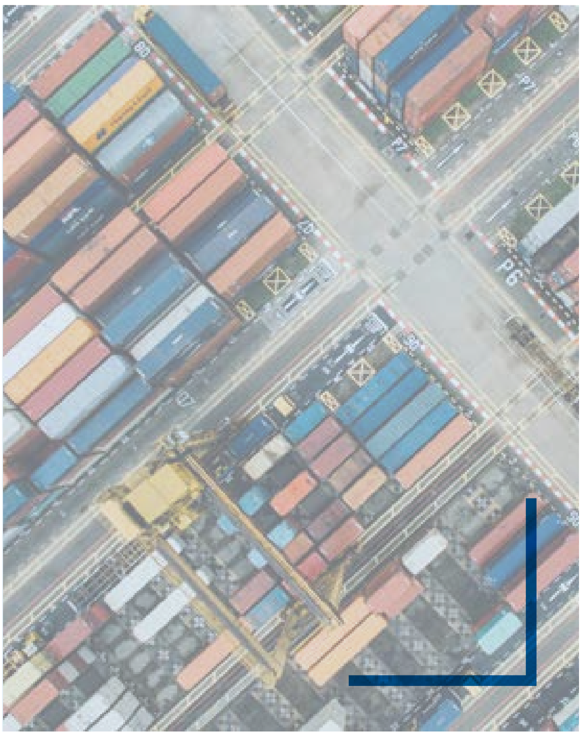


FIGURE 3.26: Mining (left) and manufacturing and other industry (right) total emissions in the modelled scenarios, by sector (2020-2050)



Most of the subsectors with large residual emissions are those that use fossil fuel as a feedstock rather than a fuel, and those that have significant non-energy emissions. These results highlight the significance of policy in reducing emissions for hard-to-abate sectors such as oil and gas extraction and LNG production, and the importance of further technological breakthroughs that do not rely on CCS. Shifting away from fossil fuel based energy exports towards renewable energy exports such as green hydrogen would also reduce emissions associated with these industrial processes.

To tackle the challenge of residual emissions, ClimateWorks and Climate-KIC are undertaking an industry-led initiative to develop pathways to net zero emissions supply chains across critical, hard-to-abate sectors in Australia (Box 3.2).



3.5. AGRICULTURE AND LAND

TABLE 3.7: Benchmarks of progress towards net zero emissions by 2050, agriculture and land

BENCHMARK	2C PATHWAYS		1.5C PATHWAY	
	2030	CHANGE versus 2020	2030	CHANGE versus 2020
TECHNOLOGY BENCHMARKS				
Carbon forestry	~ 5 Mha plantings		~ 8 Mha plantings	
EMISSIONS BENCHMARKS				
Agriculture and land emissions	37-75 $MtCO_2e$	6-54% decrease	34 $MtCO_2e$	57% decrease
+ Livestock emissions	19-53 $MtCO_2e$	5-66% decrease	18 $MtCO_2e$	69% decrease
+ Other agriculture emissions	18-22 $MtCO_2e$	7-24% decrease	16 $MtCO_2e$	31% decrease
+ Carbon forestry sequestration	31-45 $MtCO_2e$ sequestration		112 $MtCO_2e$ sequestration	

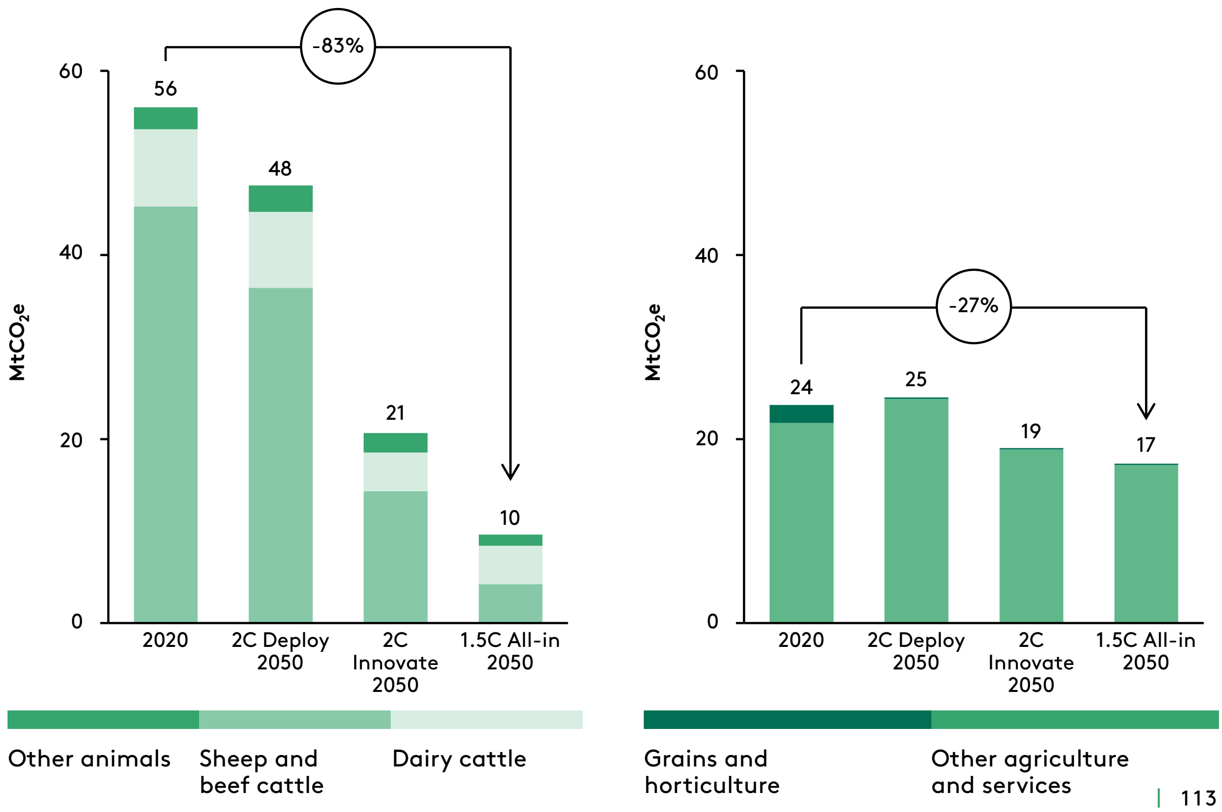
Technological breakthroughs and change driven by businesses and individuals can significantly reduce livestock emissions by 2050, but challenges such as non-energy emissions from grains and horticulture production must also be addressed.

