PATHWAYS TO DEEP DECARBONISATION IN 2050:

How Australia can prosper in a low carbon world

TECHNICAL REPORT

SUSTAINABLE DEVELOPMENT SOLUTIONS NETWORK
A GLOBAL INITIATIVE FOR THE UNITED NATIONS

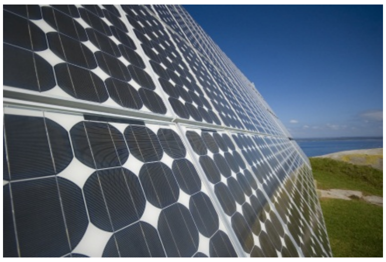
ClimateWorks AUSTRALIA

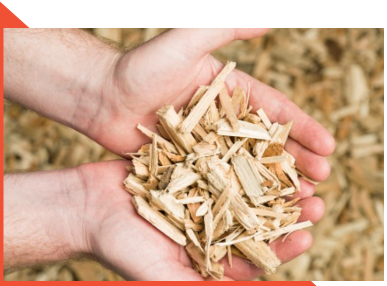
Australian National University

CSIRO

VICTORIA UNIVERSITY
MELBOURNE AUSTRALIA

September 2014





Background

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ClimateWorks Australia
Level 1, 31 Flinders Lane
Melbourne Victoria 3000
P +61 3 9902 0741
E info@climateworksaustralia.org
This report may be downloaded at
www.climateworksaustralia.org/how-australia-can-thrive-low carbon-world-pathways-prosperity-2050

Authors:

Introduction: A. Denis, ClimateWorks Australia, P. Graham, CSIRO, S. Hatfield-Dodds, CSIRO and F. Jotzo, Australia National University.

Electricity Sector: P. Graham, CSIRO, and S. Hatfield-Dodds, CSIRO.

Transport Sector: P. Graham, CSIRO, and S. Hatfield-Dodds, CSIRO.

Industry Sector: A. Denis, ClimateWorks Australia.

Buildings Sector: R. Kelly, ClimateWorks Australia.

Agriculture and Forestry Sector: S. Hatfield-Dodds, B.A. Bryan and M. Nolan

MMRF Model: P. Adams, CoPS.

Appendix A: P. Graham, CSIRO.

Appendix B: P. Adams, CoPS.

Appendix C: P. Adams, CoPS.

Other contributors: Edited and compiled by Wei Sue, ClimateWorks Australia, Scott Ferraro, ClimateWorks Australia, Niina Kautto, ClimateWorks Australia, Anna Skarbek, ClimateWorks Australia and John Thwaites, ClimateWorks Australia.

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Contents

INTRODUCTION

A. Denis, ClimateWorks Australia; S. Hatfield-Dodds and P. Graham, CSIRO; and F. Jotzo, Australia National University

1. Introduction

1.1 Context

ClimateWorks Australia and the Australian National University have been appointed to lead Australia's participation in the global 2050 Deep Decarbonisation Pathways Project (DDPP) coordinated by the UN Sustainable Development Solutions Network (SDSN) and Institute for Sustainable Development and International Relations (IDDRI).

The DDPP is a collaborative initiative to understand and demonstrate how individual countries can transition to a low carbon economy and how the world can meet the internationally agreed target of limiting the increase in global mean surface temperature to less than 2 degrees Celsius (2°C). Achieving the 2°C limit requires that global net emissions of greenhouse gases (GHG) approach zero by the second half of the century. This requires a profound transformation of energy systems by mid-century through steep declines in carbon intensity in all sectors, a transition called 'deep decarbonisation'.

Currently, the DDPP comprises 15 country research teams composed of leading researchers and research institutions from countries representing 70 percent of global GHG emissions and different stages of development, including Australia, Brazil, Canada, China, France, Germany, India, Indonesia, Japan, Mexico, Russia, South Africa, South Korea, the UK and the USA. The country research teams are acting independently of governments and do not necessarily reflect the positions or views of their national governments. Each DDPP country research team is developing a 'pathway' for deep decarbonisation.

Rather than focusing on how the global abatement task should be allocated, all country teams are developing national deep decarbonisation pathways and the technological solutions for achieving them. Country pathways will then be aggregated to form a global deep decarbonisation scenario, consistent with the objective of limiting global temperature rise to 2°C. Country pathways are being developed within a coordinated global framework, allowing collaboration and information sharing amongst country teams.

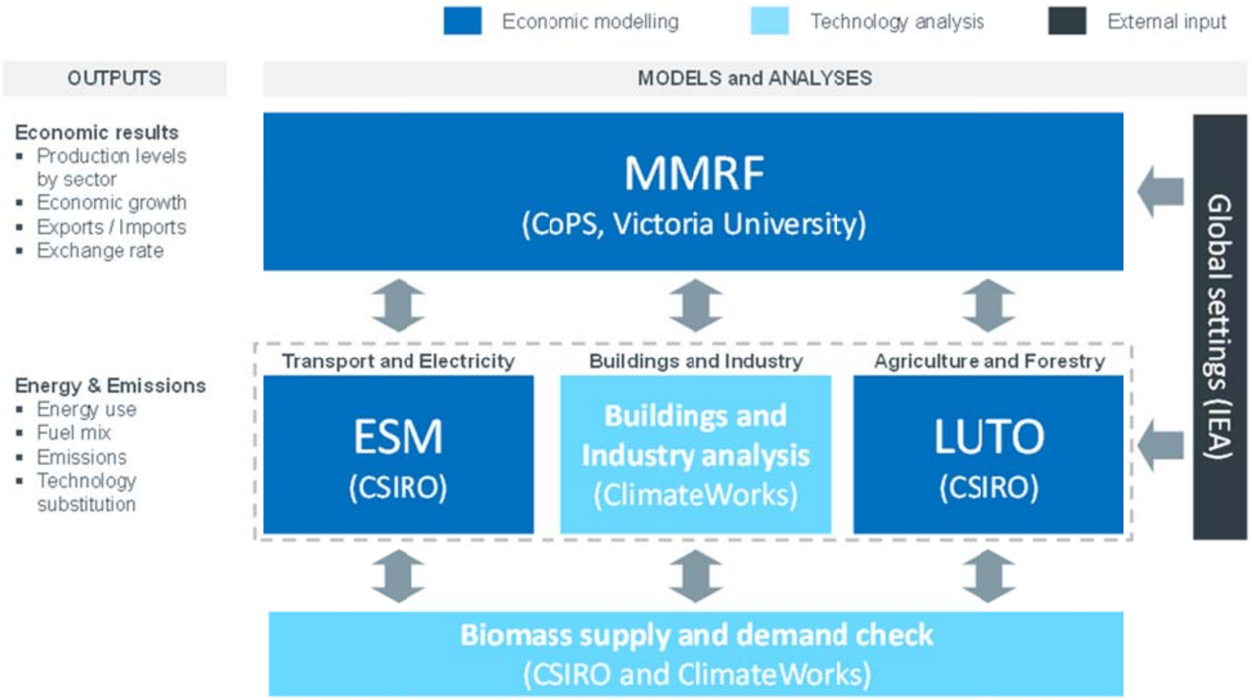
A common set of assumptions about future global trends (e.g. energy prices) is being used, however, local context and constraints are also considered (e.g. the relatively high contribution of energy-intensive industries to Australia's economy).

Figure 1.1 – Overview of project structure

1.2 Modelling framework

The analysis uses a combination of bottom-up sectoral models brought together in a national economic model. The models are well established and have been used in similar exercises before. Figure 1.2 shows a schematic diagram of the main models, processes and data.

Figure 1.2 – The modelling framework[1]



Modelling of the Australian economy was carried out by the Centre of Policy Studies (CoPS) using Monash Multi-Regional Forecasting MMRF multi-sector general equilibrium model. In line with best practice, this general equilibrium model was run in conjunction with detailed sectoral analysis of the technical and economical potential for emissions reduction.This is widely viewed as the benchmark approach in Australia and internationally, and has been the norm in recent Australian climate policy analysis, such as Treasury (2011) and Garnaut (2008).

The sectoral analysis and modelling includes:

- Economic modelling of the electricity and transport sectors. The CSIRO's Energy Sector Model (ESM) provides least-cost solutions for meeting electricity and transport demand trajectories under given abatement incentives. It builds upon an assessment of the resources and technologies available, as well as the physical constraints applying to those technologies. The results have been used to inform MMRF on the resulting fuel demand, technology mix and the activity growth in electricity generation and transport subsectors. Projected emissions trajectories for those sectors are taken from the ESM results.
- Detailed analysis of the emissions reduction opportunities in the buildings and industry sectors. ClimateWorks conducted a detailed bottom-up analysis of the potential for energy efficiency, fuel shift (e.g. from coal/oil to gas and gas to biogas/biofuel or electricity), direct emissions reduction opportunities, and deployment of carbon capture and storage in buildings and industry. The findings from this analysis are used as inputs to the MMRF analysis, and to calibrate the energy and emissions results from the model.
- Economic modelling of the carbon forestry potential. CSIRO's Land-Use Trade-Offs (LUTO) model was used to develop the potential profitable land sector sequestration of carbon from non-harvest carbon plantings (including single species eucalypt plantations and mixed species plantings providing carbon and

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[1] MMRF: Monash Multi-Region Forecasting Model; ESM: CSIRO Energy Sector Model; LUTO: CSIRO Land Use Trade-Offs Model, CCS: Carbon Capture and Storage.

biodiversity benefits), where this would be more profitable than traditional agricultural activities under projected future input and output prices and associated impacts on agricultural production. Those results are used to inform MMRF on the changes in land-use and forestry activity and the supply of land sector offsets.

- **Check on biomass supply and use.** Finally, ClimateWorks and CSIRO collaborated to ensure that the volume of biomass use across the Australian economy was consistent with available resources. The ESM is able to resolve competition for biomass resources between the electricity and transport sectors. Existing CSIRO modelling was also called upon to determine whether biomass volumes are consistent with projected agricultural and carbon forestry activities (Bryan et al., forthcoming).

This approach provides a flexible and robust framework, drawing on demonstrated and well-documented models where possible. All modelling frameworks have strengths and weaknesses, however, and the following limitations of the analysis should be noted:

- The consistency of global settings provided by the UN Sustainable Development Solutions Network (SDSN) and the Institute for Sustainable Development and International Relations (IDDRI) and the response of the Australian economy and other countries participating in the project was not tested. It is likely that the sum of individual country responses will not reflect global settings. However this was a deliberate compromise in the project to focus at a country level rather than integrated global level modelling. Of particular interest for Australia is the extent to which the demand for Australia's energy-intensive exports changes, as other countries implement their decarbonisation pathways.
- This study has checkd that biomass consumption does not exceed expected limits, which is an improvement on previous modelling of the same scale and scope, however it has not checked whether the distribution of biomass resources are economically optimal. The ESM does economically optimise biomass distribution between the electricity and transport sectors, but the remaining distribution of biomass for other energy purposes within different parts of the direct energy use sector was imposed rather than modelled.
- Except where imposed by a scenario assumption, the major driving human behavioural assumption is cost minimisation/profit maximisation, based on economic theory. This is a fairly safe assumption for projecting large asset purchases. However it may be less reliable for projecting consumer goods purchases, such as electric vehicles and solar panels, where other factors can play a significant role in decision-making.
- The UN SDSN and IDDRI provided a number of global settings for the modelling, such as global demand for energy, population and economic growth, technology costs and fuel prices, drawn primarily from the work of project partner, the International Energy Agency.

1.3 Abatement incentives

The analysis of Australia's emissions pathway is broadly policy neutral. The project assumes that a suite of policies are implemented that generate abatement across all sectors and major sources of emissions (including energy, industrial processes, livestock, fugitive emissions) and sequestration options (carbon plantings, CCS), with abatement incentives increasing over time, as well as broadly proportional across sectors at any point in time. This suite of policies could involve a mix of specific policy tools, including information programs' mandatory standards for energy efficiency; emissions standards for electricity generation; fleet-based vehicle emissions standards; support for abatement of livestock emissions; payments to landholders for carbon sequestration; and various market-based incentives. In most cases these policy instruments result in investment in lower-emissions technologies with higher capital costs and lower operating costs, with changes in costs effecting prices of carbon-intensive products and services over time. Different combinations of policy tools have different advantages and disadvantages, which is reflected in different patterns of implications for prices, investment certainty, economic efficiency, industry competitiveness and government expenditure.

This stylised policy approach is implemented in a range of ways across the set of models used for the project, including adjustments to energy efficiency and the application of a carbon price in MMRF and ESM electricity and transport modelling, application of globally calibrated efficiency and technology trends in the ESM transport analysis, modelling of cost-effective uptake of industrial sector abatement and building energy efficiency, as well as payments to landholders for carbon sequestration calibrated to an estimated international offsets price.

The level of abatement incentive in Australia is calibrated to align with international efforts as estimated by IEA (2013), such that the cost of the most expensive mitigation option in Australia is no higher than the cost borne in other high income countries. (Policy settings also mobilise lower cost abatement in Australia and other countries.) The level of international effort is represented by a global carbon price that rises from 2016 to around US$50 per tonne CO_2 (A$60) by 2020, consistent with the need for significant immediate global emissions reductions in order to limit global warming to 2°C. The rate of increase in the global carbon price gradually slows over time, with an average increase of 4.3 percent per year from 2020 to 2050 in US dollars.

1.4 Overview of modelled scenarios

1.4.1 Pillars of deep decarbonisation

Three 'pillars' of decarbonisation of national energy systems are common to all country pathways, and a fourth applies to countries where non-energy related emissions are substantial. In Australia, non-energy emissions account for over one third of total emissions.

The pillars of deep decarbonisation are

- **Energy efficiency**: Greatly improved energy efficiency in all energy end-use sectors including passenger and goods transportation, through improved vehicle technologies, smart urban design, and optimized value chains; residential and commercial buildings, through improved end-use equipment, architectural design, building practices, and construction materials; and industry, through improved equipment, material efficiency and production processes, re-use of waste heat.
- **Low carbon electricity**: Decarbonisation of electricity generation through the replacement of existing fossil fuel based generation with renewable energy (e.g. hydro, wind, solar, and geothermal), nuclear power, and/or fossil fuels (coal, gas) with carbon capture and storage (CCS).
- **Electrification and fuel switching**: Switching end-use energy supplies from highly carbon-intensive fossil fuels in transportation, buildings, and industry to lower carbon fuels, including low carbon electricity, other low carbon energy carriers synthesized from electricity generation (such as hydrogen), sustainable biomass, or lower carbon fossil fuels.
- **Non-energy emissions**: These emissions can be reduced through process improvements, material substitution best practice farming and implementation of carbon capture and storage. In addition, carbon can be stored into the soil and vegetation, in particular through reforestation, and offset some of the emissions created by other sectors.

1.4.2 Australia's options for deep decarbonisation

Australia can embark on deep decarbonisation through a number of alternative pathways. In particular, many uncertainties exist on the future structure of Australia's economy, the future costs of low-carbon technologies and the potential technological breakthroughs that could be achieved in the next few decades.

In this report and the accompanying summary report, several alternative options are explored qualitatively in all sectors and quantitatively in the electricity and land-use sectors. In additionm one illustrative pathway has been modelled in detail to demonstrate the types of technology transitions that would be involved in each sector of the economy and to explore the potential economic impacts of such transitions. The illustrative pathway is not meant to represent an optimised deep decarbonisation scenario, nor the most likely scenario for Australia, but rather one option for decarbonisation based on our understanding today. It is meant to initiate a discussion on how Australia can decarbonise and to highlight where further research and analysis is needed. In this context, the results should be interpreted as directional only.

The alternative options discussed in the report could either replace modelled technologies should they be unavailable or enable deeper emissions reductions.

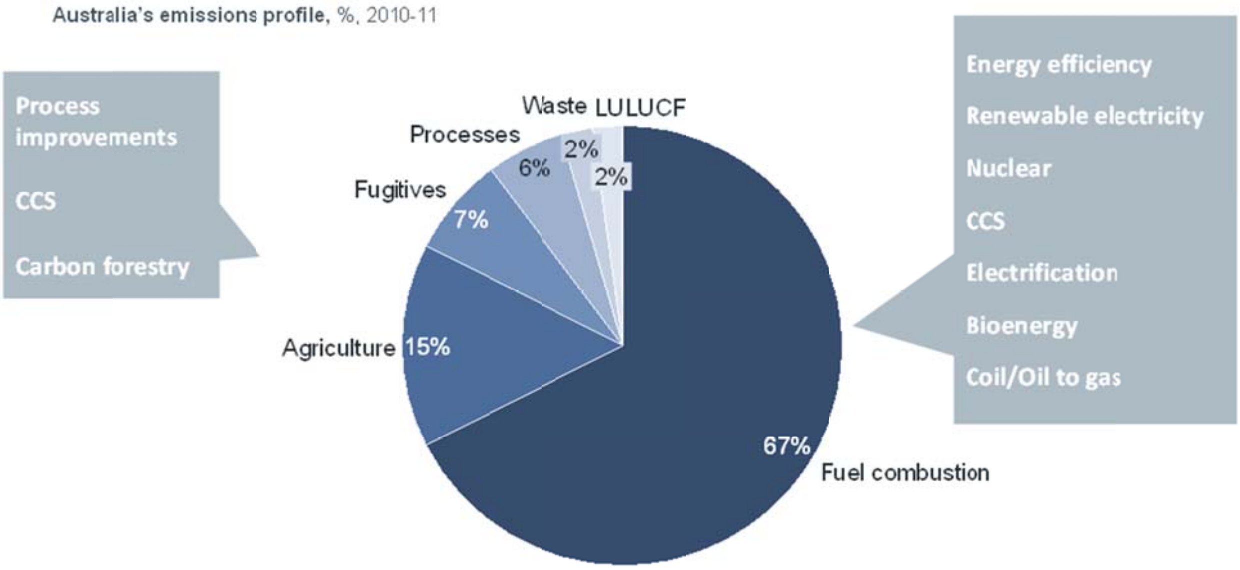
1.4.3 High-level descriptions of the modelled scenarios

The modelled scenarios prioritise continued economic growth and focus on technological solutions, with less emphasis on change in economic structure or consumption patterns beyond current projections. Indeed, modelled consumption patterns changes are limited to continuation of recent trends (e.g. continued move towards smaller cars) and modelled changes to the economic structure are limited to a reflection of assumed changes in global trends (e.g. reduced global demand for coal). In terms of technology options, as broad a range of technology options are reflected as possible, rather than focusing on one particular technology, as well as using technologies that exist today or are at some stage of development, rather than anticipating future technological breakthroughs.

By design the modelled scenarios are ambitious, given that they achieve deeper emissions reductions domestically than previous equivalent exercises, and that they are anchored in the context of a world embarking on a deep decarbonisation pathway. The analysis makes relatively conservative assumptions in terms of future technology costs in that context, as well as in terms of future industrial production. For example, it has not been assumed that Australia's heavy industry moves offshore, but instead looks at how it could be decarbonised if it remains in Australia. In a similar way, potential step changes in technology have not been included in the example pathway. Qualitatively alternative options have also been explored should some technologies included in the example pathway not be available, or end up being more costly than estimated in the modelling.

Figure 1.3 summarises the range of technologies considered in the modelled scenarios. In particular, it builds upon Australia's rich resources in renewable energy and geological storage, as well as large land area. In addition, it involves strong improvements in energy efficiency, as well as sector-specific process improvements in industry and agriculture.

Figure 1.3 – Summary of major technologies considered in the modelled scenarios



1.5 What is new compared to previous modelling exercises

A number of features of the modelling framework are new compared to previous domestic modelling exercises. In particular, it is the first time that:

- The updated carbon forestry LUTO model has been used for a whole of economy analysis;
- a much more thorough investigation of mitigation potential from industrial production, buildings and transport was used to calibrate the results of the MMRF model in terms of energy use and emissions associated with those sectors;
- a strong shift to electrification in industry and buildings was modelled in Australia;
- modelling of an Australian emissions reduction pathway occurred in the context of an harmonised international modelling exercise.

In addition, many assumptions have been updated since similar modelling was conducted by Garnaut (2008) and Treasury (2011). For example:

- The cost of many renewable generation technologies has decreased significantly, for example solar PV already costs almost half of what previous studies estimated it would cost in 2030 (IEA Photovoltaic Power Systems Programme, 2013, SKM MMA 2011 as used by Treasury 2011);
- The cost of technologies used to manage variable electricity supply has decreased significantly, in

particular the cost of batteries;

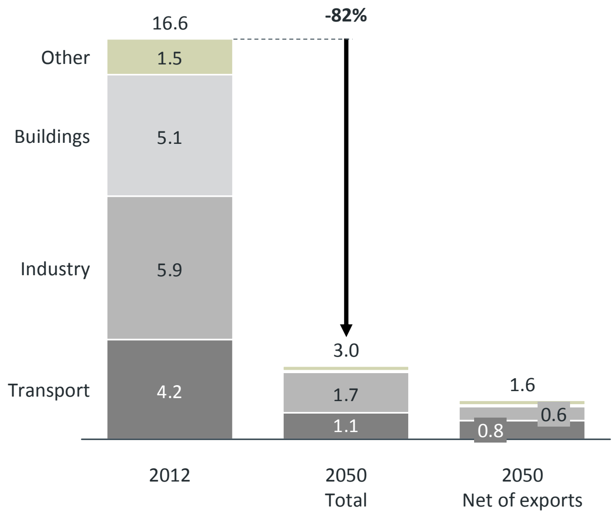
- Biofuels for aviation were thought infeasible in the original modelling by Garnaut (2008) while the first fully biofuel powered commercial, international flight was completed in 2014 (Amyris, 2014).

1.6 Overall results summary

1.6.1 Carbon emissions

For Australia to contribute commensurately to the objective of limiting global temperature to less than 2°C, our energy related emissions would need to decrease by an order of magnitude by 2050. This report presents an illustrative deep decarbonisation pathway by which these emissions are reduced by over 80% on 2012 levels (17 tCO_2 per capita) to 3.0 tCO_2 per capita in 2050, and further reduced to 1.6 tCO_2 per capita if emissions directly attributable to the production of exports are excluded.

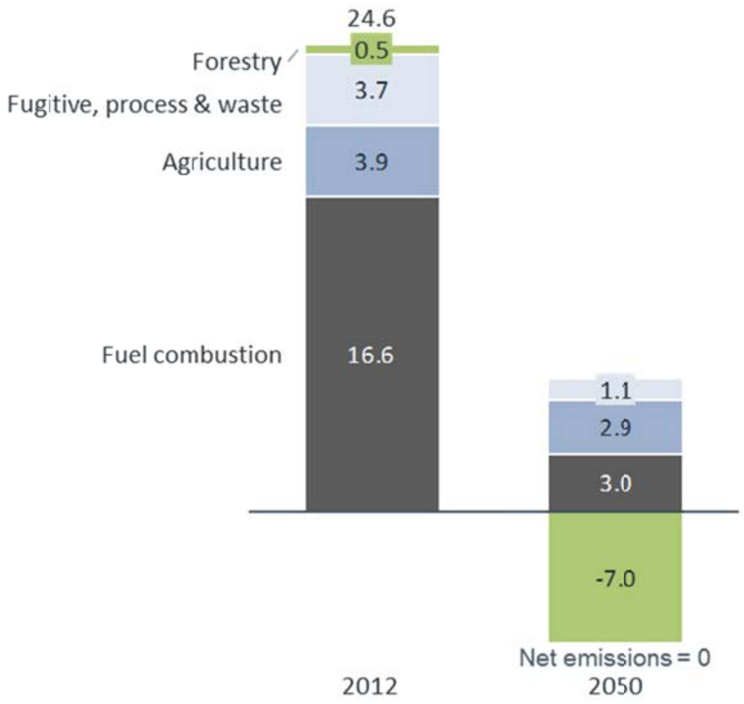
Figure 1.4 – Fuel combustion emissions per capita by sector, tCO_2e per capita, 2012 and 2050



Australia has substantial potential to offset emissions via land sector sequestration. The illustrative pathway includes a shift in land use toward carbon forestry, driven by carbon abatement incentives, where profitable for landholders, but it does not include the sale of emissions offsets into overseas markets. The modelling results find that there is more than enough economic potential to shift land use to carbon forestry to offset all residual emissions to 2050 in all the sensitivities modelled, reaching net zero emissions by 2050.

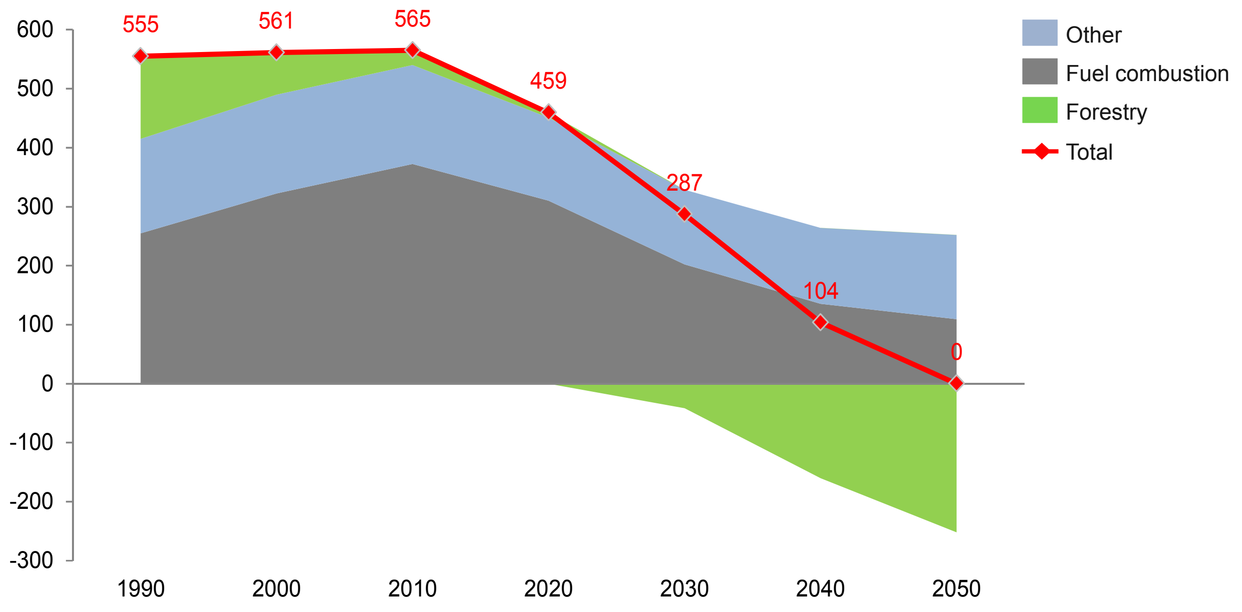
In all cases, the cumulative emissions to 2050 are compatible with Australia's carbon budget recommended by Australia's Climate Change Authority, an independent body established under the *Climate Change Act* 2011. This requires strong mitigation action in all sectors of the economy, in context of a strong global decarbonisation effort.

Figure 1.5 – Net emissions per capita by source, tCO_2e per capita, 2012 and 2050



After accounting for all emissions sources and sinks, the pathway includes intermediate emissions reductions milestones of 18 percent below 2000 levels in 2020, about 50 percent below 2000 levels[2] in 2030 and to net zero emissions by 2050. The cumulative emissions to 2050 are compatible with Australia's carbon budget recommended by Australia's Climate Change Authority (2014). This requires strong mitigation action in all sectors of the economy, in context of a strong global decarbonisation effort.

Figure 1.6 – Greenhouse gas emissions trajectory, MtCO2e, 1990 to 2050 (DOE, 2014)



Not all sectors are equal in terms of opportunities to reduce emissions and associated costs. As a result, residual emissions by 2050 differ significantly between sectors. The electricity sector in particular has multiple technologies available to reach near zero emissions, with the buildings sector benefiting from this emissions reduction, given the relative ease to electrify buildings' energy use. In contrast, opportunities to reduce emissions in the agriculture sector are limited, with emissions in this sector expected to remain high, unless global beef consumption is significantly reduced. Transport and Industry have more opportunities available than agriculture, but there are still many applications where technology options are limited, for example road freight. The large economic potential in carbon forestry is used to offset all the remaining emissions in those sectors.

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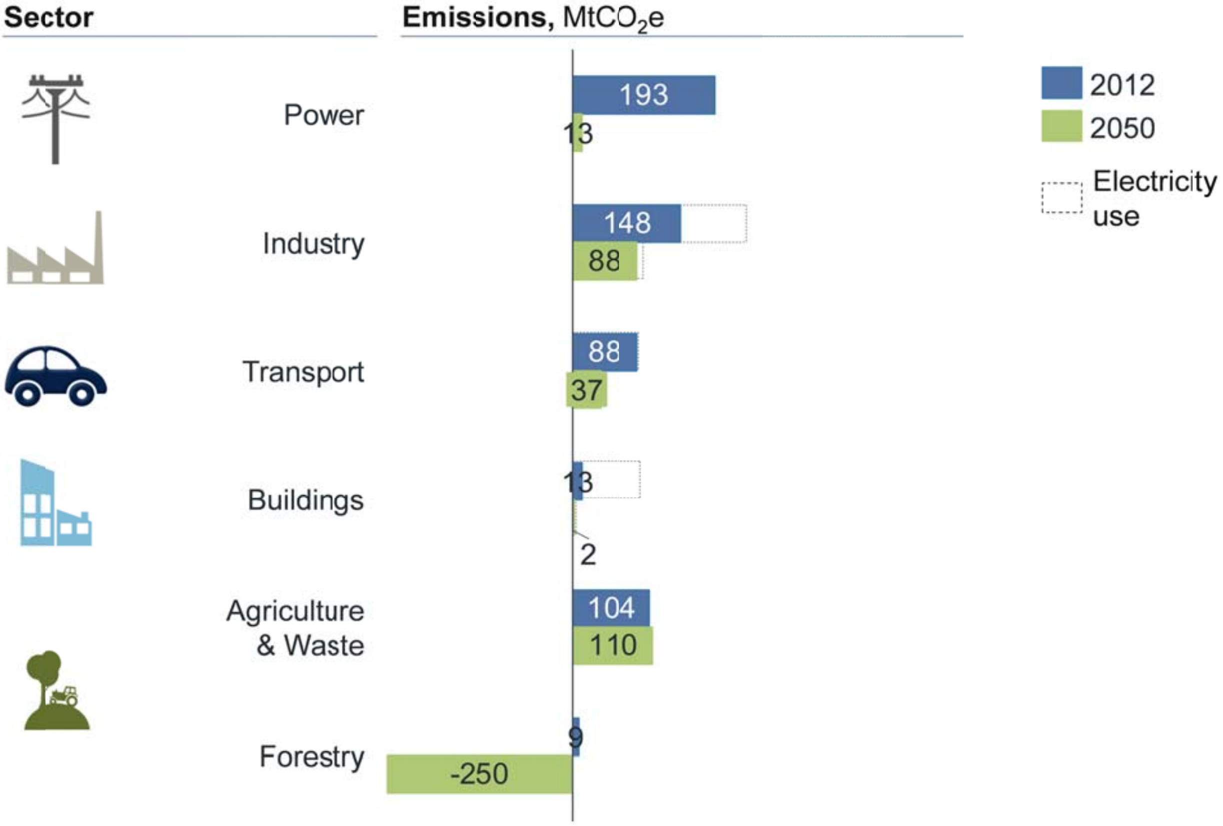
[2] Net emissions in 2000 amounted to 561 $MtCO_2e$.

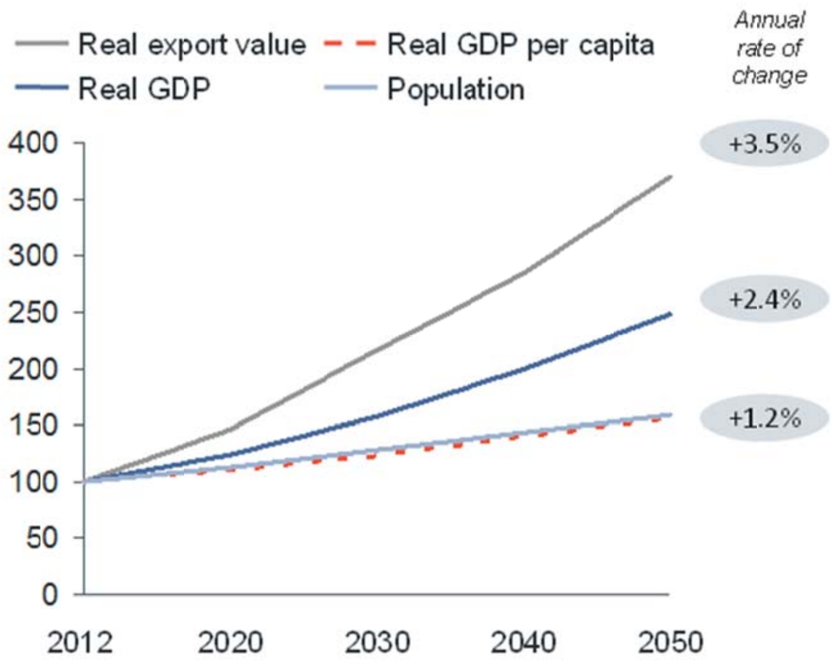
Figure 1.7 – Summary of emissions reduction by sector, MtCO$_2$e



1.6.2 Economic results

The analysis shows that deep decarbonisation can be achieved while real GDP grows at 2.4 percent per year on average, resulting in an economy nearly 150 percent larger than today in 2050. The rise in economic activity is due in equal measure to population growth and rising per capita income, so Australians are on average much richer than today. Trade would also keep growing strongly. This result is consistent with the findings of many other reports that show that decoupling GDP growth from and CO_2 emissions growth is achievable (PWC 2013, Stern 2006, Garnaut 2008, Edenhofer et al 2014).

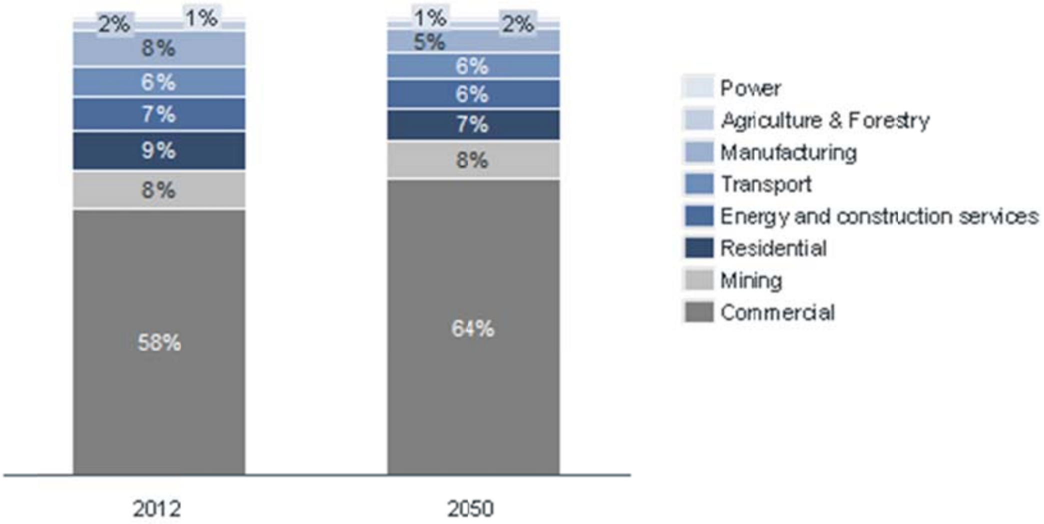
Figure 1.8 – Key economic indicators, indices



Trade also continuing to experience growth, with exports growth predicted at 3.5 percent per annum. Modelling results suggest that the overall structure of Australia's economy would not change significantly, with industry's contribution remaining significant, while services continue to grow. The sectoral contribution to the economy resulting from the modelling exercise can be seen in Figure 1.9.

The commercial sector's contribution to the economy is predicted to grow by about six percentage points, similar to the previous 38 years, which experienced an increase of about seven percentage points (ABS, 2014). In a similar manner, manufacturing's contribution to the economy is predicted to decrease by three percentage points, a continuation of past trends that saw a decrease by eight percentage points in the past 38 years (ABS, 2014). It is anticipated that mining will maintain a constant contribution.

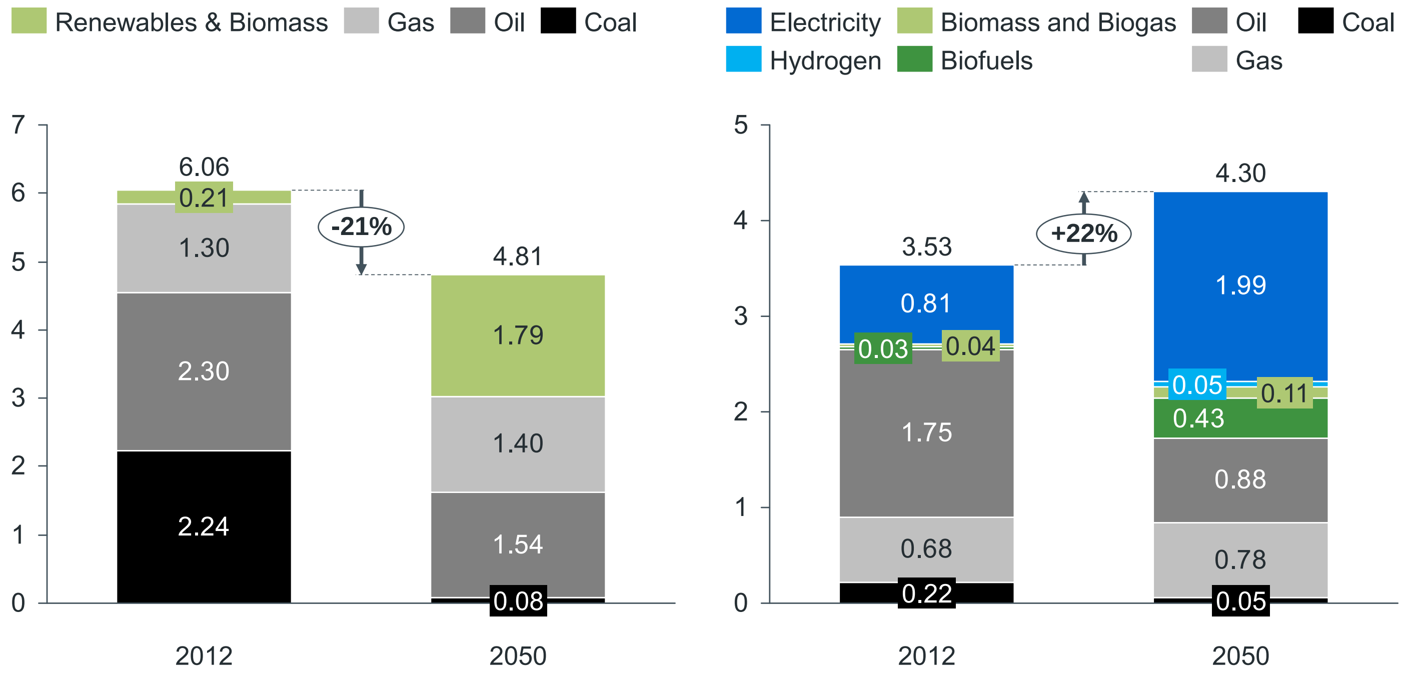
Figure 1.9 – Sectoral contribution to GDP, percentage



1.6.3 Energy use

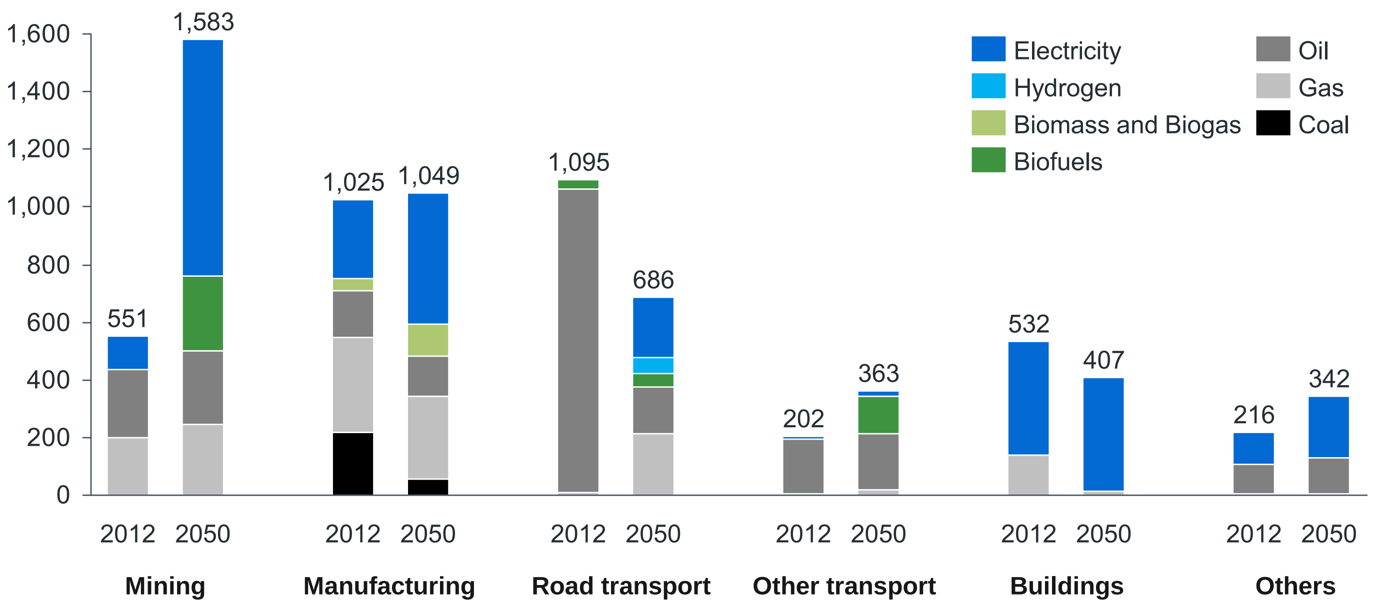
Australia's total primary energy use decreases by 21 percent from 2012 to 2050, while final energy use increases by 22 percent (see Figure 1.10). There are significant changes in the fuel mix, with coal use almost entirely phased out (the only remaining use is for coking coal in iron and steel) and an increase in renewables and biomass, as well as gas use.

Figure 1.10 – Primary energy use by fuel type, EJ (left) and final energy use by fuel type, EJ (right)



In manufacturing, road transport and buildings, energy use stays stable or even decreases, due largely to energy efficiency and electrification (one GJ of electricity can usually replace more than one GJ of direct fuel use). In other transport, energy efficiency improvements are not sufficient to counterbalance growth in activity. In the mining sector, structural energy intensity increases (due to the decline in ore grades in particular) combined with strong growth in activity lead to nearly a tripling in energy use between today and 2050. Energy efficiency and electrification help to alleviate this growth.

Figure 1.11 – Final energy use by fuel type and by sector, PJ[3]



The strong increase in electricity use is mostly driven by electrification in the industry and transport sectors, as illustrated in Figure 1.12.

Figure 1.12 – Total Australian electricity demand, TWh

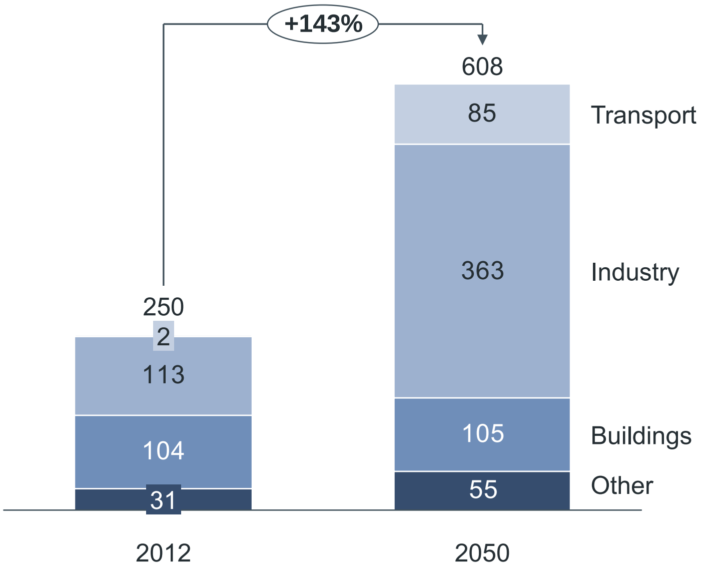


Figure 1.13 summarises the distribution of biomass between end-use sectors. As can be seen, the biomass is estimated to be used, largely, to replace oil in mining and transport. The analysis suggests that the total biofuel use would amount to about 15GL in 2050, which is equivalent to about 44 percent of today's domestic petroleum refining capacity.

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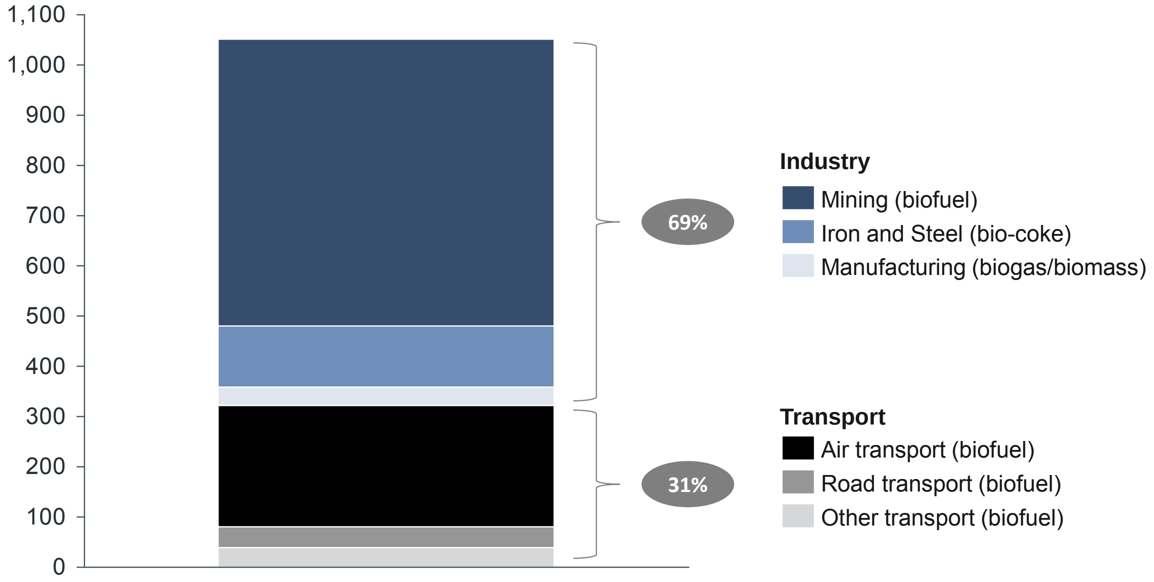
[3] Others include power generation (e.g. transmission and distribution losses), construction and services, agriculture and forestry activities. Note that the date presented for 2012 is directly extracted from the model and may in some instances differ slightly from official energy and emissions statistics.

Figure 1.13 – Primary biomass use by sector, PJ

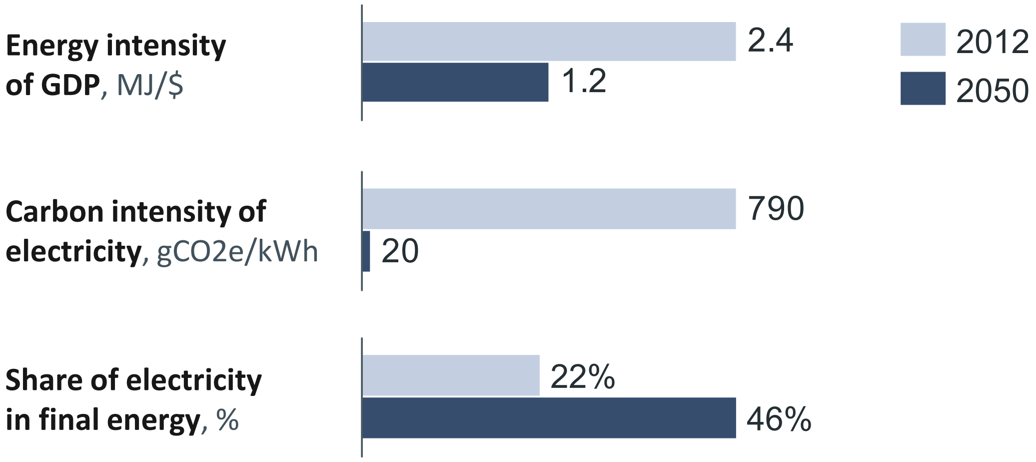


1.6.4 Pillars of decarbonisation

Decarbonisation of energy transformation (mainly electricity generation) combined with electrification (supplied by decarbonised electricity) and fuel switching, leads to a nearly 75 percent reduction in the emissions intensity of energy use across all economic sectors. The contribution of these pillars is shown in Figure 1.14, with a description provided below.