Given that livestock emissions represent around 70% of agricultural emissions, reducing these sources will have the most significant effect on overall sector emissions. If emerging technological solutions – such as algae feeds and vaccines for cattle and lab-grown meat – are developed and deployed at scale, they could help significantly reduce emissions by 2050. Non-technical solutions – such as reduced food waste across the supply chain and shifts towards less emissions-intensive meat products – could also achieve large livestock emissions reductions, facilitated by support from businesses and individuals (Table 3.7).

This is visible in the '2C Innovate' and '1.5C All-in' scenarios, which achieve, respectively, 63% and 83% reduction in livestock emissions, due to a combination of technical and non-technical solutions (Figure 3.27). By contrast, the '2C Deploy' scenario includes only limited technological and societal change. As a result, emissions are relatively flat throughout the modelled period, roughly cancelling out the sector's growing activity. The '2C Deploy' scenario sees some emissions reductions from enteric fermentation solutions, but these are limited to around 40% of the reductions achieved in the '1.5C All-in' scenario, due to lower technological innovation.

Emissions intensity of grains, horticulture and other agriculture improves in all scenarios, driven primarily by nitrification inhibitors targeting non-energy emissions from fertiliser, combined with precision agriculture and automation improving energy efficiency. Technology is important in unlocking these solutions, with emissions-intensity improvements in the '2C Innovate' and '1.5C All-in' scenarios more than offsetting growth in production and leading to a net decrease in emissions by 2050 (Figure 3.27). Due to a weaker technology driver, emissions from non-livestock sectors increases slightly in the '2C Deploy' scenario.

FIGURE 3.27: Livestock (left) and grains, horticulture and other agriculture (right) emissions in the modelled scenarios, by sub sector (2020 & 2050)



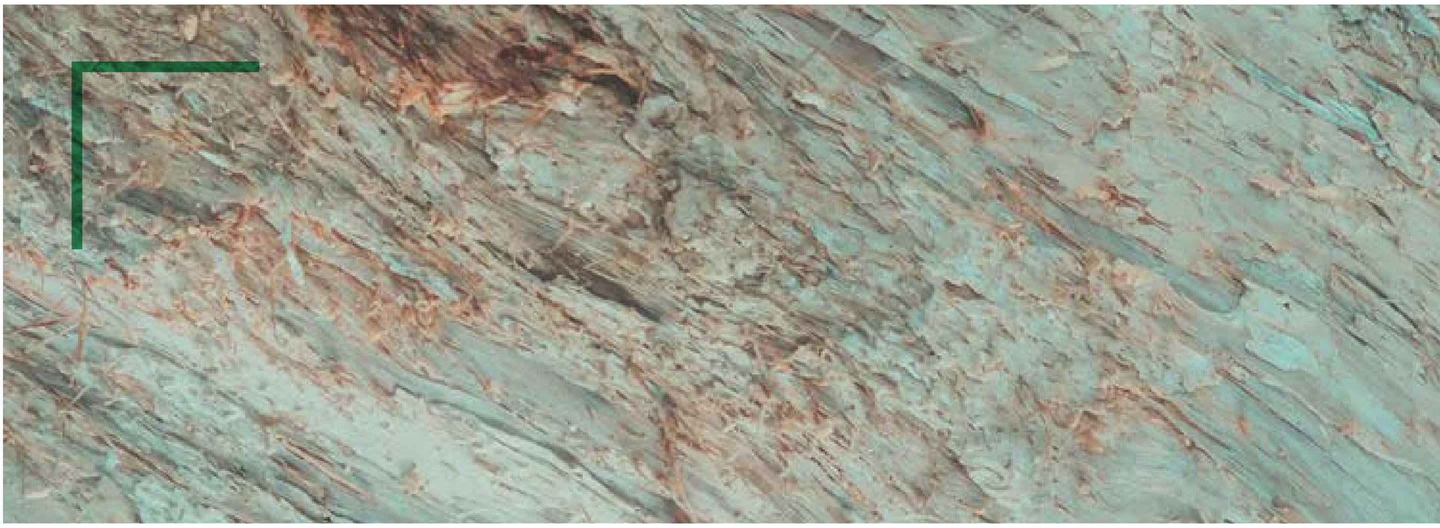
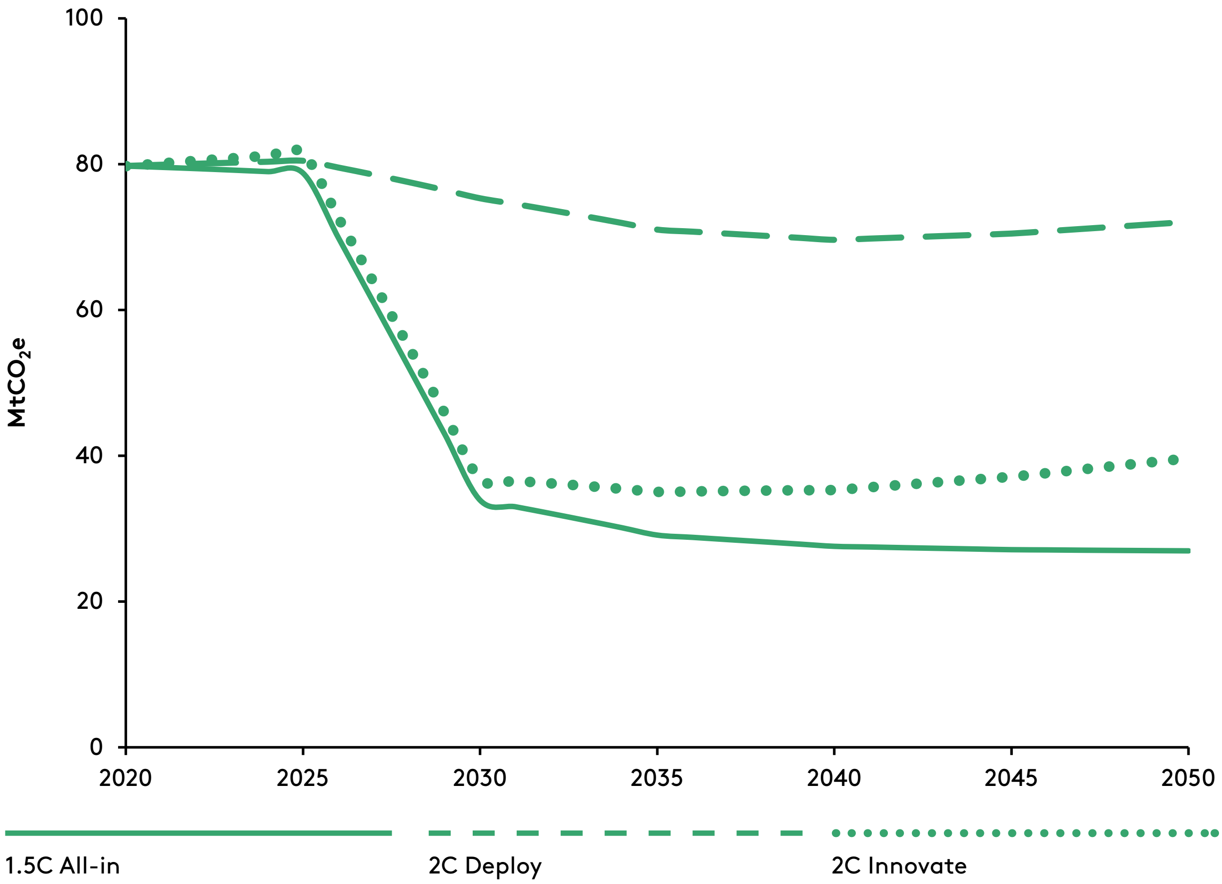
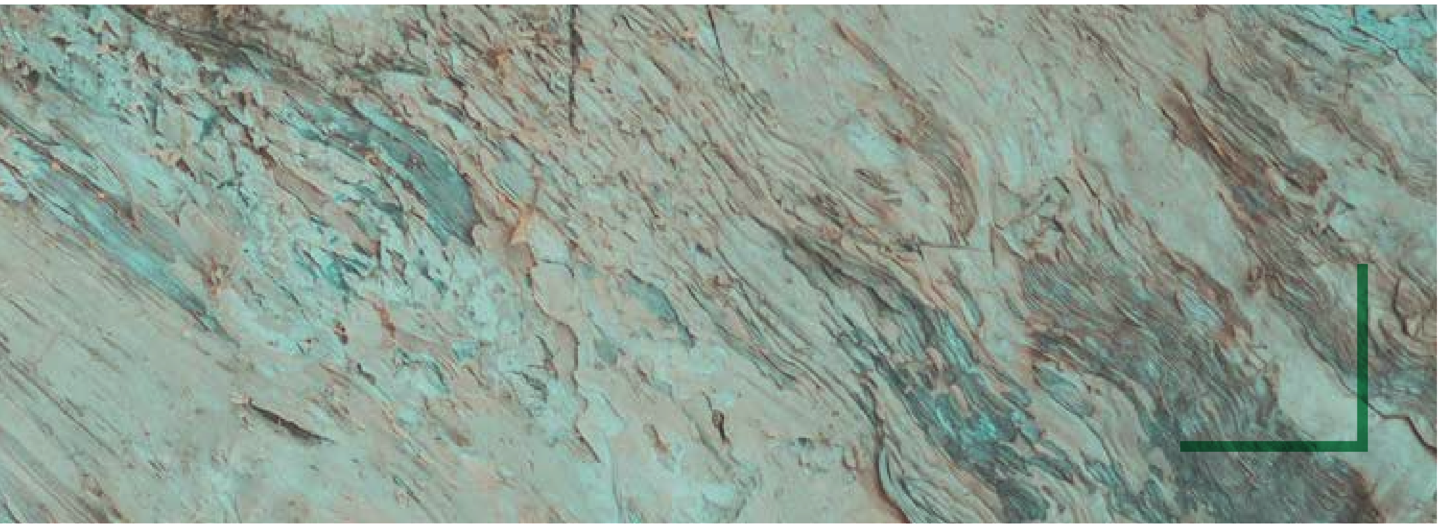