- Energy efficiency: Energy efficiency is assumed to continue to improve at current rates until 2020, but accelerates thereafter, particularly in the building and transport sectors.
- Low carbon electricity: Electricity generation is almost completely decarbonised via a choice of three scenarios: 100 percent renewable grid-integrated supply of electricity (with some on-site gas fired electricity generation, particularly in remote areas), renewables and carbon capture and storage, or renewables and nuclear.
- Fuel switching: Electrification becomes widespread, particularly for cars, buildings and industrial processes, such as heating processes or material handling. Thermal coal use in industry is considerably reduced via a shift to gas and biomass, where possible. Freight fuels move away from diesel, with a significant shift to gas. Oil use in mining equipment and aviation is reduced through a move to biofuels.

Figure 1.14 – Pillars of decarbonisation (ABS, 2012; BREE, 2013)



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ELECTRICITY SECTOR

P. Graham, S. Hatfield-Dodds, CSIRO

2. Electricity sector

Executive summary

This section provides the detail behind the electricity and transport projections underpinning the Australian contribution to the United Nations Sustainable Development Solutions Network (UN SDSN) and Institute for Sustainable Development and International Relations (IDDRI) Deep Decarbonisation Pathways Project led by ClimateWorks Australia and the Australian National University (ANU). The key role of CSIRO modelling was to provide least-cost and biophysically plausible electricity and transport sector projections. The projections are used directly to inform the development of an Australian deep decarbonisation pathway and also applied indirectly as inputs to whole of economy general equilibrium modelling. National general equilibrium modelling was conducted by Victoria University's Centre of Policy Studies and, besides CSIRO input, included inputs directly from the ClimateWorks team, particularly in relation to energy end-use efficiency and industrial energy use.

The modelling finds that these three pathways – renewable, CCS and nuclear – make valuable contributions to achieving a very high degree of decarbonisation of the electricity sector. The recent cost reductions in solar photovoltaic systems mean that it is projected to play a particularly important role across various scenarios. Managing renewable electricity generation technology variability, scaling up supply to meet stronger demand growth in a more electrified economy and overcoming resource and transmission constraints to deploying technologies into all state regions are challenges highlighted in the modelling.

The three pathways explored all arrive at a similar long-run marginal cost of electricity supply of $150/MWh by 2050 to achieve a substantially reduced greenhouse gas emission intensity of electricity generation of 0.05 tCO_2e/MWh or less. This increase in generation cost contributes to an increase in residential retail electricity unit costs to around 38c/kWh in 2012 dollars by 2050. This represents an annual average rate of increase of 0.9 percent per annum. This is less than the projected rate of growth in per capita income of 1.2 percent per annum. In addition, our modelling suggests that energy efficiency could lead to around a 50 percent reduction in energy use per household by 2050 (excluding the impact of electric vehicles). Given that income per capita is rising faster than electricity unit prices and, at the same time, electricity use per capita is falling, the share of electricity spending in household income is falling.

2.1 Scenario definition

While the modelling approach is similar to previous Australian studies, the scenarios have been developed differently to previous research undertaken. Most greenhouse gas abatement scenario modelling is designed to answer questions such as, what would it cost to achieve a given abatement target? Typically, that target is designed with a global burden sharing arrangement or global emissions trading scheme in mind. The DDP project has deliberately sought to ask a different question, which is, what could individual countries achieve if they sought to make deep greenhouse gas emission cuts? Countries were asked to use the 450ppm 2°C warming per capita abatement pathway as a general guide, but there was no obligation to achieve that.

Decarbonising the electricity sector is critical for decarbonising the Australian economy, as it enables other sectors to decarbonise their activities as well, switching from fossil fuels to electricity where feasible (e.g. buildings, passenger transport). Three scenarios have been developed throughout the modelling process. Based on the developed understanding that some renewable electricity generation technologies have in costs (discussed further below) renewables emerged as a strong feature in all three scenarios, with the main difference being how the base load and peaking requirements of the system were met. A *100 percent renewable grid* scenario was designed, where the base load and peaking functions were met by storage and base load renewable, with non-renewable technologies gradually excluded from the generation mix by 2050. A *Nuclear included* scenario allows nuclear, renewables and peaking gas to compete for market share. A *CCS included* scenario allows carbon capture and storage (CCS), renewable and peaking gas to be competitively selected.

The scenarios explore three alternative technological pathways in a least-cost manner for the electricity sector (Table 2.1). To implement the *100 percent renewable grid* scenario a minimum share of renewables that increases from 30 percent in 2035 to 100 percent by 2050 was imposed. For *CCS*, there is no renewable constraint, which means that CCS and renewables are both equally available and are competitively selected on the basis of whether they are least-cost, subject to physical constraints. To implement the *Nuclear* scenario, there is no constraint on the use of nuclear power, which is the default in ESM, reflecting current legislation. CCS is not allowed in the *Nuclear* scenario.

Table 2.1 – Scenarios and their implementation

Scenario name	Implementation
100 percent renewable grid	Impose a minimum share of renewables on the grid, increasing from 30 percent in 2035 to 100 percent by 2050.
CCS	Do not impose a minimum share of renewables.
Nuclear	Switch off the constraint in ESM, prohibiting nuclear power, and disallow CCS.

Stakeholder feedback during this project suggested two additional scenarios. One was to allow CCS, nuclear and renewables to compete together. Another was to explore a decline in the role of the grid (i.e. centrally supplied electricity), driven by high uptake of on-site generation and end-use demand management activities. Unfortunately there was insufficient time to explore these scenarios and so they remain potential directions for future research.[4]

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[4] Existing research on the topic of the changing role of grids and on-site generation is available in Graham and Bartley (2013).

2.2 Energy sector modelling methodology

As discussed in the introduction, CSIRO's Energy Sector Model (ESM) is responsible for modelling the energy sector and linking to the MMRF general equilibrium model of the national economy. As the name implies ESM provides detailed modelling of the energy sector, in particular the electricity and transport sectors. ESM has been extensively applied in Australia, including in every major analysis of climate policy in Australia since 2006 (Reedman and Graham, 2013a and 2013b; Reedman and Graham, 2011; BITRE and CSIRO, 2008) and in most cases working with MMRF. ESM is outlined in detail in Appendix 0.

CSIRO's Energy Sector Model (ESM) is applied to develop the electricity and transport sector projections. ESM is unique in Australia in that it combines both the electricity and transport markets. This is an important feature in this project, where energy and transport sector abatement are a key focus, with the project exploring in-depth road transport electrification and, as a result, cross-sectoral interaction. ESM simultaneously outlines the cost of electricity supply and the demand from electric vehicles to deliver consistent modelling results in one step.

ESM minimises the cost of meeting electricity demand and so is primarily an economic modelling framework. However a number of physical conditions are imposed that represent constraints to minimising cost, including how technologies work, limitations on where fuel and other resources are located, as well as their costs and volume, how the electricity market works in terms of requirements for both volume and capacity, both the economic or physical retirement of the stock of generating capacity and the characteristics and interconnectedness of state regions. More details are provided in Appendix A.

Due to the limited timeframe in which the modelling had to take place the electricity transmission system changes are not modelled in detail and half-hourly dispatch reliability tests have not been undertaken. However it should be noted that other studies have found that substantially altered electricity systems such as presented in this report can meet demand reliably (see for example, AEMO, 2013b; Graham et al., 2013; Reedman, 2012; Elliston et al., 2012; Wright and Hearps, 2010). There are some remaining uncertainties and these can be found in a critique by Trainer (2012).

In terms of the transmission system, existing studies find that an electricity generation mix with a high renewable share requires additional transmission capacity to source renewable resources in southern Victoria and South Australia (mainly wind resources) and north Queensland, mid-New South Wales and the Cooper basin (for solar power and enhanced geothermal). These transmission system extensions mean that transmission system costs are higher per volume of electricity delivered. These costs are incorporated into the projected retail prices presented in this report.

The key finding in existing Australian studies on reliability is that some form of generation back-up or demand management is required to assist with market supply–demand, providing the balance when variable renewable production is low at different times of the day and year, using back-up technologies, including storage (thermal and electrical), biomass and geothermal power systems. While these back-up options are employed it cannot warrant that the regulated reliability standard of the generation sector is met. This can only be determined using finer temporal scale modelling and under a wide range of simulated climate conditions.[5]

2.3 Assumptions and inputs

Two recent ESM modelling exercises outline in detail ESM's standard model assumptions and, as such, this report only details the assumptions that are key to this project or that are non-standard, given the context of the deep emissions reduction scenario explored here.

Unless otherwise addressed, electricity sector assumptions in ESM are consistent with Graham et al. (2013).

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[5] All of this presumes that electricity markets operate in the same way as present by 2050. However the reader should be aware that developments, such as widespread adoption of on-site generation and battery storage, could over time challenge conventional notions of who is responsible for reliability and where it is managed in the system.

2.3.1 Electricity consumption and peak demand

Electricity consumption is an MMRF model output and subsequently an input for ESM. Key factors in MMRF that determine electricity demand include:

- the initial input–output matrix that determines how much fixed proportion of electricity is required per unit of industry output or in the household budget
- any assumed improvement in efficiency of electricity use by industry or households (provided by ClimateWorks)
- growth in electricity-intensive sectors of the economy (manufacturing and mining are the most electricity-intensive per dollar of output), which in turn is a function of the general level of economic growth, export demand for sector outputs and the impact of abatement incentives
- electricity prices as determined by the generation mix projected by ESM
- electrification of the economy including, in particular, changes in road transport electricity demand (projected by ESM) and substitution of electricity for other direct fuel use in buildings and industry (projected by MMRF based on input by ClimateWorks).

Peak demand is estimated by drawing on existing analysis of potential peak demand growth scenarios. As the volume of (non-transport related) electricity consumption projected by MMRF varies, peak demand is calculated by applying the peak demand to consumption ratio in AEMO (2013a and 2013c) over time (which is increasing as shown in Table 2.2). This approach assumes that new electric vehicle charging is managed so that it does not add to peak demand. Detailed application of managed electric vehicle load profiles on top of existing long-term half-hourly load profiles was studied in Graham et al. (2013), establishing that this was achievable. Of course, while not included in this study, there could also be opportunities for electric vehicles to contribute to reducing peaks through vehicle to grid discharging. There are also a wide range of other technologies and processes that could be applied to manage peak demand (e.g. on-site storage, air-conditioning control systems). As such, peak demand growth in the modelling is potentially on the higher side of the likely range.

Projected electricity demand is shown in the modelling results section.

Table 2.2 – Energy and peak demand components of NEM electricity demand and their implied ratio in AEMO (2013a)

	Energy	Peak demand	Implied ratio
	TWh	MW	MW/TWh
2013	193.0	36372	188.4
2023	223.7	42578	190.4
2033	245.6	47655	194.0

2.3.2 Policy mechanisms

This project has not sought to design, test or anticipate the optimal policy mechanism to achieve deep greenhouse gas emissions reduction in Australia. On the other hand, the necessary greenhouse gas abatement action will not occur automatically if the market is left to choose its own path. For convenience, rather than a statement on optimal policy design, the modelling applies an abatement incentive, represented by a carbon price, as its primary approach to force the modelling framework to find the least-cost set of actions to achieve emissions abatement.[6] Other country teams also adopted, in general, either carbon prices or emission constraint approaches as their modelled policy mechanism.[7]

In the *100 percent renewables grid* scenario, acting in concert with the abatement incentive, is an assumed preference for renewable electricity generation plant to ensure the modelling achieves a very low electricity sector emission intensity. This is imposed by assuming a minimum share of renewables, increasing from 30 percent in 2035 to 100 percent by 2050.

In addition to the abatement incentive and renewable electricity generation preference, the modelling imposes a number of assumptions that also contribute to greenhouse gas abatement, regardless of these mechanisms. For example, increases in fossil fuel prices, in some time periods, extending the existing trend toward more efficient transport vehicles, assuming some modest transport mode shifts and lower-cost low-emission electricity generation and fuel-refining technologies. Where these are different to standard ESM model assumptions they are discussed in this section.

2.3.3 Fossil fuel cost projections

Global fossil fuel price trends are supplied by the UN SDSN and IDDRI, reflecting an expected downward price trend in the long run as fossil fuel demand growth slows and declines in some regions, with global effects to reduce greenhouse gas emissions. However this project does not rely on the global trend to drive domestic fossil fuel prices until 2020. Up to 2020 fuel costs published in the 2012 Australian Energy Technology Assessment (AETA), and developed by ACIL Tasman (2012) (see Table 2.3.1 of BREE, 2012), are assumed. After 2020, the global fossil fuel price trend is imposed.

The UN SDSN and IDDRI data provides a single price for Australia, however, fossil fuel prices differ in Australia by state. The use of ACIL Tasman (2012) prices as a starting point provides a base upon which to impose the global fossil fuel price that is different by state.

In the *Nuclear* scenario, the AETA uranium price assumptions are imposed, with these assumptions graphed in Figure 2.1, Figure 2.2 and Figure 2.3.

The initial rising trend in the gas price data reflects the recent increase in gas prices in Asia (following the increase in demand from Japan after decreased nuclear power output) and the commonly held view that East Coast gas prices will converge towards export parity as LNG export facilities are developed in Queensland. Prices flatten and then decline as emission abatement activity increases. The initial decreasing trend in coal prices reflects the weakening of that market from the slowdown in global economic growth. This trend continues as greenhouse gas emissions abatement activity increases.

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[6] See section 1.3 for more detail on the abatement incentives used in the modelling exercise.

[7] An emission constraint approach is a similar technique, but it results in a carbon price, as a model output rather than input, and forces the country to follow a specific emission pathway.

Figure 2.1 – Projected natural gas price assumption

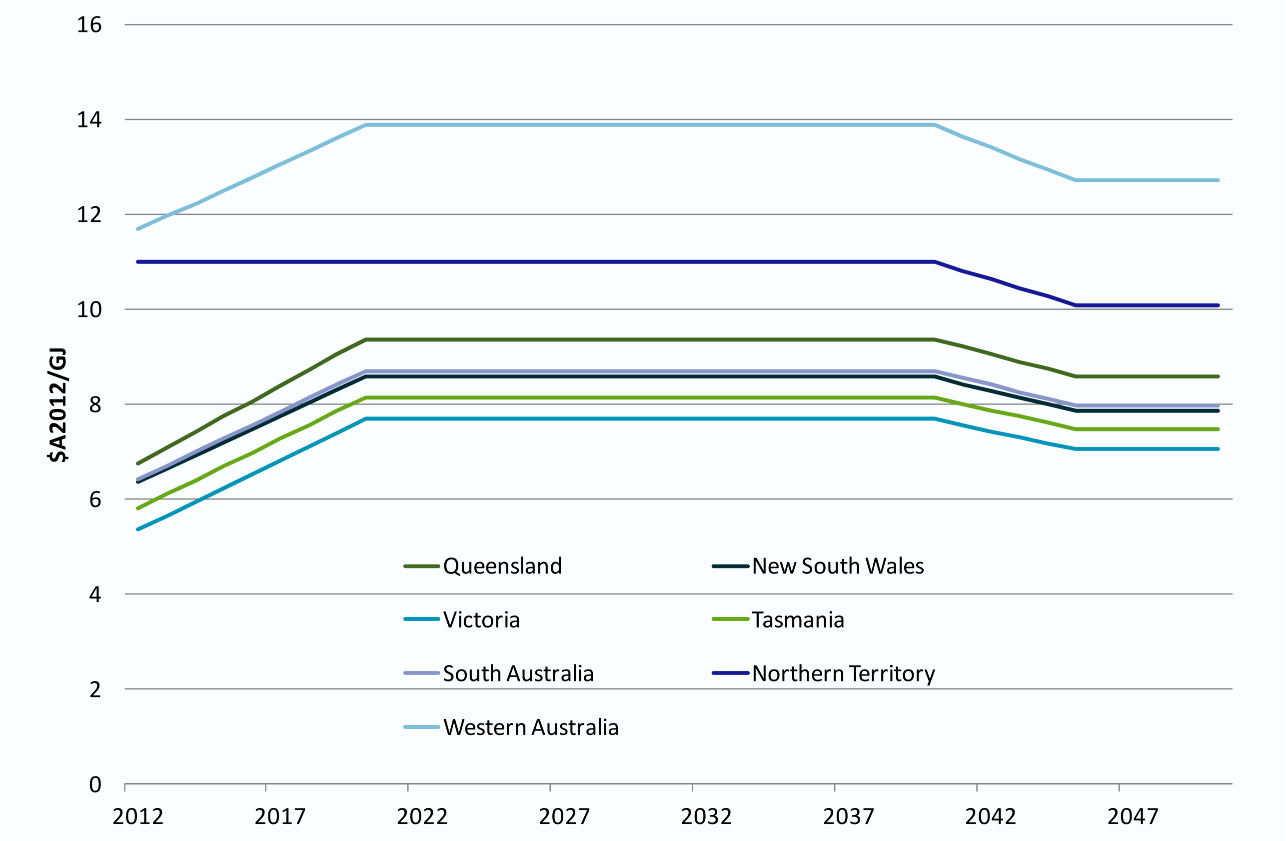


Figure 2.2 – Projected black (Western Australia, New South Wales and Queensland) and brown (Victoria) coal price assumption

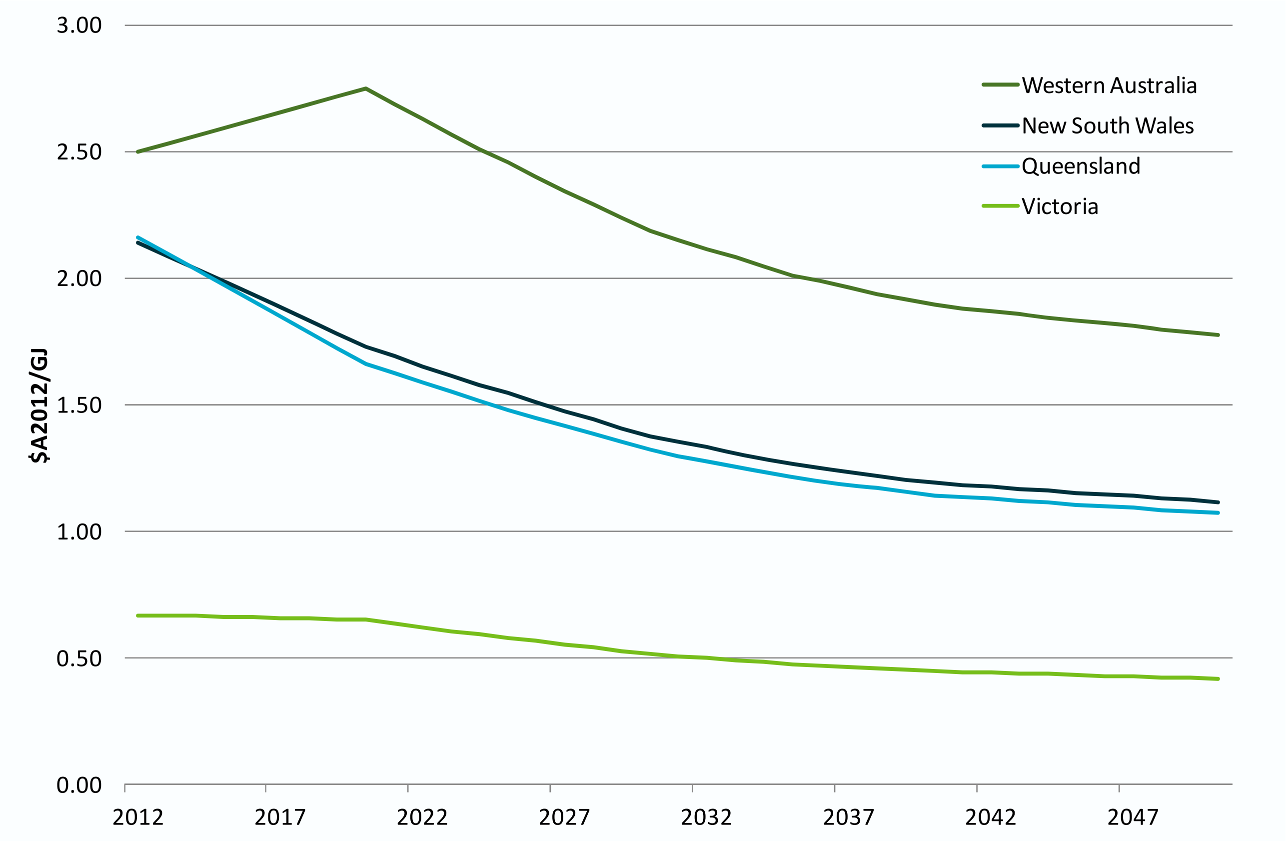
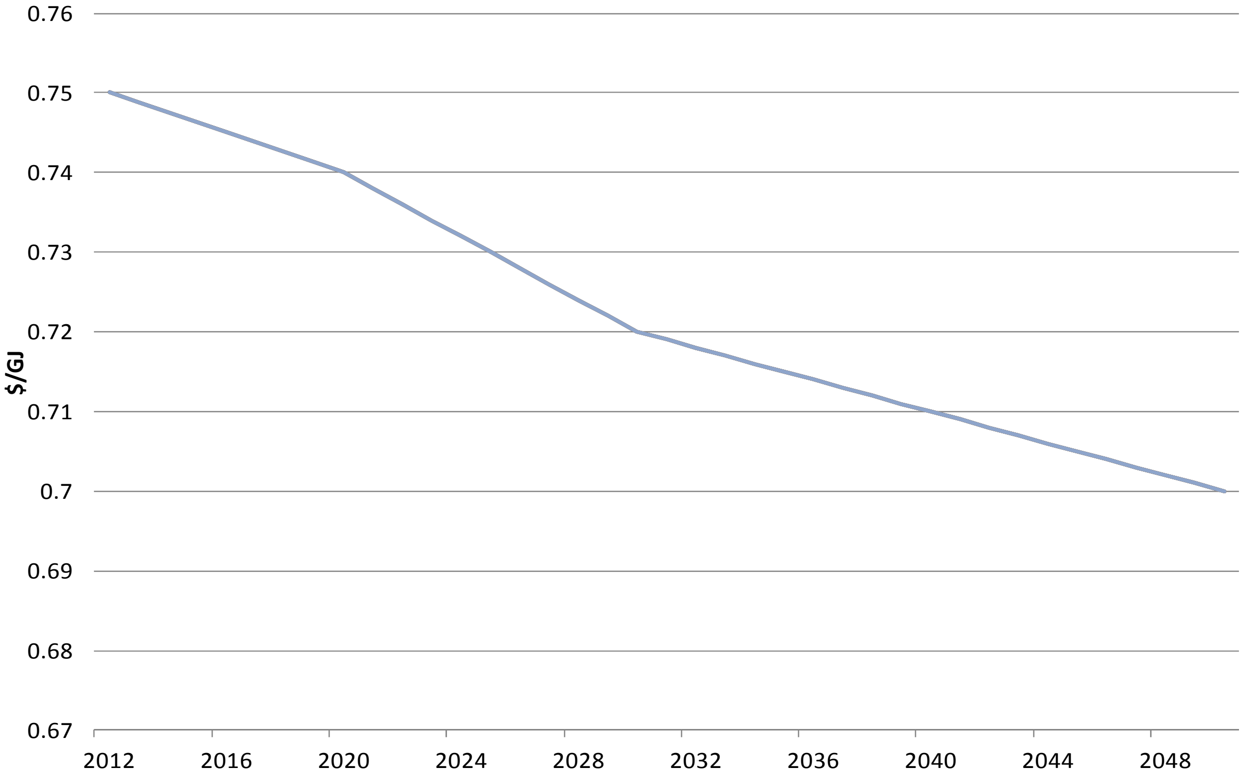


Figure 2.3 – Projected uranium price assumption



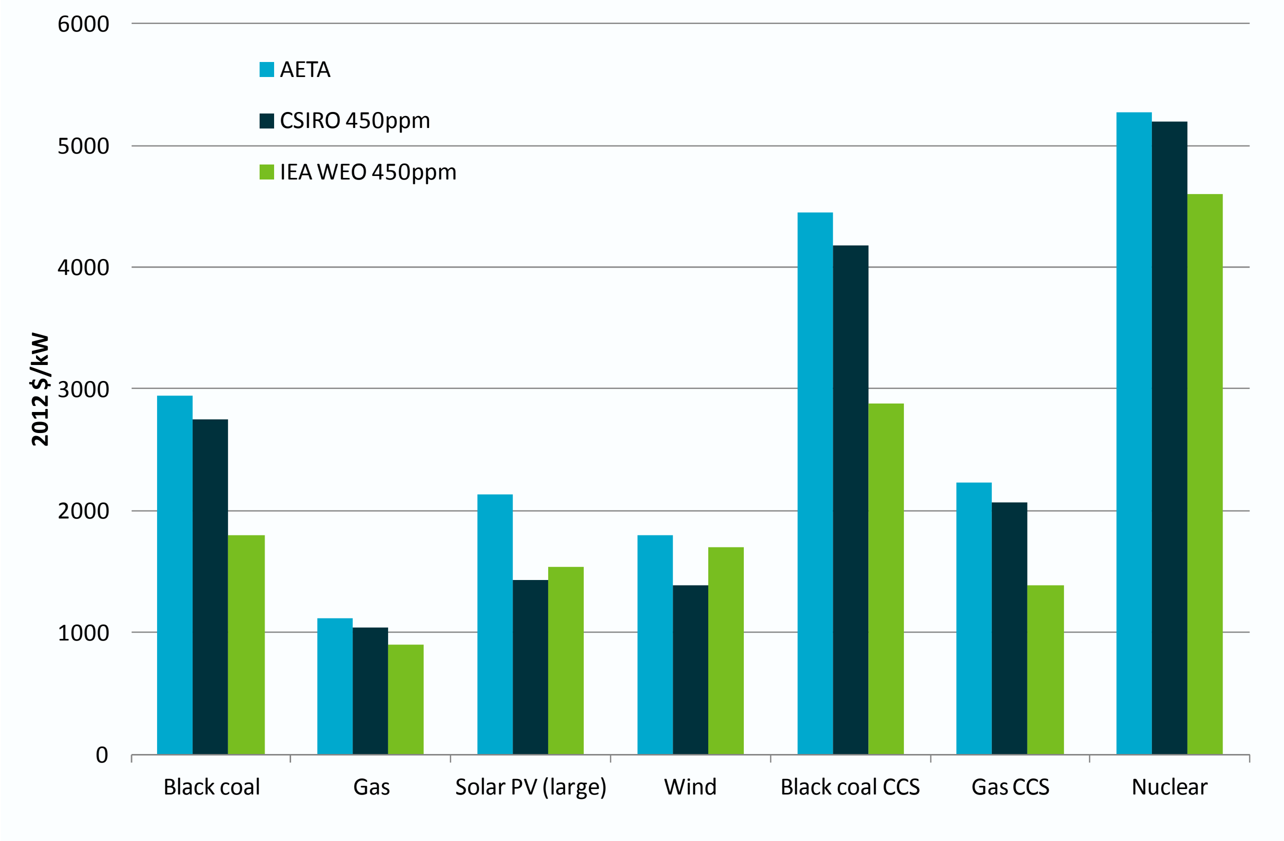
2.3.4 Electricity generation technology cost assumptions

Although there is obviously an uncertainty range around the future costs of all electricity generation technologies, the modelling requires use of a point estimate for each technology and year to 2050. The UN SDSN and IDDRI provided access to electricity generation technology cost projections from the IEA (2013) World Energy Outlook (WEO) 450 scenario. However each country was allowed to modify these projections to better reflect local conditions, provided that there was reasonable consistency.

There are two relevant Australian sources of technology costs available, the AETA 2013 and CSIRO's accelerated learning case that was developed for the AEMO 100 percent renewables study (Hayward and Graham, 2012). The AETA 2013 data is well accepted in Australia but unfortunately is based on a 550ppm background world, which underestimates the extent of technological change if applied to the 450ppm scenario here.

The CSIRO accelerated case assumes a 450ppm background world, using the AETA 2013 as the 2012 starting point. As such CSIRO data appears to be the more relevant Australian study. All three cost projection sources are compared in Figure 2.4. The key differences between the IEA WEO and the Australian data are that Australian costs for black coal and gas technologies (with or without CCS) are higher. There are also some differences with respect to wind and solar PV, but these are not consistent across the Australian studies. The CSIRO and IEA WEO 450 data has the most concordance and consequently the CSIRO data was selected for this project.

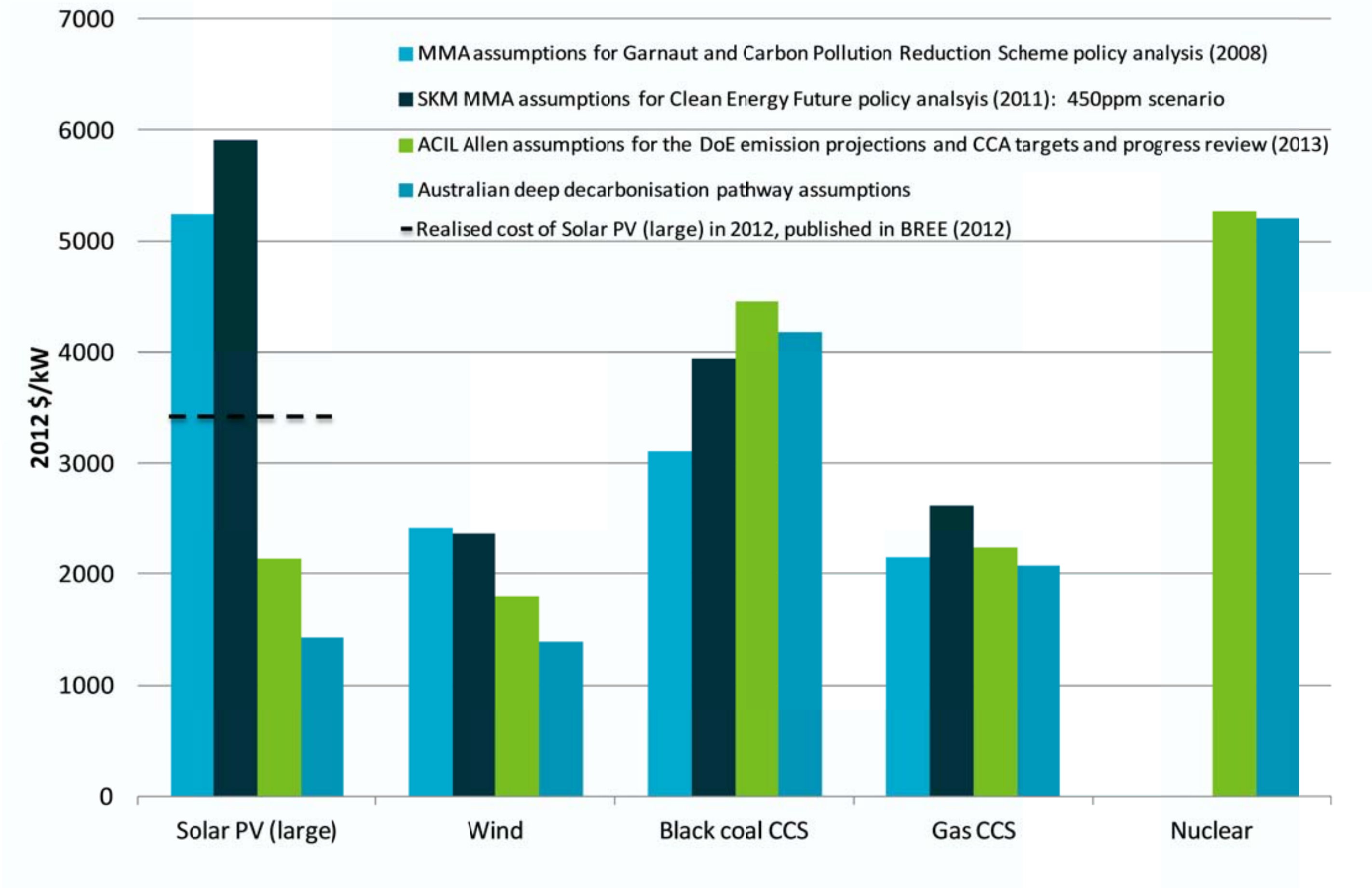
Figure 2.4 – Projected cost of selected electricity generation technologies in by 2030 by source



To put these assumptions in context of comparable studies, this project contrasts the three previous multi-model full economy greenhouse gas emission reduction policy studies conducted in Australia. The first major studies in Australia to analyse the economy-wide impact of greenhouse gas reduction to 2050 were the Australian Business Roundtable on Climate Change and the Energy Futures Forum in 2006. The Prime Ministerial Task Group on Emissions Trading concluded in 2007 but only studied the period to 2030. The Garnaut Review and the Treasury-led policy analysis of the Carbon Pollution Reduction Scheme occurred partially in parallel with each other in 2007–08 and utilised the same modelling package and assumptions. This was later followed by the Treasury-led policy analysis of the Clean Energy Future policy in 2011. The Department of the Environment and the Climate Change Authority jointly commissioned further modelling in 2013 to update Australia's emissions projections and conduct the Targets and Progress Review respectively (CSIRO, 2006; ABRCC, 2006; DPMC, 2007; Treasury, 2008, Treasury, 2011; Garnaut, 2011; Department of the Environment, 2013; CCA, 2014).

Of these, only the more recent studies transparently reports its electricity generation technology assumptions, which are available in the electricity sector reports accompanying the main reports of those climate change studies and illustrated in Figure 2.5 for the key technology groups (MMA, 2008; SKM MMA, 2011; ACIL Allen, 2013). It is important to note that only the SKM MMA (2011) study provided data for a 450ppm world (with the others based on assumptions for a 550ppm world) and so they are naturally more conservative on the projected cost levels.

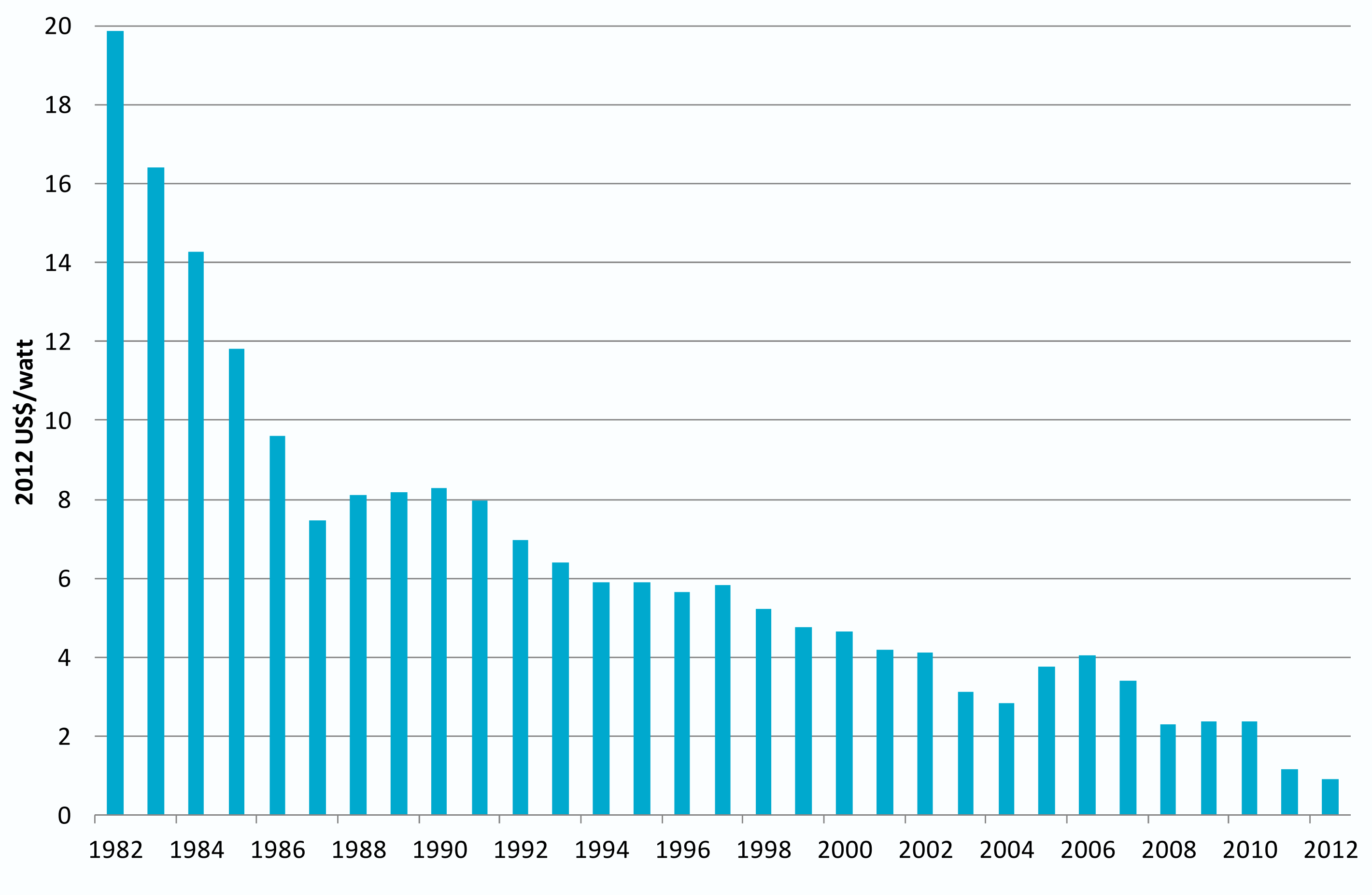
Figure 2.5 – Key 2030 electricity generation technology capital cost assumptions in comparable national greenhouse gas emission reduction studies and realised cost of solar PV (large) in 2012



There are two major trends that emerge from this comparison of key 2030 electricity generation plant cost assumptions across major national greenhouse gas emissions reduction studies. The first trend is the lack of improvement in the outlook for CCS-related technologies, which worsens considerably for black coal with CCS and remains relatively unchanged from 2008 to 2014 for gas with CCS. This reflects a number of factors, including the lack of progress in CCS deployment worldwide and the general increase in cost of black coal plant over the last decade due to high demand for their construction in Asia, particularly China, where economic growth has been strong. The technology market dynamics of the late 2000s also impacted other technologies and are discussed further in Hayward and Graham (2013).

The second major trend is that the outlook for the capital cost of wind and, in particular, solar photovoltaics in 2030 improves considerably as the studies progress through time. Much of the change in costs of solar photovoltaics is to recognise already realised cost reductions that have occurred due to the rapid increase in global manufacturing of this technology and subsequent economies of scale. For example, BREE (2012) reported that large-scale solar was already at $3400/kW in 2012 and IEA Photovoltaic Power Systems program (2013) report that commercial (> 10kW) rooftop systems are between $1500 and $2100/kW. The decrease has largely been due to rapid reduction in photovoltaic module costs. Figure 2.6 shows historical module costs in real 2012 US dollars. Module costs have fallen over 90 percent between 1982 and 1992. However the most recent change has been the most critical one in terms of changing the competitive position of photovoltaic systems, with costs falling by more than 50 percent between 2010 and 2012. During this recent historical period global manufacturing ramped up in response to the introduction of renewable energy targets and feed-in tariff policies in a large number of countries, including Australia. The technology has been manufactured for the purposes of rooftop solar panels rather than for large-scale solar plants. However the module technology component and associated cost improvements are transferable.

Figure 2.6 – Historical cost of photovoltaic modules. Source: IEA Photovoltaic Power Systems program (2013), Earth Policy Institute (2014)



The result of this changing outlook is that, compared to earlier studies, in particular the Garnaut Review/Carbon Pollution Reduction scheme and Clean Energy Future policy studies, there is less probability of CCS technology and, instead, an increase in renewables, particularly solar photovoltaics in any update of emission reduction scenarios for the electricity sector. Unfortunately, nuclear power was not a feature of these early studies and so no trend can be discovered for that technology category.

The full list of assumed technology costs based on Hayward and Graham (2012) and BREE (2012 and 2013) is shown in Table 2.3.

Table 2.3 – Capital costs assumptions for centralised generation technologies, 2012 $/kW

Technology	2013	2020	2030	2040	2050
Brown coal	3787	3783	3768	3748	3763
Brown coal IGCC	6270	6014	6134	6263	6413
Brown coal CCS	7768	7785	6130	6036	5981
Brown coal DICE	2289	2320	2378	2408	2463
Black coal	3209	2954	2947	2938	2935
Black coal IGCC	5525	5412	5524	5644	5783
Black coal CCS	5643	5656	4453	4385	4345
Nuclear	5268	5268	5198	5198	5001
Gas CCGT	1090	1097	1113	1130	1160
Gas CCS	2864	2920	2232	2230	2234
Gas OCGT	735	742	751	766	782
Biomass thermal	5140	5140	4992	4975	4965
Hydro	3350	3082	2736	2428	2155
Wind – onshore	2478	1507	1433	1416	1408
Wind – offshore	4437	3764	3481	3319	3168
Enhanced geothermal	7222	7222	7216	6192	5776
Solar thermal	4935	2433	2330	1827	1819
Solar thermal (six hours storage)	8437	5215	4240	3894	3646
Solar–gas hybrid	2133	1781	1613	1516	1443
PV – utility scale	3648	2042	1637	1403	1286
Wave	6128	6128	4364	4303	4273

Notes: CCGT: Combined Cycle Gas Turbine; CCS: Carbon Capture and Storage; DICE: Direct Injection Coal Engine; IGCC: Integrated Gasification Combined Cycle; OCGT: Open-Cycle Gas Turbine; PV: photovoltaic.

Other centralised generation assumptions

The modelling uses the other BREE (2012 and 2013) centralised electricity generation technology assumptions, which change year by year and are also state disaggregated. The following summary table provides a guide only.

Table 2.4 – Summary of AETA technology assumptions (for representative states) and CSIRO data for current power

	Capacity factor percent	Fuel efficiency percent HHV	CO2e emissions kg/MWh	Capture rate percent	Year available	Fixed O&M $/MW	Variable O&M $/MWh
Brown coal	83	32	1024	0	2015	60500	8
Brown coal IGCC	83	33	1008	0	2015	99500	9
Brown coal CCS	83	201	156	90	2023	91500	15
Brown coal DICE	83	50	700	0	2020	150000	10
Black coal	83	42	773	0	2015	50500	7
Black coal IGCC	83	38	840	0	2015	79600	7
Black coal CCS	83	31	103	90	2023	73200	12
Nuclear	83	34	0	0	2012	34400	15
Gas CCGT	83	50	368	0	2012	10000	4
Gas CCS	83	43	60	85	2023	17000	9
Gas OCGT	10	35	515	0	2012	4000	10
Biomass thermal	80	27	0	0	2012	125000	8
Hydro	16	0	0	0	2012	35000	3
Wind – onshore	38	0	0	0	2012	40000	12
Wind – offshore	40	0	0	0	2012	80000	12
Enhanced geothermal	83	0	0	0	2020	200000	0
Solar thermal	23	0	0	0	2012	60000	15
Solar thermal (six hours storage)	42	0	0	0	2012	65000	20
Solar–gas hybrid	85	51	336	0	2012	15000	10
PV – utility scale	24	0	0	0	2012	25000	0
Wave	35	0	0	0	2020	190000	0

Note: HHV: Higher heating value

LEVELISED COST OF CENTRALISED ELECTRICITY GENERATION TECHNOLOGY AND IMPLICATIONS FOR A COMPETITIVE FUTURE TECHNOLOGY MIX

The levelised cost of electricity (LCOE) for the centralised generation technologies under the assumptions previously outlined has been calculated and graphed in Figure 2.7 for the years 2030 and 2050. The LCOE is calculated by amortising capital and other fixed costs to a cost per MWh of output and combining that with other variables, such as fuel, other operating and maintenance costs. It indicates the average price that a plant would require per MWh of output to recover enough revenue to cover operation costs and make a reasonable return on capital invested. LCOE data can sometimes be a misleading indicator of future uptake of technology, since not all technologies provide the same quality of electricity and there may be other additional costs. Technologies such as wind, wave and utility-scale PV only provide variable output of electricity corresponding to climate-driven factors, whereas the remainder can provide power on-demand at any time of the day. As such, variable renewable technologies have hidden integration costs that an LCOE comparison does not include. Another key integration cost, impacting the whole technology set, is the cost of transmission network connection. Decommissioning of the generation site is also not included in LCOE calculations.

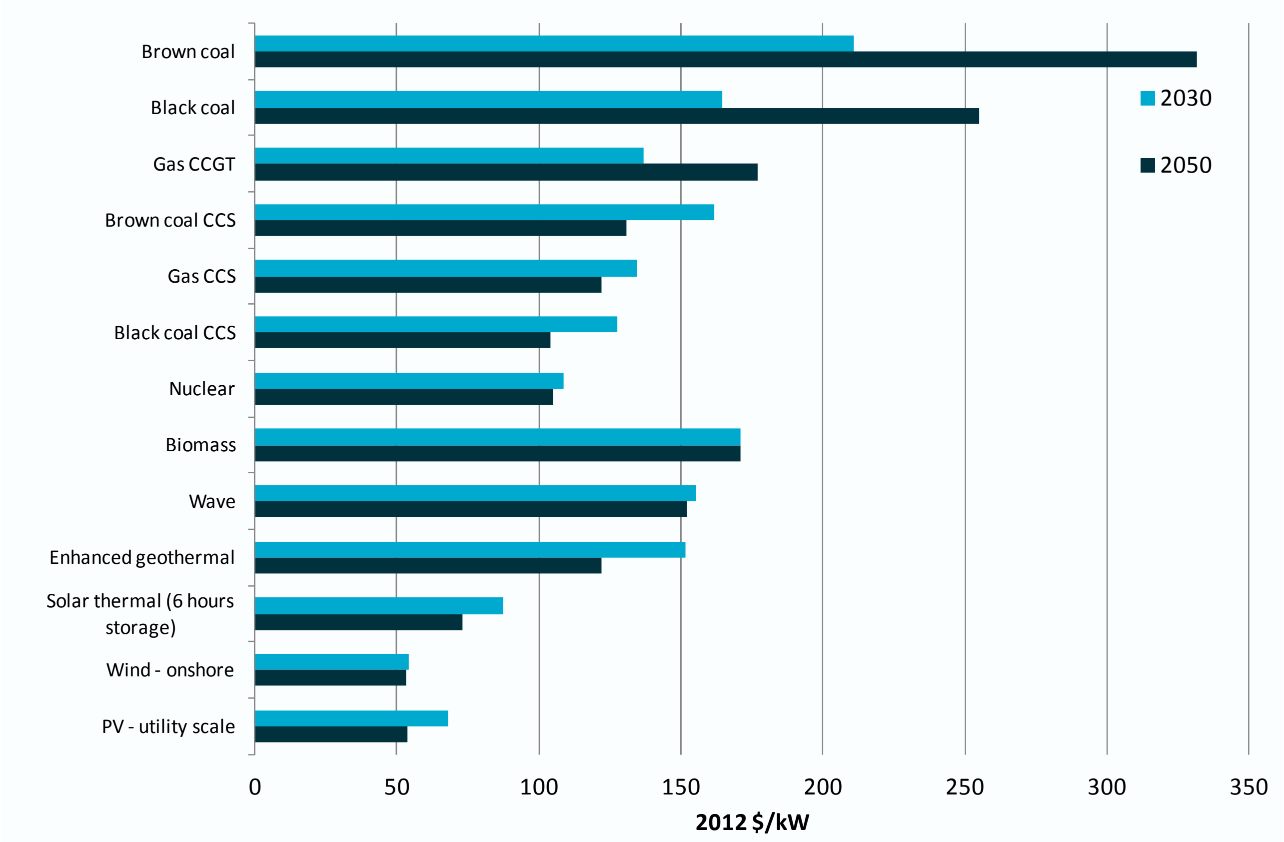
While ESM is able to take into account integration costs through various constraints and equations included in its mathematical program, there is no easy way to calculate them as a single comparable metric. Consequently, despite its flaws, LCOE remains the most useful tool available for providing an indication of the relative competitiveness of technologies under a given set of assumptions.

Based on the LCOE data, as expected, black coal, brown coal and gas electricity generation plant without CCS become less competitive under the assumed abatement incentive. The only competitive technologies are the three groups of fossil fuels with CCS, nuclear and renewables. By 2050 nuclear and CCS are a similar cost, but nuclear initially has an advantage by 2030, reflecting its relative maturity.