FIGURE 3.28: Agriculture emissions in the modelled scenarios (2020-2050)



The trajectory for agricultural emissions in the modelled scenarios is shown in Figure 3.28. Around 2025, technological innovations such as enteric fermentation treatment have the most significant impact in the '2C Innovate' and '1.5C All-in' scenarios. This leads to a sharp decline in emissions, which then levels off, growing in the '2C Innovate' scenario with increased production, and declining slightly in the '1.5C All-in' scenario due to the impact of the social drivers mentioned above. The emissions trajectory in the '2C Deploy' scenario does not show significant emissions reductions, a result that highlights technological innovation as the most important driver of emissions reductions in agriculture. Additionally, the challenge of significant residual emissions across all scenarios in 2050 highlights the need for further research and development to produce low-emissions agricultural commodities.



Australia's ample carbon forestry potential can help achieve net zero emissions, but this will need to be balanced against other land-use needs and its vulnerability to extreme weather such as bushfires and drought.

The potential amount of profitable carbon forestry in Australia was estimated at over 50 mega hectares[181] by CSIRO[182] (Brinsmead *et al*, 2019; Polglase *et al*, 2013) – around twice the land area of Victoria (approximately 23 mega hectares). This potential is more than enough to meet Australia's carbon budgets for 1.5- and 2-degree pathways. With the sectoral abatement modelled in the '2C Deploy' and '2C Innovate' scenarios, 137 and 96 MtCO_2e of carbon forestry is required, respectively, to reach net zero emissions by 2050 (Figure 3.29). This corresponds to 8-10 mega hectares of carbon forestry plantation by 2050 when accounting for profitability and planting constraints (ClimateWorks Australia, 2014).

Under the '1.5C All-in' scenario, strong sectoral emission reductions combined with higher planting rates of forestry allows net zero emissions to be reached 15 years earlier, consistent with a 1.5-degree pathway. By 2050, carbon forestry sequestration reaches 344 MtCO_2e in the '1.5C All-in' scenario, corresponding to about 24 mega hectares of plantation. This represents an estimate of the amount of sequestration which could help Australia return to a higher probability (67% chance) 1.5-degree carbon budget after overshooting it. While there is uncertainty around the overshoot-and-return mechanism, net-negative emissions only increases the chance of limiting warming to 1.5 degrees Celsius.

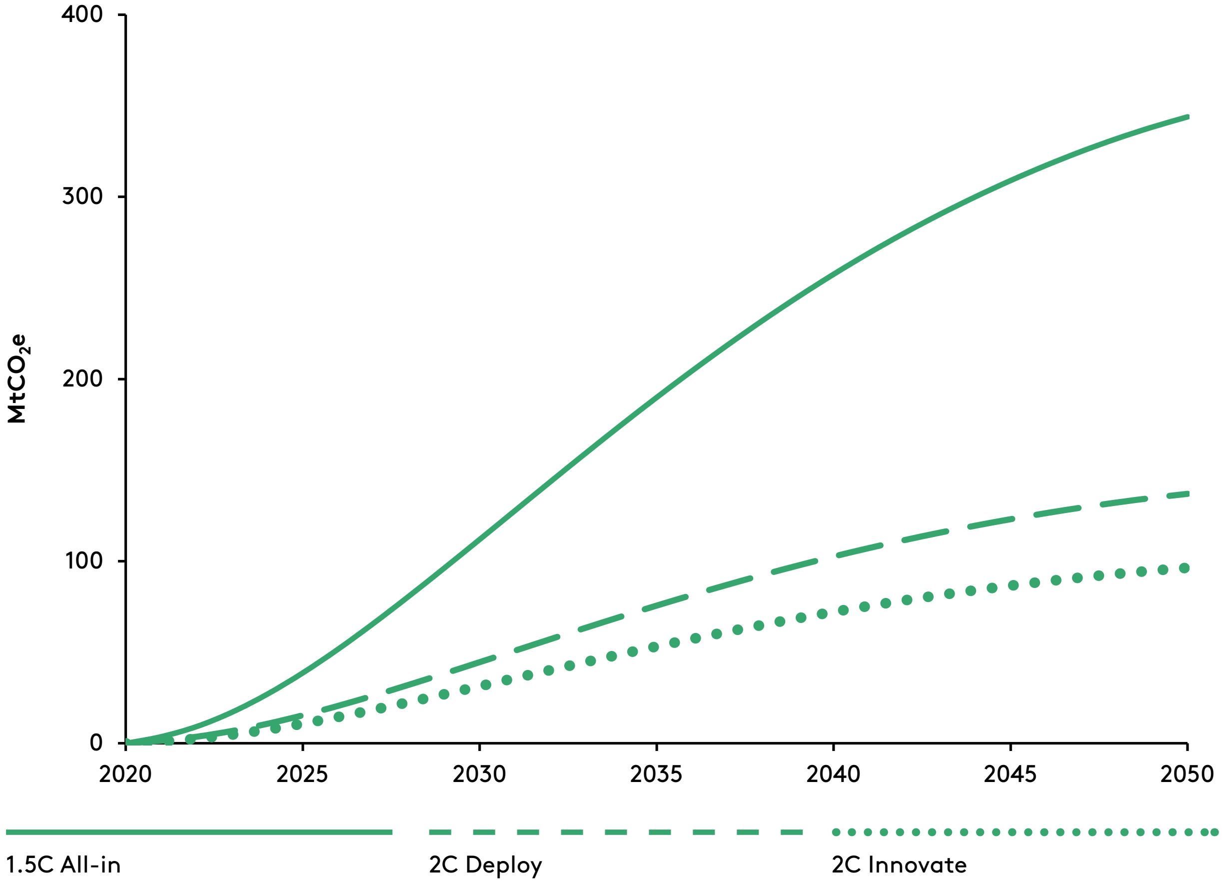
There are, however, considerable challenges and uncertainties when aiming to achieve high levels of sequestration through carbon forestry.

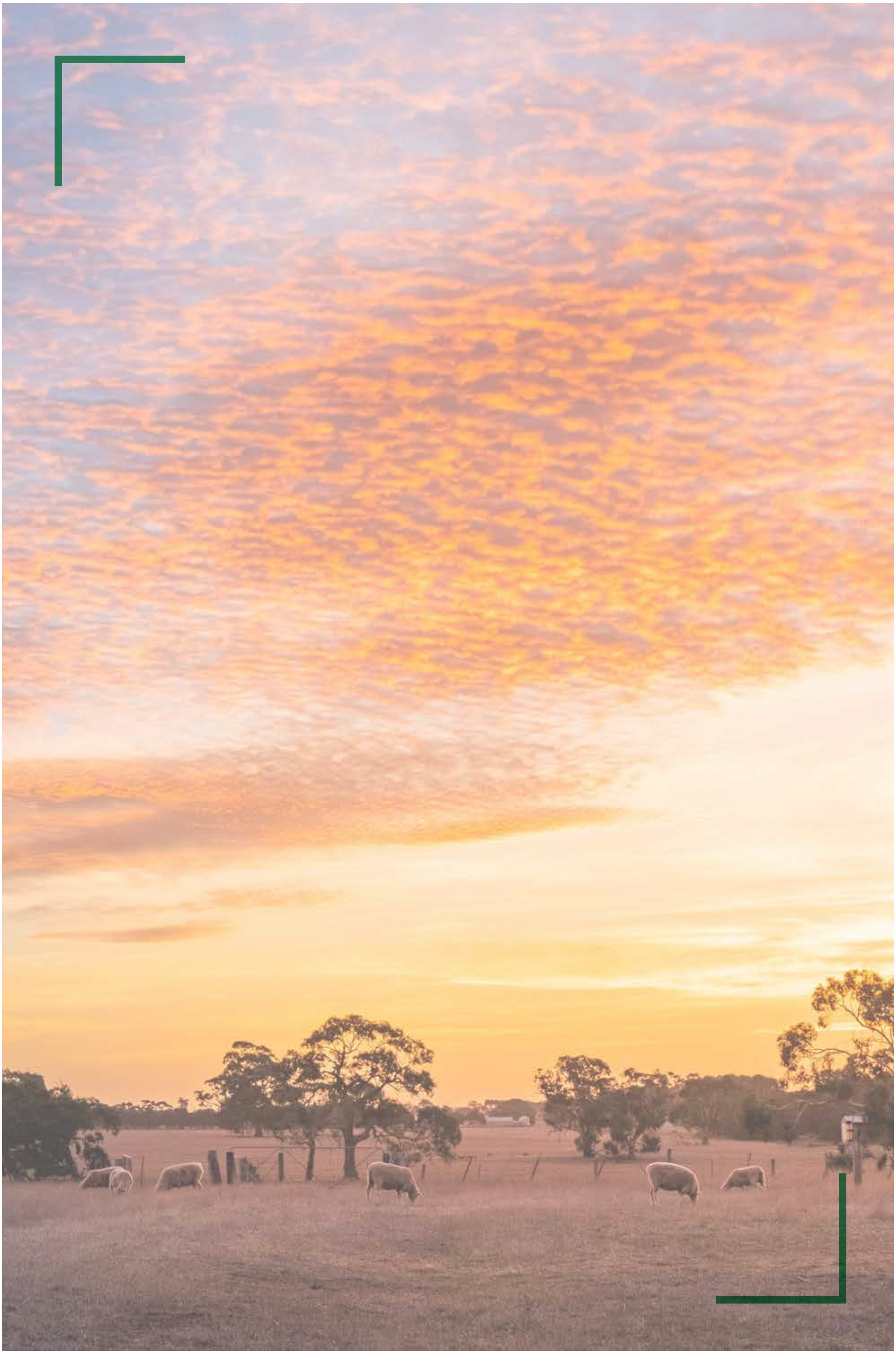
In particular, carbon forestry is vulnerable to increasingly extreme weather like bushfires, drought, heatwaves and storms. There will also be increasing competition for land to deliver food, fibre and environmental requirements. Although presented in the scenarios as a single sequestration source in carbon forestry, large-scale negative emissions may be possible from other, more diverse sources. Additionally, carbon forestry is an interim solution only. Maintaining Australia's emissions at net zero through offsets would depend on planting new trees each year to offset residual emissions in other sectors of the economy. In this regard, reducing emissions at their source and achieving a truly zero-emissions economy – rather than relying on carbon forestry to provide a significant carbon offset – is critical to staying within Australia's carbon budget in the longer term.