The range of the LCOE is wide within the renewable category. Biomass technology is relatively mature and so not expected to significantly improve and a second disadvantage is that it will be competing against other sectors with higher value uses for biomass fuel. Wave and enhanced geothermal technologies are the least mature and their costs reflect that. As discussed previously, the cost of wind and solar PV have fallen significantly recently and this is reflected in relatively lower projected LCOEs.

Based on these LCOE rankings it is expected that nuclear, CCS and renewables are all competitive, but with some renewables, particularly solar PV, solar thermal and wind, likely to dominate new investment. Even once ESM takes account of the cost of integration, these technologies are likely to have too great an advantage in terms of LCOE, under these assumptions, not to feature strongly in the projected technology mix. Other higher cost renewables, such as wave and geothermal, may still feature in the technology mix if other technologies are constrained by rising costs of integration (e.g. as high emission plant retire and are replaced with variable renewables), resource limitations (utilising lower quality resources further from the existing transmission network) and other physical limits (e.g. lack of CCS storage sites, limited state fuel resources or interconnector capacity). For the same reasons, between 2030 and 2050, the marginal cost of supply is more likely to reflect these higher-cost technologies (at around $150/MWh) rather than the lowest LCOE.

Figure 2.7 – Levelised cost of electricity from centralised electricity generation technologies under an abatement incentive in 2030 and 2050



DISTRIBUTED (ON-SITE) GENERATION CAPITAL COST ASSUMPTIONS

The CSIRO distributed (on-site) generation cost assumptions are partly derived from a previous project called the *Intelligent Grid*, which was a major report analysing the value proposition for distributed energy in Australia (CSIRO, 2009). The data has been updated and an accelerated technological change case developed for Graham et al. (2013) to match the centralised electricity generation 450ppm ecosystem. The accelerated case is shown in Table 2.5.

Table 2.5 – CSIRO projection of on-site generation capital costs, 2012 $/kW

Technology	2013	2020	2030	2040	2050
PV rooftop – residential	3142	1779	1390	945	818
PV rooftop – commercial	2513	1424	1112	756	654
Reciprocating engine-based systems					
Gas cogeneration – industrial (30MWe)	1413	1317	1191	1077	974
Gas cogeneration – industrial (1MWe)	1766	1646	1489	1346	1218
Gas cogeneration – commercial	1775	1714	1630	1550	1475
Gas trigeneration – commercial	2496	2410	2292	2180	2074
Gas trigeneration – residential	2496	2410	2292	2180	2074
Landfill or biogas cogeneration (200kWe)	2068	2068	2068	2068	2068
Gas engines – industrial (1MWe)	883	823	744	673	609
Diesel engines – remote (1MWe)	552	552	552	552	552
Fuel cell-based systems					
Gas cogeneration – residential (2kWe)	7456	7456	7456	2801	2801
Micro turbine-based systems					
Gas turbine – commercial (65kWe)	1603	1545	1528	1528	1528
Gas cogeneration – commercial (65kWe)	3883	3749	3566	3392	3226
Gas trigeneration – commercial (65kWe)	4438	4285	4075	3876	3687

2.3.5 Storage cost assumptions and managing variable renewables

The modelling requires that sufficient capacity is built to ensure that demand can be met even when there is high uptake of variable renewable electricity generation technologies. Essentially, this requires imposing a constraint in the model that the system must be able to meet a worst-case scenario, whereby peak demand can be met even when variable renewable electricity generation is low.

There are several strategies that the model employs. It makes use of trading between regions, use of existing flexible fossil fuel technologies before they retire, and after retirement of fossil plant, inclusion of flexible renewables, such as existing hydro, enhanced geothermal (see International Geothermal Expert Group, 2014) and solar thermal with thermal storage. However these measures alone are generally not enough to accommodate a very high renewable penetration system.

Previous Australian studies have employed various approaches to provide adequate back-up for maintaining reliable supply under high renewable shares, with Reedman (2012) providing a full literature review of both Australian and international approaches. Perhaps the most important is that conducted by the Australian Energy Market Operator, AEMO (2013b), which uses a combination of solar thermal with thermal storage, demand-side participation, utilising existing pumped storage, hydro and biogas-fuelled gas turbines.

ESM does not find that the electricity sector would be successful in competing for the use of biomass in biogas peaking plant and therefore this measure is not included. ESM also allows battery storage in the grid by applying battery cost assumptions from Graham et al. (2013), which projects a halving in battery costs by 2030. This cost of storage assumption is conservative, relative to other projections at the time of that study, and remains even more so with several more optimistic storage cost projections emerging (Muenzel et al., 2014). However adopting this conservative assumption here provides leeway for any underestimation of the challenges involved, given that the daily dispatch problem is not modelled in detail here, as discussed in the modelling framework section. It is assumed that the batteries are to be installed towards the generation end of the grid. However it is an open research question as to where the best location for storage is on the grid to manage reliability. Storage is currently being deployed at the user end to optimise use of solar panel systems and exposure to time of use retail pricing in households.

Given the use of AEMO peak demand projections, a demand management response is not deployed as a way of managing supply reliability. This would be an alternative way of balancing demand and supply, should this strategy not be sufficient.

2.3.6 Electricity network considerations

Within the scope of this project, it is not possible to fully resolve the changes to the network that would be required to support the reliable market balancing of the generation mix in each scenario. The relatively high demand growth will necessitate significant transmission network growth and the need to extend the grid to remote renewable resources, given their high contribution to the generation mix.

As a guide, in the absence of detailed transmission network modelling, the transmission cost results from the existing 'Renewables thrive' scenario of the Future Grid Forum project have been applied, which is a 100 percent renewable grid scenario, as outlined in Graham et al. (2013). In that study, the high-voltage transmission network development requirements were modelled. Aggregate transmission costs vary significantly between states but are estimated to represent around 2.5c/kWh in the average 2012–13 residential electricity bill. Under 'Renewables thrive', taking into account the required changes to the transmission network, the cost was projected to increase to 4.3c/kWh by 2050.

Distribution network costs will largely be a function of the growth in volume of consumption throughput in the grid, relative to peak demand in network-supplied electricity. Grid-supplied consumption is determined by:

- total non-road transport-related electricity consumption projected by MMRF
- plus road transport sector electricity consumption
- minus on-site generation projected by ESM.

The change in projected grid-supplied consumption, relative to peak demand, provides an aggregate indicator of the 'load factor' of the distribution network from which the likely trend in distribution network expenditure and unit costs per consumption can be determined. This is calculated in a module of ESM called the Distribution System Costing Model (DisCoM) and its key assumptions are outlined in Graham et al. (2013).

Projected changes in distribution unit costs are outlined in the modelling results section.

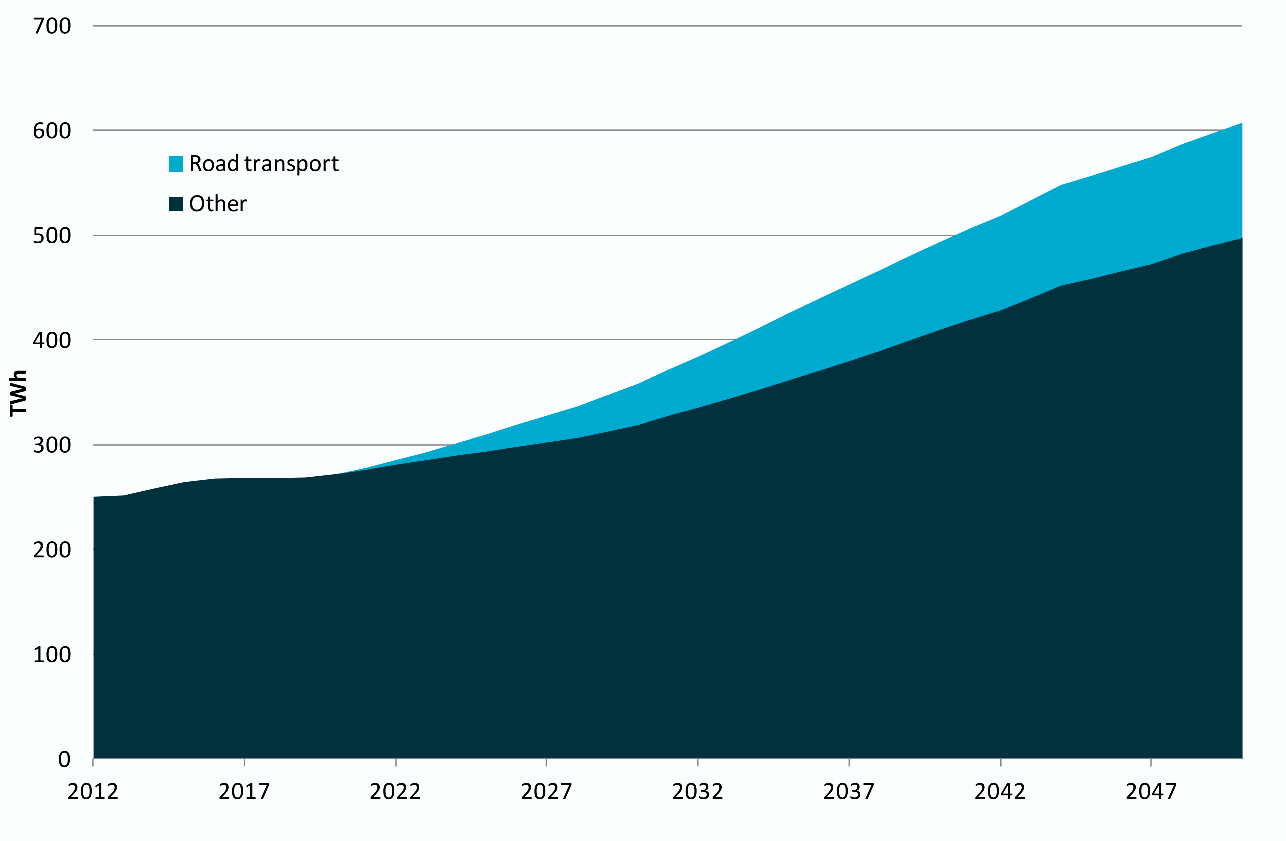
2.4 Modelling results

2.4.1 Electricity consumption

A key feature of the *Australian deep decarbonisation pathway* is that projected growth in electricity consumption is high at around 2.4 percent per annum between 2014 and 2050. This MMRF model outcome is in spite of the assumption of improved end-use electricity efficiency throughout the projection period. The main reason for this strong growth, which is against current trends for stagnant electricity demand,[8] is due to the assumed increasing electrification of buildings, transport and industrial processes and the redistribution of economic activity from fossil fuel production and export to non-fossil fuel-related minerals.

The electrification of road transport and shift in economic activity are outputs of ESM and MMRF respectively, while the electrification of buildings and industrial processes is an assumption developed by ClimateWorks. The amount of electricity ESM projects used by the road transport sector is shown in Figure 2.8. It amounts to around 110 TWh or 28 percent of electricity consumption in 2050 but is fairly negligible up until around 2025. More detail on the source of this demand is discussed in the transport part of this report.

Figure 2.8 – Contribution of road transport to national electricity consumption



An interesting outcome of the redistribution of economic activity to non-fossil fuel-related mining is that the share of electricity demand shifts between states, so that between 2014 and 2050 Western Australia moves from being the fourth largest to the number one electricity-consuming state, consuming a third of all electricity generated in 2050.

This outcome raises a number of questions that remain largely unanswered due to time constraints in this project:

- Western Australia has a high share of off-grid electricity generation. For how long would this remain the least-cost approach at this scale of demand?
- Western Australia is disconnected from the Eastern States National Electricity Market due to distance and its low share of on-grid electricity consumption. For how long would it remain least-cost to remain

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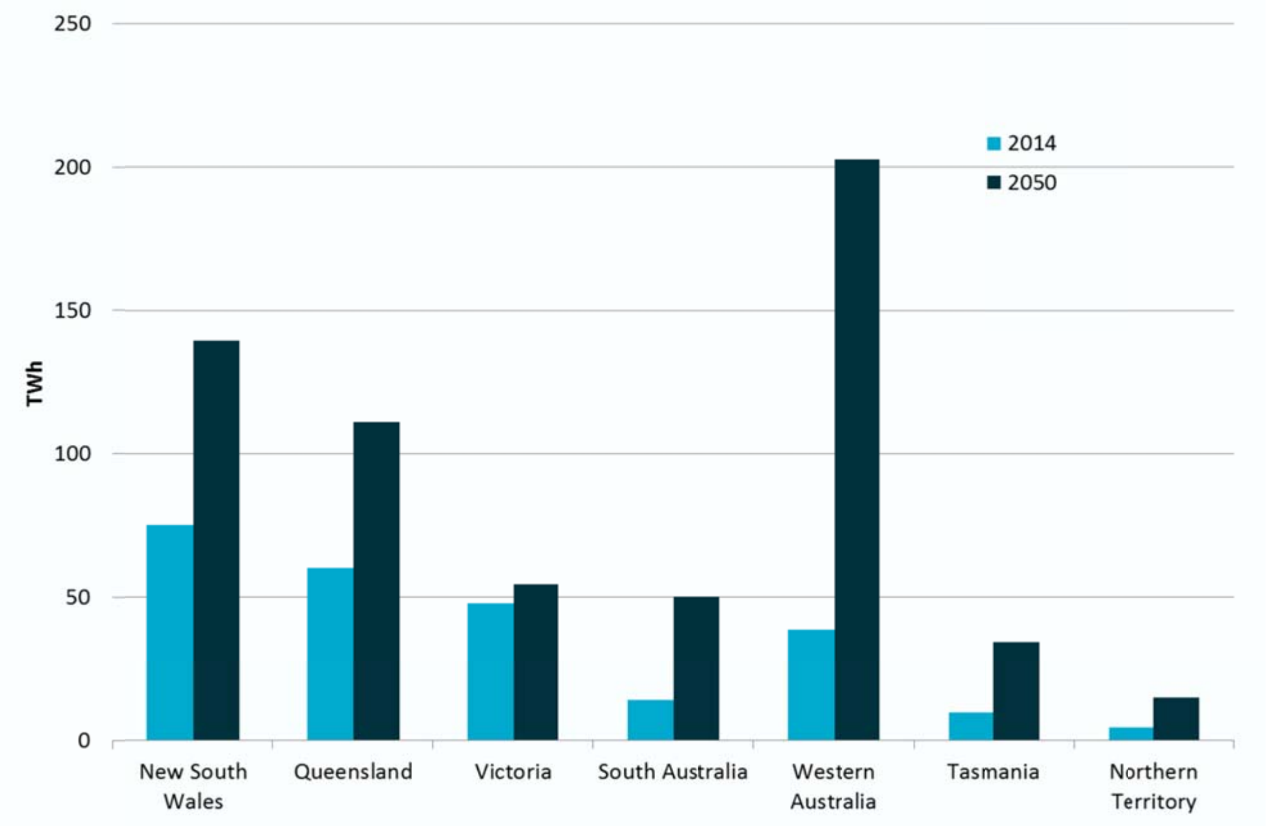
[8] The view that demand growth would be low has only developed during the last decade. See, for example, page 69 of the DPMC (2004) *Securing Australia's Energy Future*, which has a 'medium' electricity demand projection of 650TWh by 2050.

disconnected from the eastern states if it reaches a third of consumption (and also given its high-quality solar resources)?

A full investigation of these issues would require detailed modelling of alternative grid/off-grid and long-distance electricity transmission economics. There would also need to be some interrogation of the MMRF projection of growth in non-fossil fuel mining.

For the purposes of the modelling conducted here, Western Australia is assumed to remain disconnected from the eastern states, but with an increasing share of consumption and generation on-grid, implying the current weakly connected grid and distributed off-grid generation becomes more interconnected over time.

Figure 2.9 – State electricity consumption in 2050



The projected level and state distribution of electricity consumption is assumed to be the same across the *100 percent renewable grid*, *CCS* and *Nuclear* scenarios. However it happens that electricity generation is slightly lower in the *CCS* and *Nuclear* scenarios due to lower transmission losses. This reflects shorter assumed transmission distances for CCS and nuclear-based technologies. In comparison, deployment of a *100 percent renewable grid* requires accessing renewable resources that are further from end-users.

2.4.2 Electricity generation

100 percent RENEWABLE GRID

Given projected electricity consumption, the abatement incentive assumptions and preference for new generation capacity to be renewable, ESM's projected least-cost electricity generation mix is shown in Figure 2.10. The fairly rapid increase in the abatement incentive in the period to 2020 leads to the closure of conventional brown coal-fired electricity generation capacity (significant expansion of gas-fired power in the short-term is essential to achieving this) and puts black coal-fired power on a relatively steady decline down to a negligible amount by 2035. During that period, black coal and expanded gas-fired power, together with existing hydro, support the stability of the system as most new growth is met by wind and solar panels. As flexible fossil electricity generating capacity is retired, new renewable electricity generation capacity must change in character, including more flexible and load-following plant, such as solar thermal with and without thermal storage, wave and enhanced geothermal power. Any variable renewable technologies are also assumed to be increasingly deployed with some electrical storage.

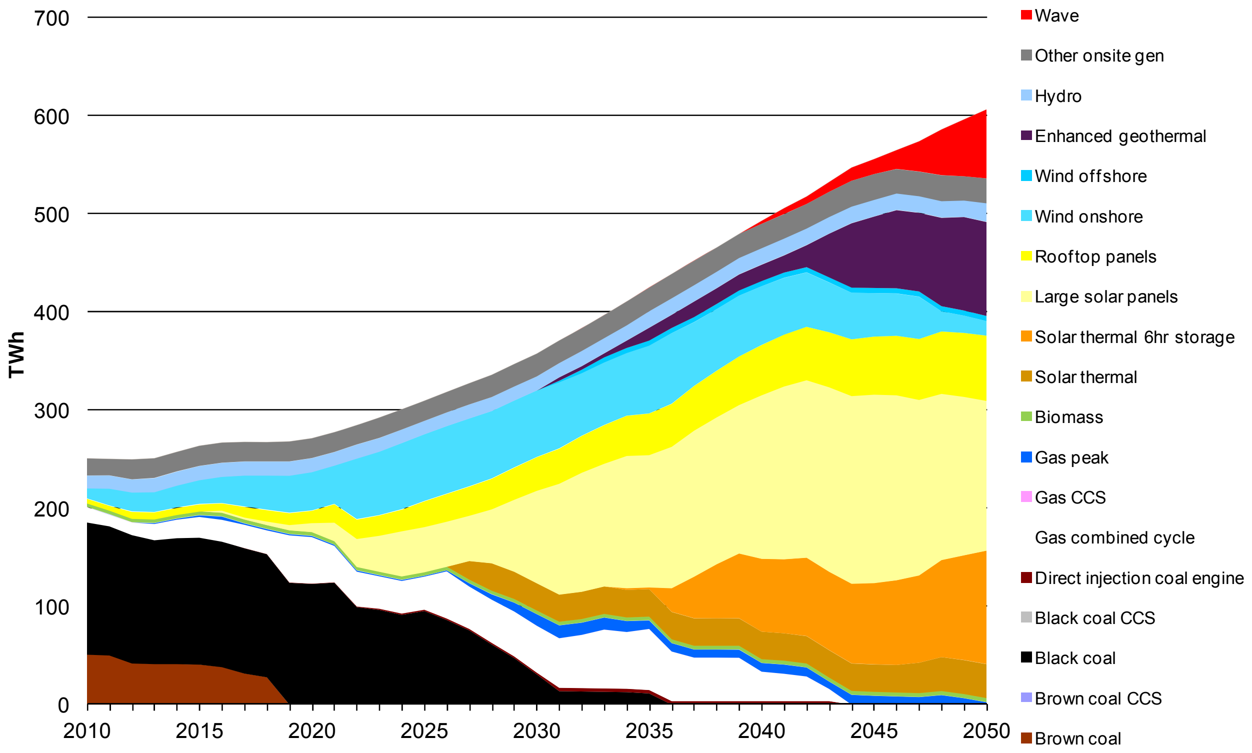
Biomass could theoretically be another useful contributor to supporting variable renewables, but is not selected by ESM for that task, reflecting its high levelised cost of electricity when competing with other industries, particularly transport, for use of biomass fuel.

The main risk to the ability of the system to accommodate such a high share of renewables and meet system reliability standards is the slow development of enhanced geothermal technology in Australia. On the other hand, battery storage technology does appear to be making significant cost improvements and this project's modelling has not included demand management, which could play a significant role in balancing the system. The King Island off-grid system currently demonstrates a system that is 65 percent renewable over the course of a year.

The high projected share of solar power (either photovoltaic or solar thermal) in the electricity generation mix is a reflection of both its cost advantages (see previous discussion of levelised cost of electricity) and also that a third of consumption has shifted to Western Australia, where solar resources are high quality. The decline in wind power toward the end of the projection period is partly due to a levelling of its competitiveness relative to solar over time and also the increasing cost of supporting wind's variable electricity output as existing flexible fossil fuel capacity is removed.

After taking account of some gas-fired generation remaining in the on-site generation sector, the share of renewable generation in total electricity generation in 2050 is 96 percent.

Figure 2.10 – Projected national electricity generation by technology, *100 percent renewable grid*, 2010–2050

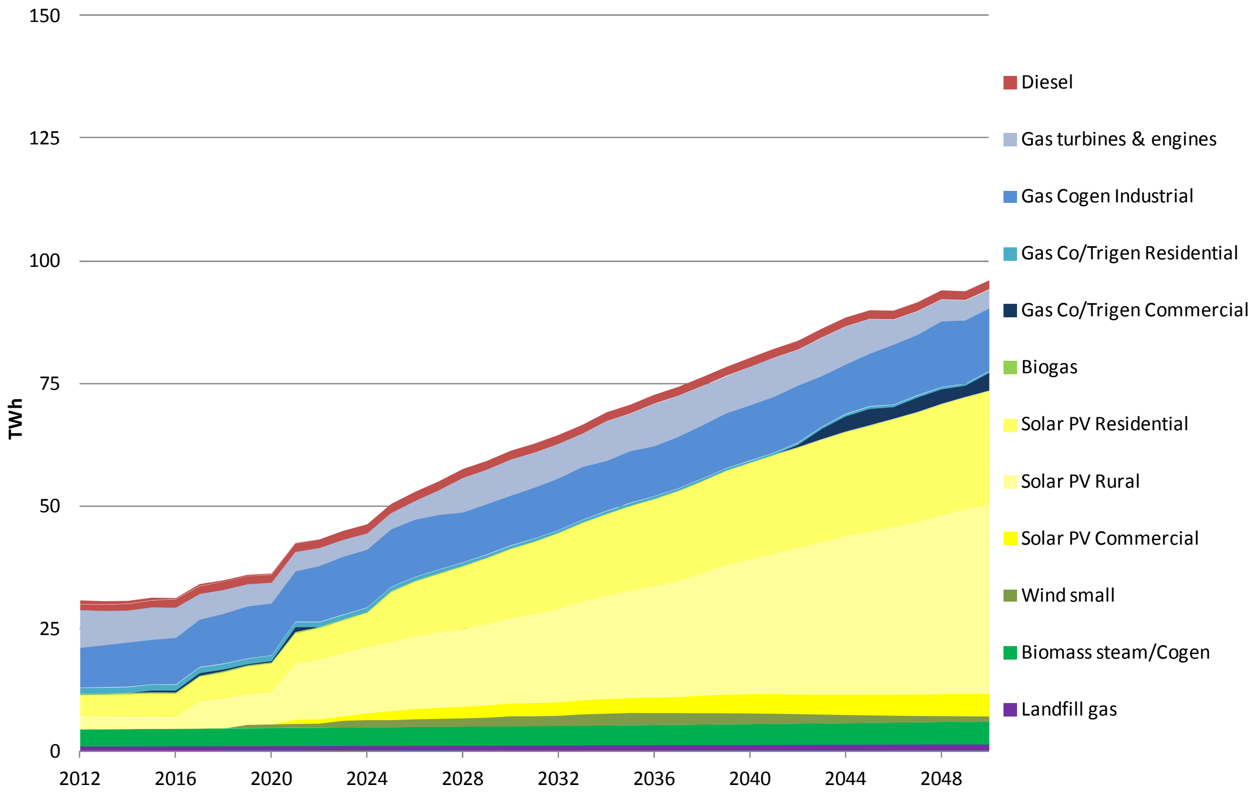


On-site electricity generation technologies increase their share of total electricity consumption from 12 percent in 2014 to 16 percent by 2050 which, given the total growth in demand, represents a more than tripling of on-site electricity generated. However in share terms this is lower than might have been expected relative to other modelling work that has examined on-site generation uptake, increasing its share to almost 50 percent (Graham and Bartley, 2013). The high rate of industrial electricity consumption growth (less suited to on-site generation), owing to industry electrification, has partially prevented this outcome. For example, if this level of on-site generation was achieved in 'Scenario 1' of Graham and Bartley (2013), where there is far more modest electrification (mainly modest adoption of electric vehicles) and resulting 2050 electricity generation of 295TWh, then the on-site generation share would have been 33 percent.

Another factor is that once the opportunities for including solar panels in buildings and use of available biogas have been exhausted, the remaining on-site generation options (mainly gas and diesel-based) are relatively high emissions and therefore less attractive in the long term under a high abatement incentive, compared to what is available as large-scale generation in the grid (although gas cogeneration and trigeneration options remain very low emissions compared to the current system).

The major source of growth in on-site generation by technology is solar panels, reflecting their strong reduction in costs relative to other on-site generation technologies and their ease of integration into the buildings of all customer types. The attractiveness of solar panels in reducing the need for grid-supplied electricity has been noted as a strong recent national and global trend. It was kick-started by the introduction of feed-in tariffs and renewable energy targets in many different countries, including Australia. While these incentives have since been reduced and may continue to decline, system costs have reduced so significantly that they may not be needed to allow for continued growth, particularly as wholesale and retail prices must rise in order to accommodate the changes in the large-scale grid-connected sector.

Figure 2.11 – Projected national on-site electricity generation mix, *100 percent renewable grid*, 2012–2050



The remainder of on-site generation needs are largely met by gas-generation, which may also be deployed as cogeneration and trigeneration, where there are opportunities to use waste heat. Much of this gas-based capacity relates to the use of gas in off-grid applications, such as in mining. As discussed, the extent to which an expanded mining sector continues to have a substantial share of its power supplied off-grid remains unanswered.

CCS

The *CCS* scenario explores the impact of allowing carbon capture and storage technology to be deployed, if it is economically viable to do so, whereas the *100 percent renewable grid* scenario preferentially deployed renewable electricity generation technology when new plant was needed. The projected electricity generation technology mix for the *CCS* scenario is shown in Figure 2.11.

Under the cost assumptions applied in ESM, CCS technology is competitive with renewable electricity generation technology, even more so than might be indicated by levelised cost of electricity (LCOE) data because the market balance constraints within ESM also take into account cost of supporting variable renewable electricity generation technology, rather than simply comparing their LCOE. The result is that the share of electricity supplied by renewable electricity generation is significantly reduced relative to the *100 percent renewable grid* scenario.

CCS technologies are adopted into the technology mix from 2025 and gradually increase their share to a maximum of 23 percent in 2043. The share declines to 20 percent by 2050 due to two constraints on CCS growth. The first constraint is that during the latter half of the projection period, electricity demand is strongest in Western Australia, which is assumed to have limited carbon dioxide storage opportunities.

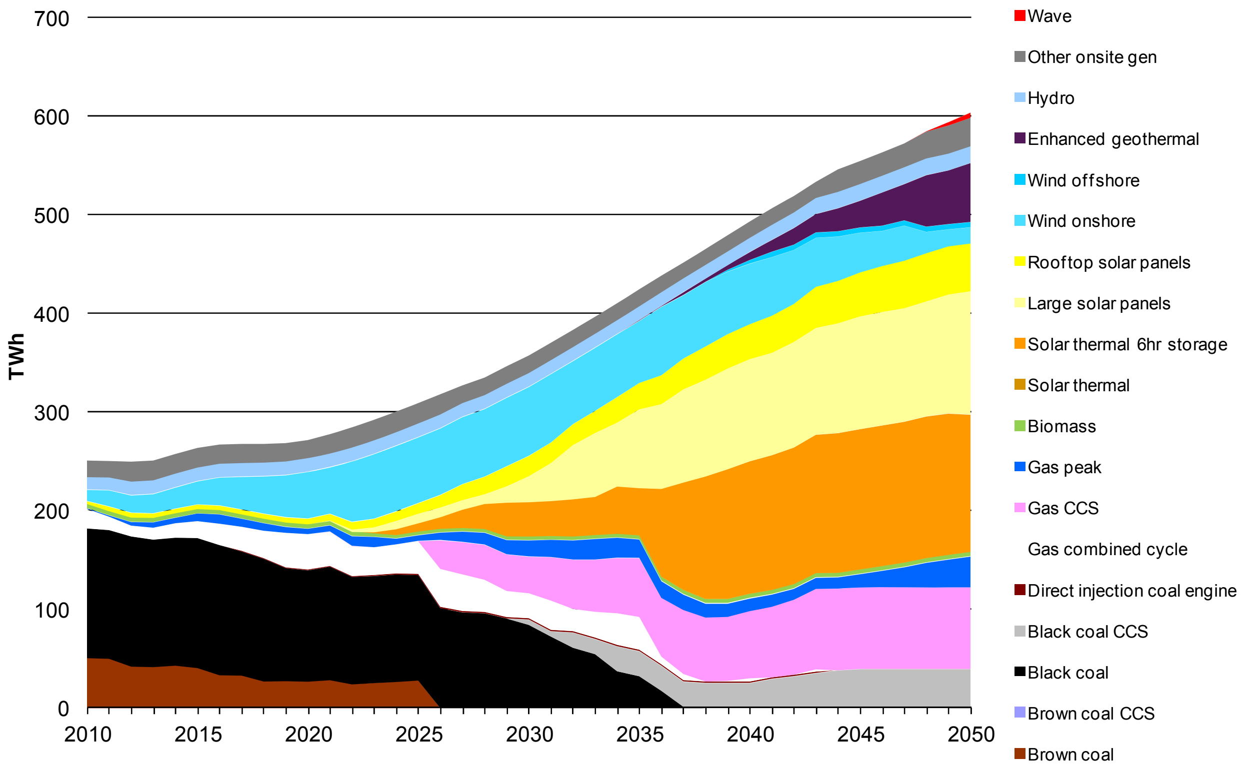
The second constraint is that carbon dioxide storage capacity in the east coast states becomes economically and quantity limited. The state with the best storage opportunities, Victoria, cannot make the best use of it due to the poor competitiveness of brown coal with CCS under a high abatement incentive. Consequently, Victorian storage opportunities are utilised by New South Wales black coal generators at additional distribution costs and Victorian gas generators at higher fuel costs.

With CCS opportunities limited, ESM expands use of renewable electricity generation technology, concentrating initially on the lower-cost solar and wind technologies, later supported by enhanced geothermal and a small amount of wave energy. Solar thermal is taken up earlier and greater than in the *100 percent renewable grid* scenario. This reflects that wind and large solar panels do not automatically have battery storage included in their development in this scenario and consequently the model has chosen to use more solar thermal with storage (together with peaking gas and enhanced geothermal) to support the management of variable renewables.

If CCS opportunities are less limited, then all else being equal, the share of CCS technologies could increase significantly beyond that projected here. The demonstrated scale of carbon dioxide storage resources in each state remains a significant uncertainty in understanding the potential of this technology.

The inclusion of CCS delays the uptake of other low-emission technologies, particularly large-scale solar compared to the *100 percent renewable grid* scenario, delaying the closure of some existing coal capacity to fill the gap before CCS is assumed to be commercially available. In the longer term, relative to the *100 percent renewable grid* scenario, the availability of CCS means there is less need to draw on the more marginal fossil and renewable technologies, such as natural gas without CCS and wave power.

Figure 2.12 – Projected national electricity generation technology mix in the *CCS* scenario, 2010–2050



NUCLEAR

The *Nuclear* scenario explores the impact of allowing nuclear electricity generation technology to be deployed. The projected electricity generation technology mix for the *Nuclear* scenario is shown in Figure 2.13.

Under the cost assumptions applied in ESM, nuclear electricity generation technology is competitive with renewable electricity generation technology. As in the *CCS* scenario, it is not just the levelised cost of nuclear power that is competitive but also its flexibility relative to variable renewables, which require some additional support. The use of gas peaking, solar thermal with storage and enhanced geothermal to provide flexible generation alongside nuclear power is similar to the *CCS* scenario.

As in the *CCS* scenario, we do include some limits on nuclear power deployment. ESM only allows nuclear power in the larger states of New South Wales, Queensland and Victoria, since nuclear power stations generally have to be a minimum size, which would preclude their deployment in the smaller states.[9] While Western Australia becomes a large power-using state in aggregate over the course of the projection period, the lack of clarity around how much power remains off-grid and how separate the South East and Pilbara grids remain meant that nuclear was not included as an option for that state. The main concern was that, without more detailed transmission modelling, it would be difficult to estimate the cost of transmitting nuclear power throughout that region.

The result of these assumptions is that all three large states take up nuclear power but are not ultimately dominated by it, indicating nuclear power is competitive under the assumptions but not by a large margin. By 2047 nuclear power has peaked at 86TWh and a 14 percent market share.

ESM was re-run to check what would have happened if Western Australia had been allowed to adopt nuclear power. Under that assumption, the share of nuclear power increases to 27 percent. This could perhaps be achieved with an expanded Western Australian transmission system or alternatively through the use of small-scale nuclear plant, which are not included in ESM's technology set, but were examined in BREE (2012). With the use of small-scale nuclear plant or a more interconnected grid there is no technical reason why nuclear power could not supply a major share of electricity consumption. The 14 percent share projected here should definitely not be interpreted as an upper limit but is rather a necessarily conservative result, given that detailed transmission network planning was outside the scope of this study.

A potential risk to high adoption of nuclear power is that as other countries take up nuclear power the uranium price may experience periods of high prices, increasing the cost of nuclear power relative to alternatives. However unless there is a genuine resource constraint relative to demand, commodity markets tend to revert to prices that reflect the cost of production over the longer term.

Similar to the CCS scenario, the use of nuclear power means that there is reduced adoption of some of the higher-cost renewable technologies.

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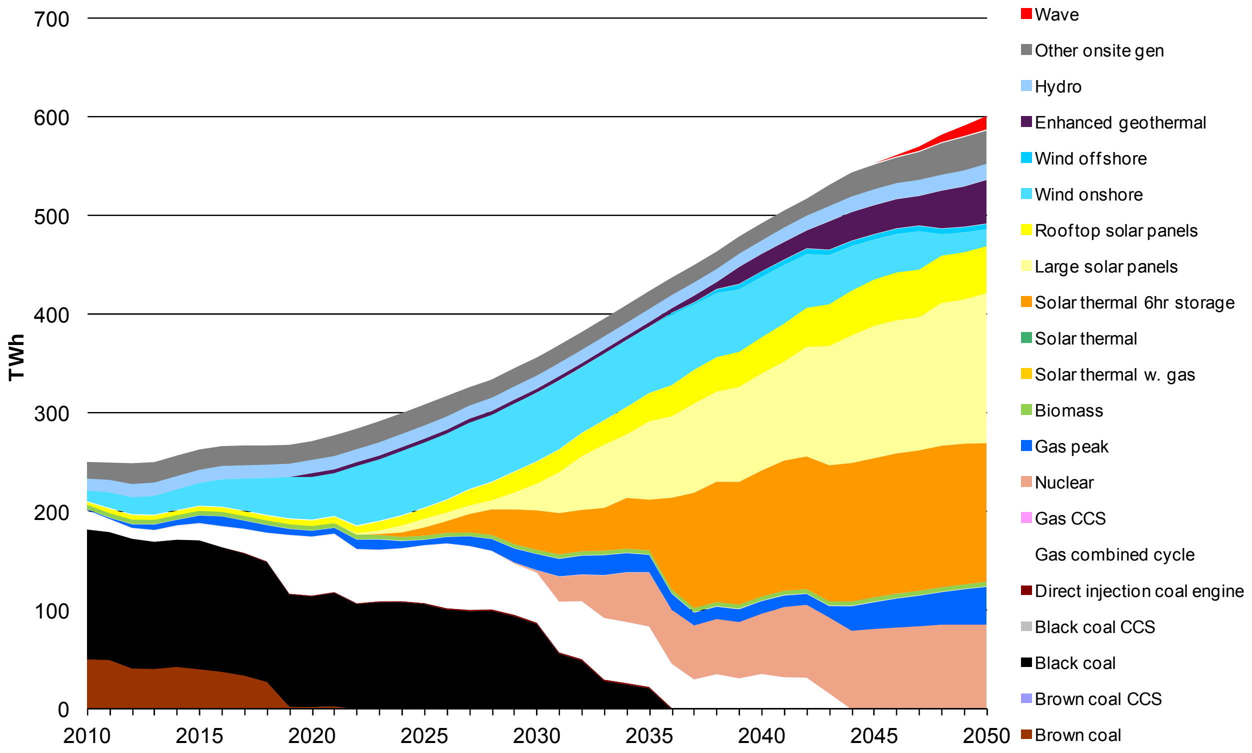
[9] There have been suggestions in general literature that smaller, modular nuclear power stations could be deployed in smaller grids. This option is not included in ESM but could warrant future consideration.

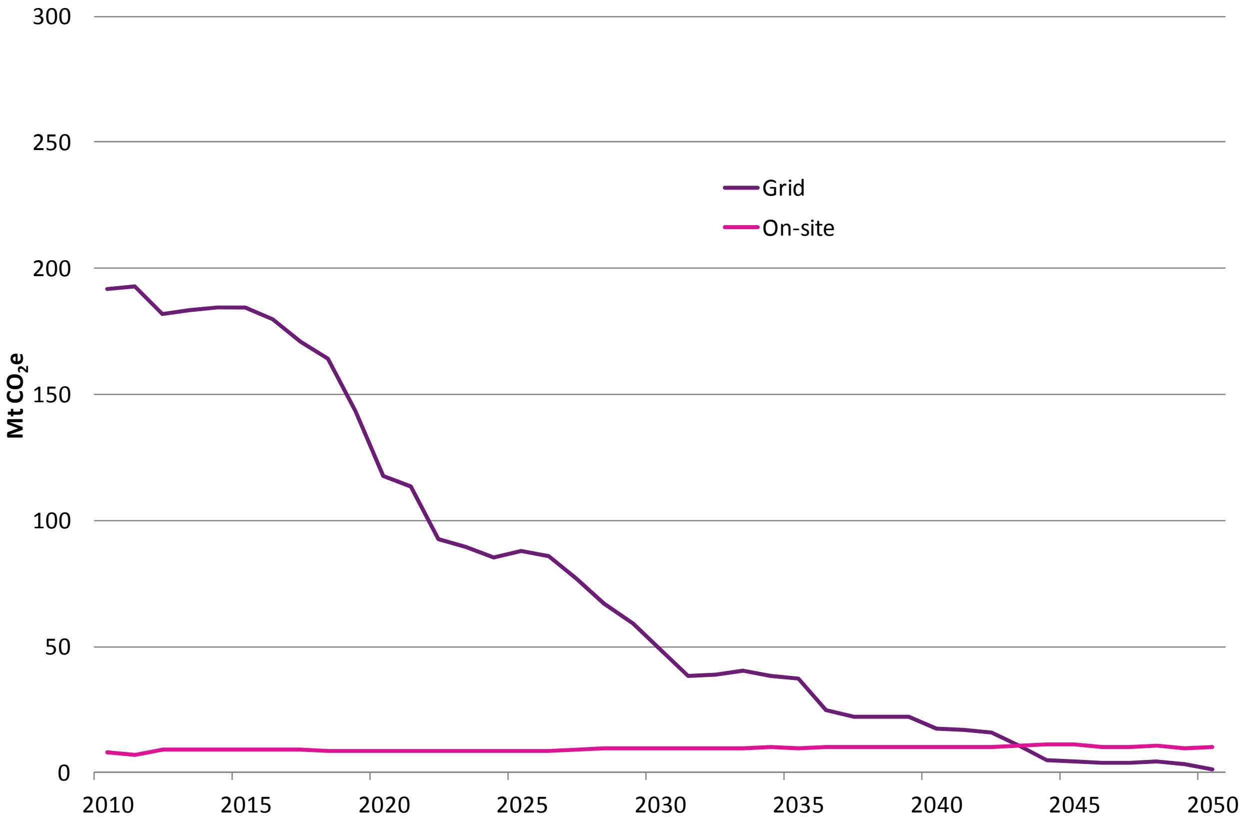
Figure 2.13 – Projected national electricity generation technology mix in the *Nuclear* scenario, 2010–2050



ELECTRICITY SECTOR GREENHOUSE GAS EMISSIONS

In the *100 percent renewable grid* scenario, following the recent mothballing of coal-fired electricity generation and reduced electricity demand, the modelling projects a brief period of stability in emissions up to around 2016 (Figure 2.14). Thereafter, the projected greenhouse gas emissions over time reflect the changes in the emission intensity of electricity generation. As coal-fired electricity generation is retired during the period 2017 to 2035, electricity sector greenhouse gas emissions rapidly decline. By 2050, greenhouse gas emissions are negligible in grid-supplied electricity but remain positive in the on-site generation sector, owing to the use of natural gas in on-site generation (particularly off-grid applications).

Figure 2.14 – Projected greenhouse gas emissions from grid and on-site electricity generation, *100 percent renewable grid* scenario, 2010–2050



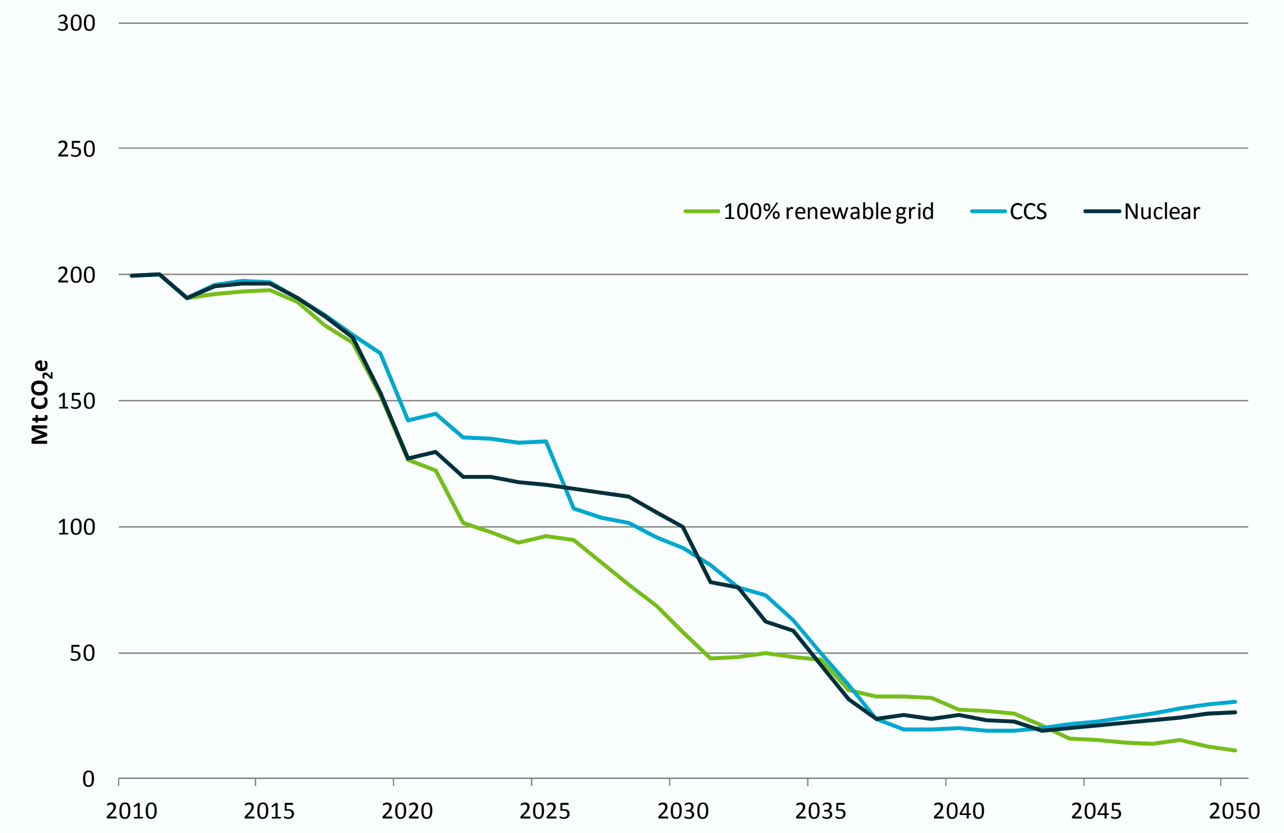
The projected outcome for greenhouse gas emissions for the *100 percent renewable grid, CCS* and *Nuclear* scenarios is compared in Figure 2.15. The projection indicates that all the technology mixes are capable of reducing greenhouse gas emissions from electricity generation by 2050 from between 85 to 94 percent relative to 2010. The greenhouse gas emissions intensity of electricity generation achieved in the *100 percent renewable grid, CCS* and *Nuclear* scenarios are 0.02, 0.05 and 0.04tCO_2e/MWh respectively.

Not surprisingly, the *CCS* scenario has the highest final greenhouse gas emissions intensity of electricity generation and absolute level of emissions. This reflects the assumption that CCS technology can only capture a maximum of 90 percent of emissions from fossil fuel combustion. The cost of capturing the final 10 percent would be prohibitively high.

Nuclear power is 100 percent emissions free, but the *Nuclear* scenario does not achieve the same greenhouse gas emissions intensity of electricity generation as the *100 percent renewable grid* scenario because the limitations on nuclear power towards the end of the projection period and absence of the requirement for all grid power to be renewable encourages slightly more gas-based grid and on-site electricity generation.

While rapid deployment of large-scale CCS or nuclear power plant in the late 2030s temporarily accelerates emissions reduction in the *Nuclear* and *CCS* scenarios below that of the *100 percent renewable grid* scenario, on balance, across the whole projection period, the *100 percent renewable grid* scenario is a more rapid emissions reduction pathway. Consequently, the amount of cumulative emissions for the *100 percent renewable grid* scenario in the period between 2010 and 2050 is around 11 percent lower than the *CCS* and *Nuclear* scenarios.

Figure 2.15 – Comparison of projected national greenhouse gas emissions for the *100 percent renewable grid*, *CCS* and *Nuclear* scenarios, 2010–2050



ELECTRICITY WHOLESALE AND RETAIL PRICES

ESM projects the wholesale electricity price as the marginal cost of delivering a balanced electricity market in a given year. In other words, it is a cost-based price projection methodology. In reality, bidding behaviour and other market features could lead to a different outcome, but all models, regardless of what degree of real world market features they include, will eventually assume the price returns to long-run marginal cost over the long term.[10]

With a strong rising abatement incentive driving the modelling results, it is not surprising that ESM forecasts rising wholesale electricity prices in the *100 percent renewable grid* scenario. The increase occurs in two distinct periods. The first is up to 2020, where prices rise to cover the costs of building new gas-fired, wind and solar plant to meet new demand and replace the loss of brown coal-fired plant.

The second steep increase in prices is between 2025 and 2035, where substantial investment must take place to meet new demand and replace black coal-fired electricity generation. On this occasion, the system requires investment in higher cost renewables, such as enhanced geothermal and solar thermal (with and without storage), so that the system has enough flexible plant to support other variable renewable electricity supply.

After 2035, wholesale electricity prices are stable. This reflects the fact that given new renewable capacity has no carbon emissions its costs are fairly stable, despite rising abatement incentives. It also reflects that the costs of some renewable electricity plant are still improving (due to global and local learning), although this can be offset by higher costs in relation to connecting renewables to the grid. In the early 2040s the decreasing costs of renewable

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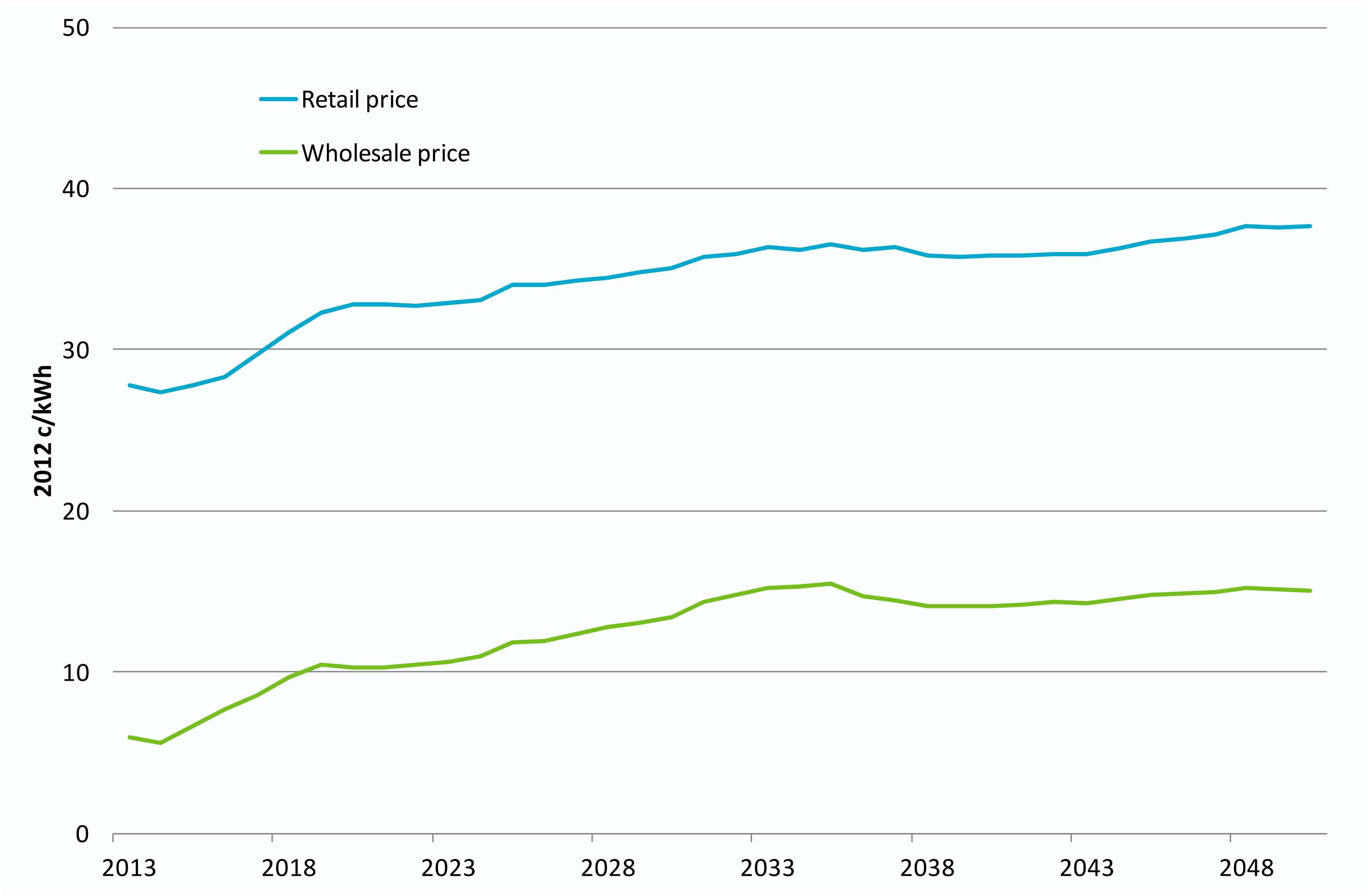
[10] This is to avoid one of two logical inconsistencies: 1) that investors would continue to build new plant with the knowledge that they will not make a reasonable return on investment in a period of sustained prices below long-run marginal cost; or, 2) that governments would not intervene to make the market more competitive in the event of a sustained period of prices being above long-run marginal costs. This is not say that ESM does not project shorter periods where prices are above or below long-run marginal costs. These are possible and are fully consistent with electricity markets, where long-lived assets and investment delays mean that supply is slow to respond to market conditions.

plant appears to be the stronger driver but towards 2050, connecting to higher-cost resources is beginning to assert a stronger impact.

Figure 2.16 – Projected national average wholesale and retail electricity prices, *100 percent renewable grid* scenario, 2013–2050



Wholesale electricity prices are only the second largest component of retail prices. The largest component is distribution network costs. The major driver for distribution unit costs is the amount of network that must be built to reliably meet peak demand and the volume of electricity consumption using that infrastructure. If peak demand rises faster than volume then, all else equal, the cost of distribution per volume of electricity must rise. There are other factors such as unevenness in the rate of replacement of assets, the cost of finance and changes to reliability standards, which can and have also impacted the rate of change in distribution costs.

In this scenario, distribution costs increase slightly in the short term due to peak demand growing faster than volume but decrease slightly in the long term, as volume growth begins to outpace peak demand growth. Stronger volume growth in the latter half of the projection period is due to the strong uptake of electric vehicles in road transport. This change increases growth in volume without adding to peak demand (we assume vehicle charging is ubiquitously well managed).

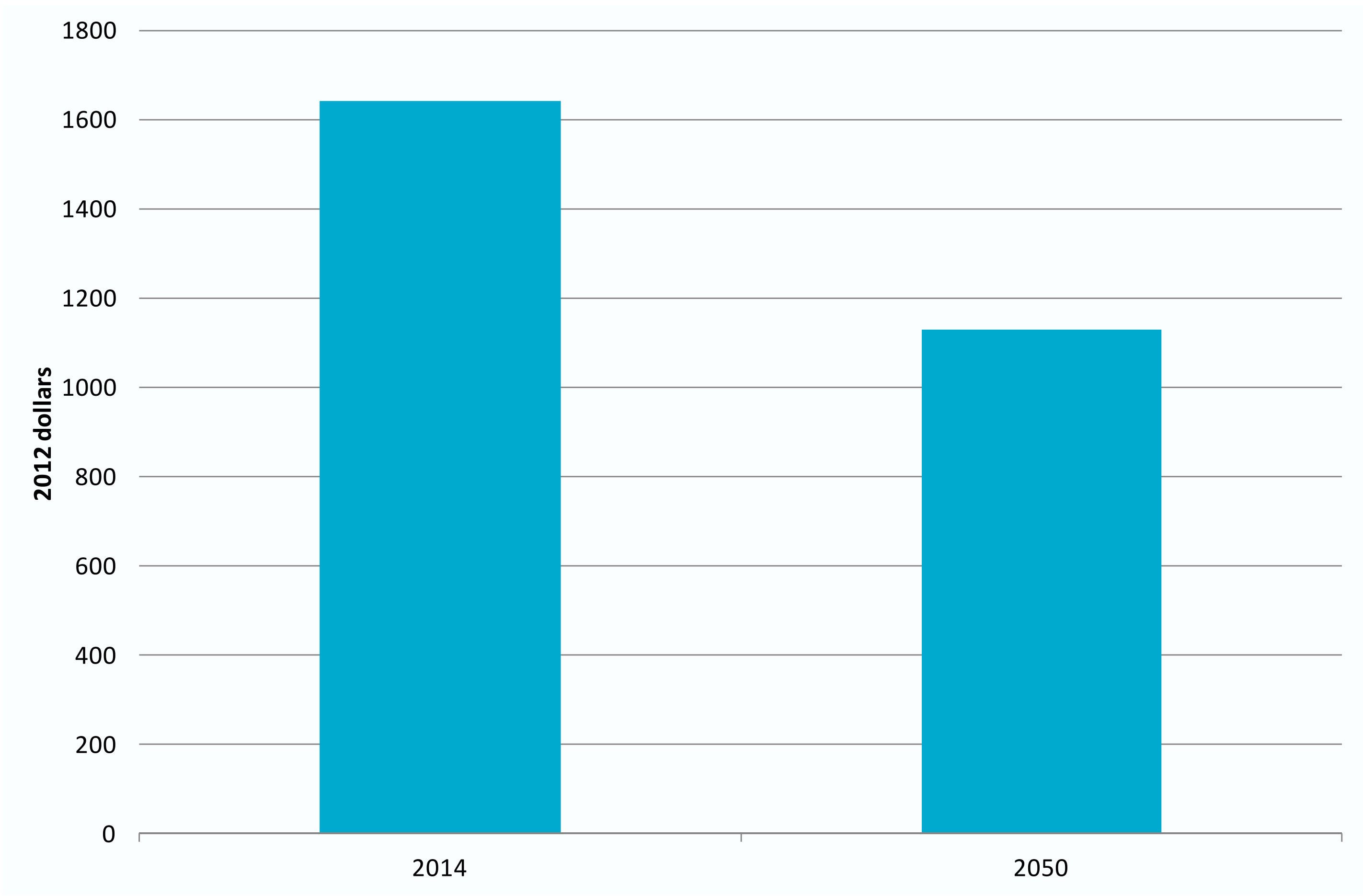
The remainder of residential retail costs are made up of state and federal policies, which are generally phased out, retailer's margin (which is held constant) and transmission network costs. Transmission costs are assumed to rise significantly during the period between 2035 and 2050, as renewable are deployed to more remote locations as outlined in the assumptions and based on Graham et al. (2013).

Adding up these individual components leads to a residential retail electricity unit cost projection of around 38c/kWh in 2012 dollars by 2050. This represents an annual average rate of increase of 0.9 percent per annum, or around 40% to 2050. Our modelling suggests that energy efficiency could lead to around 50% reduction in average electricity use per household by 2050 (excluding energy for electric vehicles, which is legitimately excluded as it replaces costs for petrol, diesel or LPG). This implies that the average household electricity bill would be around 30% lower (adjusted for inflation) in 2050 than today, because energy efficiency gains outweigh power cost rises.

In addition, the annual rate of growth in per capita income is 1.2 percent, for a total increase of 56% until 2050. As a result of falling absolute expenditure on electricity and rising incomes, the share of electricity expenditure in household income falls by around half, on average.[11]

However, even if income were not rising, the total electricity bill (again excluding electric vehicle charging costs) is falling, because the 38 percent increase in residential retail electricity prices is more than offset by a 50 percent reduction in household electricity consumptions. This is demonstrated in Figure 2.16, where we show the electricity cost for a typical 6000 kWh/year electric appliance-only household at around $1600 in 2014 and declining to around $1100 in 2050. Households that retain some use of gas appliances may face higher costs under abatement incentives. Also note, of course, that any costs involved in reducing household electricity use via energy-efficiency measures, would need to be included in a full analysis of household costs.

Figure 2.17 – Projected annual cost of electric appliance-only household electricity consumption in 2014 and 2050, excluding cost of EV-charging and energy-efficiency investments, *100 percent renewable grid* scenario



While not provided as a separate projection, it can be said qualitatively, and with confidence, that large commercial and industrial retail electricity prices would be rising faster than residential retail prices under this scenario. This is because wholesale prices are a much larger component of their retail electricity bill and wholesale prices are rising faster than any other component. This impacts the manufacturing sector the most, due to their relatively high electricity intensity per dollar of output. MMRF provides more detail on changes in industry output resulting from this increase in electricity input costs.

Moderating the higher volume of electricity use (through substitution of electricity for other energy sources) and increase in retail prices experienced by large electricity customers is an expected 50 percent improvement in energy use per square metre in commercial buildings, and about 40 percent improvement in energy use per volume of production in manufacturing.

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[11] If there were any costs involved in reducing electricity use per capita via energy efficiency measures, the cost of these measures would need to be included in a full analysis of electricity supply and end-use costs.

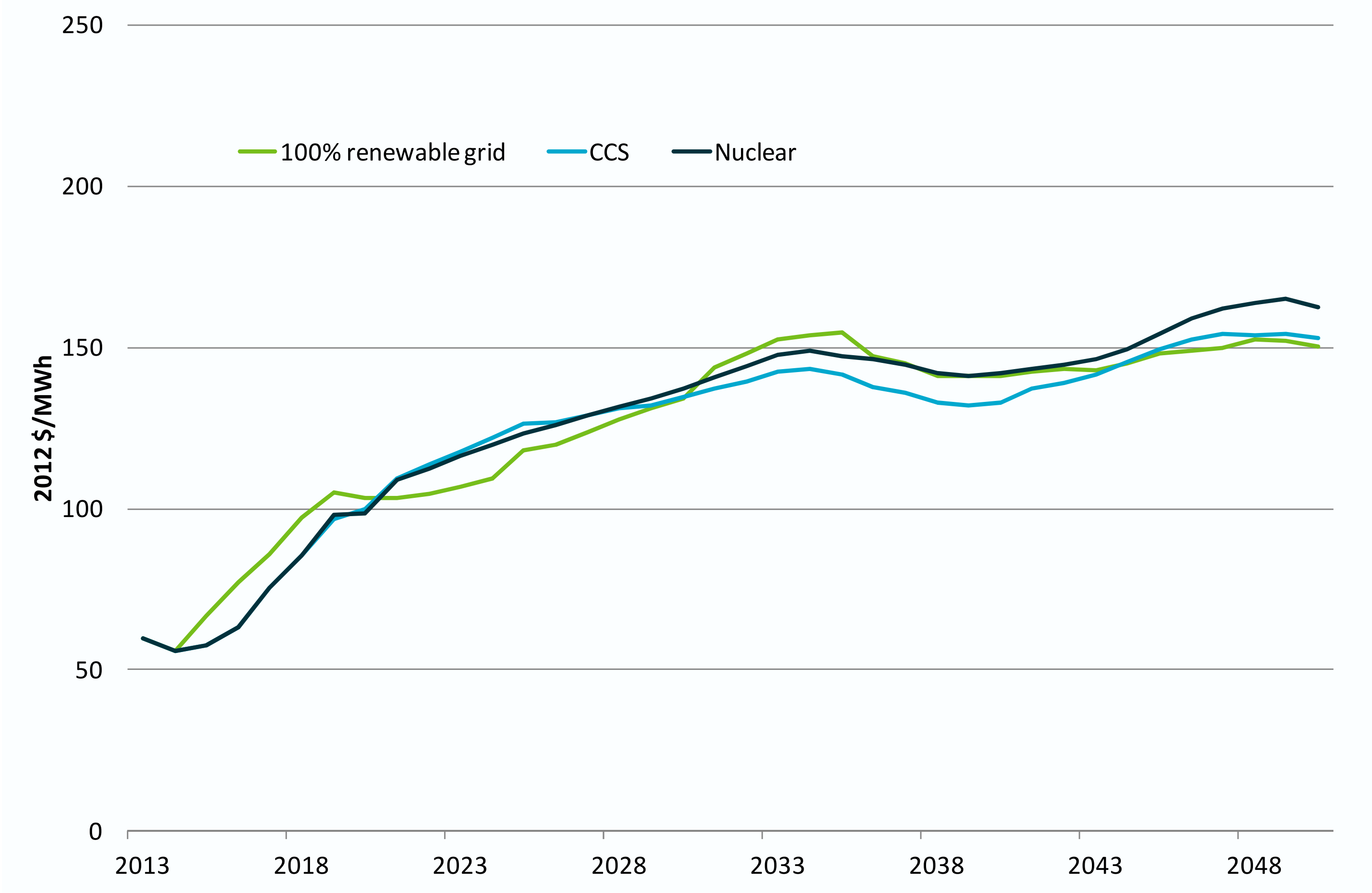
PRICE AND GREENHOUSE GAS EMISSIONS COMPARISONS

A comparison of projected wholesale electricity prices for the *100 percent renewable grid*, *CCS* and *Nuclear* scenarios is shown in Figure 2.18. The comparison indicates that there is very little difference between the wholesale price outcomes when taken as a whole over the projection period, reflecting that the costs are in a similar range. There are some small differences at various times.

In the early part of the projection period, the *CCS* and *Nuclear* scenarios are lower cost, as they are able to make plant choices that are not influenced by the need to build towards a long-term objective of a 100 percent renewable grid by 2050. This means delaying purchases of new, higher-cost renewable plant until later and deploying the minimum and lowest cost plant required to meet the existing (nominal) 20 percent Renewable Energy Target by 2020.

In the 2020s, the *CCS* and *Nuclear* scenarios can no longer delay shifting to higher-cost low-emission technology and this new investment increases their costs relative to the *100 percent renewable grid* scenario. In the 2030s the *CCS* scenario breaks away from the *Nuclear* scenario, indicating a higher rate of CCS technology deployment is delivering some cost benefits. The *CCS* and *Nuclear* price paths merge and move apart again later during the 2040s when they both begin to hit competitive or resource constraints to their deployment. Note that the increasing price trend in the last five to ten years of the projection period is common across all scenarios and is mostly related to the cost of connecting to more remote renewable resources.

Figure 2.18 – Comparison of projected national average wholesale electricity prices for the *100 percent renewable grid, CCS* and *Nuclear* scenarios, 2013–2050



2.5 Summary of alternative pathways and deeper emissions reductions opportunities

There are alternative options that exist, which could either replace modelled pathways should they be unavailable, or enable deeper emissions reductions. Below is a summary of the key options that could be considered in future work in the electricity sector.

Demand side

- **Strong improvements in materials efficiency in industry** – would reduce the need for the extraction of resources and the production of emissions-intensive commodities, which make up a large part of the additional demand by 2050.
- **Very deep efforts in energy efficiency** – for example deep improvements in energy efficiency through complete process redesign (particularly in mining, which has increasing energy intensity and would be responsible for the majority of electricity use in 2050).
- **More efficient electrification of buildings and industry processes** – replacing a larger amount of direct fuel for each unit of electricity would also reduce the additional electricity demand to 2050.
- **More responsive demand through implementation of smart grid technologies** – opening up demand response markets and deploying technologies, such as on-site storage, could change the notion of how demand and supply are balanced across the system and support renewable integration.

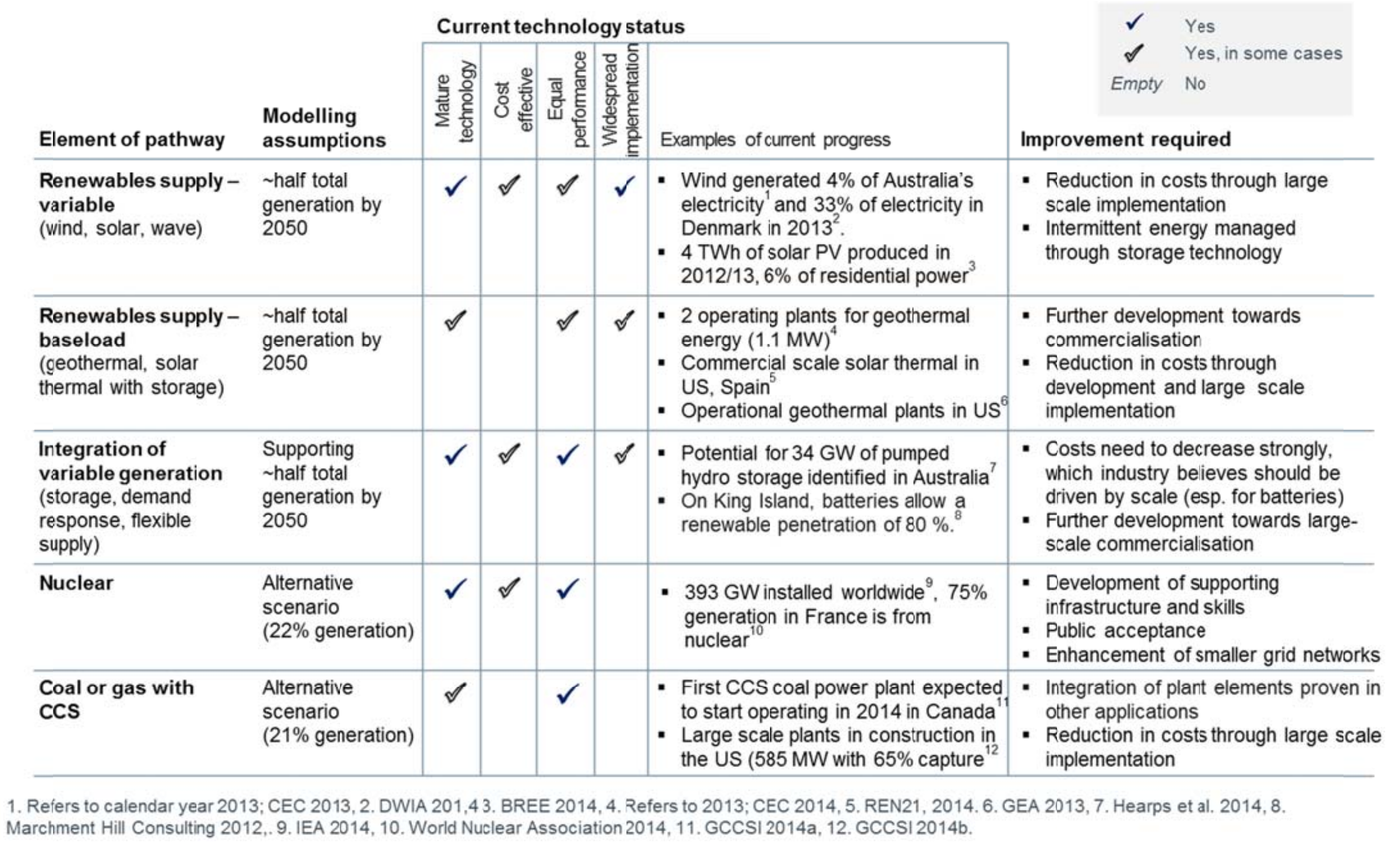
Supply side

- **Increased decentralisation of generation** – further analysis could be conducted to understand the cost and benefits of increasing the share of decentralised generation, as well as the potential role for localised grids.
- **Biomass with CCS** – could be used to generate electricity with net negative emissions intensity, should the remainder of the generation mix be more emissions-intensive than modelled.
- **Greater connectivity of state electricity systems and CO_2 storage resources** – a more interconnected electricity system would assist in supporting variable renewables and allowing the outputs of large-scale systems such as CCS and nuclear power to reach more states. Similarly, a national CO_2 pipeline would increase the reach of CCS technology.
- **Small-scale nuclear power** – could be used where an expanded transmission system is not economically viable.

2.6 Technology status overview

Table 2.6 below summarises the status of the major technologies involved in the deep decarbonisation scenario for the electricity sector. As can be seen below, the technologies required for decarbonisation are already being developed, with integration and commercialisation requiring the most progress. Enhanced geothermal power is perhaps the least mature. A full discussion of its pathway to commercial adoption has recently been published by the International Geothermal Expert Group (2014).

Table 2.6 – Summary of technology status in the electricity sector



✓	Yes
✔	Yes, in some cases
Empty	No

		Current technology status					
Element of pathway	**Modelling assumptions**	Mature technology	Cost effective	Equal performance	Widespread implementation	Examples of current progress	**Improvement required**
Renewables supply – variable (wind, solar, wave)	~half total generation by 2050	✓	✔	✔	✓	▪ Wind generated 4% of Australia's electricity[1] and 33% of electricity in Denmark in 2013[2]. ▪ 4 TWh of solar PV produced in 2012/13, 6% of residential power[3]	▪ Reduction in costs through large scale implementation ▪ Intermittent energy managed through storage technology
Renewables supply – baseload (geothermal, solar thermal with storage)	~half total generation by 2050	✔		✔	✔	▪ 2 operating plants for geothermal energy (1.1 MW)[4] ▪ Commercial scale solar thermal in US, Spain[5] ▪ Operational geothermal plants in US[6]	▪ Further development towards commercialisation ▪ Reduction in costs through development and large scale implementation
Integration of variable generation (storage, demand response, flexible supply)	Supporting ~half total generation by 2050	✓	✔	✓	✔	▪ Potential for 34 GW of pumped hydro storage identified in Australia[7] ▪ On King Island, batteries allow a renewable penetration of 80 %.[8]	▪ Costs need to decrease strongly, which industry believes should be driven by scale (esp. for batteries) ▪ Further development towards large-scale commercialisation
Nuclear	Alternative scenario (22% generation)	✓	✔	✓		▪ 393 GW installed worldwide[9], 75% generation in France is from nuclear[10]	▪ Development of supporting infrastructure and skills ▪ Public acceptance ▪ Enhancement of smaller grid networks
Coal or gas with CCS	Alternative scenario (21% generation)	✔		✓		▪ First CCS coal power plant expected to start operating in 2014 in Canada[11] ▪ Large scale plants in construction in the US (585 MW with 65% capture[12]	▪ Integration of plant elements proven in other applications ▪ Reduction in costs through large scale implementation

1. Refers to calendar year 2013; CEC 2013, 2. DWIA 201,4 3. BREE 2014, 4. Refers to 2013; CEC 2014, 5. REN21, 2014. 6. GEA 2013, 7. Hearps et al. 2014, 8. Marchment Hill Consulting 2012,. 9. IEA 2014, 10. World Nuclear Association 2014, 11. GCCSI 2014a, 12. GCCSI 2014b.

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TRANSPORT SECTOR

P. Graham, S. Hatfield-Dodds, CSIRO

3. Transport sector

Executive summary

This section provides the detail behind the transport projections underpinning the Australian contribution to the United Nations Sustainable Development Solutions Network (UN SDSN) and Institute for Sustainable Development and International Relations (IDDRI) Deep Decarbonisation Pathways Project led by ClimateWorks Australia and the Australian National University (ANU). The key role of CSIRO modelling was to provide least-cost and biophysically plausible transport sector projections. The projections are used directly to inform the development of an Australian deep decarbonisation pathway and also applied indirectly as inputs to whole of economy general equilibrium modelling. National general equilibrium modelling was conducted by Victoria University's Centre of Policy Studies and, in addition to CSIRO input, included inputs directly from the ClimateWorks team, particularly in relation to energy end-use efficiency and industrial energy use.

The modelling predominantly utilises technological and fuel-related solutions to reducing emissions. This is because these solutions are relatively easy to parameterise and are broadly applicable at a national scale. This is in contrast to solutions such as non-motorised transport (walking, cycling) and public transport, which are difficult to model without representing those solutions in context of redesigning elements of each of our major cities. As such our approach tends to favour an outcome that largely maintains our current lifestyles. However this should not be interpreted as an optimised outcome. While it is internally optimised to be technological least-cost, it is only one of several pathways that could be employed to achieve substantial reductions in transport greenhouse gas emissions.

The modelling projects that vehicles with only internal combustion engines will be gradually phased out of light-duty road vehicles by 2050 in favour of hybrid, fully electric, plug-in hybrid electric and fuel cell vehicles, which make use of very low-emission intensity electricity as their primary fuel source (hydrogen fuel cells are assumed to source hydrogen from the use of electrolysis). Light-duty vehicles are the largest source of transport emissions.

Long-haul heavy-duty road, aviation, marine and rail freight transport (as opposed to electrified urban passenger rail) is less amenable to electrification. Aviation emissions are the largest of the non-road emissions and we use a combination of fuel efficiency, bio-derived jet fuel, mode shifting to fast train travel and reduced demand growth via teleconferencing to moderate growth in emissions. The heavy-duty road transport, marine and rail freight sectors primarily adopt fuel efficiency, natural gas and some biofuels as abatement strategies.

Overall, road transport greenhouse gas emissions decrease by 69 percent to 23 $MtCO_2e$ by 2050. Non-road transport emissions increase to five percent above their current level by 2050, reflecting the greater challenges in abating emissions from those transport modes.

3.1 Energy sector modelling methodology

As discussed in the overview of the modelling framework, CSIRO's Energy Sector Model (ESM) is responsible for modelling the energy sector and linking to the MMRF general equilibrium model of the national economy. As the name implies ESM provides detailed modelling of the energy sector, in particular the electricity and transport sectors. ESM has been extensively applied in Australia, including in every major analysis of climate policy in Australia since 2006 (Reedman and Graham, 2013a and 2013b; Reedman and Graham, 2011; BITRE and CSIRO, 2008) and in most cases working with MMRF. ESM is outlined in detail in Appendix A.

CSIRO's Energy Sector Model (ESM) is applied to develop the transport sector projections. ESM is unique in Australia in that it combines both the electricity and transport markets. This is an important feature in this project, where energy and transport sector abatement are a key focus, and the project explores a substantial amount of road transport electrification and, as a result, cross-sectoral interaction. ESM simultaneously solves for the cost of electricity supply and the demand from electric vehicles to deliver consistent modelling results in one step.

ESM minimises the cost of meeting transport demand and is primarily an economic modelling framework. A number of physical conditions have been imposed that represent constraints to minimising cost, including how vehicles and fuels work, consumer vehicle preferences, limitations on where fuel and other resources are located, as well as their costs and volume and both the economic or physical retirement of the fleet. More details are provided in Appendix A.

3.2 Assumptions and inputs

Two recent ESM modelling exercises outline in detail ESM's standard model assumptions and, as such, this report only details the assumptions that are key to this project or that are non-standard, given the context of the deep emissions reduction scenario explored here.

Unless otherwise addressed, transport sector assumptions remain consistent with those set out in detail in Reedman and Graham (2013a) and Graham et al. (2013).

3.2.1 General strategy to achieve transport emission reductions

To address the DDP project brief, a combination of traditional economic instruments and additional social and technical assumptions have been applied to achieve an emissions reduction pathway in the transport sector, which is modest in cost, technically achievable and will not require significant lifestyle change. Key strategies implemented in ESM for the transport sector are listed in Table 3.1. Note that Table 3.1 includes a mix of strategies that were input assumptions agreed with ClimateWorks but also strategies that emerged from the modelling as outputs after imposing an economic instrument that results in a least-cost response. These strategies represent a limited set of potential pathways for deep decarbonisation in electricity and transport, as included in the modelling. Alternative strategies are elaborated on that could be deployed should deeper emissions reduction or alternative pathways be required at the conclusion of the modelling results discussion.

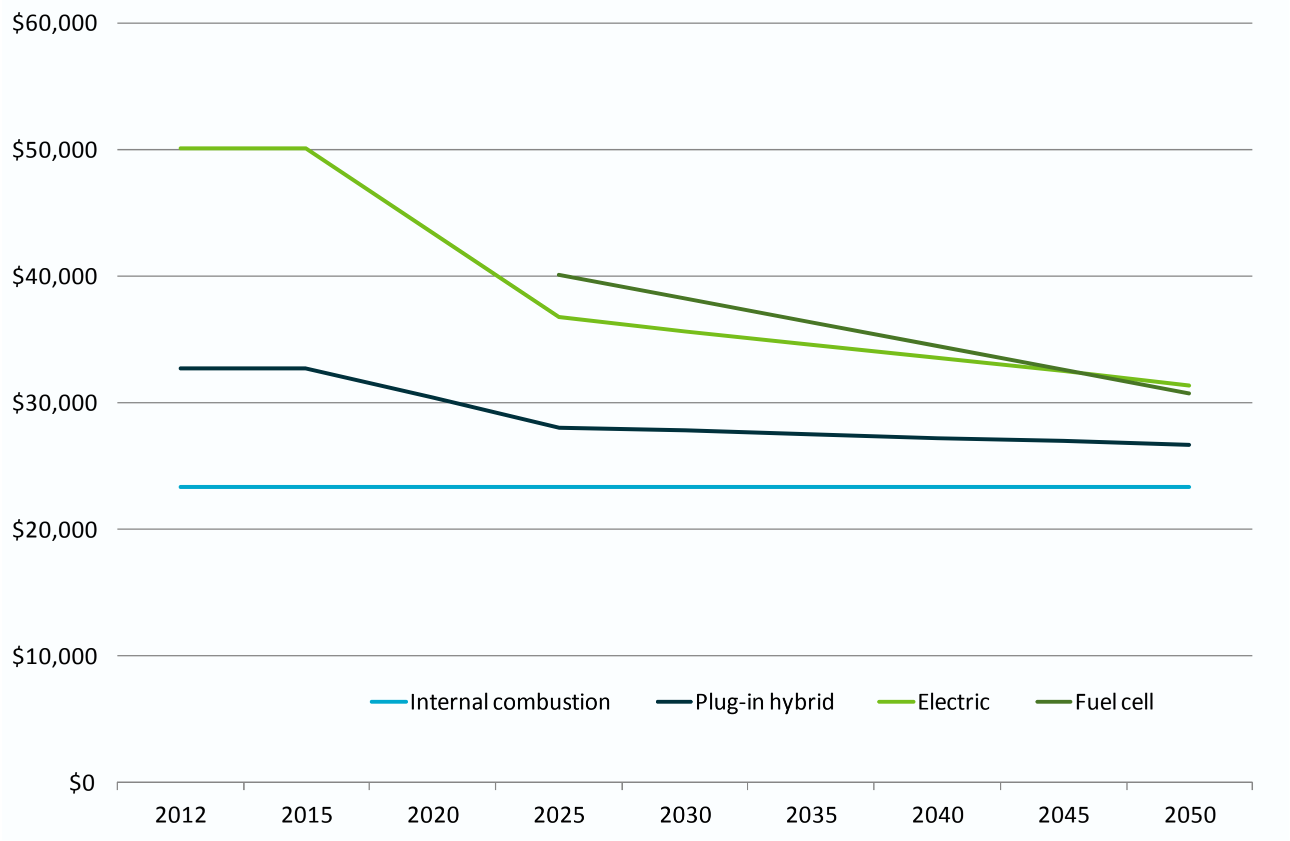
Table 3.1 – Key strategies applied in ESM transport sector for achieving the Australian deep decarbonisation pathway

	Structural change	Technical energy efficiency	Fuel switching	Decarbonisation of energy transformation
Road passenger	Trend toward smaller passenger vehicle sizes continues.	Passenger vehicle efficiency improves substantially after 2020, due to increasing electrification.	A mix of fully electric, hybrid plug-in electric and fuel cell vehicles dominate by passenger road transport by 2050.	Hydrogen and electricity is sourced from the electricity grid, which has decarbonised to 0.02-0.05 tCO_2e/MWh (see electricity modelling). Biofuels are sourced from second-generation feedstocks, with minimum 50 percent full fuel cycle emission reduction relative to petroleum fuels.
Road freight	Limited road to rail mode shifting due to logistical constraints.	Truck internal combustion efficiency improves by 15 percent by 2030 diverging from the flat trend of the last two decades. Some electrification of shorter haul trucks is also assumed.	Road freight adopts LNG, biofuels and electricity (where possible).	Biofuels are sourced from second-generation feedstocks, with minimum 50 percent full fuel cycle emission reduction relative to petroleum fuels.
Aviation	Fast rail shifts 15 percent of passenger travel away from aviation. Aviation is further reduced (five percent) by teleconferencing.	Aviation fuel efficiency improves 1 percent per annum.	Up to 50 percent of aviation can adopt biofuels.	As above.
Other freight transport	Limited road to rail mode shifting due to logistical constraints.	Shipping and rail fuel efficiency improves around 0.4 percent per annum. Past trend improvements in task efficiency (tonnes per km) are assumed to continue to be available.	Rail and shipping adopt 10 percent each of biofuels and natural gas.	As above.
Liquid fuels	Conventional petroleum refining continues to decline but is partially replaced with new biofuel refining plant.	Fuel efficiency improvements in transport internal combustion engines and through electrification and fuel cells anticipated.	A substantial amount of liquid fuel is replaced by electricity. Biofuels account for 33 percent of remaining liquid fuels.	Only second-generation (non-food) biofuels of greater than 50 percent full fuel cycle improvement in emissions are adopted.
Gas fuels	Greater use in transport for heavy trucks, shipping and rail.	Improved efficiency when combined with use of waste heat in electricity cogeneration.	Declining use in buildings, contributing to higher demand for electricity.	LNG provides around a 20 percent reduction on diesel emissions in trucks.

3.2.2 Road transport vehicle costs

The US SDSN provided projections of the future global costs of electric, plug-in electric and fuel cell vehicles. These are for a medium-sized passenger vehicle and are shown in Figure 3.1. These broad trends are applied to the nine representative vehicle types in ESM, ranging from small passenger vehicles up to trucks and buses.

Figure 3.1 – Projected global vehicle costs by type of drivetrain



3.2.3 Hydrogen

Hydrogen fuel cell vehicles have not featured strongly in previous ESM modelling of the road transport sector, due to higher cost assumptions. Under the US SDSN assumptions fuel cell vehicles are included in the Australian vehicle mix, reflecting greater confidence in future costs. The modelling assumes no supply constraints on hydrogen fuel, but the rate of vehicle supply to Australia is constrained in the medium-term, due to lack of fuel cell vehicle models available. There has been significant research conducted in the past on how to establish hydrogen supply chains (Graham and Smart, 2011) and while there would be significant inertia in establishing new infrastructure, there is no shortage of delivery methods or primary energy resources that would justify imposing hydrogen fuel constraints in the long term.

Although there are many potential sources of hydrogen, for simplicity and consistency, it is assumed that hydrogen is generated via electrolysis from the grid at a conversion loss of 30 percent.

3.2.4 Electric vehicle adoption upper limits

In previous ESM modelling, upper limits on electric vehicle adoption have been imposed based, in the short term, on global vehicle supply and, in the long term, on not sacrificing the ability to travel long distances, which is a feature of Australian driving conditions. It was typically assumed that limited range vehicles such as fully electric vehicles would be limited in the residential market by 30 percent owing to only 60 percent of households having two cars (meaning they could adopt a limited range vehicle second car and use their first car for longer journeys and thereby not impact their current lifestyle). For the rigid truck and bus category this was arbitrarily limited to 20 percent, representing the number of trucks and buses that would only operate by travelling less than their battery storage limit per day.

Fuel cell and plug-in hybrid electric vehicles, although not range-limited, are also limited, to around 20 percent uptake, on the grounds that consumers would be less willing to accept an unconventional vehicle type.

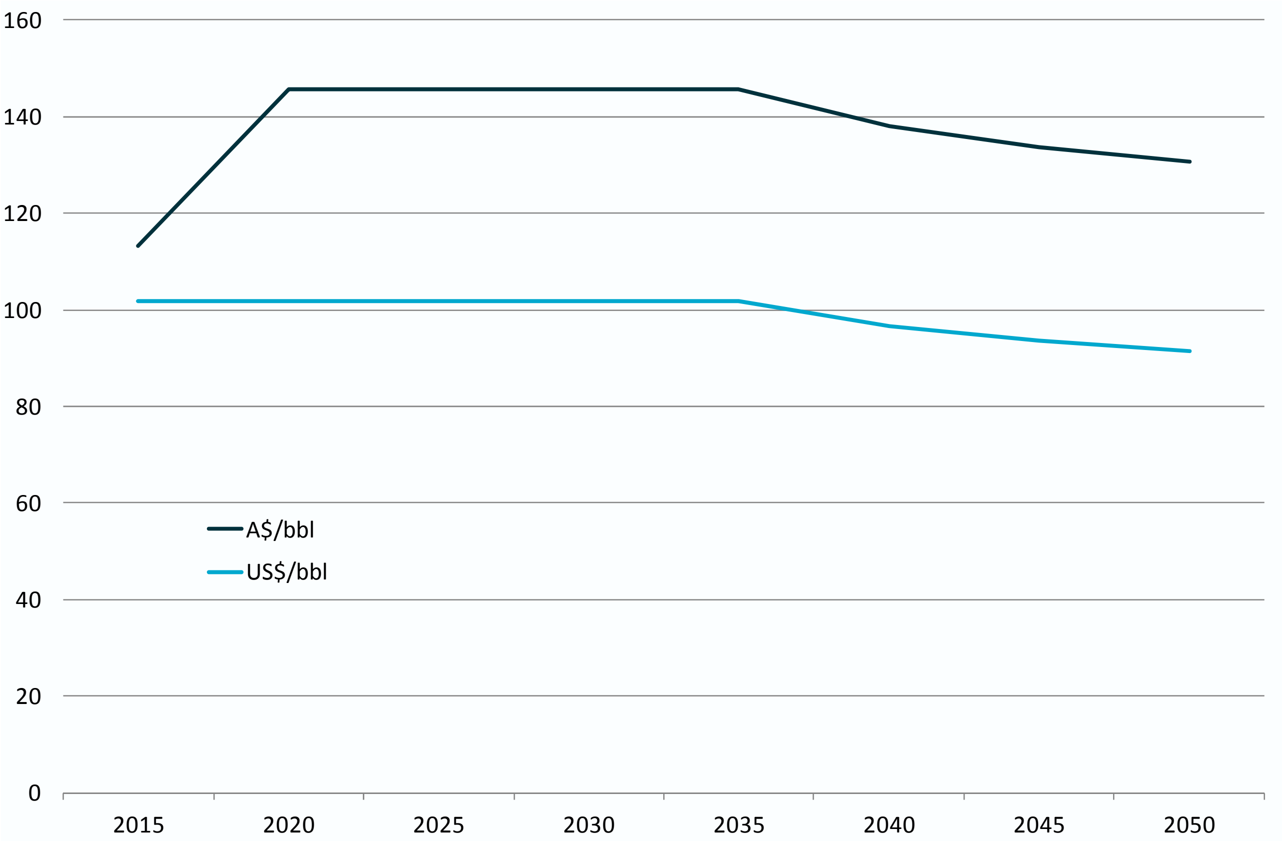
However for this project it was considered appropriate to relax some of these assumptions. In context of modelling a world that is committed to deep decarbonisation it is reasonable to expect this will include some willingness by more consumers to adopt alternative drivetrain vehicles, including some with limited range. The assumptions for this project are outlined here.

- There are no limitations on adoption of limited range electric vehicles in the small-size passenger vehicle category in ESM. Many of these vehicles may be second cars in any case.
- Adoption of medium and large-size limited range electric passenger vehicles in ESM must be smaller than 20 percent each.
- Limitations on uptake of electric-only drivetrains in rigid truck and bus categories increases from 20 to 30 percent.
- All limitations on full-range (plug-in electric and fuel cell) alternative drivetrains are removed (i.e. increased to 100 percent).

3.2.5 Oil prices and excise

Fuel prices assume an international oil price trend very similar to natural gas prices (as you would expect given partial substitutability in some applications), increasing by 24 percent to 2020, remaining flat up to 2035 at just over US$100/bbl and decreasing by 10 percent to US$90/bbl by 2050 as accelerating abatement measures reduce the demand for oil. The assumed decline in the $A/$US exchange rate by 2020 means that this international trend becomes an upward trend in Australian dollars in the short term before tracking the global trend.

Figure 3.2 – Assumed oil price paths in US and Australian currency



In the 2014–2015 Federal Budget, the Australian Government announced the reintroduction of transport fuel excise indexation (via the consumer price index). The modelling phase of this project concluded before indexation of fuel excise could be included in the model assumptions. This means the real value of excise is lower in the modelling than it may be if the changes are legislated.

Another issue in relation to excise revenue is that, as the road sector becomes more efficient and transitions away from traditional liquid fuels, excise revenue per kilometre travelled will fall. Since there are no concrete proposals for how to manage this scenario, no assumptions have been made to address this issue in the modelling. For further details, the road revenue impacts and drivers have been previously described in NTC (2014) and Graham (2012).

3.2.6 Aviation, teleconferencing and rail substitution

ESM is not capable of independently determining the future amount of transport mode substitution. This is an assumption that must be imposed from other sources. MMRF does endogenously project mode substitution between the passenger rail and road sectors, but not between other sectors.

The substitution of some long-haul aviation for high-speed passenger rail and teleconferencing provides a key opportunity for mode substitution in this modelling program. The Australian Low Carbon Transport Forum identified the potential for high-speed rail and teleconferencing as substitutes for air travel using an expert review process (Cosgrove et al., 2012). In that study aviation demand is reduced by 20 percent as demand for long-distance travel is substituted by teleconferencing (roughly five percent) and high-speed rail (roughly 15 percent). On high-speed rail this level of substitution appears also to be supported by a more recent study by Beyond Zero Emissions (2014).

No specific costs of this substitution are included in the modelling. Beyond Zero Emissions (2014) argue that the high-speed rail network would pay for itself and remain competitive with aviation under certain assumptions.

To capture these mode changes the increased demand for passenger rail and decreased demand for aviation is imposed on MMRF and then on ESM.

3.2.7 Bioenergy supply

CSIRO has been reviewing potential biomass resources for use in the energy sector over many years, with the number and depth of study of potential feedstocks expanding with each publication (see O'Connell et al., 2007; Graham et al., 2011; Farine et al., 2012 and Crawford et al., 2012). Two recent non-CSIRO studies include Jacobs SKM (2014) and Lang et al (2014). The estimates in these studies of the potential bioenergy resource available in Australia do not align well in detail but do in aggregate at around 1000 petajoules (PJ) per year. The differences in individual categories of feedstocks reflect differences in the relative expertise and depth of each study, as well as the large number of assumptions that must be made about the fractions diverted from existing activities.

Given the aggregate numbers are similar, CSIRO estimates are used, with a cost curve already programmed into ESM's standard assumptions (see Figure 3.4). Note, in the CSIRO estimates, extraction of these volumes are on the basis of not having any significant impact on agricultural production.

Figure 3.3 – Estimates of available biomass resources in petajoules by source

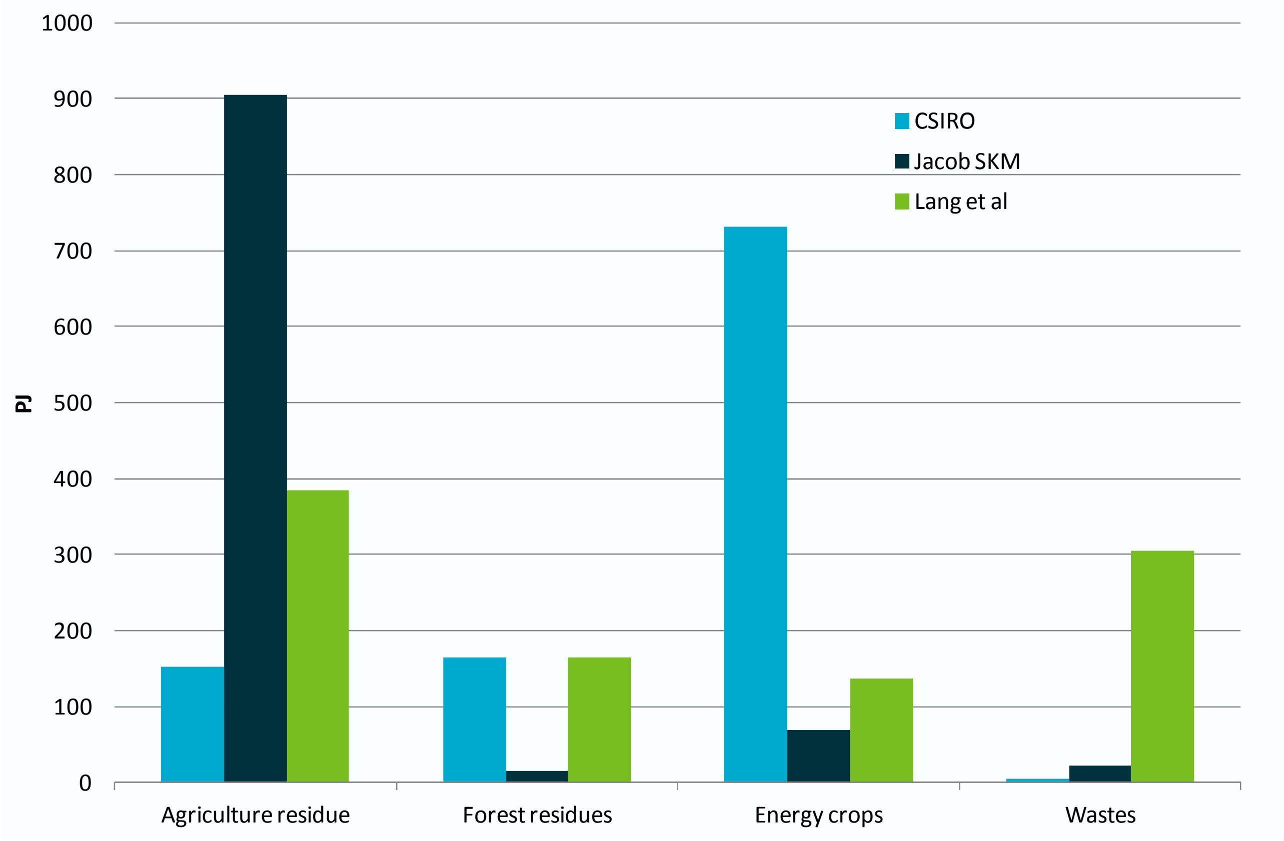
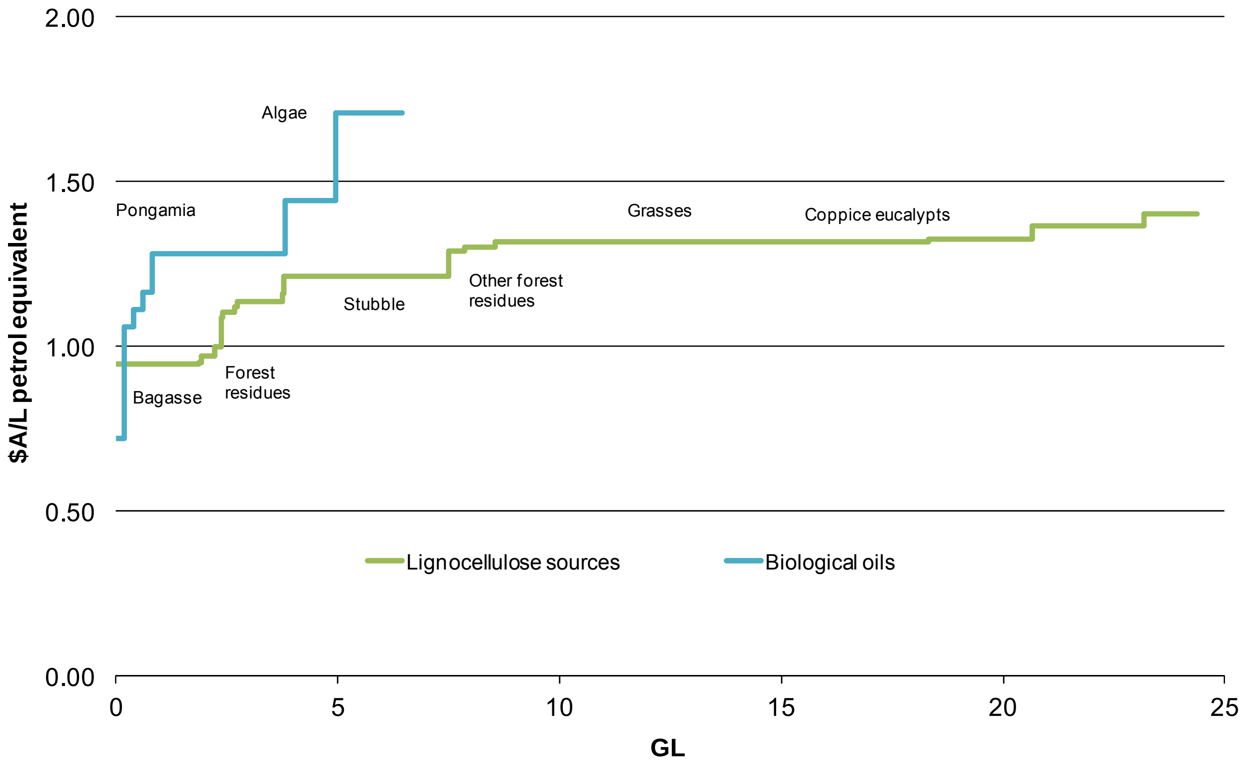


Figure 3.4 – CSIRO biomass to liquid 2020 cost-quantity curve



Bagasse (sugar cane waste) and stubble (the stems from wheat and other crops) are agricultural residues. Pongamia (a type of oil seed tree), grasses, algae and coppice eucalypts (Mallee) are dedicated energy crops, which would be grown for that single purpose. Forest residues include sawmill, stem, chip, pulp log and saw log residues. Each feedstock production and fuel refining system has its own unique set of challenges and strengths, which are described in detail in Graham et al. (2011), Farine et al. (2012) and Crawford et al. (2012). However, briefly, the refining processes for harvesting lignocelluloses are least mature, whereas biological oils are more easily converted into transport fuels. There are several types of lignocellulosic fuel conversion pathways vying to be the most competitive in the long run (e.g. gasification, pyrolysis, saccharfication). Achieving a low cost of conversion at the scale of the available biomass is a particular challenge.