181 One mega hectare is equivalent to one million hectares

182 Under a range of scenarios modelling various carbon prices, establishment costs and discount rates

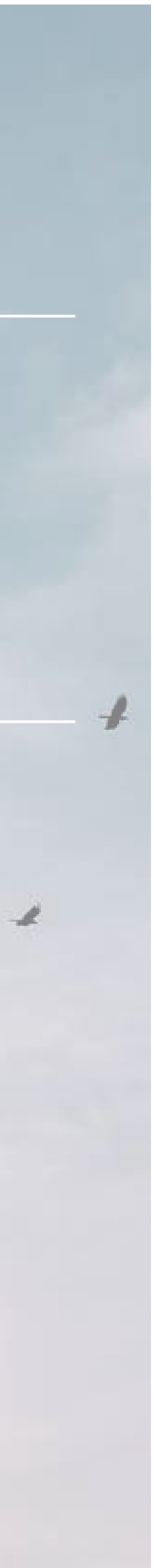
FIGURE 3.29: Carbon forestry sequestration in the modelled scenarios (2020-2050)





CONCLUSION

SECTION 04



The ongoing usage in the Australian economy of carbon emissions means that the fulfilment of commitments made under the Paris Climate Agreement requires an intensification of emissions-reduction efforts.

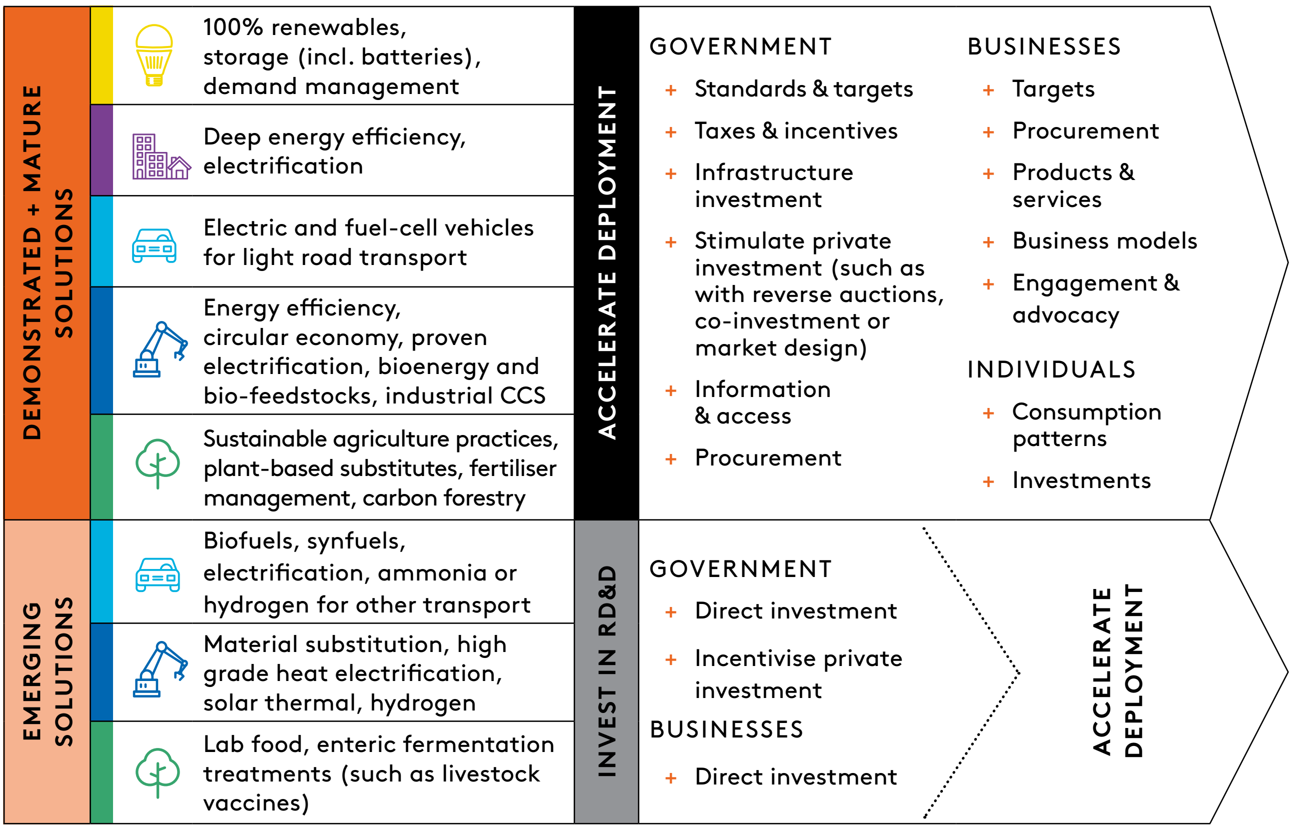
The pathway to a zero-emissions future has, in many respects, become clearer in recent years. As this report has emphasised, solutions such as renewable energy, energy storage and electric vehicles have developed unexpectedly quickly. These are now cheaper and more viable than had been anticipated. Many solutions are well-positioned for widespread adoption, with reductions in the cost of generation and storage exceeding even the most optimistic projections of the past.