In terms of feedstock production Pongamia, algae and coppice eucalypts have a long lead-time to establish capacity, whereas other feedstocks already exist and the challenges are more related to cost-effective harvesting or diversion processes. A number of limits are imposed on the amount that can be harvested relative to the technical upper limit to maintain agricultural soil health, forest habitats and take account of other environmental considerations.

The bioenergy cost-quantity curve is applied in ESM as a *generic* volume of lignocellulose and plant oil. As such, it doesn't exclude the possibility that this volume of bioenergy may be supplied by a different set of feedstocks than that envisaged by CSIRO's studies. Only the costs are specific to CSIRO work.

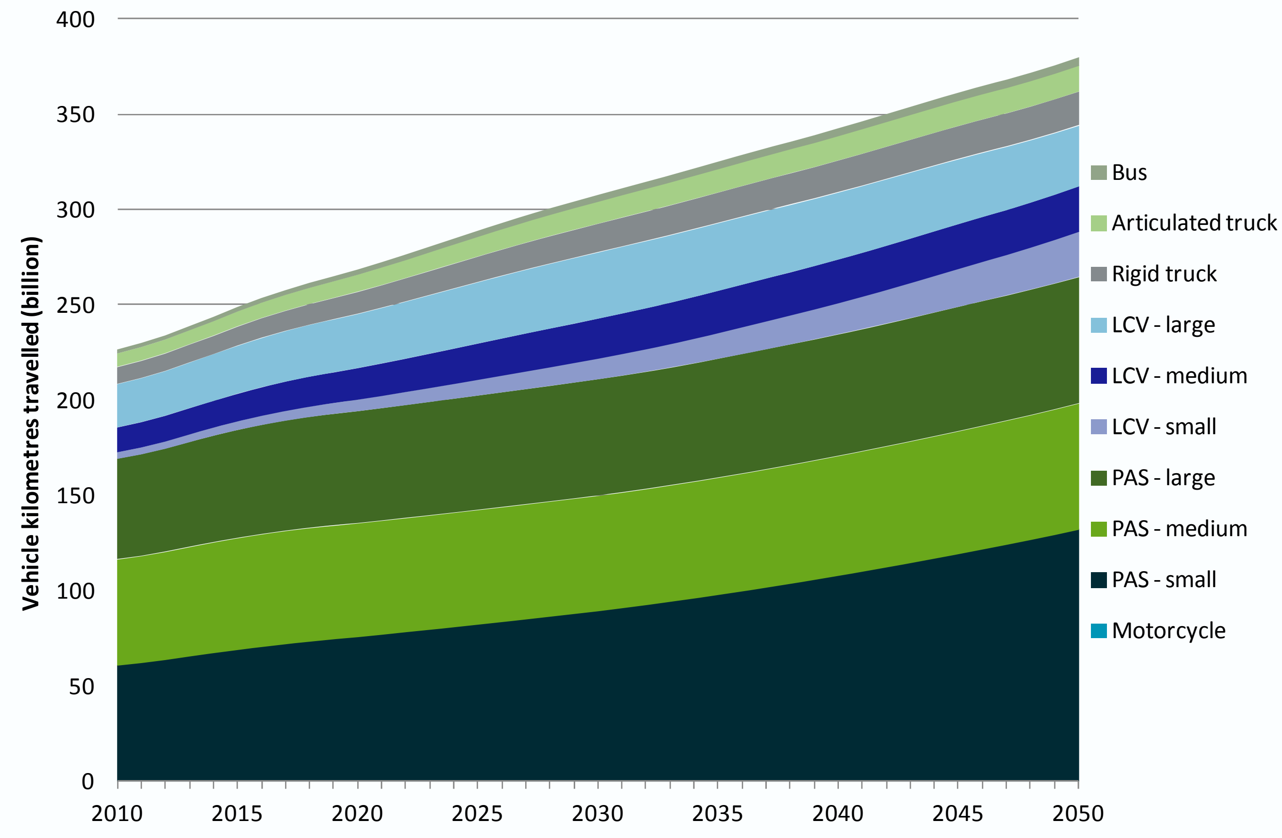
The volume of bioenergy feedstock could be supplied by more waste or agricultural residues if the other studies prove more correct in their supply sources. There is also the possibility of harvesting some biomass as a co-product of carbon forestry. This has not been included in any of the estimates and so could provide an additional source of biomass or replace other sources.

3.3 Modelling results

3.3.1 Road transport results

Road passenger demand is largely governed by growth in population, given car ownership and use in Australia is near saturation point. On the other hand, road freight demand (supplied by rigid and articulated trucks) is more closely linked to the general rate of growth in the economy and therefore grows slightly faster (but are a much smaller share of road kilometres). A standard assumption in ESM is that the light-duty vehicle markets (passenger and light commercial vehicles) experience an increase in preference for smaller vehicle sizes, which continues the trend observed in Australia's light-duty fleet since oil prices increased in the mid-2000s. The results for road sector transport demand in Figure 3.5 reflect all of these features. The average rate of growth in total road transport demand is 1.2 percent per annum between 2014 and 2050.

Figure 3.5 – Projected national road transport demand in vehicle kilometres, 2010–2050



FUEL MIX

The projected road transport fuel mix is shown in Figure 3.6. The projection includes a number of distinct phases, starting from the present fuel mix dominated by petrol, diesel, liquefied petroleum gas (LPG) and E10 (ethanol mixed at a 10 percent ratio with petrol). In the period to 2020, biofuels and natural gas begin to increase their market share. Natural gas is taken up as liquefied natural gas (LNG) in the articulated (long-haul) truck fleet[12]. Biofuel is taken up as biodiesel and ethanol across the light and heavy-duty vehicle fleets. These supplies would initially need to draw on first-generation feedstocks (mostly waste and agricultural residues) due to delays in constructing supply chains for second-generation feedstocks. However it is assumed the very strong abatement incentive in the *Australian deep decarbonisation pathway* is able to accelerate second-generation biofuel supply chain activity out of its current malaise. Imported biofuels, with appropriate sustainability certification, could be an alternative option if domestic supply chain development is delayed.

While these alternative fuels are being adopted, LPG use is declining. This represents a continuation of an existing trend whereby a combination of factors is reducing the attractiveness of this fuel – increasing LPG fuel excise, the end of local dedicated LPG vehicle manufacturing and the strong association of LPG pricing with world oil price movements.

From 2020 to 2035 we see a consolidation of these trends in LPG, LNG and biofuel. In addition, this is the period when vehicle electrification begins to rapidly ramp up, such that almost every new light-duty vehicle has a hybrid, electric, hybrid plug-in electric or fuel cell drivetrain, with the exception of many truck freight tasks that are not amenable to electrification.

In the remainder of the projection period, electricity in light-duty vehicles and natural gas in articulated trucks consolidate their share of fuel use. Biofuels reduce some of their market share, due to it becoming viable to partially switch to supplying the aviation industry, which, not having a viable electrification or natural gas fuel option is willing to pay more for low-carbon liquid fuels by this time. The final remaining change in the fuel mix is the introduction of hydrogen at a large scale around 2040 in light-duty vehicles.

The remaining use of petrol in the light-duty fuel mix is mainly associated with plug-in hybrid electric vehicles, which, while using electricity only for most trips, include an internal combustion engine for use on longer trips.

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[12] At present there are difficulties in sourcing LNG truck engines specific to Australia's preferred truck size. However it is assumed that manufacturers would overcome this issue in the event of a determined industry effort to switch to natural gas.

Figure 3.6 – Projected national light-duty road vehicle transport fuel mix, 2010–2050

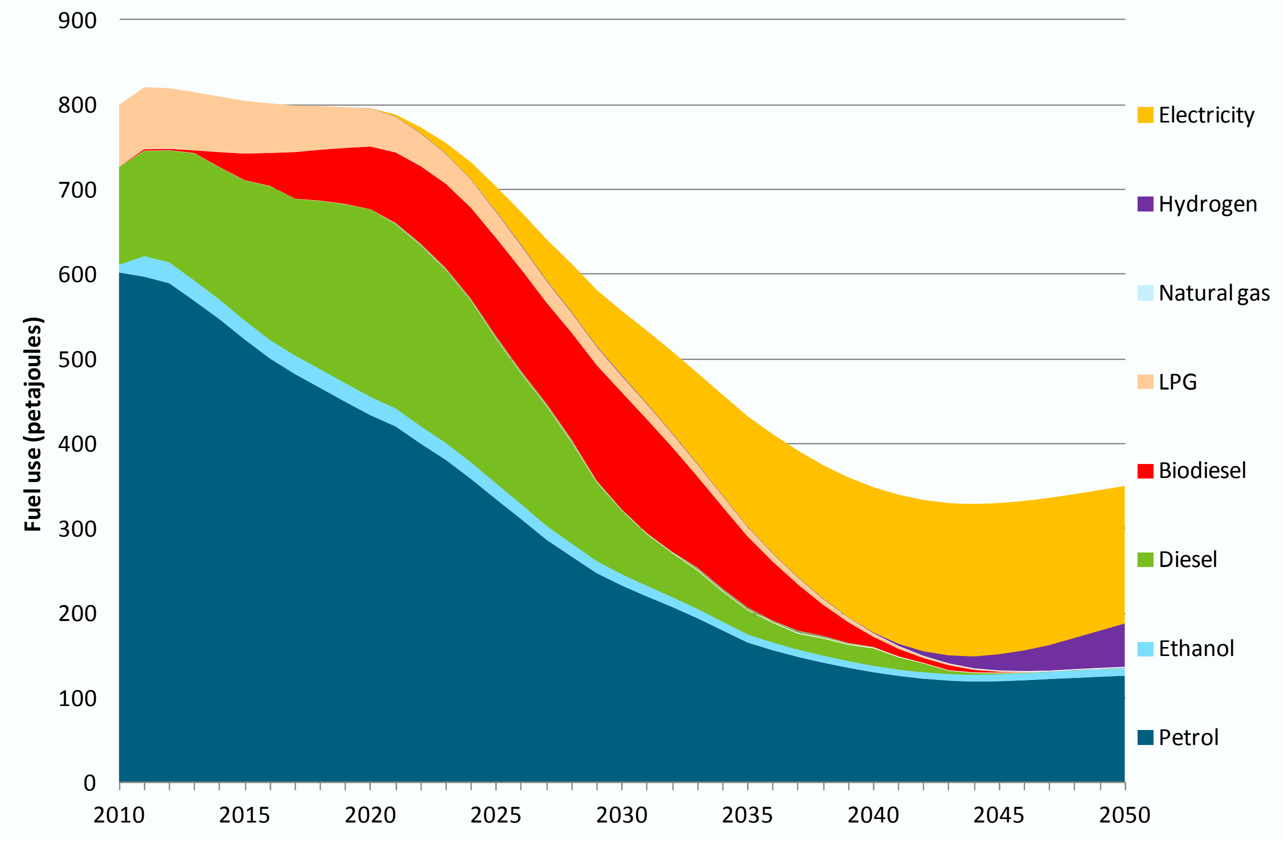
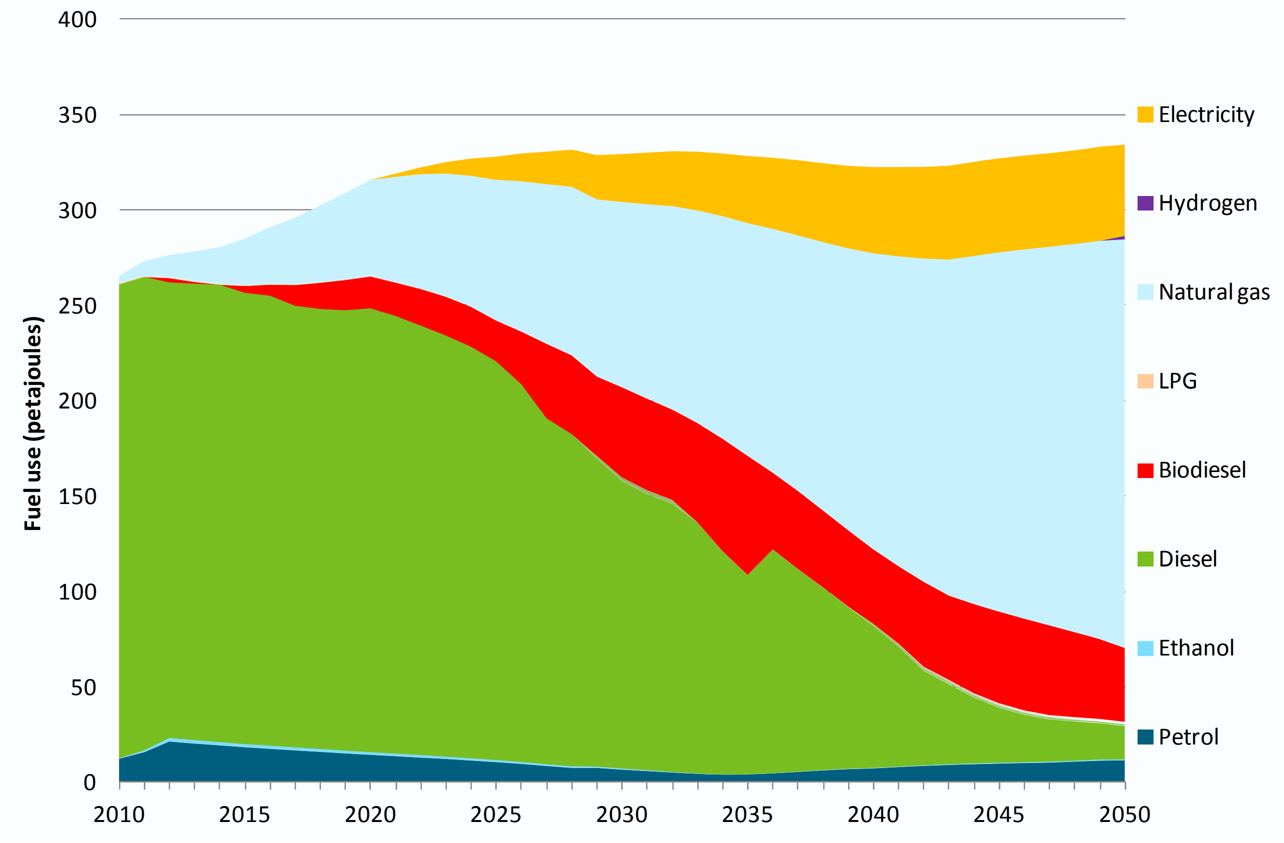


Figure 3.7: Projected national heavy-duty road vehicle transport fuel mix, 2010–2050



DRIVETRAIN

The contribution of alternative drivetrain vehicles to the total road kilometres travelled is shown in Figure 3.8 and Figure 3.9. The drivetrain uptake pattern reflects the assumptions in relation to alternative drivetrain vehicle costs and assumed consumer adoption limitations.

Under the abatement incentive imposed, hybrid, electric and plug-in hybrid electric vehicles are cost-effective for most light-duty and some heavy-duty vehicles for consumers, relative to a conventional internal combustion vehicle from 2020. Both short-range (electric) and longer-range plug-in hybrid electric vehicles (PHEVs) are adopted into the fleet. The heavy-duty sector reaches saturation point in the 2040s due to limits to electrification of freight tasks. In contrast, internal combustion-only vehicles are completely removed from the light-duty vehicle fleet in the same period. Reflecting the vehicle cost assumptions the fuel cell vehicle adoption begins later, but makes a substantial contribution to light-duty vehicle kilometres by 2050. The slower adoption of fuel cells also reflects fuel cost disadvantages relative to electric vehicles. Hydrogen fuel is a higher cost than electricity due to conversion losses, but also partly reflecting that there is no existing re-fuelling infrastructure to deliver it. On the other hand, plug-in hybrid vehicles use some liquid fuels when driving longer distances, the costs of which are rising due to abatement incentive assumptions, so this disadvantage of fuel cells is less significant over time.

The importance of range limitations in consumer adoption and the costs of alternative drivetrain configurations remain major sources of uncertainty in long-term road transport modelling.

Figure 3.8 – Projected growth in light-duty vehicle kilometres travelled by drivetrain type, 2010–2050

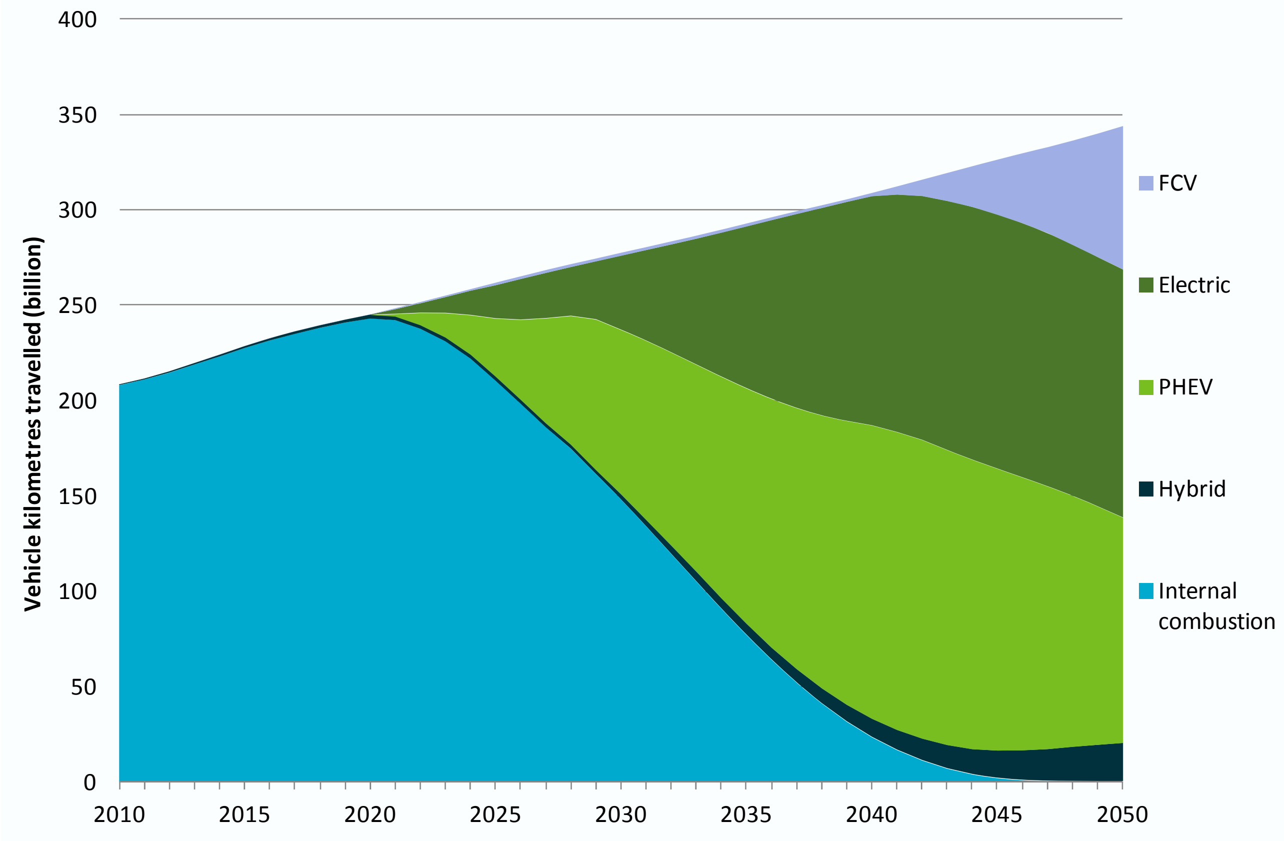
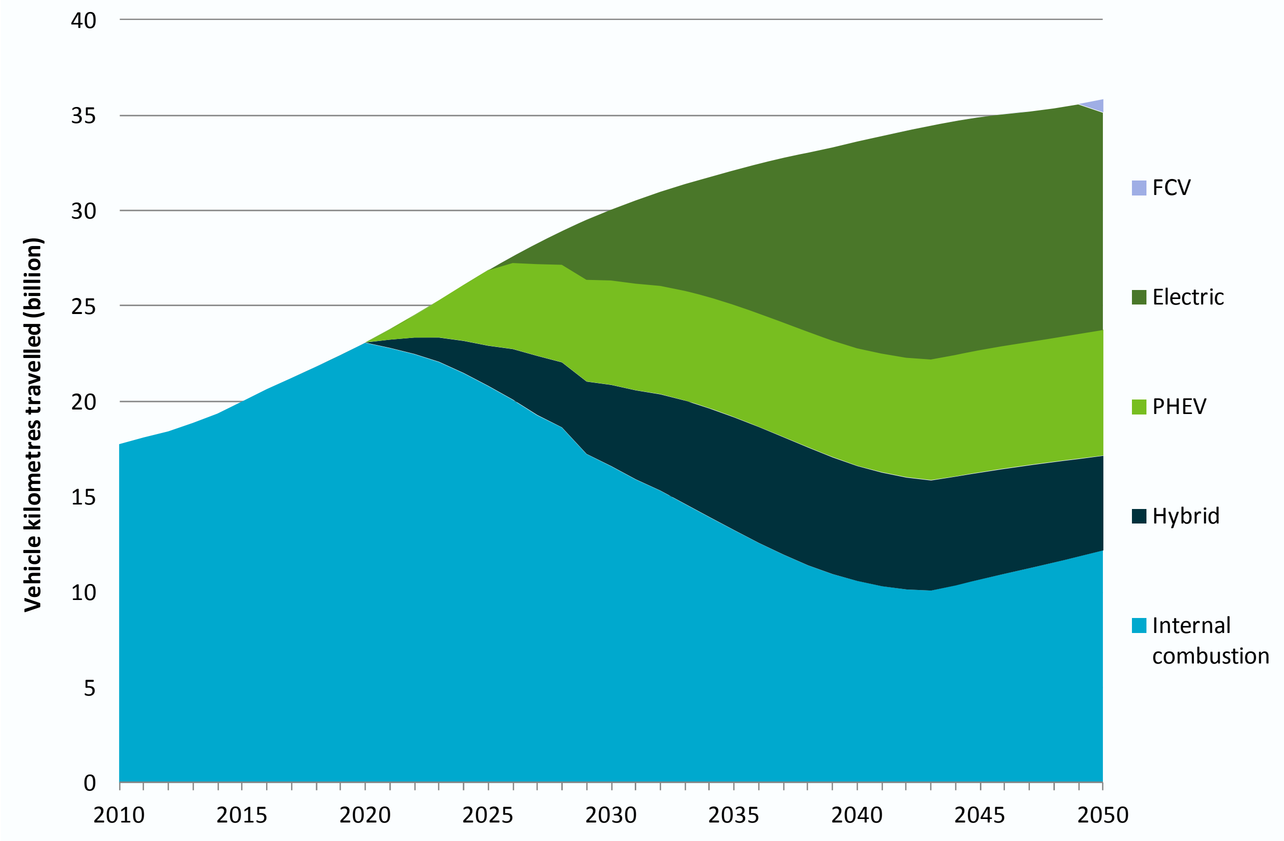


Figure 3.9 – Projected growth in heavy-duty vehicle kilometres travelled by drivetrain type, 2010–2050

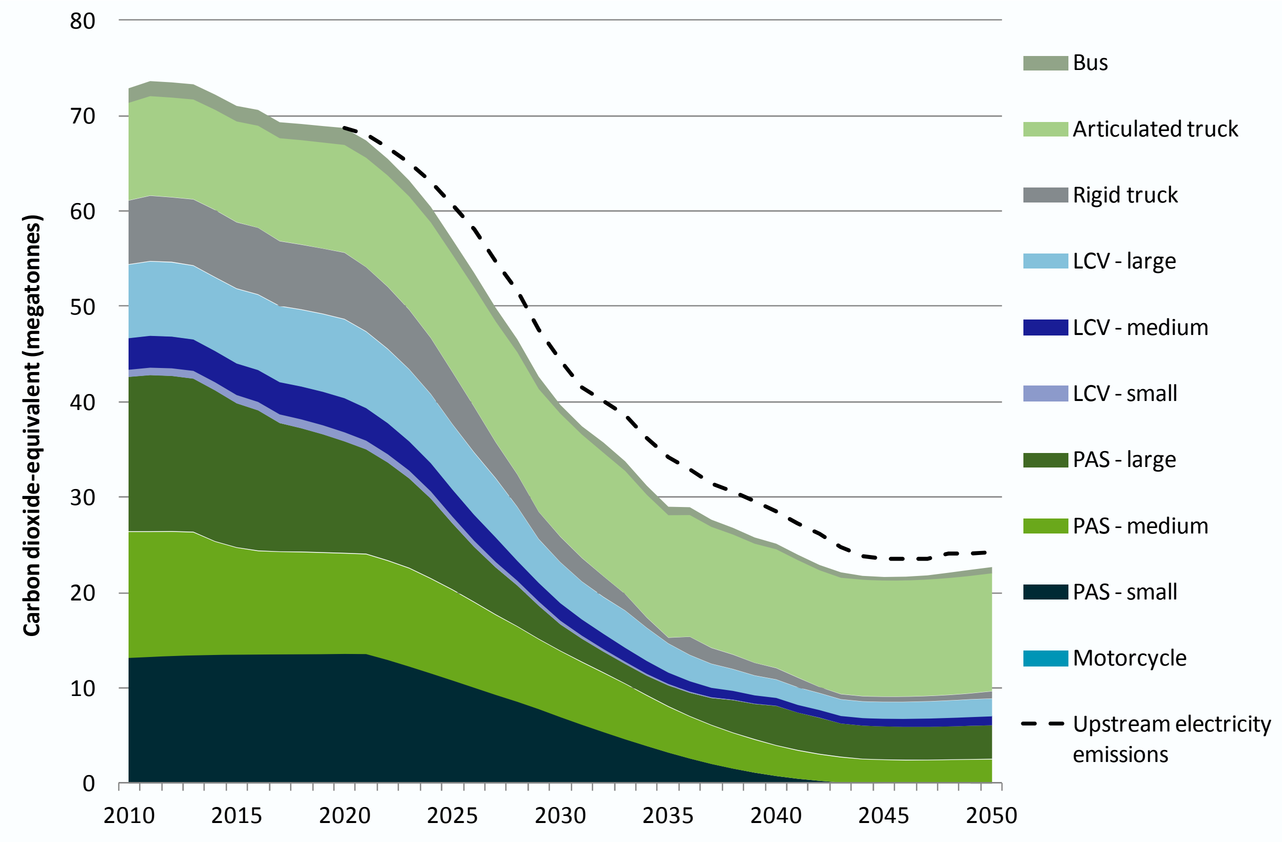


GREENHOUSE GAS EMISSIONS

The direct greenhouse gas emissions from the road transport sector by vehicle category are shown in Figure 3.10. Indirect electricity emissions are accounted for in electricity sector emissions (see chapter 2). Upstream emissions from biofuel and petroleum refining are captured in industry emissions in MMRF. For vehicles that are amenable to electrification, which includes mainly light-duty vehicles, the direct road sector greenhouse gas emissions fall very rapidly from just after 2020. Articulated trucks, which are not suitable for electrification due to their focus on long-haul freight transport, experience a slight increase in emissions during the projection period (freight activity growth is partially offset by fuel efficiency improvements and use of lower-emission natural gas and biofuel in place of diesel).

Overall, road transport greenhouse gas emissions decrease by 69 percent to 23MtCO2e by 2050.

Figure 3.10 – Projected national road transport greenhouse gas emissions by vehicle category, 2010–2050



3.3.2 Non-road transport results

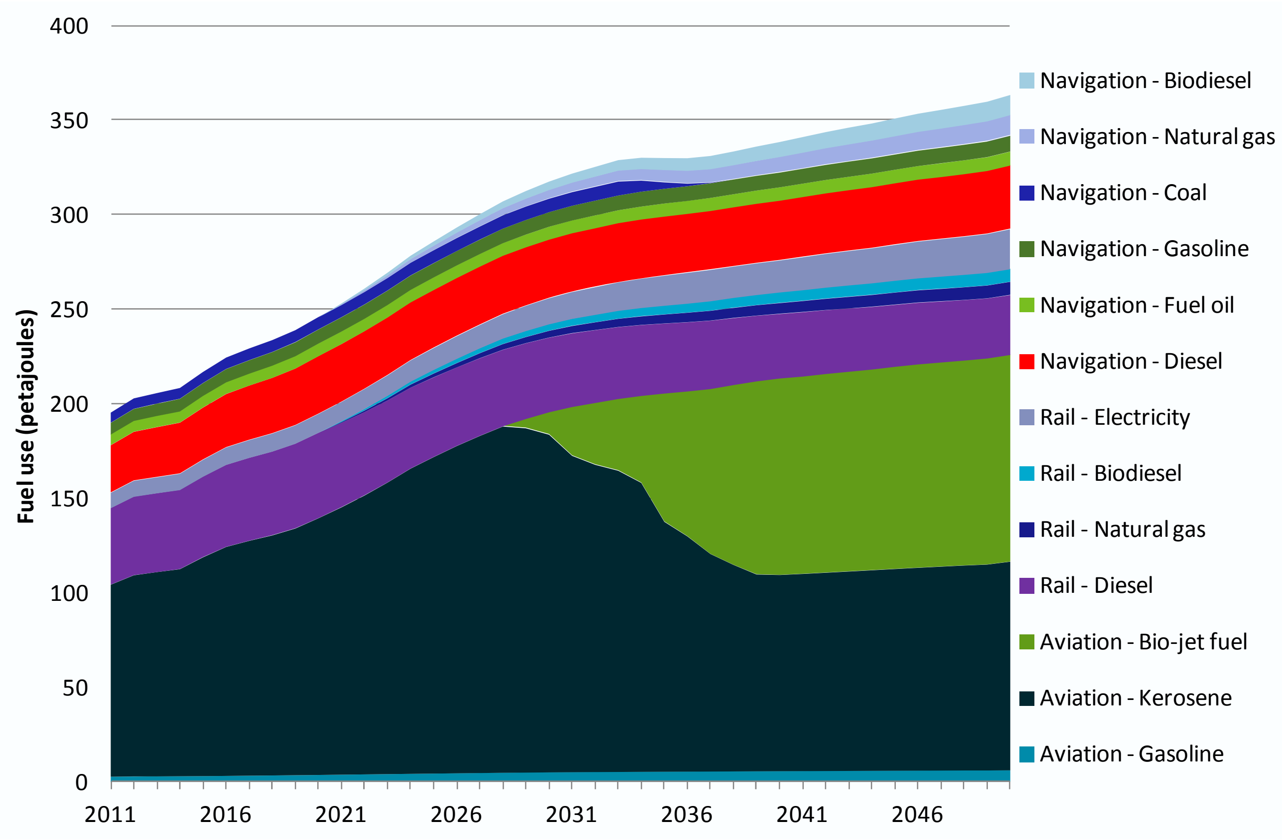
FUEL MIX

Figure 3.11 shows projected fuel use in the domestic non-road transport sectors. Inclusion of international transport would roughly double aviation fuel use and increase navigation (marine) fuel use by two thirds, but it is conventional to exclude these from domestic fuel and emissions accounting.

The major change in domestic fuel use for the aviation sector is that the uptake of bio-derived jet fuel commences in 2029 and continues to grow rapidly to reach a 50 percent share by 2040. The willingness of the aviation sector to compete for biofuels against demand from the road transport sector is due to the lack of alternative low-emission fuels that can be accessed, meeting the aviation sector's unique fuel requirements. Owing to favourable excise arrangements[13] the road sector is initially willing to pay the highest price for available biofuels. However, as the road sector adopts electricity and natural gas as major new fuel sources from 2020, these two fuels begin to set the market price that the road sector is willing to pay for fuels, so that it eventually falls to a level which aviation is prepared to pay, giving them greater access to available biofuel supplies.

By 2050, total conventional and bio-derived jet fuel demand is 220PJ, reflecting strong underlying growth in long-distance travel moderated by assumed aviation fuel efficiency improvements and some substitution of aviation for rail and teleconferencing. Use of aviation gasoline in light aircraft remains relatively small at 6PJ.

Figure 3.11 – Projected national fuel use in non-road transport, 2011–2050



Both rail and marine freight experience modest growth in fuel demand, reflecting growth in the economy moderated by fuel efficiency and task efficiency improvements. Rail passenger growth, which mainly utilises electricity, is stronger, reflecting the use of high-speed rail to substitute 15 percent of aviation passenger demand by 2050.

A modest amount of biofuels and natural gas is substituted for diesel in the rail and marine sectors by assumption. The small amount of coal used in the marine sector is phased out by 2035.

Overall, non-road transport fuel use is projected to grow at 1.2 percent per annum to 363PJ by 2050.

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[13] New excise arrangement announced in the 2014–2015 Federal Budget has not been included in this modelling.

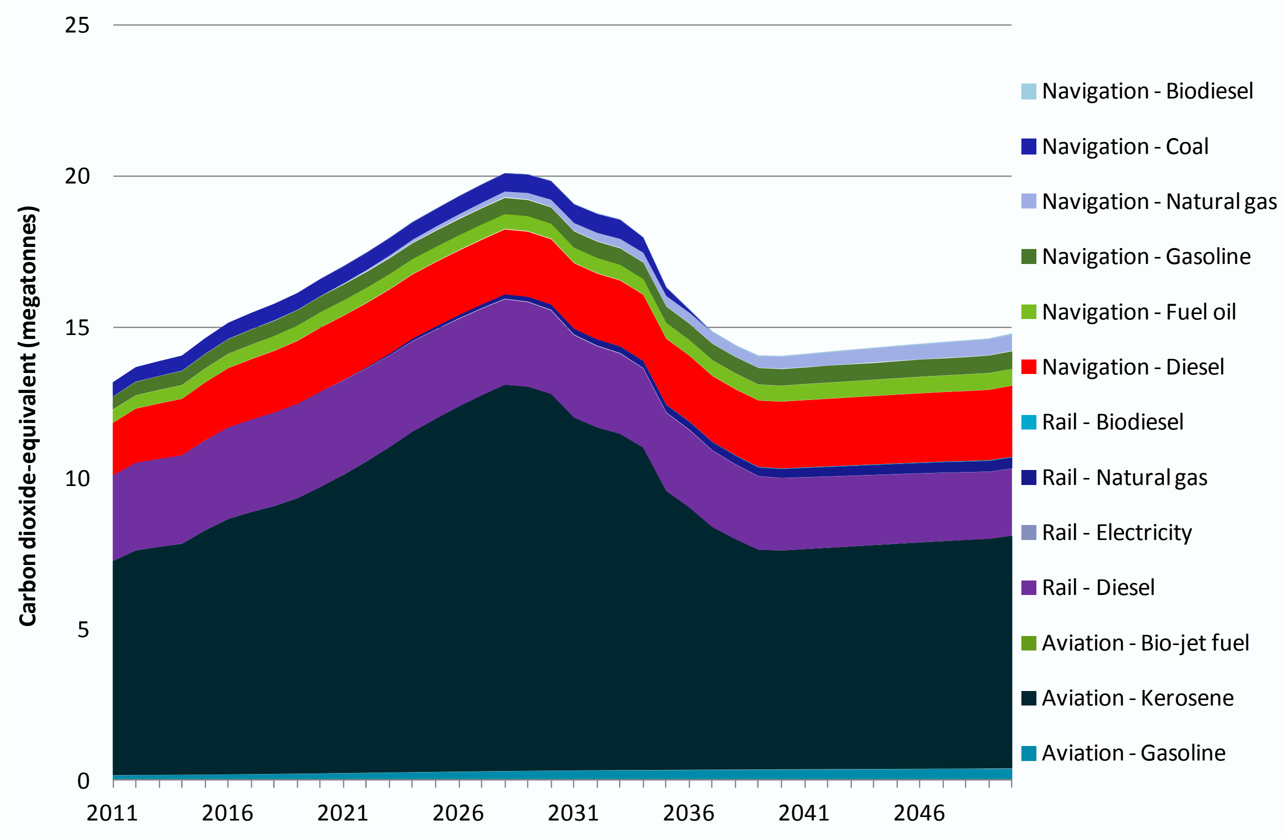
GREENHOUSE GAS EMISSIONS

Projected non-road transport emissions are shown in Figure 3.12. As with fuel use, only emissions associated with domestic activities are included. In regards to biofuel, due to carbon dioxide combustion emissions being equal to the amount of carbon dioxide absorbed when biomass is regrown, direct emissions from this fuel are close to zero. Emissions associated with biofuel refining are captured in the industry sector in MMRF.

Emissions from the rail passenger sector's use of electricity are captured in the electricity sector total emissions (see chapter 2).

Owing largely to the use of bio-derived jet fuel in aviation and despite significant growth in transport activity, non-road transport sector emissions increase by only five percent (or less than 1MtCO2e in absolute terms) between 2014 and 2050.

Figure 3.12 – Projected national non-road transport greenhouse gas emissions by fuel, 2011–2050



3.4 Summary of alternative pathways and deeper emissions reductions opportunities

There are alternative options that exist, which could either replace modelled pathways should they be unavailable, or enable deeper emissions reductions. Below is a summary of the key options that could be considered in future work in the transport sector.

Activity levels

- **Reduced transport activity** – for example, in passenger transport through behaviour change and mode shift to public transport, biking/walking and teleconferencing. This would also deliver substantial co-benefits, such as reduced congestion and healthier lifestyles.
- **Local product sourcing** – could reduce the need to transport goods.

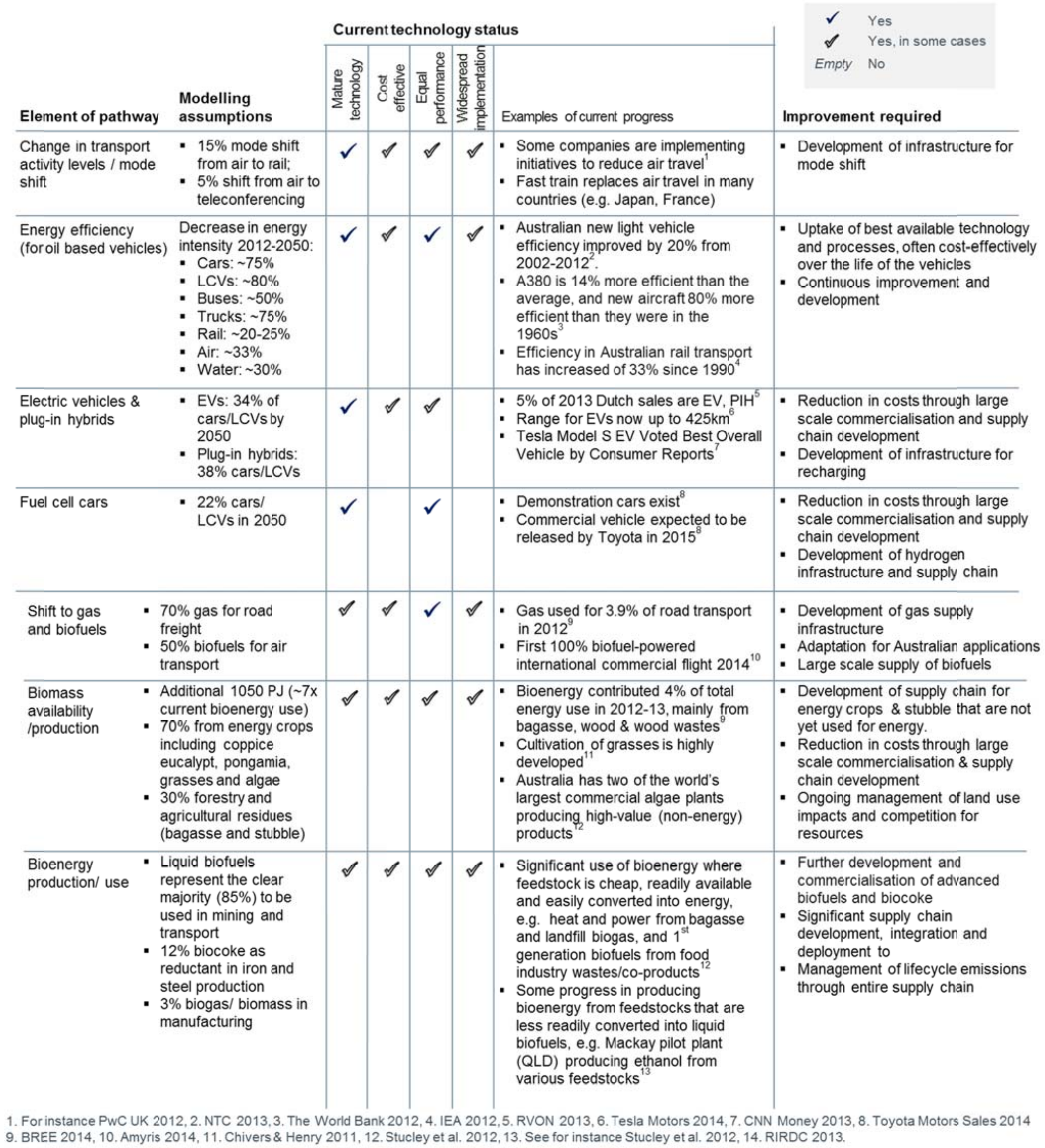
Technology

- **Very deep efforts in energy efficiency** – in particular in road freight, both in terms of operations and equipment improvements.
- **Strong shift to hydrogen** – if road freight could be powered by hydrogen created from electricity, then it could significantly reduce residual emissions.
- **Mode shift** – for example strong shift from road and air transport to rail, facilitated by construction of infrastructure and redesign of urban areas.
- **Managing carbon forests to co-produce biomass** – this could replace or add to existing sources of bioenergy feedstock included already.

3.5 Technology status overview

The following Table 3.2 summarises the status of the major technologies involved in the deep decarbonisation scenario for the transport sector. As can be seen, the technologies required for decarbonisation are already being developed; integration and commercialisation is where most progress is needed.

Table 3.2 – Summary of technology status in the transport sector



✓ Yes
✔ Yes, in some cases
Empty No

Element of pathway	Modelling assumptions	Current technology status Mature technology	 Cost effective	 Equal performance	 Widespread implementation	Examples of current progress	Improvement required
Change in transport activity levels / mode shift	▪ 15% mode shift from air to rail; ▪ 5% shift from air to teleconferencing	✓	✔	✔	✔	▪ Some companies are implementing initiatives to reduce air travel[1] ▪ Fast train replaces air travel in many countries (e.g. Japan, France)	▪ Development of infrastructure for mode shift
Energy efficiency (for oil based vehicles)	Decrease in energy intensity 2012-2050: ▪ Cars: ~75% ▪ LCVs: ~80% ▪ Buses: ~50% ▪ Trucks: ~75% ▪ Rail: ~20-25% ▪ Air: ~33% ▪ Water: ~30%	✓	✔	✓	✔	▪ Australian new light vehicle efficiency improved by 20% from 2002-2012[2]. ▪ A380 is 14% more efficient than the average, and new aircraft 80% more efficient than they were in the 1960s[3] ▪ Efficiency in Australian rail transport has increased of 33% since 1990[4]	▪ Uptake of best available technology and processes, often cost-effectively over the life of the vehicles ▪ Continuous improvement and development
Electric vehicles & plug-in hybrids	▪ EVs: 34% of cars/LCVs by 2050 ▪ Plug-in hybrids: 38% cars/LCVs	✓	✔	✔		▪ 5% of 2013 Dutch sales are EV, PIH[5] ▪ Range for EVs now up to 425km[6] ▪ Tesla Model S EV Voted Best Overall Vehicle by Consumer Reports[7]	▪ Reduction in costs through large scale commercialisation and supply chain development ▪ Development of infrastructure for recharging
Fuel cell cars	▪ 22% cars/ LCVs in 2050	✓		✓		▪ Demonstration cars exist[8] ▪ Commercial vehicle expected to be released by Toyota in 2015[8]	▪ Reduction in costs through large scale commercialisation and supply chain development ▪ Development of hydrogen infrastructure and supply chain
Shift to gas and biofuels	▪ 70% gas for road freight ▪ 50% biofuels for air transport	✔	✔	✓	✔	▪ Gas used for 3.9% of road transport in 2012[9] ▪ First 100% biofuel-powered international commercial flight 2014[10]	▪ Development of gas supply infrastructure ▪ Adaptation for Australian applications ▪ Large scale supply of biofuels
Biomass availability /production	▪ Additional 1050 PJ (~7x current bioenergy use) ▪ 70% from energy crops including coppice eucalypt, pongamia, grasses and algae ▪ 30% forestry and agricultural residues (bagasse and stubble)	✔	✔	✔	✔	▪ Bioenergy contributed 4% of total energy use in 2012-13, mainly from bagasse, wood & wood wastes[9] ▪ Cultivation of grasses is highly developed[11] ▪ Australia has two of the world's largest commercial algae plants producing high-value (non-energy) products[12]	▪ Development of supply chain for energy crops & stubble that are not yet used for energy. ▪ Reduction in costs through large scale commercialisation & supply chain development ▪ Ongoing management of land use impacts and competition for resources
Bioenergy production/ use	▪ Liquid biofuels represent the clear majority (85%) to be used in mining and transport ▪ 12% biocoke as reductant in iron and steel production ▪ 3% biogas/ biomass in manufacturing	✔	✔	✔	✔	▪ Significant use of bioenergy where feedstock is cheap, readily available and easily converted into energy, e.g. heat and power from bagasse and landfill biogas, and 1st generation biofuels from food industry wastes/co-products[12] ▪ Some progress in producing bioenergy from feedstocks that are less readily converted into liquid biofuels, e.g. Mackay pilot plant (QLD) producing ethanol from various feedstocks[13]	▪ Further development and commercialisation of advanced biofuels and biocoke ▪ Significant supply chain development, integration and deployment to ▪ Management of lifecycle emissions through entire supply chain

1. For instance PwC UK 2012, 2. NTC 2013, 3. The World Bank 2012, 4. IEA 2012, 5. RVON 2013, 6. Tesla Motors 2014, 7. CNN Money 2013, 8. Toyota Motors Sales 2014 9. BREE 2014, 10. Amyris 2014, 11. Chivers & Henry 2011, 12. Stucley et al. 2012, 13. See for instance Stucley et al. 2012, 14. RIRDC 2013.

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INDUSTRY SECTOR

A. Denis, ClimateWorks Australia

4. Industry sector

Executive summary

This report details the assumptions behind the illustrative deep decarbonisation scenario discussed in the report 'How Australia can thrive in a low carbon world', as well as alternative approaches that could be used in future deep decarbonisation scenarios.

For the industry sector, the modelling was conducted using the Centre of Policy Studies' Monash Multi-Region Forecast (MMRF) general equilibrium model and adjusted based on sectoral analysis by ClimateWorks Australia.

Below are some of the key assumptions made for the illustrative scenario:

- The growth in **activity by sector** was calculated by MMRF based on international demand data from the International Energy Agency (IEA) and some specific project assumptions. In particular, the production of coal was expected to go down, while gas extraction and other mining (including uranium and lithium) are expected to increase significantly.
- It is assumed that recent levels of **energy efficiency** improvements could be sustained until 2030 and then accelerated after 2030, with new technology developments and increased financial incentives to reduce carbon emissions. This leads to around 1.2 pecent improvement per annum for manufacturing and 1.0 percent improvement per annum for mining. Please note that in the mining sector, it is assumed that this was more than counterbalanced by structural increases in energy intensity in line with recent trends (3.0 percent per annum).
- **Electrification** has been identified as a key component of deep decarbonisation. It is likely to be driven by three major technology groups: increase in iron and steel production from electric arc furnace (EAF) technology, shift to electricity for heating processes and shift from trucks to conveyors for materials handling in mining. The share of fuel shifted to electricity is calculated within MMRF, within boundaries defined by the project team.
- Regarding further **fuel shift** to low-carbon energy sources, it is assumed that most coal and oil use in manufacturing could be switched to gas, with half of the remaining oil use able to be shifted to biofuels in mining, and that 15 percent of remaining gas use could be shifted to biomass/biogas in manufacturing.
- In most sectors, it is assumed that **process emissions intensity** could be reduced by over two thirds through a combination of sector specific measures and implementation of carbon capture and storage (CCS).
- Similarly, it is have assumed that **fugitive emissions intensity** could be reduced by around half to three quarters in resource extraction sectors, mostly through the use of methane flaring/oxidation and CCS. Non-energy emissions are well suited for the use of CCS, given the relatively high purity of CO_2 outflows.

As a result, **industrial value added would more than double** in real terms between 2012 and 2050. In parallel, **emissions would decrease by more than 50 percent.** Most of the reduction in energy emissions intensity would result from the reduction in emissions intensity of the fuel mix, in particular through electrification.

This scenario illustrates the type of emissions reductions that could be achieved in this sector through technologies known of, but not necessarily available commercially, today. There are **alternative options** that exist, which could either replace modelled technologies should they be unavailable, or enable deeper emissions reductions. Below is a summary of the key options, which could be considered in future work:

- strong improvements in material efficiency would reduce required production levels
- very deep energy efficiency could reverse increasing energy intensity in mining
- more efficient electrification would reduce the growth in electricity demand
- use of hydrogen to power mining equipment could increase the electrification of mining
- more bioenergy could reduce direct energy emissions if additional feedstock can be sourced
- wide deployment of CCS in industry could capture most residual emissions if commercial.

An analysis of the **status of the technologies** included in the scenario suggests that most technologies required for decarbonisation are already being developed; integration and commercialisation is where most progress is needed.

4.1 Scenarios definition

This report examines a single main scenario, which is the Australian deep decarbonisation pathway. This scenario explores how Australia could achieve the budget recommended by the Climate Change Authority (2014) with technologies already known today. The key strategies used in the modelling to achieve this goal are listed in Table 4.1 and are explained in more detail in the rest of this report.

Please note that this table describes one illustrative scenario and alternative options exist to decarbonise Australia's industry. Some alternative approaches are discussed in this report, which could either replace some of the strategies used in the illustrative scenario, or allow deeper emissions reductions.

Table 4.1 – Summary of the scenario strategies in the industry sector

	Structural change	Technical energy efficiency	Fuel switching	Non-energy emissions
Manufacturing	● Natural retirement of existing assets in heavy industry, not always replaced by new assets – e.g. no more petroleum refining in Australia after 2025, only partially replaced by biofuels refining. ● Small ‘rebirth of the aluminium and iron and steel sectors after 2030, with production in 2050 37 percent higher than in 2012.	● Limited improvements in iron and steel and aluminium, due to use of wetted drained cathode and inert anode technology. ● Deep energy efficiency, leading to average 1.2 percent improvement per annum between today and 2050 in other manufacturing sectors.	● Doubling of electric arc furnaces (EAF) production in iron and steel, using domestic scrap which is exported today. ● New industrial assets are electrified, where possible, mostly through increased electrification of heating processes (electricity share increases from about 16 percent to 31 percent of energy use by 2050 for sectors other than iron and steel, and aluminium). ● Coal and oil use are shifted to gas where possible, excluding coking coal and transport equipment. ● 15 percent of remaining gas use replaced by biomass in industrial equipment, coupled to cogeneration equipment where possible.	● Aluminium process emissions near eradicated by 2050, due to inert anode technology, ● New blast furnace or basic oxygen steelmaking (BF/BOS) iron and steel assets use bio-coke substitution and/or carbon capture and storage (CCS) to reduce their emissions (~75 percent reduction in emissions intensity achieved overall). ● Clinker substitution and CCS allow ~⅔ reduction in emissions intensity of cement production. ● CCS allows reduction of about 30 percent of emissions from lime, limestone and dolomite. ● ~90 percent reduction in N2O emissions from chemicals thanks to broad use of catalysts; CCS used to reduce remaining process emissions resulting in overall decrease in emissions intensity of ~⅔. ● Near eradication of refrigerant gases emissions by 2050, with all new equipment using natural refrigerants from 2020 onwards.

	Structural change	Technical energy efficiency	Fuel switching	Non-energy emissions
Mining	● Change in global demand for minerals assumed to drive domestic production of coal and oil (respectively -60 percent and -30 percent value added between 2012 and 2050). ● Strong growth in gas production (~350 percent growth between 2012 and 2050), higher than global demand growth (+15 percent). ● Strong growth in other mining, mostly driven by global demand trends (metal ore mining growth ~150 percent, other mining growth ~330 percent).	● In the mining sector, structural increases in energy intensity amount to about 3.0 percent per annum and are only partially compensated by improvement in energy efficiency amounting to ~1.0 percent improvement per annum on average. ● Gas production improvements in line with heavy manufacturing.	● New assets are electrified where possible, mostly through increased electrification of material handling processes (electricity share increases from about 21 percent to 52 percent of energy use by 2050). ● 50 percent remaining diesel use replaced by biofuels in mining equipment by 2050.	● Coal fugitive emissions decreased by ~75 percent thanks to ventilation air methane (VAM) oxidation and shift to non-gassy mines. ● Fugitive emissions from the oil and gas sector decreased by ~⅔ through increased flaring of methane and CCS of venting emissions. ● Better processes in transmission and distribution (T&D) equipment and lower use of distribution networks (from decrease in gas use in buildings) lead to around 50 percent reduction in gas T&D emissions intensity.

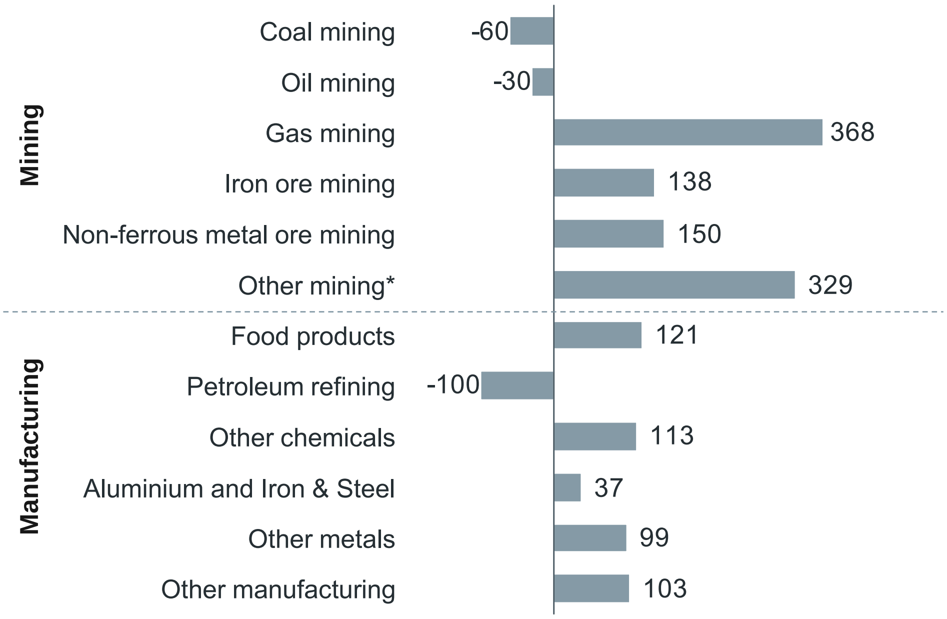
4.2 Assumptions and input

4.2.1 Activity growth levels

OVERVIEW

The growth in activity by sector was calculated by MMRF based on international demand data and some specific project assumptions. In particular global demand data from IEA publications was used to inform the analysis. Energy commodities demand was estimated based on IEA (2013) World Energy Outlook as provided by the DDPP secretariat team and demand for other commodities was derived from IEA's (2009) analysis of energy technology transitions for industry by the Australian project team. Figure 4.1 summarises the resulting growth in value added for key industrial sectors.

Figure 4.1 – Growth in real industrial value added between 2012 and 2050, percentage

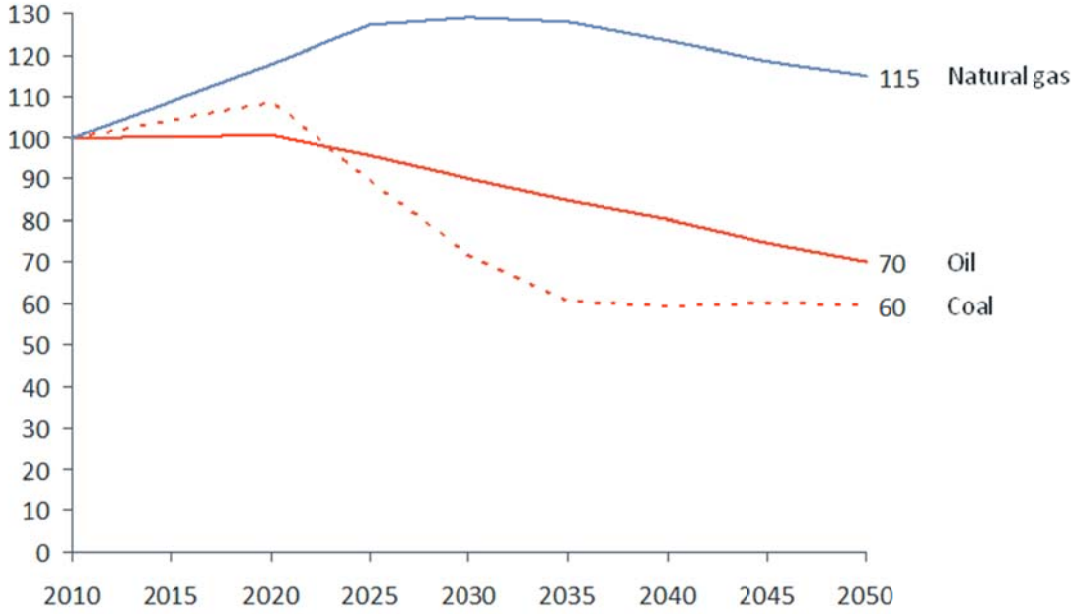


*Includes uranium and lithium

PRODUCTION OF FOSSIL FUELS

Global demand for fossil fuels is likely to be strongly affected by strong international action to reduce emissions. For this project, all country research teams have used IEA (2013) data as a first estimate of global demand for fossil fuels. Figure 4.2 shows the expected changes in demand over time. These assumptions could be refined in the future when country modelling results are finalised.

Figure 4.2 – World fossil fuels primary production, indices



No analysis has been conducted at this stage on the expected relative competitiveness of each country's assets and therefore on where the production is likely to come from. As a result, the default approach for countries was to assume that their production levels would broadly align with global demand, unless they have a strong rationale for diverting from this approach.

Following the reduction in global demand for coal, IEA (2013) estimated that its unit price would also decrease significantly (by around 40 percent in real US dollars between 2010 and 2050). This leads to a further reduction in the value added from the coal mining sector compared with the decrease in production.

Gas production levels are calculated through MMRF (in the context of the IEA global demand) and the resulting growth is significantly higher than expected international demand growth. This is driven by the fact that Australia already has projects under development that correspond to over 250 percent growth in production by 2020 (CWA, 2013). Given that Australia is currently a relatively minor gas producer, with about 1.5 percent of the world's gas production in 2010 (BREE, 2013), a very strong growth of Australia's production is not incompatible with a slow global growth.

PRODUCTION OF METALS AND METAL ORES

There is a lot of uncertainty today on how global deep decarbonisation is likely to impact on global demand for major commodities. For example, strong efforts in material efficiency or product substitution towards low-carbon materials could transform the current industrial demand for metals and other basic commodities.

In this study, data from IEA's analysis of energy technology transitions for industry (IEA, 2009) is used to inform the modelling exercise. This could be revised in the future should better data become available.

IEA expects demand for steel to increase by between 85 percent and 122 percent between 2006 and 2050 in a low carbon world (IEA 2009). Production levels have already increased by 24 percent between 2006 and 2012 (Worldsteel Association, 2013), meaning that an increase of between 50 percent and 80 percent is expected between 2012 and 2050.

In parallel, IEA (2009) expects that the share of recycled materials in steel production will increase from around a third in 2006 to about half by 2050. This means that demand for iron ore is likely to grow more slowly than overall production; high-level estimates range between 0-40 percent.

Strong growth is expected in global demand for primary aluminium. Indeed, IEA estimates that annual production of primary aluminium is likely to reach between 91 and 123 Mt by 2050 (IEA, 2009). Given that primary production was 48 Mt in 2012 (World Aluminium, 2014), this means that production would grow between 90 percent and 156 percent between 2012 and 2050. A similar trend is expected to apply to alumina and bauxite as a result.

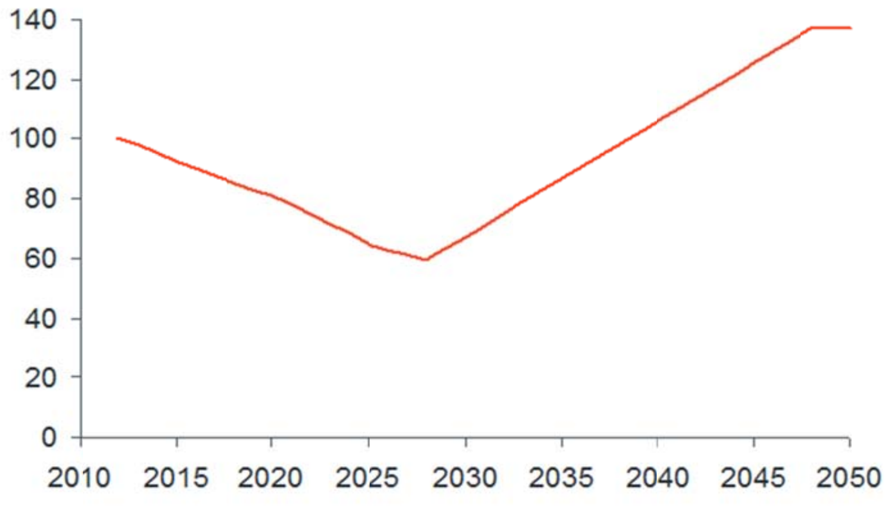
Once again, there is a lot of uncertainty on where the production will take place to meet the global demand. It will primarily depend on local production costs and changes in exchange rates. For iron ore production for example, the economic modelling results show Australian production growing strongly despite low growth in global demand, mostly based on recent production trends.

For the production of iron and steel and aluminium, a constraint has been applied to the model in the short term, reflecting the recent economic context. Until about 2030, no new investment is made in Australia to replace naturally retiring assets. This is in line with recent closure announcements in these two sectors (CWA, 2013). From 2030 onwards, the constraint on new investments is lifted to represent the possibility that Australia will develop a competitive advantage to produce low carbon metals. Results for iron and steel and aluminium are then aligned for consistency, given that the rationale is similar for both sectors. Figure 4.3 shows the resulting production levels for aluminium and iron and steel. The net growth between 2012 and 2050 is 37 percent, which is below the overall growth of the economy due to the reduction in production in the first half of the period.

This potential competitive advantage is due to both Australia's relatively low-cost decarbonised electricity and availability of geological storage for CCS (relevant to iron and steel). This is based on the fact that in a decarbonising world, demand for electricity will increase significantly. Thus, the important factor is not so much the availability of inexpensive low carbon electricity today, but the ability for the marginal additional low carbon electricity supply to be low cost. Given that Australia has abundant resources for low carbon electricity (see summary report), it is likely that Australia is well placed to provide marginal low carbon electricity at a lower cost than many other countries.

At this stage, this rationale is based on a qualitative comparative analysis of countries rather than a quantitative assessment. It is anticipated that additional research as part of the international DDPP will test this hypothesis further. This is one of the reasons why the results of the project are now presented as interim as it is expected that a number of assumptions will be refined in the future.

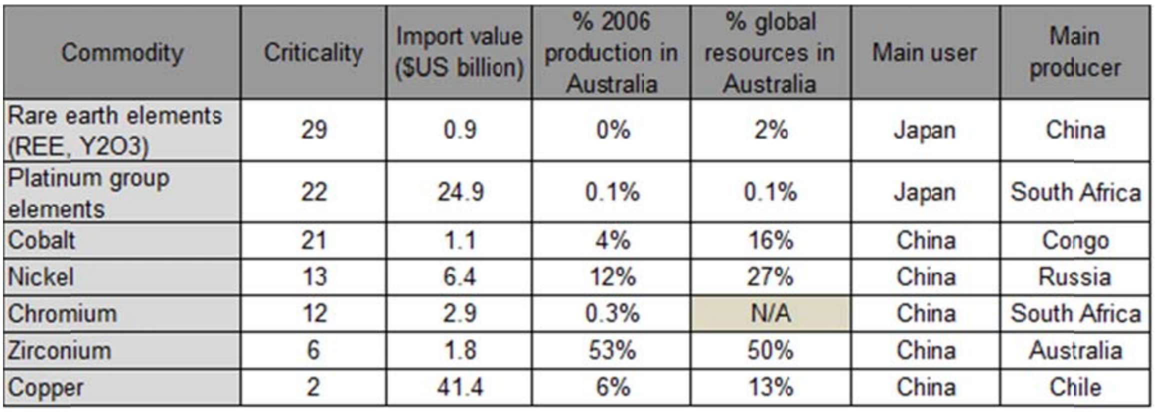
Figure 4.3 – Aluminium and iron and steel production levels, index (2012 = 100)



With regards to demand for other metals, IEA doesn't provide overall production estimates, but gives qualitative analysis of the likely impact of decarbonisation on demand levels. For example, demand for copper could increase significantly due to additional requirements in the transport and buildings sectors from the implementation of low carbon technologies.

In addition, Skirrow et al. (2013) identified key commodities that are likely to play a critical[14] role in a high-tech world and where Australia has significant resources. The following seven commodities have been identified as having the highest potential based on their level of criticality, market size, growth outlook and Australia's resources and potential for new discoveries: rare earth elements, platinum group elements, cobalt, nickel, chromium, zirconium and copper. See Table 4.2 for details on the seven commodities.

Table 4.2 – High potential commodities in a high-tech world (based on Skirrow et al. 2013)



Commodity	Criticality	Import value ($US billion)	% 2006 production in Australia	% global resources in Australia	Main user	Main producer
Rare earth elements (REE, Y2O3)	29	0.9	0%	2%	Japan	China
Platinum group elements	22	24.9	0.1%	0.1%	Japan	South Africa
Cobalt	21	1.1	4%	16%	China	Congo
Nickel	13	6.4	12%	27%	China	Russia
Chromium	12	2.9	0.3%	N/A	China	South Africa
Zirconium	6	1.8	53%	50%	China	Australia
Copper	2	41.4	6%	13%	China	Chile

Note: The import value is based on key importing countries only.

OTHER MINING PRODUCTION

IEA (2009) estimates that global demand for uranium and lithium is likely to exceed the currently known economic resources. The preliminary country results from the SDSN and Institute for Sustainable Development and International Relations (2014) interim report supports this analysis. Indeed, the 12 completed country chapters show a quadrupling of demand in uranium between 2010 and 2050, driven primarily by China and the USA. Electric vehicles are also a key element of decarbonisation of the transport sector, with many countries having a high share of renewables in their power mix, suggesting a strong growth in batteries use and lithium demand.

Australia owns a substantial share of economically recoverable resources of these minerals globally: about a third of uranium and eight percent of lithium resources (Geoscience Australia, 2014). Of significance, Australia contributed only 11 percent to total uranium production in 2011 (Geoscience Australia, 2014), indicating considerable growth potential.

PETROLEUM REFINING

All petroleum refining capacity has been assumed to close down in Australia to reflect the current economic context, with many refineries closures announced in the last few years.

Biofuel refinery capacity will replace it partially in a decarbonising world due to the increased use of biofuels in Australia. The total volume of domestic biofuel use by 2050 is equivalent to about 44 percent of the current petroleum refining activity today (see section 1.6.3).

ALTERNATIVE PATHWAYS AND DEEPER EMISSIONS REDUCTIONS OPPORTUNITIES

If strong efforts are made to improve material efficiency, or a significant shift to low carbon materials is undertaken (for example using wooden materials in buildings in place of bricks, cement and steel), then this could have a very substantial impact on production levels of basic metals and minerals extraction. Little information exists of the potential for such shifts, which is why they have not been included in this scenario. However they could be explored in future work on potential alternative pathways, especially when looking at opportunities for deeper emissions reductions.

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[14] A commodity is critical if it is both economically important and has a high risk of supply disruption.

4.2.2 Energy efficiency opportunity

CURRENT ENERGY USE

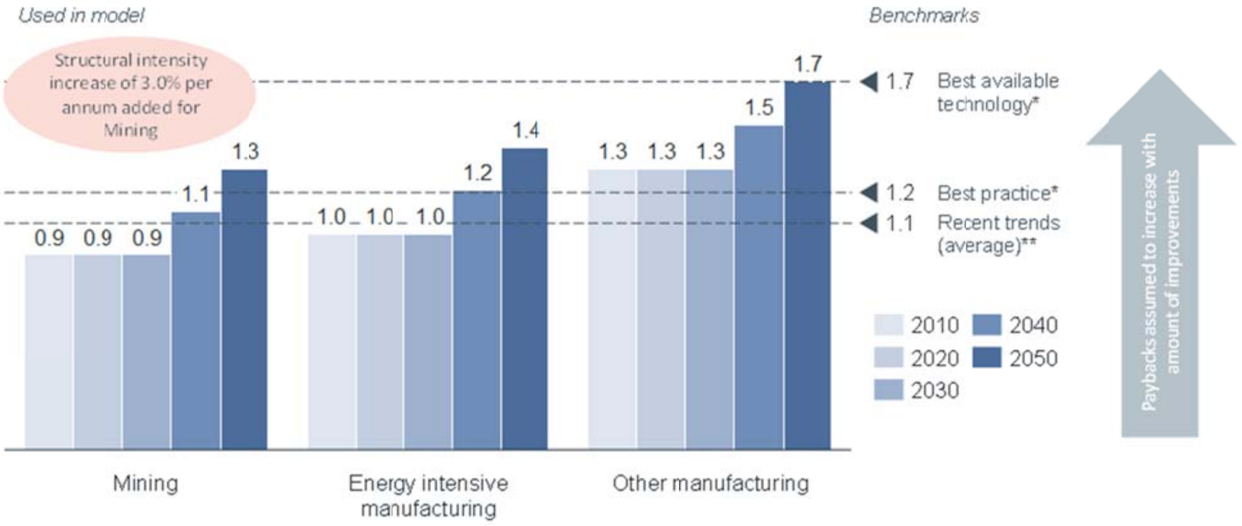
Current energy use by sector and fuel type was based on existing MMRF data adjusted based on most recent publicly available data on Australia's energy statistics (BREE, 2014a), the National Greenhouse Gas Inventory (DOE, 2014a) and ClimateWorks' publications on industry energy efficiency opportunity (CWA and DRET, 2012; 2013).

ENERGY EFFICIENCY IMPROVEMENTS

General assumptions

It is assumed that recent levels of improvements could be sustained until 2030 and then accelerated after 2030, with new technology developments and increased financial incentives to reduce carbon emissions. Figure 4.4 summarises the rates of improvement,[15] which have been assumed achievable in mining, energy intensive manufacturing[16] and other manufacturing.

Figure 4.4 – Estimated energy efficiency improvement, percentage improvement per annum



Recent improvement trends were obtained from ClimateWorks' Tracking Progress analysis (CWA, 2013), which showed that since 2007-08, the energy efficiency improvement rate in manufacturing had approximately tripled from 0.4 percent (long-term trend) to 1.2 percent per annum. The last two years of data showed an average improvement rate of 1.1 percent, which is the rate extrapolated in this analysis. This improvement was then allocated between energy-intensive manufacturing and other manufacturing.

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[15] Energy-efficiency improvement rates are calculated as the energy savings, which can be delivered in a particular year divided by the energy use that year.

[16] Aluminium and iron and steel are treated separately, based on specific technology assumptions.

For the mining sector, recent data suggests that the change in net energy intensity has decreased from 2.6 percent per annum (long-term trend) to 2.1 percent per annum since 2007-08 (CWA, 2013).

The following two separate effects influence this outcome:

- a structural energy intensity increase of around three percent per annum, driven by the degradation of ore quality and the increased difficulty of accessing good quality resources (e.g. underground or remote)[17]
- an increase in energy efficiency uptake as demonstrated by company reporting through the Energy Efficiency Opportunities Program (CWA and DRET, 2012; 2013), resulting in an increase in the energy efficiency improvement rate from 0.4 percent (long-term trend) to 0.9 percent per annum.

The United Nations Industrial Development Organisation (UNIDO, 2010) provided the following benchmark levels of energy efficiency improvement rates:

- 1.0 percent per annum corresponds to business-as-usual
- 1.2 percent per annum corresponds to Best Practice Technologies (BPT)
- 1.7 percent per annum corresponds to Best Available Technologies (BAT).

While this is mostly based on developing and in-transition economies, it provides an idea of achievable improvements in a fast transitioning world.

Other studies considered identify opportunity of a similar order of magnitude:

- McKinsey & Company (2010) identified energy efficiency potential between 2010 and 2020 corresponding to a reduction in 17.6 percent of final energy use. This would lead to a 1.9 percent improvement per annum over the period.
- Laitner (2004) suggested that potential exists to reduce energy intensity by 1.4 percent per annum. This would be the result of doubling energy efficiency and material efficiency by 2100. Laitner also refers to the Factor of 10 Club, which suggests a possibility of -2.3 percent decline in energy intensity.

The resulting changes in energy intensity are summarised in Figure 4.5

Figure 4.5 shows mining energy intensity approximately doubling by 2050, while manufacturing energy intensity decreases by nearly 40 percent.

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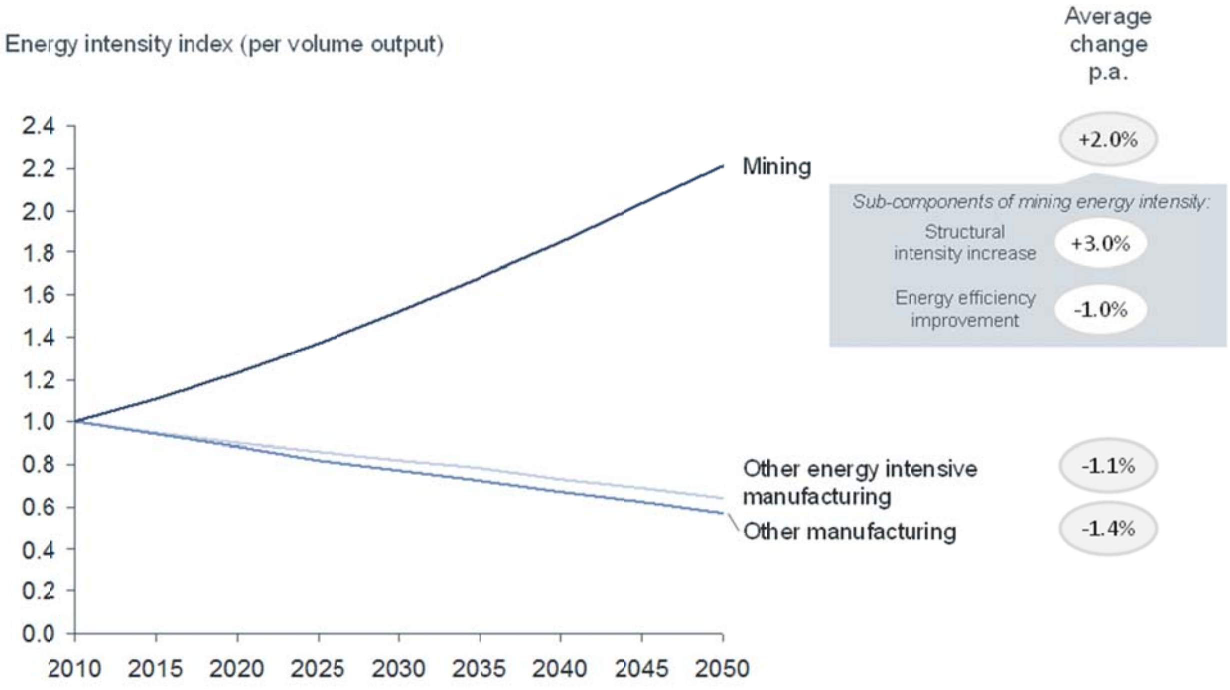
[17] This rate of increase was assumed to continue to 2050. If structural energy intensity increases faster, it is likely that energy-efficiency improvements would also increase, given the strong financial incentives to reduce energy use. Slower rates of growth are discussed in the alternative pathways section below.

Figure 4.5: Resulting change in energy intensity, index



Aluminium

Assumptions in aluminium and iron and steel are based on technology assessment rather than rates of improvements.

In the aluminium sector, it is assumed that all assets in 2050 would be using drained wetted cathode and inert anode technology. The drained wetted cathode technology decreases energy consumption by reducing the distance between the anode and the cathode in aluminium production. It can achieve energy savings of about 20 percent and could reach price neutrality compared to current technologies around 2030 (CWA, 2010). The inert anode technology can drive the near eradication of industrial process emissions but drives an increase in energy consumption of about five percent (Carbon Trust, 2011a). In total, it is assumed that energy intensity improvements of around 15 to 20 percent would be achievable in this sector.

ALTERNATIVE PATHWAYS AND DEEPER EMISSIONS REDUCTIONS OPPORTUNITIES

It is possible that increased energy efficiency improvement rates can be achieved in industry, in particular in the mining sector, where new operating models could be developed in response to declining ore grades.

For example, opportunities exist to start mining landfills and processing recycled material should ore quality degrade too much. Many valuable materials are indeed present in landfills and they can already have a higher concentration than in many mines. Other opportunities to achieve step changes in mining energy efficiency include more targeted geographical exploitation, using new technologies to identify exact location of highest quality ores; and in-pit processing, which could reduce very significantly the amount of material that needs to be moved in the mine (A Pears 2014, pers. comm. 21 May).

Also, as mentioned in the previous section, strong increases in material efficiency (e.g. through virtualisation, dematerialisation, light-weighting and material substitution) could decrease demand for ores, which are becoming highly energy intensive. Fuller (1992, pp.113-115) tracked resource curves over a 55-year period and found that metals recirculated on average every 22.5 years. Given improvements in material efficiency in such a time period, he posited that there would be no need to mine anymore in the future (Fuller, 1992).

4.2.3 Electrification

In the electricity sector, substitution of fossil fuels for renewables, fossil fuels with CCS and nuclear results in strong reductions in the emissions intensity of electricity generation. As a result, from around 2030, switching from gas-based processes to electricity-based processes results in emissions reductions. The benefits of electrification increase to 2050 as the emissions intensity of electricity generation decreases to near zero. See chapter 2 for more detail on the decarbonisation of the electricity sector.

TECHNICAL POTENTIAL

Electrification is likely to be driven by three major technology groups:

- increase in iron and steel production from electric arc furnace (EAF) technology
- shift to electricity for heating processes
- shift from trucks to conveyors for materials handling in mining.

Iron and steel

EAF technology produces steel from scrap using electricity. It currently represents about a third of total steel production in the world (IEA, 2009) and its share is expected to grow in the future.

EAF technology offers significant benefits compared to primary steelmaking (based on blast furnace/basic oxygen furnace technology). In particular, it greatly reduces the energy required (IEA, 2009), but it also allows more flexibility for production volumes. The share of total steel production from EAF technology is usually constrained by the volume of steel scrap available and the requirements of the end use.[18]

Existing supply of steel scrap in Australia suggests that an increase in the share of EAF production is possible. Indeed, in 2007–08 about 3.5Mt of steel scrap was collected for recycling and about half that volume (1.7Mt) was exported (Steel Stewardship Forum and Energetics, 2012). A volume approximately equivalent to the other half was used in EAF production. This suggests that if the scrap that is currently exported was used in domestic production, then EAF production could approximately double. This is what has been modelled in the deep decarbonisation pathway.

This would bring the share of EAF production from around 28 percent in 2012 to around 42 percent in 2050. This is a similar growth to IEA analysis, which estimates that the share of recycled materials in iron and steel production will grow from about a third in 2006 to slightly over 50 percent by 2050 (IEA, 2009).

Heating processes

Literature suggests that most heating systems will be electrifiable in the future if electricity generation is decarbonised (EPRI 2009). The technologies available to do so are many, with heat pumps showing most potential, and already being attractive in some cases, in particular for low-heat processes.

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[18] EAF steel products depend on the quality of the scrap steel fed in and may have residual impurities that make them unsuited for purposes where cold rolling and malleability are required (T. Baynes, personal communication, 3 September 2014).

Table 4.3 shows the list of technologies already known today and analysed by Electric Power Research Institute (2009).

Table 4.3 – Efficient electric end-use technologies analysed in EPRI review (2009)

End-use area	Displaced fossil fuel technology	Efficient electric end-use technology
Boilers	Natural gas, fuel oil or coal-fired boiler	Electric boiler Electric drive
Space heating	Natural gas furnace	Heat pump
Process heating	Natural gas furnace	Heat pump Electric induction melting Plasma melting Electrolytic reduction
	Direct-fired natural gas	Induction heating Radio frequency heating Microwave heating Electric infrared heating UV heating
	Coke blast furnace	Electric arc furnace

Åhman, Nikoleris and Nilsson (2012) conducted a comprehensive analysis of the potential for the electrification of industrial heating processes in Sweden. They identified that decarbonising industrial heating could be achieved through direct solar heating or electricity for heating – using direct resistance heating, heat pumps or a range of electrothermal technologies. They found that solar heating systems can provide heat today of up to 120 °C, which has applications in many sectors such as food and textile manufacturing. Existing technology developments could double the temperate range and it could be increased further through concentrated solar collectors. Heat pumps are already used for low temperature applications in the Swedish industry, in particular in the paper and pulp sector (Åhman, Nikoleris and Nilsson, 2012). While current heat pumps can replace boilers in a number of industrial applications – producing hot air up to 120 °C and steam up to 165 °C (IEA-ETSAP and IRENA, 2013) – development for high temperature heat pumps (up to 300 °C) is underway (IEA Heat Pump Centre, 2014). Their efficiency is also expected to improve by 20 to 50 percent by 2030 and by 30 to 60 percent by 2050 (IEA-ETSAP and IRENA, 2013).

Electrothermal technologies allow creation of heat on a very specific area through the generation of electromagnetic radiation. They are already used in applications that need exact and well-controlled temperatures, for example in the food (e.g. for drying) or automotive (e.g. for coating) industries. Infrared dryers could also be used in paper drying, increasing efficiency. Overall, solar and heat pump systems present future potential to meet the heating process needs in the moderate temperature range (100 to 400°C) while plasma, induction technology and concentrated solar power could help supply high temperature ranges (over 1000°C) (Åhman, Nikoleris and Nilsson, 2012).

Other studies have identified significant potential for electrification of manufacturing. For instance, process heat in Canadian manufacturing can be produced directly or indirectly with electricity and with industrial heat pumps (Wolinetz and Bataille, 2012). Wolinetz and Bataille (2012) identified that heat pumps offer higher energy efficiency but there is currently a high level of uncertainty around the relative cost-effectiveness of heat pumps compared to other technologies depending on the application.

Mining

Mining is also an area where electrification could occur at a large scale, provided low carbon electricity can be supplied at reasonable costs.

- Using conveyors to replace trucks – this is already used in Australian brown coal operations and many underground mines.
- Trolley-assisted mining trucks – trucks would be able to use grid electricity when connected to overhead wires (Wolinetz and Bataille, 2012).

Electrification presents benefits, but also challenges. Key considerations for switching to electricity-powered material handling systems include the following (Wolinetz and Bataille, 2012).

- Amount of material to move – electricity is more profitable than diesel when there are large amounts of material to be moved to access the ore; this could lead to a natural shift towards electrification as mines get deeper and ore grades decrease.
- Productivity improvements – electrification is often associated with improvements in productivity (through automation in particular) and staff health.
- Reduced energy risk – if renewable electricity can be supplied to the mining site to replace diesel use, then it will reduce the risk linked to fluctuations of fossil fuel prices.
- Reduced operations flexibility – electricity equipment is often fixed, making changes to mine configuration more costly.
- Higher upfront cost – electricity equipment often requires setting up more infrastructure upfront, e.g. conveyors, overhead wires, electricity transmission and distribution.

Further opportunities to electrify mining processes involve in-pit crushing and conveyance of ore and coal, as well as coal drying using microwaves, improving coal quality (Wolinetz and Bataille, 2012).

MODELLING METHODOLOGY

Electrification is calculated within MMRF, within boundaries defined by the project team. The parameters provided by the team are listed below:

- 2GJ of direct fuel can be replaced by 1GJ of electricity
- economic benefits purely judged on relative fuel costs (given lack of information of likely upfront costs).

These parameters should be refined in the future when more information is available. In particular, in certain applications it is likely that upfront costs would be higher for electric equipment but then energy use would be lower than modelled. Mining equipment is an example of this situation. This could also be emphasised by the shift towards more capital-intensive electricity generation assets (see chapter 2).

MMRF calculated the electrification in manufacturing and mining based on economic cost-benefits. Results are then checked against estimates of technology potential, which are described below.

ALTERNATIVE PATHWAYS AND DEEPER EMISSIONS REDUCTIONS OPPORTUNITIES

As mentioned above, some technologies might offer a better conversion rate from fossil fuel to electricity. In particular, this might be the case for mining equipment and use of heat pumps. If this was the case then it could make a higher penetration of electricity-based technology profitable in a deep decarbonisation scenario. It could also alleviate the increase in electricity demand and reduce costs of decarbonising the power generation sector.

In addition, there might be opportunities for mining trucks to be powered by hydrogen in the future. The Clean Energy Finance Corporation (CEFC) CEO, Oliver Yates, recently announced that his organisation is interested in helping finance this technology, stating that 'CEFC is keen to work with miners on hydrogen-powered vehicles'. He said that hydrogen fuel cell technology would be well suited to large mining vehicles and that hydrogen production facilities could be powered by on-site solar panels, which would be particularly attractive in remote areas, where fuel usually needs to be brought in from distant locations.

4.2.4 Direct fuel shift

COAL TO GAS

It is assumed that all coal use could be shifted to gas, unless it is coking coal used as a carbon reductant in iron and steel production.

BIOENERGY

Details of assumptions on biomass supply availability are given in section 3.2.7 and on end-use distribution in section 1.6.3. Bioenergy resources are primarily allocated to sectors where limited options exist to abate energy emissions, in particular air transport, mining and iron and steel production.

The allocation to the mining sector corresponds to shifting 50 percent of remaining diesel use to biofuels by 2050.

It is also assumed that 50 percent of the coking coal used in iron and steel production could be substituted by biomass by 2050. Indeed, CSIRO, BlueScope Steel and OneSteel are currently developing technologies to replace the coking coal used in the carbon reduction process by charcoal made from biomass with similar chemical characteristics. This could reduce emissions intensity by 32 to 58 percent without significantly increasing production costs (CSIRO, 2013).

Finally, after all other uses were taken into account, the residual biomass was allocated to manufacturing uses. It corresponds to 15 percent of industrial gas use in 2050 and could be used by companies either in biomass form or after transformation into biogas. This bioenergy is likely to be used primarily in heating systems that could not easily or profitably be shifted to electricity, for example for assets that have already been built or will be built in the near future. Today, biomass use in manufacturing amounts to around 100 PJ (BREE, 2014a), so that the modelled increase corresponds to about 150 percent growth in biomass use in manufacturing.

ALTERNATIVE PATHWAYS AND DEEPER EMISSIONS REDUCTIONS OPPORTUNITIES

If it was possible to source further biomass, then there would likely be a greater potential to shift gas to biomass in manufacturing. Indeed, IEA (2009) identifies that the use of biomass in industry is likely to rise two to four-fold, driven especially by the chemical and petrochemical sectors, as well as cement and iron and steel production.

Åhman, Nikoleris and Nilsson (2012) also suggest that most fossil energy use in industry could be shifted to bioenergy based on a review of several climate-economic mitigation studies. In particular, bioenergy for heating processes is identified as a relatively technically easy application, while some more specialised use could require pre-treatment of the biomass (e.g. into biofuels, biogas or biochar).

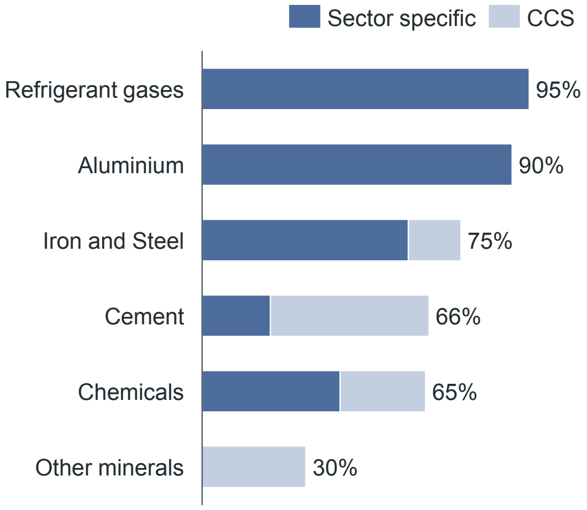
4.2.5 Industrial process emissions

OVERVIEW

Figure 4.6 summarises the assumptions regarding the achievable emissions reductions in industrial processes by sector, identifying how much is likely to come from sector-specific technologies and how much from use of carbon capture and storage (CCS). Further detail is provided below on sector-level assumptions.

Figure 4.6 – Overview of modelling assumptions for industrial processes emissions reductions

Non-energy emissions intensity reduction between 2012 and 2050, %



Key sector specific technologies participating in emissions reductions

Refrigerant gases	Natural refrigerant gases can replace HFCs & HCFCs
Aluminium	Inert anode technology can be introduced from 2030
Iron and Steel	Bio-coke can substitute 50% coking coal, EAF share increase will reduce emissions
Cement	Clinker substitution can increase to 40% (or more if new technologies are developed)
Chemicals	Catalysts can reduce N_2O emissions by 90%
Other minerals	

POTENTIAL FOR CARBON CAPTURE AND STORAGE IN AUSTRALIA

Many basins exist in Australia that present good potential for geological storage, as shown in Figure 4.7 (Cooperative Research Centre for Greenhouse Gas Technologies [CO2CRC], 2014). In particular, potential storage locations exist close to major industrial areas. In addition, several demonstration projects are under way in Australia, both for capture and storage technologies, as shown in Figure 4.7. This suggests that Australia has good potential for implementing CCS if it embarks on a deep decarbonisation pathway.

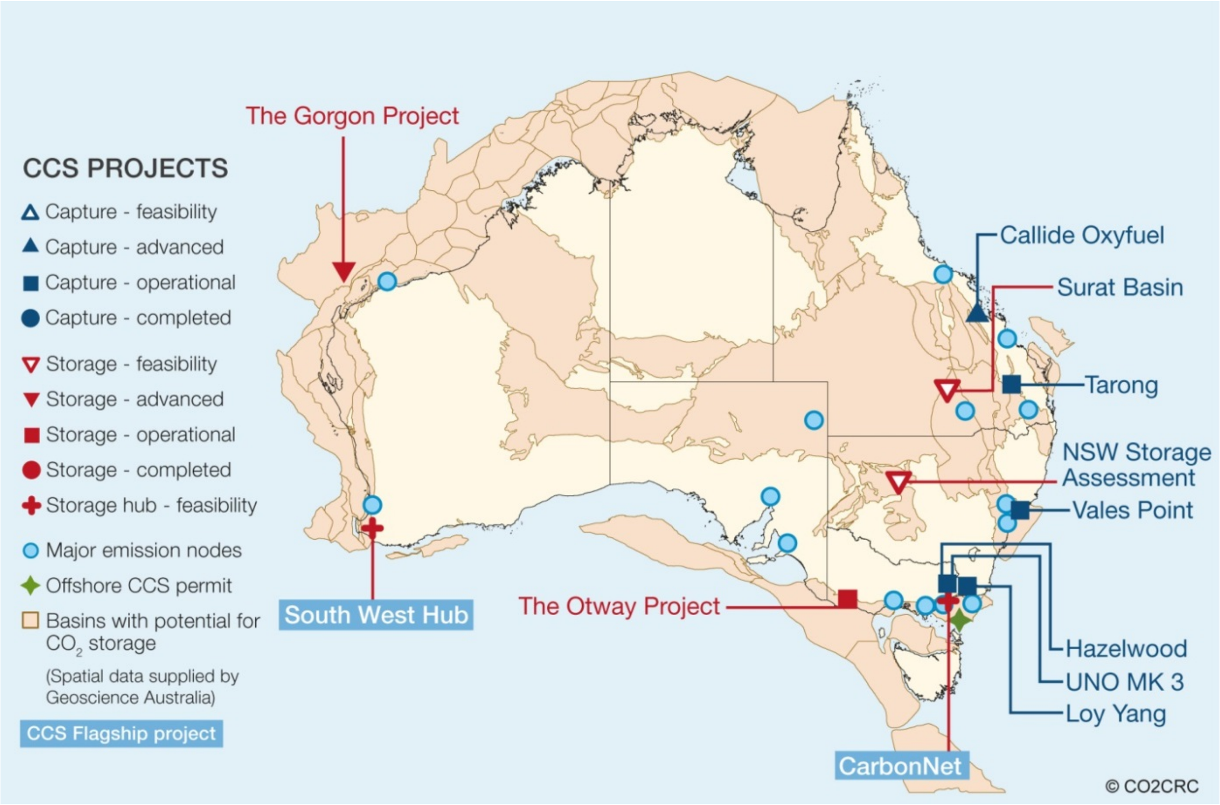
In terms of costs, the Low Carbon Growth Plan for Australia (CWA, 2010) estimated that operational costs could amount to about \$70/tCO$_2$e and capital costs to about \$400/tCO$_2$e by 2030 for CCS applied to industrial process emissions. This would add up to a total annualised cost of about \$110/tCO$_2$e by 2030, which means the technology could become profitable to implement around that time, given our abatement incentive assumptions.

IEA and UNIDO (2011) estimate that the costs of CCS for industrial processes could be lower than this, with for example CCS applications in iron and steel estimated to cost between US\$60/tCO$_2$e and US\$80/tCO$_2$e in annualised terms. The lowest costs are likely to be achievable in cases where the gas emitted is almost 100 percent pure CO$_2$, such as ammonia production and natural gas extraction. For these so-called high purity sources, limited processing is required and costs could range from around US\$30 to US\$70/tCO$_2$e (IEA and UNIDO, 2011; Åhman, Nikoleris and Nilsson, 2012). It is worth noting that applying CCS to industrial activities is likely to increase energy use as a result of the additional processes and equipment (Åhman, Nikoleris and Nilsson, 2012).

In this modelling exercise, penetration of CCS was assumed to range between around 25 percent and 50 percent in most of the sectors where it was implemented. This is meant to represent a constraint both on the location of assets (not all assets will be located near favourable storage reservoirs) and on the additional cost of retrofitting compared to implementing it at the time of construction (CCS would primarily be implemented on new assets). If needed, some CCS retrofits could also be implemented on assets with a long remaining lifespan in 2030, especially assets built in the coming years, which could be made CCS-ready at the time of construction.