The stable and reliable decarbonisation of electricity generation, through renewable energy and storage, opens up exciting possibilities, facilitating abatement in transport, buildings and industry. In several sectors, the technologies necessary for decarbonisation on the scale required by the Paris agreement already exist.

Decarbonisation Futures identifies the priority technologies and actions for achieving net zero emissions across all sectors of the Australian economy (Figure 4.1). It shows that Australia can still play its part in meeting the Paris climate goal of limiting global temperature rise to 2 degrees Celsius, and as close as possible to 1.5 degrees Celsius, by:

+ immediately accelerating the deployment of mature and demonstrated zero-emissions or best-available technologies,
+ rapidly developing and commercialising emerging zero-emissions technologies in hard-to-abate sectors.

FIGURE 4.1: Summary of emissions-reduction solutions and actions to support a transition aligned with the Paris goals



The scenarios in *Decarbonisation Futures* model significantly accelerated technology deployment and emissions reductions in the next decade compared to current trends, as shown in Tables 4.1 and 4.2.

TABLE 4.1: Benchmarks of progress towards net zero emissions by 2050, technology

TECHNOLOGY				
BENCHMARK	2C PATHWAYS		1.5C PATHWAY	
	2030	CHANGE versus 2020	2030	CHANGE versus 2020
Emissions intensity	220-252 tCO_2e/GWh	63-67% decrease	177 tCO_2e/GWh	74% decrease
Share of renewable electricity generation	70-74%	2020 = 25%	79%	2020 = 25%
New renewable capacity added between 2020 and 2030		24-28 GW added		29 GW added
New storage capacity added between 2020 and 2030		4-5 GWh added		5 GWh added
Rooftop solar electricity generation	22-26 TWh	85-116% increase	26 TWh	116% increase
Electric cars (battery electric vehicle and fuel cell electric vehicle)	50% of new-car sales, 15% of total fleet	2020 = <1% of sales and total fleet	76% of new-car sales, 28% of total fleet	2020 = <1% of sales and total fleet
Electric trucks (battery electric vehicle and fuel cell electric vehicle)	25-39% of new-truck sales, 8-13% of total fleet	2020 = <1% of sales and total fleet	59% of new-truck sales, 24% of total fleet	2020 = <1% of sales and total fleet
Volume of zero-emissions fuels (bioenergy and hydrogen)	83-111 PJ	171-265% increase	134 PJ	338% increase
Share of electricity in energy used for steel production	16-20%	2020 = 11%	27%	2020 = 11%
% clinker in cement	45-75%	2020 = 75%	15%	2020 = 75%
Share of new large buildings built using timber	7-20%	2020 = negligible	20%	2020 = negligible
Carbon forestry	~ 5 Mha plantings		~ 8 Mha plantings	

TABLE 4.2: Benchmarks of progress towards net zero emissions by 2050, energy

ENERGY				
BENCHMARK	**2C PATHWAYS**		**1.5C PATHWAY**	
	2030	**CHANGE versus 2020**	**2030**	**CHANGE versus 2020**
Total final energy use		3-8% decrease		16% decrease
Share of electricity and zero-emissions fuels in final energy use	31-32%	2020 = 23%	35%	2020 = 23%
Share of electricity in total energy	24%	2020 = 20%	27%	2020 = 20%
Residential building energy intensity		44-48% decrease (improvement)		49% decrease (improvement)
Commercial building energy intensity		16-25% decrease (improvement)		28% decrease (improvement)
Share of electricity in residential buildings	76-78%	2020 = 49%	75%	2020 = 49%
Share of electricity and zero-emissions fuels in transport energy	9-11%	2020 = 3%	16%	2020 = 3%
Share of electricity and zero-emissions fuels in road energy use	5-9%	2020 = 2%	17%	2020 = 2%
Fossil fuel use in non-road transport	226-233 PJ	5-8% decrease	203 PJ	17% decrease
Total energy use	1684-1785 PJ	4-10% decrease	1580 PJ	15% decrease
Share of electricity and zero-emissions fuels in total energy use	30-32%	2020 = 25%	33%	2020 = 25%

For instance, government figures project national emissions will decline by 16% on 2005 levels by 2030. In contrast, both the '2C Deploy' and '2C Innovate' scenarios benchmark a decrease of 48–53%, while the '1.5C All-in' scenario puts the figure at 74%. Likewise, government projections have Australia generating 48% of electricity from renewables by 2030, compared with 74% and 70% respectively in the '2C Deploy' and '2C Innovate' scenarios, and 79% in the '1.5C All-in' scenario.

Such examples reveal the extent of the challenge ahead.

Although the modelled benchmarks might seem ambitious, they are by no means impossible. To reach net zero emissions before 2050, Australia must accelerate the deployment of mature and demonstrated zero-emissions technologies, and quickly develop zero-emissions technologies in sectors facing greater challenges.

Those mature and demonstrated technologies include, in the electricity sector, demand management, the use of power produced from 100% renewable sources and a reliance on new storage capabilities; in the building sector, deep energy efficiency and electrification; in transport, electric and fuel cell vehicles for road and short-haul routes; in the industry sector, energy efficiency, circular economy principles, and industrial CCS; and in the agriculture and land sector, sustainable practices, plant-based substitutes, fertiliser management and carbon forestry.

The accelerated deployment of these solutions will require action from governments as well as from businesses and individuals. Governments can set standards and targets to encourage uptake of best-practice solutions; levy taxes on emissions-intensive activities and products; provide financial support to non-commercial solutions; and invest in relevant infrastructure. Governments can also improve information and accessibility to consumers; provide incentives for early development; create demand through government procurement; and de-risk private investments. Businesses can set targets for operations and supply chains, and create new models that accelerate the uptake of best-practice technologies. Individuals will be required to shift their behaviour and consumption preferences.

The plausible emerging technologies for hard-to-abate sectors include (for transport) biofuels, synfuels, ammonia or hydrogen for long haul; (for industry) material substitution, electrification, bioenergy, solar thermal, geothermal and hydrogen; and (for agriculture and land) laboratory food and enteric fermentation treatments.

The development of such solutions at the speed and scale required will entail both public and private investment in RD&D (with governments providing incentives to encourage business investment).

This is a crucial decade for carbon emissions.

To reiterate, this report offers a positive message. In the face of extreme weather and other frightening manifestations of a changing climate, it presents a narrative of hope, buttressed by the best-available science.

The evidence shows that emissions reduction avoiding the most severe effects of climate change remains possible. The '2C Deploy' scenario modelled in this report outlines one pathway compatible with a two-degree Celsius global temperature limit; the '2C Innovate' scenario presents a different approach to the same outcome. The '1.5 All-in' scenario models reductions compatible with a rise of 1.5 degrees Celsius, a best-case outcome predicated on the collaboration of all relevant actors.

But that collaboration requires will. If there is nothing inevitable about disaster, there is also nothing inevitable about its avoidance. Decarbonisation will not happen on its own. It depends on action by a variety of agents across every sector of the economy.

A future based on decarbonisation requires ambition from political and business leaders. The report calls attention to the solutions already available, the new opportunities developing, and the tools for tracking progress. But it emphasises the necessity of those opportunities being seized; and concerted, coordinated and collaborative action across all sectors, involving individuals, organisations and all tiers of government.

Increasingly, the goal of net zero emissions by 2050 or earlier is becoming the norm, both in Australia and around the world. **By setting targets immediately, decision-makers can focus attention on new technologies and prevent missed opportunities in technological investment.**

While the path to zero emissions remains clear, the research shows that the coming decade will be crucial, with the years before 2030 offering a window for action that will not stay open. In the face of such a challenge, everyone must step up.

CLIMATEWORKS AUSTRALIA WELCOMES FEEDBACK ON THIS REPORT AND IS AVAILABLE TO SUPPORT ITS APPLICATION TO SPECIFIC SECTORS AND AUDIENCES.

By setting targets immediately, decision-makers can focus attention on new technologies and prevent missed opportunities in technological investment.

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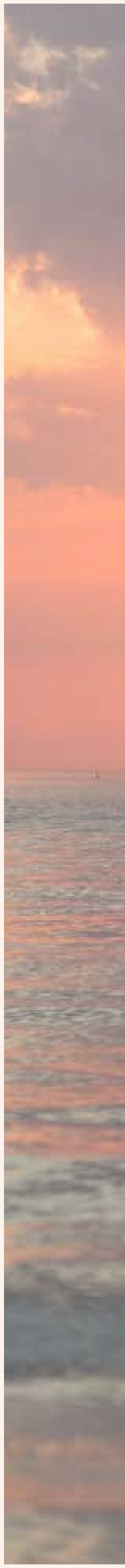

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ABOUT US

ClimateWorks Australia is an expert, independent adviser, committed to helping Australia, South East Asia and the Pacific region transition to net zero emissions by 2050.

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