The total volume of carbon captured is around 38MtCO$_2$e in 2050. About two third of this volume results from carbon capture in the gas production sector (mostly fugitive emissions), where the cost of implementation is expected to be low compared to most other applications.

Figure 4.7 – Australian CCS projects (CO2CRC, 2014)



CEMENT

We have assumed that the emissions intensity of cement production could be reduced by two thirds by 2050, based on the potential for increased clinker substitution and implementation of CCS.

In 2012 the use of supplementary cementitious materials amounted to 31 percent of all cementitious materials sold (CWA, 2013). The use of these supplementary materials allows for the reduced use of clinker, which is the primary material used to make cement and drives most of the production of process emissions in this sector. Best practice for use of supplementary cementitious materials is currently at 40 percent, above which cement properties might be affected. This suggests there is potential for a further 17 percent reduction in emissions intensity through this opportunity (CWA, 2013).

In addition, cement production is a good candidate for the use of CCS. IEA and UNIDO (2011) identifies potential for CCS to capture 50 percent of cement emissions in the OECD Pacific. In Australia, the Low Carbon Growth Plan for Australia (CWA, 2010) identified that two existing plants could be big enough and situated in favourable locations for CCS retrofits. In the deep decarbonisation scenario, it is assumed that CCS could capture about 50 percent of process emissions in Australia by 2050.

LIME, LIMESTONE AND DOLOMITE

Carbon dioxide is created as a by-product of the production of lime and there is currently no known technology to reduce these emissions. We have therefore assumed that the only technology available in this sector is CCS. The potential for emissions reductions was estimated at approximately 30 percent, lower than in the cement sector, based on an assumption that the improvements in the cement sector could be transferred over time to this sector.

CHEMICALS

Chemical process emissions are mostly composed of nitrous oxide and carbon dioxide, mostly from the production of ammonia.

Technologies exist to abate nitrous oxide (N_2O) emissions by up to 90 percent through use of catalysts to transform N_2O into inert gases. Several Australian plants have already implemented pilots and it is expected that the technology will be implemented at large scale in the near term (CWA, 2013). By 2050, it is expected that N_2O emissions will be nearly eradicated through this technology.

Regarding CO_2 emissions, the only technology currently available to reduce them is CCS, which it is assumed could lead to approximately 25 percent emissions reductions by 2050. According to IEA (2009), the costs of using CCS for ammonia production are estimated to be below US$50/t$CO_2$e.

In total, this could lead to a reduction in process emissions of about two thirds in the chemicals sector by 2050.

IRON AND STEEL

The potential to reduce process emissions by 75 percent is assumed based on the potential for shift to electric arc furnace production from scrap, a shift from coking coal to bio-coke and from implementation of CCS.

As explained in section 4.2.3, the production of iron and steel from EAF could increase from about 28 percent to about 42 percent. This would lead to a direct reduction in emissions from steel production, given that this technology does not lead to any process emissions.

In addition, as outlined in section 4.2.4, assumptions for a shift to bio-coke, it is estimated could replace about half of the use of coking coal in primary steel making. Combined, these two technologies could lead to a reduction of industrial process emissions in steel making of about 60 percent.

Finally, it is assumed that further reductions could be achieved through some implementation of CCS. Indeed, iron and steel is a good candidate for implementation of CCS given the relatively low cost of CCS for this application as discussed above (IEA, 2009, IEA and UNIDO, 2011). CCS implementation could be pushed further and even bring total emissions to below zero if used in combination with bio-coke (Carbon Trust, 2012b). Limiting assumptions regarding CCS implementation, given the existing uncertainty of large-scale bio-coke implementation, enables CCS to act as an alternative technology to reduce emissions in the sector.

ALUMINIUM

In the aluminium sector, new technologies are likely to be able to nearly eradicate industrial process emissions. Indeed, the use of inert anodes to replace carbon anodes could eliminate direct CO_2 emissions, which come from the consumption of carbon anodes in the manufacturing process. This technology is expected to be available within 10 to 15 years (CWA, 2010; Carbon Trust, 2011a).

Once this technology is available, it is likely that the costs of inert anodes would be similar to the costs of traditional carbon anodes (CWA, 2010), given that carbon anodes currently need to be replaced approximately every four weeks.

Inert anode technology is likely to increase energy intensity slightly, but this should be more than offset through the implementation of energy-saving technologies, such as the drained wetted cathode technology (CWA, 2010; Carbon Trust, 2011a).

REFRIGERANT GASES

There is a high potential to eradicate emissions from refrigerant gases by substituting HFCs and HCFCs with 'natural refrigerant' gases. These gases are called natural because they also occur in nature and include ammonia, carbon dioxide and hydrocarbons.

For example, ammonia has zero ozone-depletion and global warming potential and could be used in refrigeration systems. Its potential has already been demonstrated, primarily in large industrial applications. While upfront costs are higher and gases sometimes require additional safety equipment, the additional costs can be recovered over the life of the equipment through operational energy and maintenance savings. Some companies are using it in combination with other gases to decrease the associated safety risks (CWA, 2013).

The Australia Refrigerant Association is advocating for all new equipment to use natural gases by 2020, which would support a near complete eradication of process emissions from this sector by 2050 as modelled in the deep decarbonisation scenario.

ALTERNATIVE PATHWAYS AND DEEPER EMISSIONS REDUCTIONS OPPORTUNITIES

As mentioned above, there could be increased opportunities for emissions reductions in the iron and steel sector, in particular through the combined use of CCS with bio-coke. This sector could even generate net negative process emissions by 2050.

Further implementation of CCS in other sectors such as chemicals, cement and lime, limestone and dolomite could also result in lower residual emissions. This will mostly depend upon technology developments and cost reductions of CCS in the coming decades, as well as on the access to good storage reservoirs. Access could be provided if either new facilities can be located next to favourable geological areas, or if a network for CO_2 transport can be established in Australia.

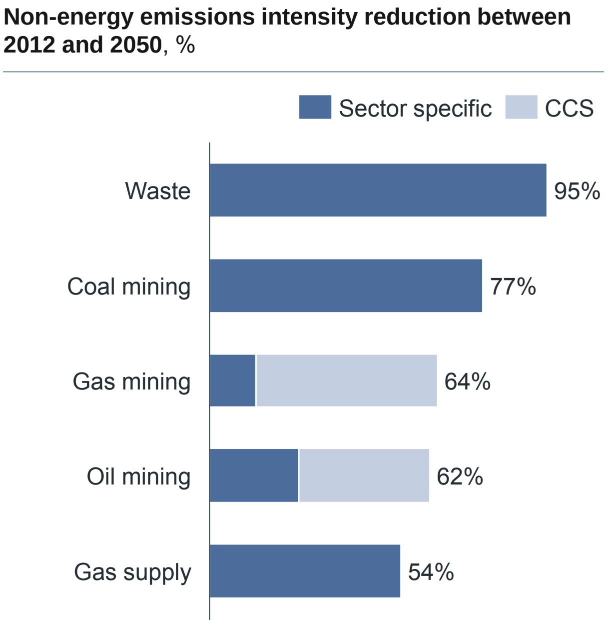
In addition, structural changes could lead to further reductions in process emissions intensive activities. For example, it is possible that production of clinker for cement would be mostly exported offshore, with only cement manufacturing activities remaining in Australia.

4.2.6 Fugitive emissions

OVERVIEW

Figure 4.8 summarises the assumptions regarding the achievable reductions in fugitive emissions by sector, identifying how much is likely to come from sector-specific technologies and how much from use of CCS. Further detail is provided below on sector-level assumptions.

Figure 4.8 – Overview of modelling assumptions for fugitive emissions reductions



Key sector specific technologies participating in emissions reductions

Increased combustion of methane

VAM oxidation can cut ~70% of VAM emissions from gassy underground mines & industry can shift to non-gassy mines as production decreases

Increased flaring of methane

Increased flaring of methane

Better processes & lower use of distribution networks

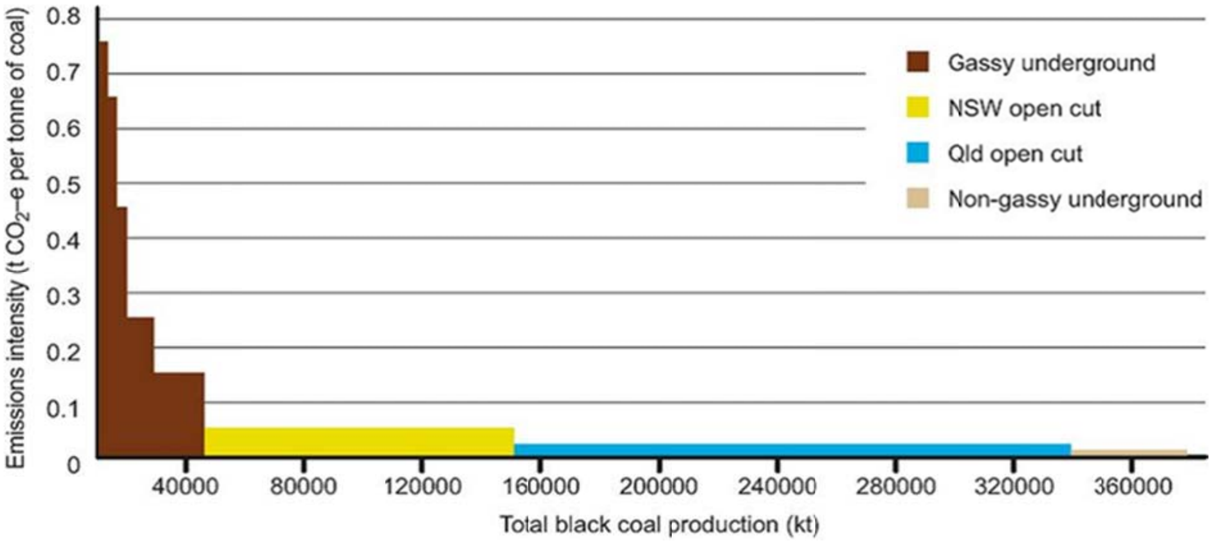
COAL MINING

We have assumed that approximately a three quarter reduction in coal mining emissions intensity is possible. This would be achieved through a combination of activities, in particular:

- increased drainage of methane
- implementation of Ventilation Air Methane (VAM) oxidation technologies in underground gassy mines
- shift to non-gassy mines.

Figure 4.9 provides background information on the major sources of fugitive emissions in coal mining. As can be seen, most of the emissions come from a small number of mines. In particular, a large share of emissions comes from about 10 percent of the production – in gassy underground mines.

Figure 4.9 – Emissions intensity distribution of Australian coal mines, tCO_2e per tonne of coal by kt of black coal production (Commonwealth of Australia, 2008)



Emissions from underground mines can be, in large part, abated through implementation of existing technologies: increased drainage, in particular during pre-operations, and implementation of VAM oxidation once the mine is operating.

The Low Carbon Growth Plan (CWA, 2010) found that VAM oxidation technologies could abate around 70 percent of VAM emissions from gassy mines, which represent 60 percent of total coal mining fugitive emissions. The difficulty with VAM emissions is that methane concentrations are very low (below one percent), which makes it impossible to combust it through traditional methods to reduce its greenhouse potential and so today it is usually released directly into the atmosphere. Existing VAM oxidation technologies are allowed to capture methane above 0.2 percent and either simply oxidise it or use it to produce on-site electricity. This can generate revenues for the mine site, bringing the net cost of abatement from the technology around $\$10/tCO_2e$ (CWA, 2010). A pilot for VAM oxidation at the West Cliff mine has created an estimated abatement of $250ktCO_2e$ a year for the past five years (CWA, 2013). Further improvements to the technology could potentially allow a greater share of methane to be captured and oxidised in the future.

In addition, given that a significant reduction in coal production is expected by 2050 (see section 4.2.1), it is possible that operations could be shifted to mines with lower emissions intensity.

OIL AND GAS EXTRACTION

We have assumed that fugitive emissions from oil and gas extraction can be reduced by approximately 60 to 65 percent using a combination of increased flaring and CCS.

Most fugitive emissions from this sector come from venting and flaring today, with about a sixth composed of methane and the rest of CO_2 (DOE, 2014b).

Emissions inventory data over the last decade shows that fugitive emissions from flaring and venting from oil and gas industries has decreased by seven percent, driven by a 46 percent reduction in methane emissions, offsetting an eight percent increase in emissions of CO_2 (CWA, 2013). Given these recent trends, we have assumed that continued reductions in methane emissions through improved flaring practices would be possible to 2050.

In addition, gas production is a very suitable for CCS implementation, given the high purity of the CO_2 outflow, which requires minimum processing. This is illustrated by the current CCS project at the Gorgon gas development. The Gorgon Carbon Dioxide Injection project is expected to become the world's largest commercial sequestration project with injection of CO_2 planned to commence in 2016; it is forecast to reduce the site's emissions by about 40 percent, leading to an estimated abatement of approximately 3.4-4.0MtCO$_2$e each year (Global CCS Institute (GCSSI), 2014a). This project should contribute to improving the technology for future applications in the gas industry in Australia.

GAS TRANSMISSION AND DISTRIBUTION

It is assumed that gas transmission emissions could be reduced by more than half by 2050, mostly through improved processes, as well as through reduced use of distribution networks.

The vast majority of emissions from the gas transmission and distribution networks are composed of methane, mostly from leaks in the pipeline equipment. Those emissions can be reduced through improved maintenance and planning processes, for example, leading to increased leak detections and reduced frequency of unnecessary (de-)pressurisation.

In addition, with the modelled electrification of buildings' energy use, it is likely that the utilisation of the distribution network used to service residential and commercial customers will decrease strongly. Today, over 90 percent of fugitive emissions in this sector come from the distribution network so this should have a strong impact on emissions intensity by 2050.

ALTERNATIVE PATHWAYS AND DEEPER EMISSIONS REDUCTIONS OPPORTUNITIES

It is possible that fugitive emissions from gas production, transmission and distribution could be decreased further.

For example, should the distribution network be retired in most locations, then the emissions from gas transmission and distribution will be decreased tremendously.

In addition, CCS could reach a higher penetration in the gas extraction sector, given the relatively low cost of the technology for this application.

4.3 Modelling results

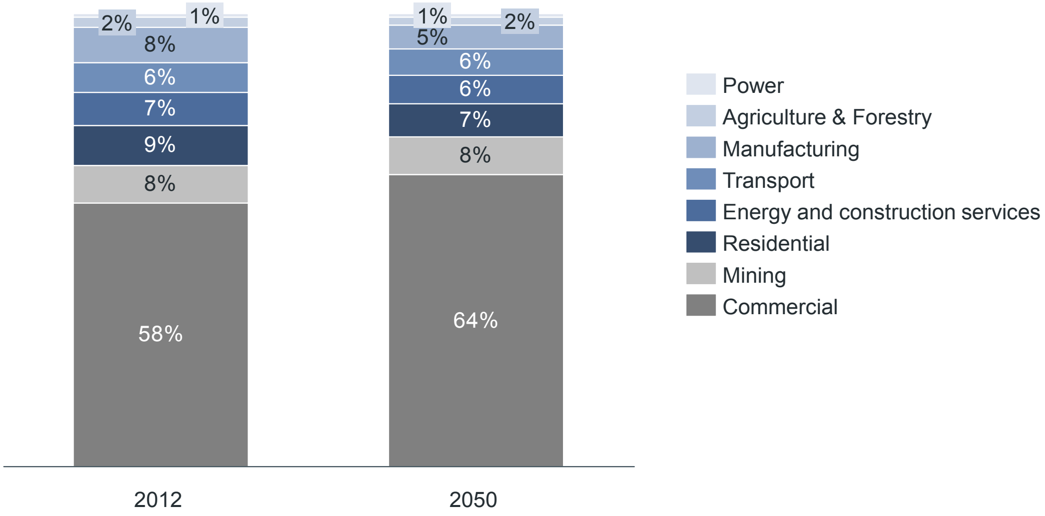
4.3.1 Economic structure

Modelling results suggest that the overall structure of Australia's economy would not change significantly, with industry's contribution remaining significant, while services continue to grow. The sectoral contribution to the economy resulting from the modelling exercise can be seen in Figure 4.10.

The commercial sector's contribution to the economy would grow by about six percentage points, which is very similar to the past 38 years which saw an increase of about seven percentage points (Australian Bureau of Statistics [ABS], 2014). In a similar manner, manufacturing's contribution to the economy would decrease by three percentage points, a continuation of past trends, which saw a decrease by eight percentage points in the past 38 years (ABS, 2014).

In absolute terms, this corresponds to a doubling of manufacturing value added between 2012 and 2050 and to a 134 percent growth in mining value added (in real terms).

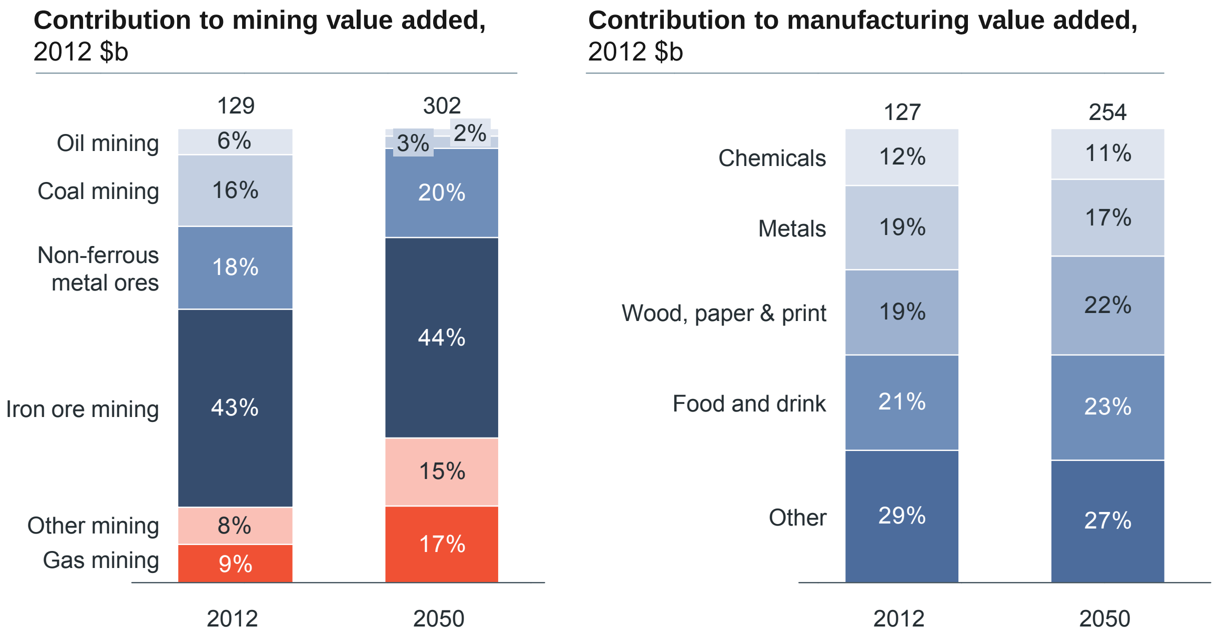
Figure 4.10 – Sectoral contribution to GDP, percentage



Mining would keep a constant contribution. However the sub-sectoral contribution to the mining sector value added would change quite significantly, as shown in Figure 4.11. As discussed previously, global deep decarbonisation would lead to a decrease in both global demand and global prices for coal, and as a result coal mining's contribution to the sector's value added would decrease significantly. In contrast to this trend, it is expected that gas mining and other mining (including uranium and lithium) would grow strongly, counterbalancing the decrease in coal production so that the sector's growth would be in line with the overall economic growth.

In the manufacturing sector, the modelling results suggest that no significant restructuring would occur, with a similar breakdown in sub-sector contribution in 2050 compared to today.

Figure 4.11 –Sub-sectoral contribution to mining and manufacturing value added, percentage



4.3.2 Emissions

In the illustrative scenario, industry emissions decrease by more than 50 percent while value added more than doubles. Figure 4.12 illustrates the overall change in emissions, as well as the breakdown by source. It shows that indirect emissions are decreased by nearly 90 percent and non-energy emissions are about halved, but emissions from direct fuel combustion are harder to abate with around 25 percent reduction.

Figure 4.12 – Industrial emissions by source in 2012 and 2050, MtCO2e

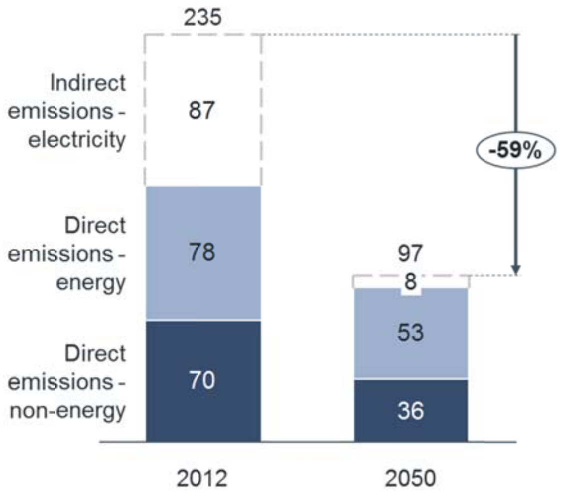
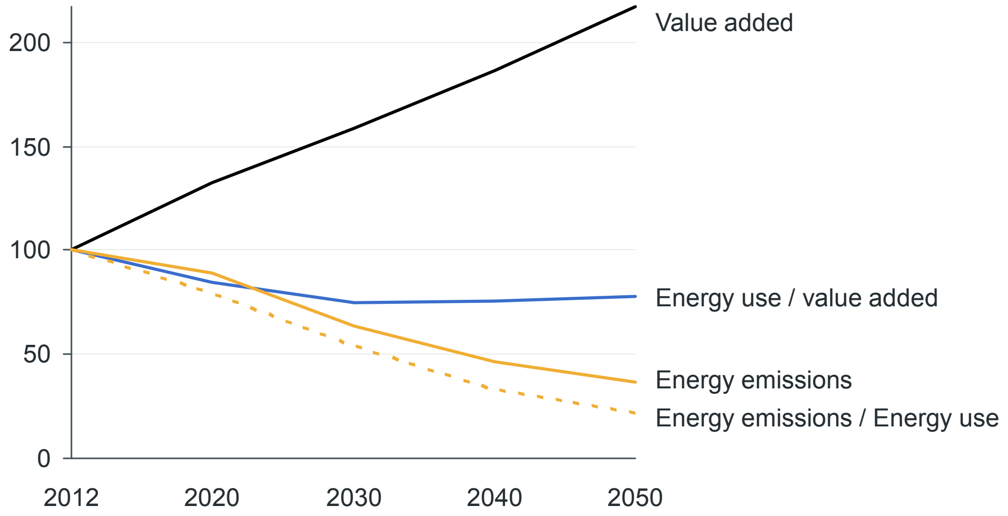


Figure 4.13 shows the Kaya decomposition of industrial energy emissions between 2012 and 2050. As can be observed, the reduction in emissions comes from a combination of an improvement in energy intensity (blue line) and mostly an improvement in the average emissions intensity of the energy used (dotted yellow line). The relatively limited improvement in energy intensity comes from the assumptions regarding the continued increase in structural energy intensity of mining operations. If this could be avoided, then energy emissions from industry could decrease significantly more than in the illustrative scenario.

Figure 4.13 – Kaya decomposition of industrial energy emissions trajectories, indices



4.3.3 Energy use

Figure 4.14 shows the industrial fuel mix in 2012 and 2050. The fuel mix change is significant, in particular with a significant reduction of coal, a tripling of electricity and nearly a nine-fold increase in bioenergy use (mostly driven by biofuels in mining). The consumption of oil and gas is expected to remain stable. This drives the nearly 80 percent reduction in the emissions intensity of energy use shown in Figure 4.13.

The growth in electricity use is in particular driven by the electrification of mining processes (where the share of electricity increases from 21 percent today to 52 percent in 2050) combined with the strong growth in energy demand from that sector. The share of electricity about doubles from 16 percent today to 31 percent in 2050 in the manufacturing sector (in sectors other than aluminium and iron and steel).

Figure 4.14 also shows that energy use increases by around 60 percent. This is mostly driven by the increase in energy intensity in the mining sector, associated with strong growth in activity. Figure 4.15 summarises the change in relative contribution to energy use from the manufacturing and the mining sector. It indicates that mining overtakes manufacturing by 2050, representing about 58 percent of industrial energy use, in particular with a very large share attributed to metal ore mining.

Figure 4.14 – Final energy use, PJ

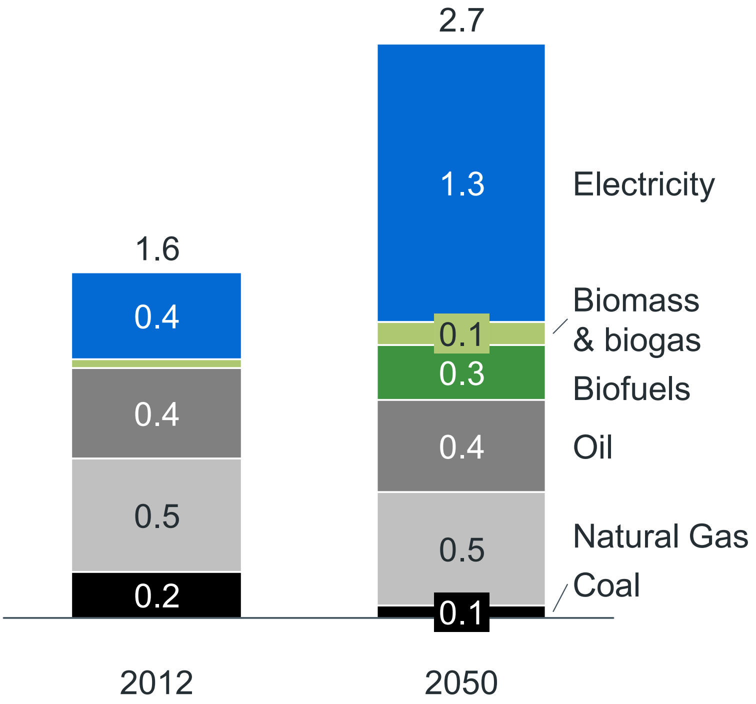
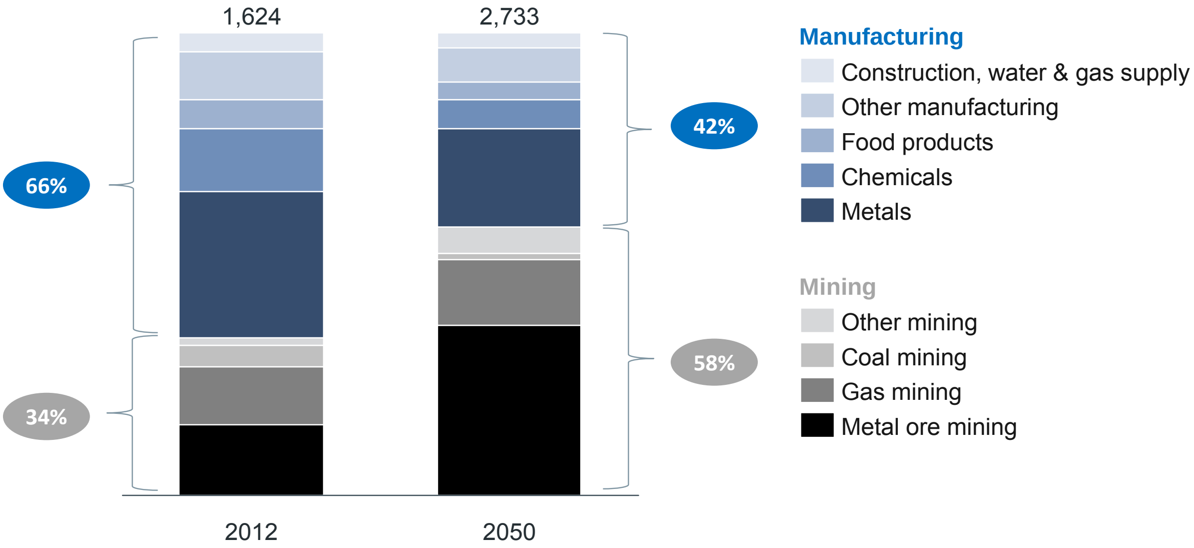


Figure 4.15 – Distribution of final energy use by industrial sub-sector, percentage



4.4 Summary of alternative pathways and deeper emissions reductions opportunities

There are alternative options that exist, which could either replace modelled technologies should they be unavailable or enable deeper emissions reductions. Most of these options are discussed in the relevant sections of this report.

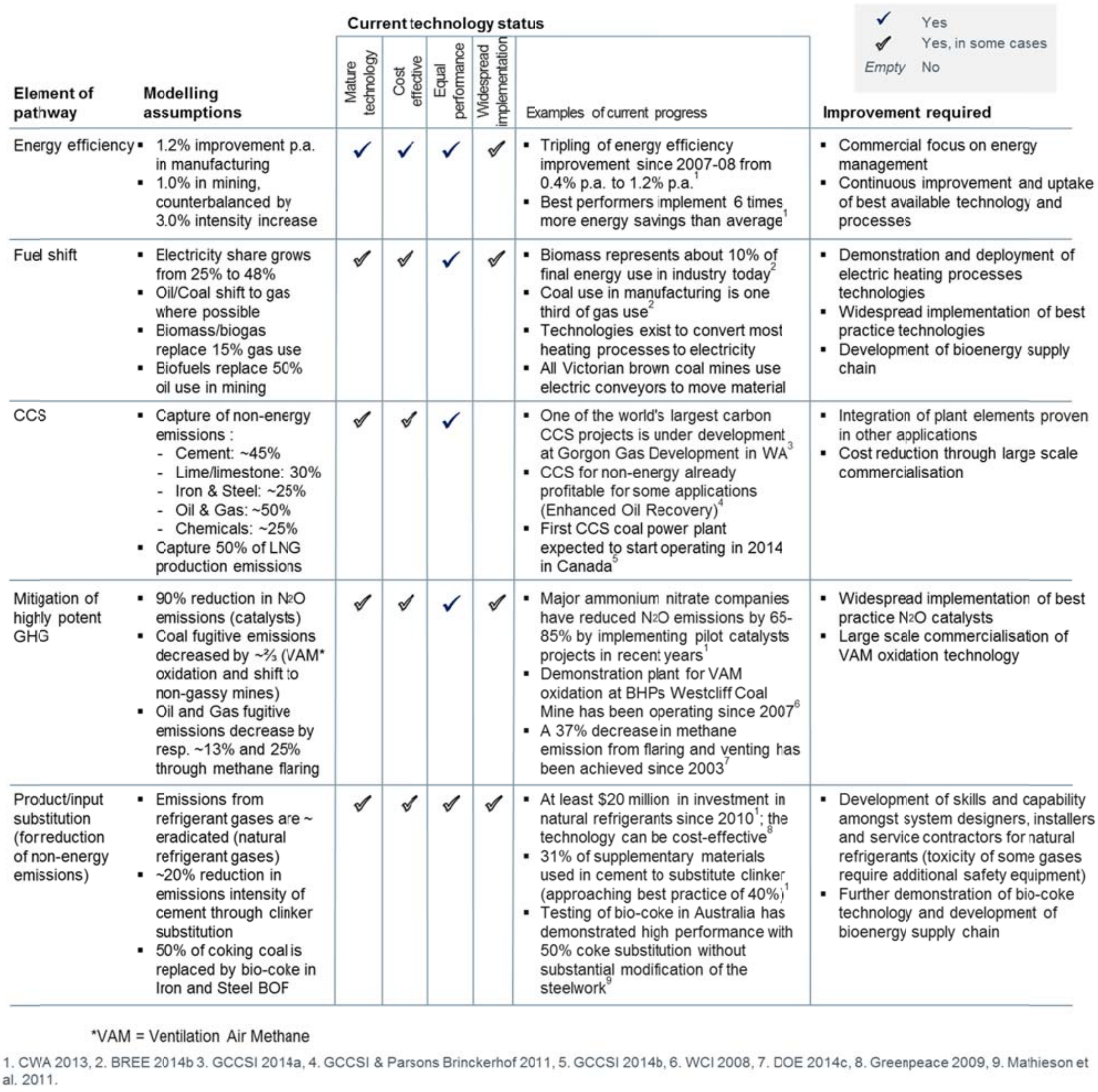
Below is a summary of the key options that could be considered in future work.

- **Strong improvements in material efficiency** – would reduce the need for the extraction of resources and the production of emissions-intensive commodities.
- **Very deep efforts in energy efficiency** – for example, deep improvements in energy efficiency through complete process redesign could reverse the recent trends in increasing energy intensity of mining activity.
- **More efficient electrification of industrial processes** – could in particular be achieved for mining equipment and heating processes, which can be replaced by heat pumps; this would reduce the cost of electrification and the growth in electricity demand.
- **Use of hydrogen to power mining equipment** – this could increase the share of electrification of mining activity, reduce the diesel and biofuel consumption in the sector and provide a more flexible path towards electrification.
- **Further fuel shift to low carbon sources** – further use of bioenergy in industrial processes could significantly reduce direct energy emissions from industry; it would require sourcing of additional bioenergy feedstock or could be achieved through decreasing the use of bioenergy in mining equipment (see above).
- **Wide deployment of CCS in industry** – if small-scale CCS becomes commercial, then it could capture most of the residual emissions in the industrial sector.

4.5 Technology status overview

Table 4.4 summarises the status of the major technologies involved in the deep decarbonisation scenario for industry. As can be seen below, most of the technologies required for decarbonisation are already being developed; integration and commercialisation are areas in which most progress is needed.

Table 4.4 – Summary of technology status in industry



✓	Yes
✔	Yes, in some cases
Empty	No

Element of pathway	**Modelling assumptions**	**Current technology status** Mature technology	Cost effective	Equal performance	Widespread implementation	Examples of current progress	**Improvement required**
Energy efficiency	▪ 1.2% improvement p.a. in manufacturing ▪ 1.0% in mining, counterbalanced by 3.0% intensity increase	✓	✓	✓	✔	▪ Tripling of energy efficiency improvement since 2007-08 from 0.4% p.a. to 1.2% p.a.[1] ▪ Best performers implement 6 times more energy savings than average[1]	▪ Commercial focus on energy management ▪ Continuous improvement and uptake of best available technology and processes
Fuel shift	▪ Electricity share grows from 25% to 48% ▪ Oil/Coal shift to gas where possible ▪ Biomass/biogas replace 15% gas use ▪ Biofuels replace 50% oil use in mining	✔	✔	✓	✔	▪ Biomass represents about 10% of final energy use in industry today[2] ▪ Coal use in manufacturing is one third of gas use[2] ▪ Technologies exist to convert most heating processes to electricity ▪ All Victorian brown coal mines use electric conveyors to move material	▪ Demonstration and deployment of electric heating processes technologies ▪ Widespread implementation of best practice technologies ▪ Development of bioenergy supply chain
CCS	▪ Capture of non-energy emissions : - Cement: ~45% - Lime/limestone: 30% - Iron & Steel: ~25% - Oil & Gas: ~50% - Chemicals: ~25% ▪ Capture 50% of LNG production emissions	✔	✔	✓		▪ One of the world's largest carbon CCS projects is under development at Gorgon Gas Development in WA[3] ▪ CCS for non-energy already profitable for some applications (Enhanced Oil Recovery)[4] ▪ First CCS coal power plant expected to start operating in 2014 in Canada[5]	▪ Integration of plant elements proven in other applications ▪ Cost reduction through large scale commercialisation
Mitigation of highly potent GHG	▪ 90% reduction in N_2O emissions (catalysts) ▪ Coal fugitive emissions decreased by ~⅔ (VAM* oxidation and shift to non-gassy mines) ▪ Oil and Gas fugitive emissions decrease by resp. ~13% and 25% through methane flaring	✔	✔	✓	✔	▪ Major ammonium nitrate companies have reduced N_2O emissions by 65-85% by implementing pilot catalysts projects in recent years[1] ▪ Demonstration plant for VAM oxidation at BHPs Westcliff Coal Mine has been operating since 2007[6] ▪ A 37% decrease in methane emission from flaring and venting has been achieved since 2003[7]	▪ Widespread implementation of best practice N_2O catalysts ▪ Large scale commercialisation of VAM oxidation technology
Product/input substitution (for reduction of non-energy emissions)	▪ Emissions from refrigerant gases are ~ eradicated (natural refrigerant gases) ▪ ~20% reduction in emissions intensity of cement through clinker substitution ▪ 50% of coking coal is replaced by bio-coke in Iron and Steel BOF	✔	✔	✔	✔	▪ At least $20 million in investment in natural refrigerants since 2010[1]; the technology can be cost-effective[8] ▪ 31% of supplementary materials used in cement to substitute clinker (approaching best practice of 40%)[1] ▪ Testing of bio-coke in Australia has demonstrated high performance with 50% coke substitution without substantial modification of the steelwork[9]	▪ Development of skills and capability amongst system designers, installers and service contractors for natural refrigerants (toxicity of some gases require additional safety equipment) ▪ Further demonstration of bio-coke technology and development of bioenergy supply chain

*VAM = Ventilation Air Methane

1. CWA 2013, 2. BREE 2014b 3. GCCSI 2014a, 4. GCCSI & Parsons Brinckerhof 2011, 5. GCCSI 2014b, 6. WCI 2008, 7. DOE 2014c, 8. Greenpeace 2009, 9. Mathieson et al. 2011.

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BUILDINGS SECTOR

R. Kelly, ClimateWorks Australia

5. Buildings sector

Executive summary

Modelling as part of the Deep Decarbonisation Pathways Project shows emissions from residential and commercial buildings reducing by 97 percent between 2012 and 2050, even with a substantial increase in the number of households and size and output of the commercial sector. This emissions reduction is achieved through energy efficiency and a switch to a decarbonised energy supply.

In the modelled pathway, energy use per household reduces by over 50 percent, while heating and cooling and other equipment use continues to increase. In the commercial sector energy use per square metre reduces by just under 50 percent and energy use per dollar of value add in the commercial sector reduces by almost 70 percent.

Converting direct fuel combustion such as gas stoves, gas hot water and boilers to electrical systems powered by decarbonised electricity supply, results in substantial emissions reductions in the modelled pathway. Achieving these emissions reductions requires a near full conversion of the energy system to low-emissions generation, such as renewables, fossil fuels with carbon capture and storage or nuclear, as outlined in the power sector modelling in section 2.

In order to achieve this substantial decarbonisation, rates of improvement in energy efficiency need to increase from current low levels. This will not require a substantial technological leap from today's best available technology and the cost of energy saved is likely to offset the costs required for investment in more efficient buildings and equipment.

Current programs underway will go some way to improving the rates of energy efficiency, however, more will need to be done, particularly in the short term to avoid the lock-in of energy-intensive buildings and equipment in households and services sectors.

5.1 Scenarios definition

This report examines a single main scenario, which is the Australian deep decarbonisation pathway. This scenario explores how Australia could achieve the budget recommended by the Climate Change Authority (2014) with technologies already known today. The key strategies used in the modelling to achieve this goal are listed in Table 5.1 and are explained in more detail in the rest of this report.

Please note that this table describes one illustrative scenario and alternative options exist to decarbonise Australia's industry. Some alternative approaches are discussed in this report, which could either replace some of the strategies used in the illustrative scenario or allow deeper emissions reductions.

Table 5.1 – Summary of the scenario strategies in the buildings sector

	Structural change	Technical energy efficiency	Fuel switching
Residential buildings		● Deep energy efficiency, leading to average 1.7 percent improvement per annum per household (or about halving of energy intensity per household by 2050). ● Most improvements achieved through new builds and new equipment. ● 40 percent increased use of electricity and gas for heating, cooling and ventilation in residential buildings (before any energy efficiency effect) and a 1.5 percent per annum increase in equipment use – in line with recent trends.	95 percent electrification, driven by: ● 100 percent electrification of new builds of new appliances after 2030 in grid-connected areas. ● Electrification of heating starting prior to 2030 (e.g. use of heat pumps).
Commercial buildings	● Current trends pursued in terms of densification of activity – around 1.5 percent reduction per annum in square metres per $ commercial gross value add over the period.	● Deep energy efficiency, leading to average 1.3 percent improvement per annum per square metre between today and 2050 (or about halving of energy intensity per square metre by 2050). ● 1.5 percent per annum increase in equipment and appliance use allowing the commercial sector to be more productive per square metre.	>95 percent electrification, driven by: ● 100 percent electrification of new builds of new appliances after 2030 in grid-connected areas. ● Electrification of heating starting prior to 2030 (e.g. use of heat pumps).

5.2 Assumptions and input

5.2.1 Energy use

Emissions from residential and commercial buildings modelled in this section represent approximately 19 percent[19] of total Australian emissions when accounting for direct combustion of gas and indirect emissions from electricity use.

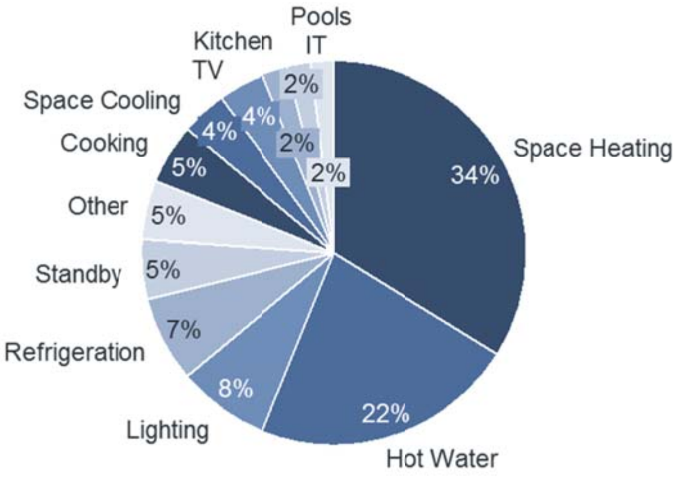
These emissions from energy use in buildings are fairly evenly split between residential (51 percent) and commercial (49 percent) sectors. Due to the higher current emissions intensity of electricity in most Australian energy markets, the emissions from electricity consumption is far higher than for gas, accounting for 77 percent of emissions.

Emissions reductions in residential and commercial sectors have been modelled by calibrating the Monash Multi-Regional Forecasting (MMRF) model (discussed in Appendix 0) based on assumptions of energy-efficiency improvement rates (discussed below) and the likely payback period of these interventions. The energy-efficiency opportunities are calibrated based on available technologies and rates of improvement, while allowing for an increase in the use of equipment such as air-conditioning, information technology and entertainment.

RESIDENTIAL BUILDINGS

The majority of energy use from the residential sector is from central buildings services, such as space heating and cooling (38 percent) and hot water (22 percent), as shown in Figure 5.1 below. Other energy use is from lighting (eight percent) and other equipment, such as refrigeration, cooking and entertainment.

Figure 5.1 – Typical distribution of energy use in an average Australian household, percentage [EES 2013]



Growth in activity

Energy use from residential buildings is assumed to grow as a result of an increased number of households and increased energy use from space heating, cooling and appliances.

The Australian Bureau of Statistics (ABS, 2010) expects the number of households to increase faster than the rate of increase in the population due to a reduction in the number of people per household and an increase in the proportion of lone person households. This forecast expects the increase in number of households to be 34 percent greater than the increase in population. For the purposes of this modelling it is assumed that this relationship continues to 2050 and the total number of households will increase by 69 percent from an increase in population of 50 percent from 2012 to 2050.

The electricity and gas use from heating and cooling has increased significantly since the late 1990s due to the increased penetration of air conditioning and a switch away from wood heating (DEWHA 2008). From 2000 to 2005, the penetration of air conditioners almost doubled from 35 percent to 60 percent (DEWHA 2008). Electric and gas space heating also increased during this period by almost 25 percent, mirroring the decline in wood heating

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[19] This value may differ from other publications (for example National Greenhouse Gas Inventory (NGGI) and BREE's Australian Energy Statistics) due to differences in sectoral definitions in the model.

(DEWHA 2008). These trends are assumed to slow somewhat as the penetration of air conditioners reaches high penetration of about 80 percent. For the purposes of modelling it is assumed that electricity and gas use for heating and cooling before energy efficiency increases by three percent per year to 2030, with the rate of increase decreasing to 0.3 percent per year to 2050 as these effects saturate.

There has been an observed trend of increasing appliance use in households increasing by approximately 1.5 percent per year between 1995 and 2005 (DEWHA 2008). This trend is assumed to continue in the modelled pathway with an increased use of appliances before energy efficiency of 1.5 percent per year.

There is an increasing rate of distributed generation, particularly from rooftop solar in the residential sector. The further uptake of distributed generation is modelled through the power sector analysis and discussed in more detail in chapter 2.

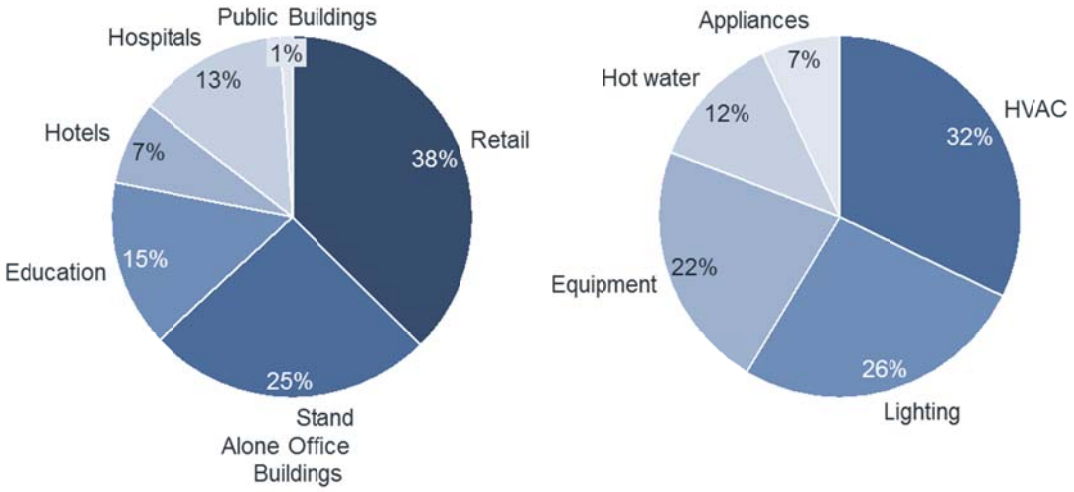
COMMERCIAL BUILDINGS

Methodology

Energy use from commercial buildings comes from a wide variety of building types as shown in Figure 5.2. The greatest proportion of energy is used in retail buildings and offices.

The majority of energy use from the commercial sector is from central buildings' services, such as space heating and cooling (32 percent), lighting (26 percent) and equipment (22 percent), as shown in Figure 5.2 below. Other energy use is from hot water (12 percent) and appliances (seven percent).

Figure 5.2 – Distribution of energy use in commercial buildings by buildings type (left) and end use (right), percentage [DCCEE 2012]



Growth in activity

The growth in energy without energy efficiency is estimated based on the historical relationships between commercial sector value added, commercial floorspace and energy use observed from sector value add data from ABS (2014) and commercial buildings floor area data from DCCEE (2012).

The rate of increase in the floor area of commercial buildings is modelled based on the increase in commercial sector production through MMRF modelling and the observed relationship between floor area and growth in the services sector. Over the past decade, the ratio of commercial value add per square metre of floor area has increased at 1.5 percent per annum, calculated from recent trends over the last decade.

5.2.2 Overall energy efficiency potential

CURRENT TRENDS IN ENERGY EFFICIENCY

Residential buildings

The energy consumption of the average household has remained fairly constant in the past, with a slight reduction of two percent of energy use over a 10-year period from 2002–03 to 2010–11 (ClimateWorks Australia, 2013) as shown in Figure 5.3below.

CimateWorks (2013) analysis estimated that energy use per household is expected to decrease by seven percent between 2010–11 and 2020 as a result of various factors, such as energy requirements of the buildings code, technological advancement (such as LED lighting), minimum energy performance standards for appliances and equipment and behaviour change in response to increased energy prices as shown in Figure 5.4.

Figure 5.3 – Historical energy consumption trends per household (incl. solar), index 2002–03 = 1.00

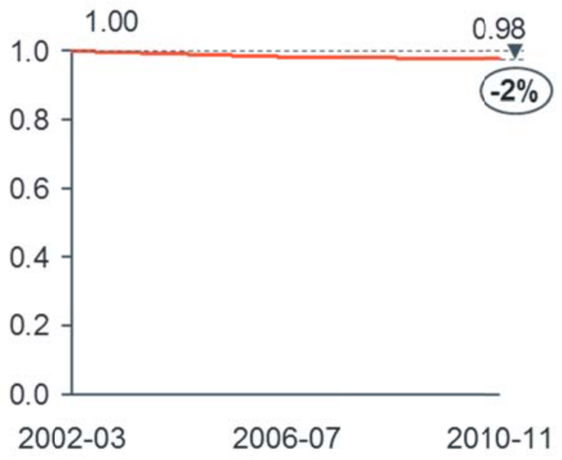
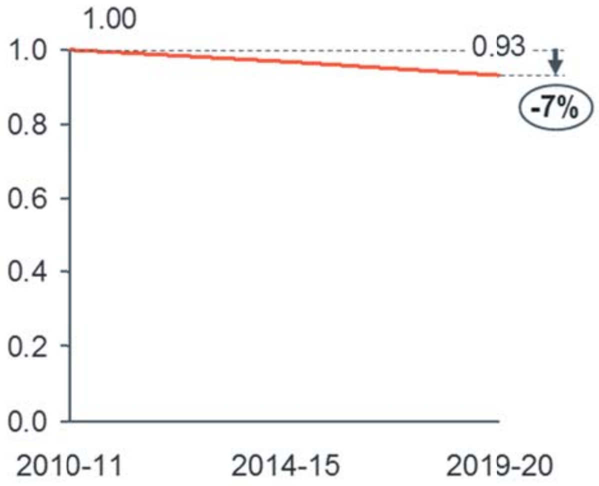


Figure 5.4 – Expected trends in future energy consumption per household (incl. solar), index 2010–11 = 1.00



Commercial buildings

The energy use per square metre of commercial space has decreased recently, driven by improvements in the energy efficiency of base buildings, yet slightly offset by increased tenancy energy use from increased use of equipment and appliances, as well as increased density of staff and longer operating hours (ClimateWorks Australia, 2013).

The energy consumed per square metre of commercial buildings area has followed a similar trend to residential buildings' energy intensity and has also improved slightly by two percent of energy use over a nine-year period from 2002–03 to 2010–11 (CWA 2013), as shown in Figure 5.5. There are fewer indications of improvement in this rate with current trends expected to lead to reductions in energy use per square metre of three percent between 2010–11 and 2019–20, as shown in Figure 5.6.

Figure 5.5 – Historical energy consumption trends in commercial energy intensity per square metre, (index 2002–03 = 1.00)

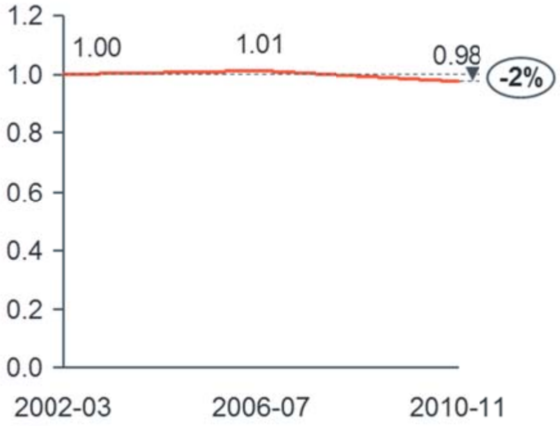
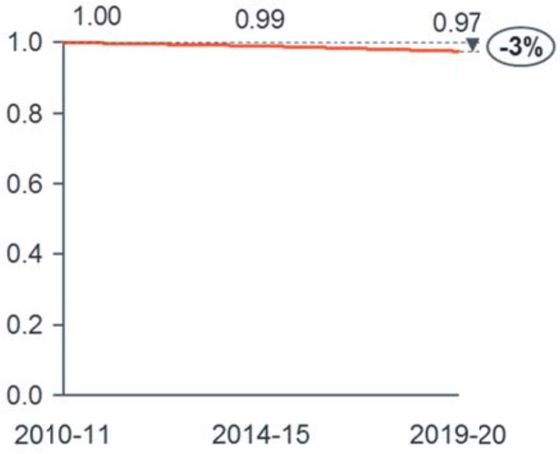


Figure 5.6 – Expected trends in future energy consumption per square metre of commercial buildings space, (index 2010–11 = 1.00)



5.2.3 Energy efficiency from heating and cooling

FACTORS DRIVING IMPROVEMENTS IN HEATING AND COOLING ENERGY INTENSITY

The energy used for heating and cooling is a function of several factors, with the main factors investigated in this analysis including:

- temperature and comfort of the buildings
- thermal efficiency of 'base' buildings
- efficiency of equipment used to heat and cool.

Temperature and comfort of the buildings

The temperature control of residential buildings has been enhanced through increased use of air conditioning, which has improved the comfort of homes significantly in the last decade (DEWHA, 2008). As presented in section 5.2.1, the increased penetration of air conditioning is assumed to continue, particularly in the period from 2012 to 2020 and continue to rise at a slower rate from 2020 to 2050 as the penetration reaches saturation.

Thermal efficiency of building

The thermal efficiency of buildings refers to the ability of the building structure to passively regulate the internal temperature.

The impact of different measures to improve the efficiency of heating and cooling of the building varies depending on the climate zone. In cooler southern or alpine climates, retaining heat is the most important factor in reducing energy use, whereas in hotter climates building orientation can be improved to reduce the heat absorbed by the building.

New residential and commercial office buildings have both been found to be far more efficient than existing stock (ClimateWorks Australia, 2013). This is because of more stringent buildings codes, improved construction practices and greater awareness of owners and tenants on the value of energy efficiency through accreditation programs.

The average rate of improvement in new buildings and the proportion of new buildings that make up the total building stock are driven by energy efficiency of central building services outlined in the modelled pathway. In order to estimate the impact of buildings' turnover on overall energy use, building stock estimates were established for both commercial and residential buildings.

The modelling has assumed that approximately two percent of existing buildings are demolished each year, which assumes an average building lifespan of 50 years. There is poor availability of data on the average rates of building demolition or the relative ages of buildings making up the residential building stock, however, where this overestimates the turnover of buildings, this rate of replacement could be achieved through deep retrofits of buildings.

Retrofits of the building envelope has not been included in the modelling but could also deliver significant savings through improvement to the central building envelope however this would be likely to come at a higher cost than new buildings and it could be hard in many cases to achieve as strong energy-efficiency improvements.

Efficiency of equipment used to heat and cool

Upgrading old inefficient equipment used to heat and cool can also achieve significant energy savings in existing buildings (BZE, 2012). In order to achieve the substantial emissions reductions required for deep decarbonisation, heating and cooling must be driven by a decarbonised energy source, such as decarbonised electricity. This energy could also be supplied through bioenergy (e.g. biogas), however, the limited supply is assumed to be taken up in transport and industry, where there are fewer options to substitute away from fossil fuels.

Heating and cooling through electric heat pump systems are among the most efficient systems available. These systems can provide far more heat than the energy drawn from the grid, as the systems use gradients in ambient temperatures to provide energy for heating four times greater than the electric energy drawn (BZE, 2013).

There are two high-efficiency technologies that are both readily available and have the potential to significantly reduce energy use, namely solar (thermal, not PV) and heat pumps. These technologies are both capable of reducing energy use by 50 to 70 percent compared to traditional technologies such as gas and electric element systems (BZE, 2013).

Residential buildings

New residential buildings are significantly more efficient than average existing buildings; with new residential buildings designed to a minimum standard of at least six stars in most states through the Building Code of Australia (ABCB, 2014). Based on analysis of the performance of buildings in the most populated climate zones in Australia, these new buildings will be 59 percent more efficient than the current stock, which perform to the equivalent of a two-star rating on average (ATA. 2013).

Increasing the minimum performance standards for new residential buildings could significantly reduce their energy consumption. Analysis of the requirements for energy use by star band across climate zone (NatHERS, 2013) suggests that achieving eight-star new build by 2050 would result in reduced energy use for heating and cooling of more than 80 percent on a weighted average basis across the major urban centres in Australia compared with the current building stock. This would require improvements in thermal performance of the building envelope of up to three percent per annum and improvements in the performance of the equipment used for heating and cooling of up to two percent per annum.

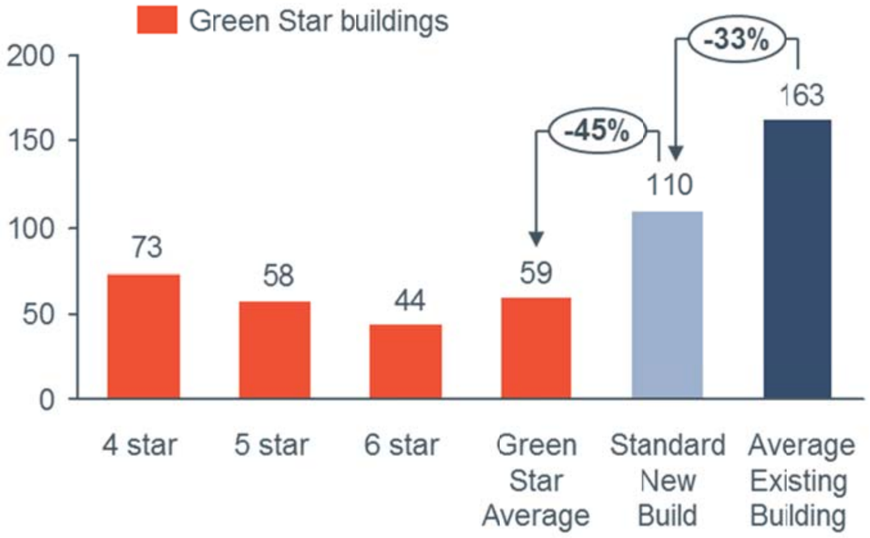
Commercial buildings

Commercial buildings are more diverse than residential buildings and data on the performance is not as readily available. There is strong evidence that significant improvements have been made in some new commercial buildings, particularly offices (GBCA, 2013).

New office buildings currently use far less energy, with corresponding emissions 33 percent lower than the average existing building stock as shown in Figure 5.7. These could be improved further by adopting best practice, as illustrated by the Green Star benchmarks. The average Green Star office building has 45 percent less emissions per square metre than the standard new build (GBCA, 2013).

In the illustrative pathway modelled, energy efficiency of heating and cooling in commercial buildings improves at a rate of up to four percent.

Figure 5.7 – Comparison of emissions intensity factors for offices, kgCO2e/m² (GBCA, 2013)



Hot water

Energy use from hot water can be reduced through reductions in the use of hot water or from improved efficiency of equipment used for heating (BZE, 2013).

The implementation of best practice hot water system technologies is assumed to lead to 3.5 percent reductions in energy intensity to 2050 in residential buildings through the implementation of best practice heat pump and solar hot water systems. Today, those technologies already deliver emissions reductions of around 75 percent and 43 percent respectively compared to an average existing home (CWA, 2013), without counting the benefits of decarbonised electricity.

The efficiency of hot water systems has been modelled to improve by three percent per annum in commercial buildings. This rate is slightly lower than for residential buildings, as there is greater requirement for higher temperature heat and steam in commercial buildings, which may preclude the use of solar thermal and heat pump technologies from all applications.

Lighting

There is significant potential for energy savings from lighting in both commercial and residential buildings due to the significant progress in new lighting technologies, such as LED, as well as through better controls and passive measures, such as improved daylighting. LED lighting has improved performance over other alternatives for low-energy lighting alternatives, such as compact fluorescent lamps (CFLs). LEDs can reduce energy use by almost 80 percent compared to halogen globes and can provide 25 percent savings compared to CFLs (CWA, 2013). LED lighting also has many other advantages over other low-energy lighting – it can be more easily controlled, has a quicker start-up time and a warmer light than alternatives such as fluorescent (BZE, 2013).

The lighting performance of LEDs has increased significantly in recent years (US DOE, 2009) with lumens per watt increasing rapidly since becoming commercially available for space lighting in the early 2000s. LED lighting is already more efficient than compact fluorescent lighting in terms of lumens produced per watt of electricity and is improving at a considerable rate.

Lighting has been a major source of increased energy use in the past as the penetration of higher intensity technologies such as halogens increased (Wilkenfeld, 2007). Recently, more energy-efficient lighting such as LED has the potential to reverse this trend, leading to significant energy savings.

The energy used for lighting can exceed 25W/square metre of floor area in some homes (BZE, 2013). From 2011 building codes stipulate that new homes are not to use electrical energy for lighting in excess of 5W/square metre, although the latest technology could reduce the energy used per square metre to 2W/square metre (BZE, 2013).

This rapid improvement in technology could result in improvements in energy use for lighting per household of up to four percent per year to 2050.

Energy-efficient lighting technologies such as fluorescent are more widespread in commercial applications than in residential, with savings likely somewhat lower in commerical than in residential from switching technologies, although controls and task lighting may be more applicable to commercial.

Appliances and equipment

Energy use modelled under 'appliances and equipment' represents a diverse range of technologies in residential and commercial buildings. Refrigeration represents a large proportion of this energy use in both residential and commercial buildings. Other end uses include cooking, entertainment, IT equipment and lifts, as well as a diverse range of specialist equipment across education, health and government buildings.

Studies have identified significant energy savings potential from appliances and equipment and government programs, such as minimum energy performance standards (MEPS) and labelling schemes, which have had an influence in reducing energy use and are expected to contribute to substantial energy savings over the coming decades (DOI, 2014).

Projecting or extrapolating future appliances and equipment energy use has many challenges and uncertainties. The use of appliances, particularly related to information technology and entertainment, has increased significantly throughout the last decades as the number and penetration of devices has increased (DEWHA, 2008).

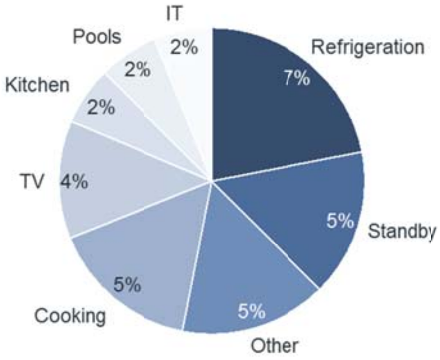
The use of energy from appliances and equipment will also be impacted by the introduction of new products and consumer equipment, as has occurred in the past. For example, new smaller fridges and wine coolers can use as much energy or more as a full-size family fridge (Pears, 2013). A high rate of penetration of these or similar consumer goods may substantially increase energy use.

The introduction of new household equipment could on the other hand act to reduce overall energy use. Innovations such as home teleconferencing, 3D printing or other in-home manufacturing, for example, could increase the use of energy in the home, but lead to lower overall energy use by reducing the need for manufacturing and transport.

Residential buildings

Appliances and equipment are responsible for approximately 32 percent of residential energy use, with refrigeration and cooking equipment responsible for the greatest shares, using seven percent and five percent of all energy used in households respectively (EES, 2013). Energy used when appliances and equipment are left idle accounts for five percent of all energy used in the average house, with entertainment, kitchen and other equipment accounting for the remainder as shown in Figure 5.8 below.

Figure 5.8 – Typical energy use from appliances and equipment in an average Australian household, percentage (EES 2013)



In recent decades, the energy use for appliances and equipment in households has increased significantly, with energy use estimated to have grown from 9.5 GJ per household to 14.5 GJ per household between 1990 and 2005 (DEWHA, 2008). More recently, the introduction of minimum performance standards for equipment has reduced this rate of increase.

Energy-efficiency opportunities

While energy use for appliances and equipment has increased with new consumer products and equipment, substantial opportunities exist to reduce the overall use of energy from appliances and equipment to 2050. Harrington, Foster and Hawkins (2013) estimated that the energy use from appliances could be reduced by approximately 30 percent to 2020, assuming implementation of best available technology at the natural rate of replacement. This rate of improvement would not be challenging in terms of technological feasibility, but would require significant changes to regulation and appliance sales in Australia.

Due to the challenges in implementing systems for improving appliance efficiency that keeps pace with changes in technology and consumer activity, an improvement rate of two percent per annum has been assumed for residential appliances. Although this level of improvement is significantly lower than the technical potential, it remains at the high level of annual maximum achievable savings observed in studies over longer time periods (Neubauer, 2014).

Commercial buildings

Like residential buildings, there is also substantial savings potential in commercial buildings. Implementation of best practice electronics and appliances will have similar potential to residential buildings, given the similarities in technology.

An evaluation of measures in the E3 program found that commercial refrigeration is likely to be the source of the largest savings from energy programs in train, resulting in 7.5PJ of energy saved by 2030 with an additional 2.4PJ of energy saved through programs scheduled to start before 2020 (DOI, 2014). This is equivalent to approximately 16 percent of electricity use in appliances and equipment in the commercial and services sector.

Energy savings from commercial appliances and equipment have been modelled between one and two percent improvement per annum. As with residential appliances and equipment, these savings are not likely to capture the full technological potential from the application of best practice technology along with continuous learning and innovation. This rate of improvement reflects the challenges associated with implementing these energy savings across such a diverse range of end uses.

Modelled energy efficiency to 2050

As shown in Figure 5.9 and Figure 5.10 below, the assumptions detailed in the sections above lead to significant energy efficiency in both residential and commercial buildings. Energy use before any assumed rate of energy efficiency would grow substantially in residential buildings by over 40 percent to 2050, due to increased heating, cooling and equipment use, however, after implementation of energy efficiency the energy use per household reduces by about half. Energy use in commercial buildings also reduces substantially by approximately 50 percent of 2010 energy use per square metre of commercial buildings floor area by 2050.

Figure 5.9 – Energy use and efficiency assumptions per household, index (2010=1.0)

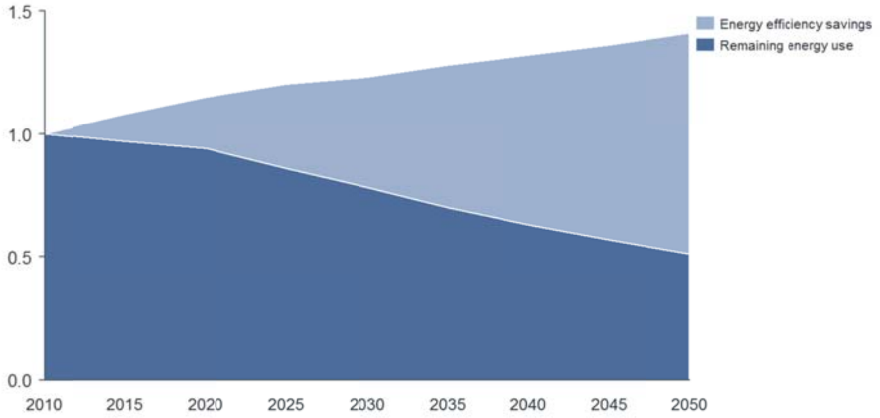
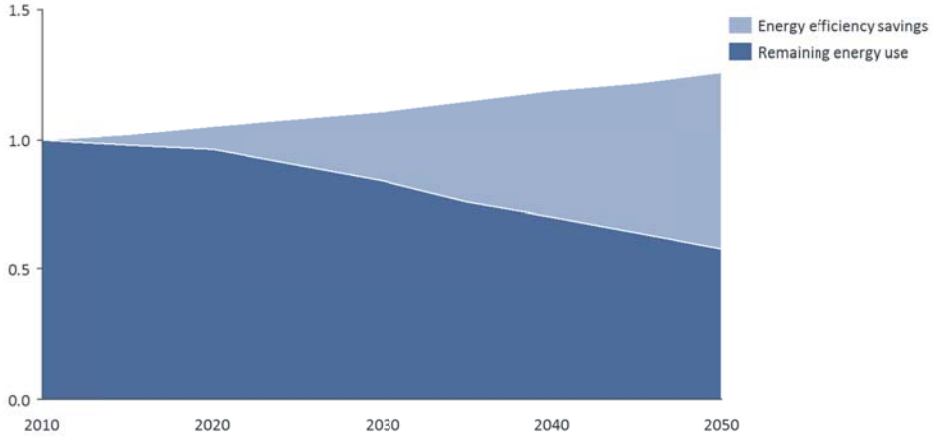


Figure 5.10 – Energy use and efficiency assumptions per square metre of commercial buildings, index (2010=1.0)



Key uncertainties

Many uncertainties exist on the actual improvements in energy efficiency achievable by 2050, with some key factors influencing increased energy-efficiency savings including:

- a reduction in the rate of increase in the use of equipment compared to historical trends
- accelerated technological improvement in currently available equipment, resulting in high energy efficiency performance
- development of highly efficient technology for new uses of energy in buildings that evolve in the future
- the retirement of old inefficient appliances (e.g. old fridge kept as second fridge when a new model is purchased), which currently counterbalances some of the efficiency improvements in new equipment
- increased turnover of building stock or high rate of deep retrofits.

Opposite trends in those factors would lead to lower energy efficiency savings.

ELECTRIFICATION

Overview

Given the current electricity generation mix in Australia, a switch from electricity use to gas use for many applications will result in emissions reductions. Under the decarbonisation scenario, the emissions intensity of grid electricity decreases to close to zero, enabling significant emissions reductions from switching energy use from direct fuels (such as gas) to electricity.

The switch from gas to electricity is feasible and low cost. This will require changes to the energy transmission and distribution network as gas decreases relative to electricity supply.

This relative increase in electricity demand may be met in some part by an increase in distributed generation (for example from solar PV).

In some cases an early switch is desirable, even though there will be an increase in emissions in short run, as over the life of the equipment there will be an overall reduction in emissions as the emissions intensity of electricity decreases. For example, given the "lock in" effect of new infrastructure, forward planning to phase out gas use in the residential sector will be needed unless new technologies for the development of large low emissions biogas substitutes can be proven.

This planning should precede the emissions parity of electricity and gas, to ensure that gas use is phased out as close as possible after electricity becomes the lower emissions source of energy.

The large scale switch from mains gas to electricity presents significant regulatory issues for gas and electricity markets. This transition will reduce the value of gas distribution infrastructure built to deliver gas to buildings.

In terms of modelling, the conversion between gas and electricity is determined by the MMRF model as consumers are assumed to prefer the least cost alternative.

Residential buildings

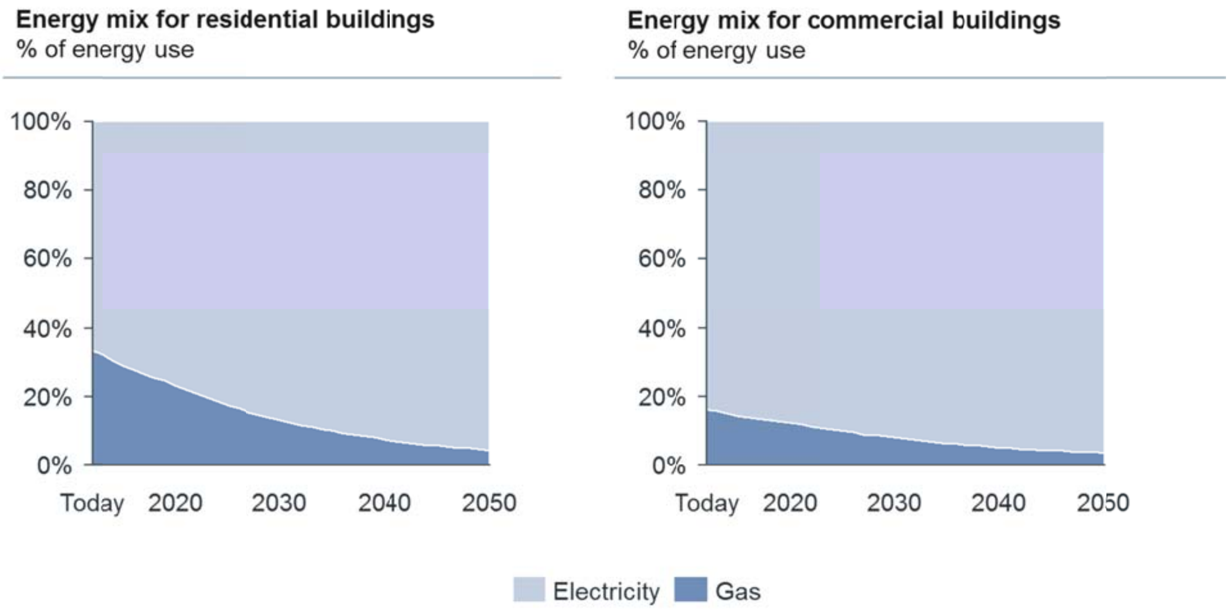
As electricity approaches very low levels of emissions intensity, electrification of buildings offers relatively attractive abatement. The cost of electrification will be the difference between the costs of electricity and gas energy inputs, the difference between the costs of electrical and gas equipment and costs of infrastructure after accounting for the abatement incentive. The costs of equipment are assumed to be comparable over the long run.

100 percent electrification of residential buildings is feasible and is already commonplace in many areas without developed gas distribution networks.

Commercial buildings

Electricity is already used for a high proportion of energy use in most commercial buildings, with over 85 percent of energy use in supermarkets, shopping centres and offices (DCCEE, 2012). Hospitals had the lowest observed proportion of energy use from electricity, with just under half of energy use (DCCEE, 2012).

Figure 5.11 – Modelled energy use by fuel type (percentage)

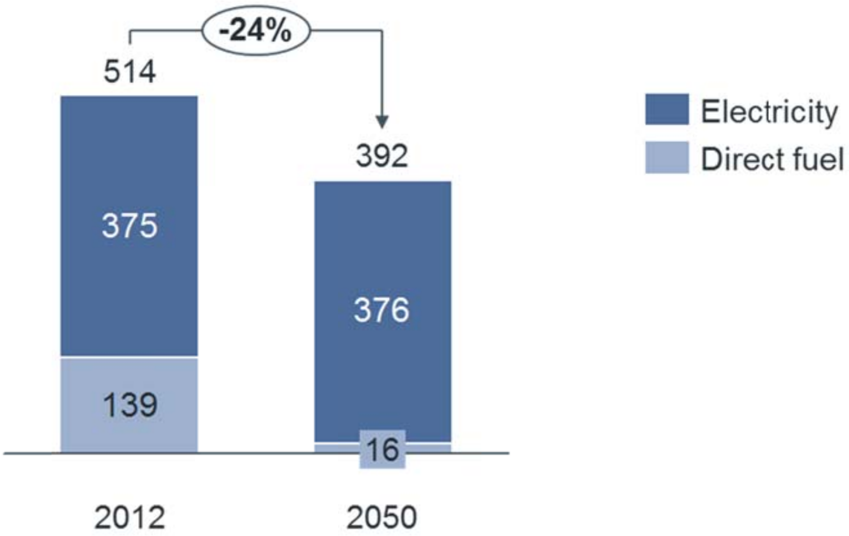


5.3 Modelling results

5.3.1 Energy use

The combined efforts of energy efficiency and switching end-use energy to decarbonised electricity supply result in a reduction in energy use of 24 percent from 2012 to 2050, as shown in Figure 5.12 below. This reduction in energy is achieved with an increase in housing and commercial building stock and an increase in demand for energy-using services such as heating, cooling and equipment use.

Figure 5.12 – Modelled energy use in buildings, 2012 and 2050 (PJ)



Similar efficiencies are achieved in residential and commercial buildings, with each using approximately half of the energy used in 2012 per household and per square metre respectively. The growth in demand for energy services is particularly strong in the residential sector due to a continuation in the growth in demand for heating and cooling and a continued switch away from firewood to electricity and gas.

5.3.2 Emissions

The combined impacts of energy efficiency and the switch to a decarbonised energy supply result in a reduction in emissions of 97 percent in 2050 compared to 2012 levels in the modelled pathway as shown in Figure 5.13 below. Of the emissions from buildings, 2MtCO$_2$e comes from electricity use generated from fossil fuels and 1MtCO$_2$e per year is from gas use.[20]

The 1MtCO$_2$e of emissions from gas use is likely to be the result of energy use from specialised applications such as in hospitals, education facilities and some residential buildings not supported by a reliable grid supply.

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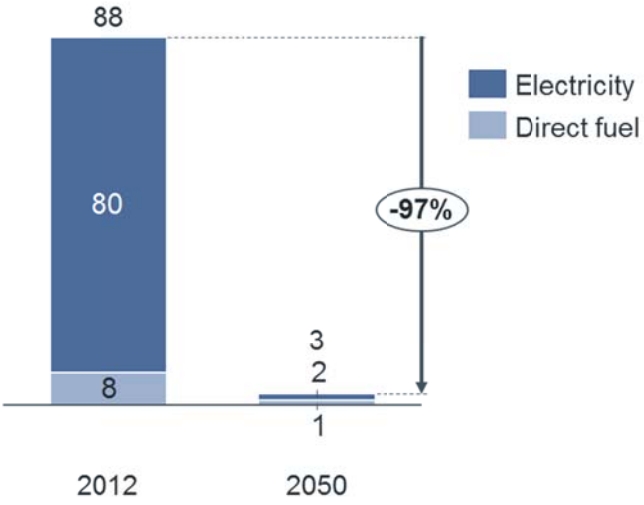
[20] This is based on the emissions intensity from the *100 percent renewables grid* scenario. See the electricity sector chapter for more details on this and other modelled scenarios.

Figure 5.13 – Modelled emissions from buildings 2012 to 2050, $MtCO_2e$



5.4 Alternate pathways

There are alternative options that exist which could either replace modelled technologies should they be unavailable, or enable deeper emissions reductions. Most of these options are discussed in the relevant sections of this report.

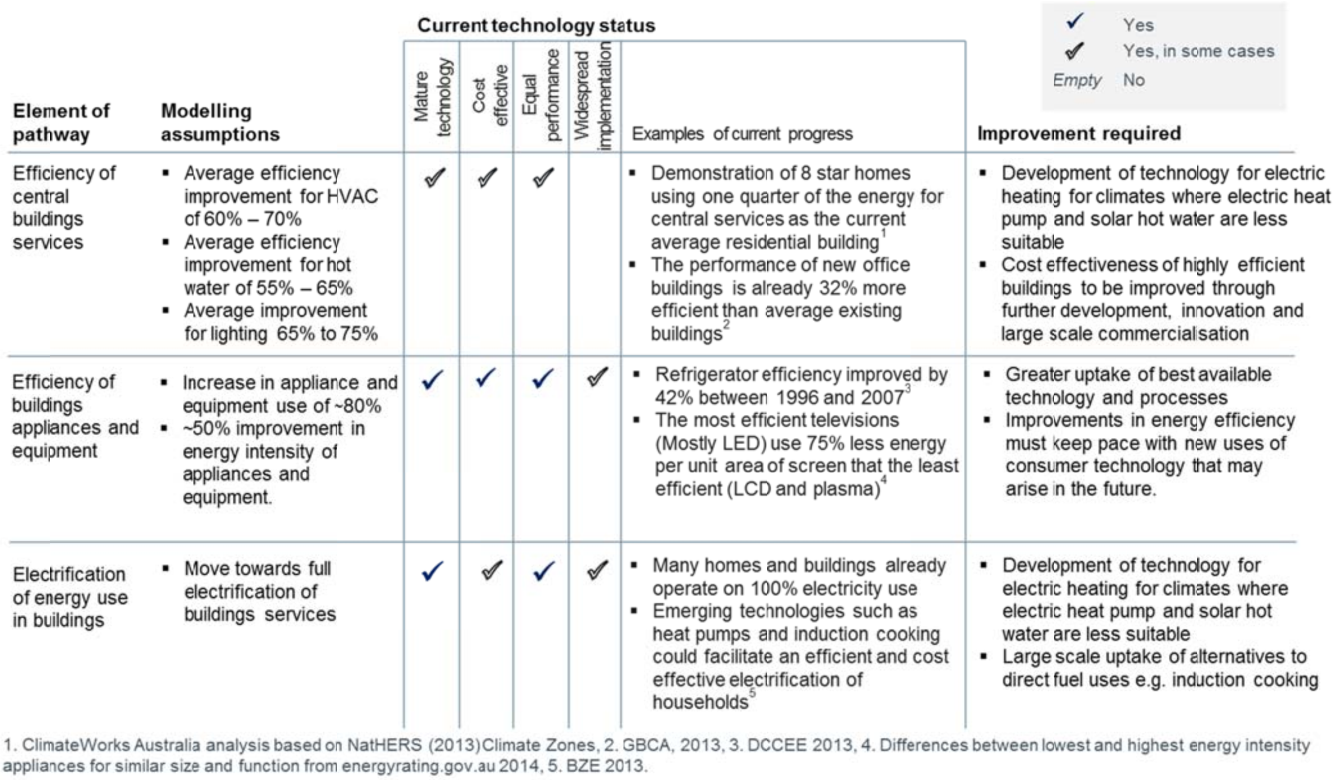
Below is a summary of the key options that could be considered in future work.

- **Very deep efforts in energy efficiency** – further potential exists to reduce energy use in the buildings sector, in particular if rebound from new end-uses is minimised. For example, standards could be used to set minimum performance of buildings and equipment earlier than what has been modelled in the pathway, improving the energy efficiency of the building stock. This may not reduce the emissions from the sector, as most energy is supplied by decarbonised electricity however it could reduce the cost of developing the power generation system as less capacity would be required.
- **Decentralised, decarbonised electricity** such as rooftop solar PV, allows for decarbonisation of the buildings sector that is independent of generation on the grid.
- **Gas for residential and commercial heating** could be supplied through bioenergy, although with a limited projected supply, this sector will have to compete for bioenergy supply with transport and industry, where alternative abatement solutions are more limited.

5.5 Technology status overview

Table 5.2 summarises the status of the major technologies involved in the deep decarbonisation scenario for buildings. As can be seen below, the technologies required for decarbonisation are already being developed; integration and commercialisation is where most progress is needed.

Table 5.2 – Summary of current technology status in buildings



✓ Yes
✔ Yes, in some cases
Empty No

		Current technology status					
Element of pathway	**Modelling assumptions**	Mature technology	Cost effective	Equal performance	Widespread implementation	Examples of current progress	**Improvement required**
Efficiency of central buildings services	▪ Average efficiency improvement for HVAC of 60% – 70% ▪ Average efficiency improvement for hot water of 55% – 65% ▪ Average improvement for lighting 65% to 75%	✔	✔	✔		▪ Demonstration of 8 star homes using one quarter of the energy for central services as the current average residential building[1] ▪ The performance of new office buildings is already 32% more efficient than average existing buildings[2]	▪ Development of technology for electric heating for climates where electric heat pump and solar hot water are less suitable ▪ Cost effectiveness of highly efficient buildings to be improved through further development, innovation and large scale commercialisation
Efficiency of buildings appliances and equipment	▪ Increase in appliance and equipment use of ~80% ▪ ~50% improvement in energy intensity of appliances and equipment.	✓	✓	✓	✔	▪ Refrigerator efficiency improved by 42% between 1996 and 2007[3] ▪ The most efficient televisions (Mostly LED) use 75% less energy per unit area of screen that the least efficient (LCD and plasma)[4]	▪ Greater uptake of best available technology and processes ▪ Improvements in energy efficiency must keep pace with new uses of consumer technology that may arise in the future.
Electrification of energy use in buildings	▪ Move towards full electrification of buildings services	✓	✔	✓	✔	▪ Many homes and buildings already operate on 100% electricity use ▪ Emerging technologies such as heat pumps and induction cooking could facilitate an efficient and cost effective electrification of households[5]	▪ Development of technology for electric heating for climates where electric heat pump and solar hot water are less suitable ▪ Large scale uptake of alternatives to direct fuel uses e.g. induction cooking

1. ClimateWorks Australia analysis based on NatHERS (2013)Climate Zones, 2. GBCA, 2013, 3. DCCEE 2013, 4. Differences between lowest and highest energy intensity appliances for similar size and function from energyrating.gov.au 2014, 5. BZE 2013.

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AGRICULTURE AND FORESTRY SECTOR

S. Hatfield-Dodds, B.A. Bryan and M. Nolan, CSIRO

6. Agriculture and Forestry sector

Executive summary

The CSIRO Land-Use Trade Offs (LUTO) model is used to estimate the volume of carbon that would be profitable to supply, where delivery of carbon credits would provide higher economic return than competing agricultural land uses. To illustrate different options available, we explore a range of potential scenarios involving different mixes of native vegetation, total area of plantings, rates of land-use change and cumulative carbon sequestration. Within each option the analysis uses three profitability thresholds for carbon plantings: all plantings (carbon plantings are at least as profitable as the next most economics land use), at least twice as profitable, and most profitable (planting that are at least five times as profitable as the next most economic land use).

The illustrative scenarios are calibrated to provide 4.3 and 4.8GtCO$_2$e over the period to 2050, exactly offsetting the difference between the cumulative emissions budget assumed for the project and the projected emissions from all sources for the *100 percent renewables energy* scenario and the *CCS* (carbon capture and storage) scenario.

The projected supply of profitable sequestration is up to 16GtCO$_2$e over the period and three to four times the volume of credits required to achieve the project's cumulative emissions budget, with zero net emissions by 2050. More generally, the required total volume of abatement could be delivered even if constraints are applied to the pace or patterns of plantings,, such as capping the annual planting rate to 0.6Mha per annum (to reflect potential persistent supply-side constraints) or modifying policy settings to achieve potential biodiversity benefits in addition to carbon sequestration. These variations results in 20 to 30 percent more land being required to offset residual national emissions than would be required in an unconstrained approach, giving no attention to biodiversity, but without compromising the ability to achieve the required sequestration levels.

The set of illustrative scenarios can be summarised into the following three groups:

- *Carbon-focused scenarios* delivering 4.3GtCO$_2$e of land sector sequestration in the most cost-effective way, giving no weight to biodiversity objectives. These scenarios do not impose a constraint of the annual area of land that can be planted.
- *Carbon-focused scenarios assuming the rate of land-use change is constrained*. These scenarios deliver 4.3GtCO$_2$e of land sector sequestration, giving no weight to biodiversity objectives. The annual area of land that can be planted in a year is limited to around 0.6Mha per annum in the scaled scenarios.
- *Balanced scenarios* that deliver 4.8GtCO$_2$e of land sector sequestration, assuming incentives are provided to promote biodiversity benefits, as well as carbon. This approach involves a larger area of plantings to achieve a similar volume of sequestration. These scenarios do not impose a constraint of the annual area of land that can be planted.

Key results are summarised in Table 6.1.

Table 6.1 – Summary of key results for land sector sequestration analysis

Approach	Carbon focused	Carbon focused	Balanced
rate of land use change	*not constrained*	*constrained*	*not constrained*
Required cumulative sequestration (a)	4.3 $GtCO_2e$	4.3 $GtCO_2e$	4.8 $GtCO_2e$
Profitable potential (b)*	10.0-16.0 GtCO2e	5.6-6.1 GtCO2e	8.5-13.7 GtCO2e
Required sequestration (a) as a share of profitable potential (b)	27% of all plantings	70% of all plantings	35% of all plantings
Peak planting rate* (scaled results)	1.0-1.3 Mha per year	0.6 Mha per year	1.2-1.7 Mha per year
Scaled results in 2050, for most profitable plantings**			
Sequestration	202 $MtCO_2e$	266 $MtCO_2e$	261 $MtCO_2e$
Area of plantings	14.6 Mha	17.4 Mha	21.3 Mha
Mix of plantations	99% single species, 0.2 Mha mixed native	99% single species, 0.1 Mha mixed native	65% single species, 7.5 Mha mixed native

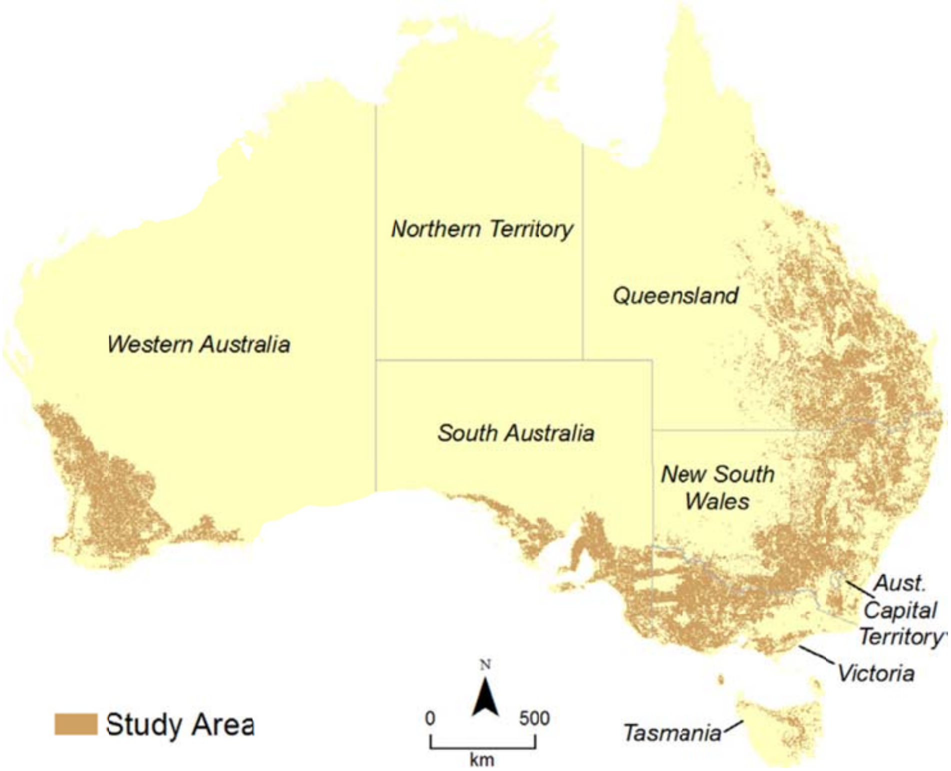
*The range is for different profitability thresholds, as shown in Table 6.2 ** The analysis for most profitable plantings only allows carbons planting where this is at least five times as profitable as the next most economic land use.

6.1 Methods

6.1.1 Land-use modelling framework and input assumptions

The CSIRO Land-Use Trade-Offs model provides spatially detailed analysis of the relative profitability of 23 agricultural commodities, hardwood carbon plantations and mixed species environmental plantings. The analysis covers the Australian intensive use zone, comprising 85.3Mha of non-contiguous cleared cropping and intensive grazing agricultural land, as shown in Figure 6.1. This land is interspersed by areas of natural ecosystems, water bodies, urban development and other land uses such as extensive grazing. Analysed by area, the intensive use zone is dominated by beef and sheep grazing (23 percent and 41 percent) and cereal cropping (32 percent). Remnant natural ecosystems are generally of value from a conservation perspective.

Figure 6.1 – Study area for LUTO – the Australian intensive use zone (Bryan, Nolan et al. , 2014)

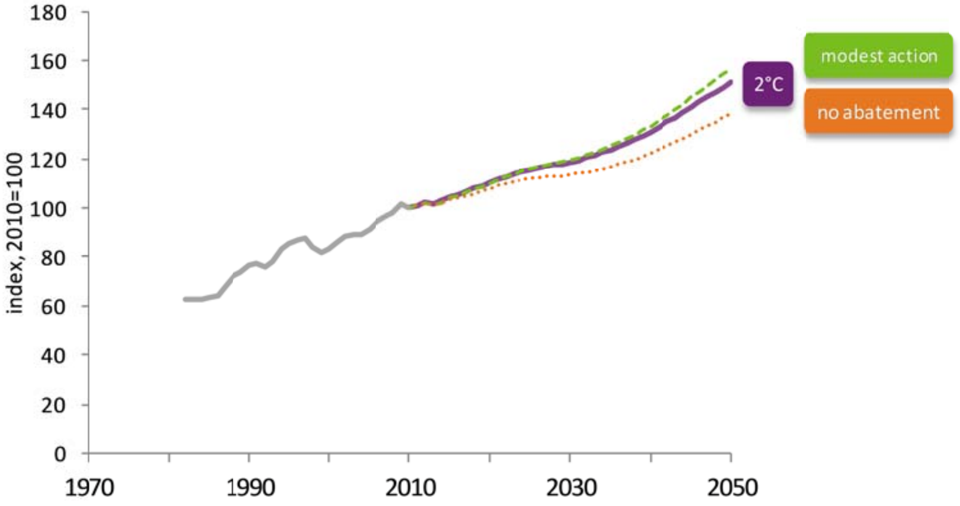


The analysis is undertaken at around a 1.1km^2 grid (812,383 cells). Inputs include historical and projected data for average yields, output prices, production costs, carbon sequestration potential, water licence costs, plantation establishment costs, future climate (particularly potential changes in rainfall), fire risk and biodiversity restoration priorities (accounting for potential future climate change). Projected economic returns are calculated for each type of potential land use for each cell, accounting for multiple commodities where relevant (such as wool and meat from sheep), providing projections of the most profitable land use for each cell over time and the associated supply of agricultural commodities, carbon and biodiversity. Economic returns are calculated as profit at full equity, defined as returns to land, capital and management assuming no financial debt. Payments for carbon sequestration are represented as being equivalent to being paid a guaranteed annuity over 100 years, based on the expected capital value of the carbon yield calculated using prices and sequestration rates at the year of planting (ignoring projected future increases in payments to landholders per tonne of sequestration).

An advantage of this approach is that it effectively calculates a land value surface for the intensive use zone, for each year into the future that is consistent with projected future agricultural prices, rather than relying on historical land values (which reflect historical prices and expectations). Details of the modelling framework and sensitivity analysis are provided in Bryan, Nolan et al., 2014.

Payments to landholders for carbon sequestration and abatement incentives applied to livestock emissions are based on the assumed DDPP abatement incentive trajectory. Projected export prices are drawn from relevant scenarios developed for the forthcoming CSIRO Australian National Outlook. The global scenario consistent with the DDPP project assumes low UN population projections (8.1 billion in 2050) and is calibrated to achieve cumulative global emissions to 2050 that match the Representative Concentration Pathway 3-PD, a variant of RCP 2.6 (see van Vuuren et al., 2011). This scenario sees continuing trend increases in Australian export prices for crops and livestock commodities, with around a 50 percent increase in real grain prices, reflecting continuing global population growth and increased competition for land (including as a result of incentives to limit deforestation and promote carbon plantings globally). Livestock emissions are assumed to be subject to the abatement incentives (see Herrero et al., 2013).

Figure 6.2 – Grains export prices (Australian producers, AUD), 1970–2050



Notes: The purple 2°C scenario assumes low UN population projections (8.1 billion in 2050) and abatement effort to result in cumulative emissions equal to RCP3PD in 2050. The green dashed line shows an equivalent scenario with medium population (9.3 billion) and abatement effort to achieve RCP4.5. The orange dotted line shows the equivalent scenario with high population (10.6 billion) and no abatement, matching RCP8.5. Historical prices are the five-year moving average of the ABARES grains price index (ABARES, 2012).

Source: GIAM for the Australian National Outlook.

The analysis for this project also draws on Australian National Outlook scenario variants exploring synergies and trade-offs between carbon sequestration and the supply of biodiversity benefits. A 'strong carbon' or 'carbon-focused' approach provides payments to landholders based solely on the projected volume of carbon sequestered (accounting for fire and other risks). This is compared to a 'balanced' approach that harnesses carbon payments in a way that provides stronger incentives for mixed species plantings yielding both carbon and biodiversity benefits. This reorientation of incentives is achieved in two ways: by reducing the effective payment per tonne of carbon to single species plantations by 15 percent; and using these resources to establish a competitive biodiversity fund. Payments under the fund are calculated to cover the gap, or shortfall, between economic returns to the most profitable land use and mixed environmental plantings (calculated as net present values) and allocated to spatially maximise the biodiversity benefits per dollar spent in each year (drawing on the biodiversity priorities layer). More details of projected land use and trade-offs and synergies between carbon and biodiversity are provided in Bryan, Hatfield-Dodds et al. (forthcoming). Implications and the outlook for agriculture are discussed in Grundy et al. (forthcoming).

6.1.2 Development of illustrative scenarios to meet DDPP sequestration requirements

The methods described above have been used to generate a 'carbon-focused' and 'balanced' scenario based on the DDPP abatement incentive trajectory.

We find the profitable potential volume of land sector sequestration is three to four times the volume required to entirely offset residual emissions from the policy scenarios and to meet the Australian emissions budget recommended by the Climate Change Authority (2014) as Australia's fair share of emissions in a world acting to limit temperature increases to 2°C or lower. Details of profitable potential supply relative to required sequestration are shown in Table 6.2 below.

In order to match the target volume of credits specified for the project, the raw projections are scaled down to match the required 4.3 or 4.8GtCO$_2$e cumulative sequestrations for the different scenarios, reducing the projected volume of carbon sequestration and area of new plantings. Given that only a fraction of profitable land is used for plantings under this approach, the scaled scenarios used to illustrate different supply options are based on the most profitable potential plantings (defined in as carbon plantings being at least five times as profitable as the next most profitable land use). This approach involves the lowest reduction in agricultural output in order to supplying the required carbon sequestration.

The LUTO analysis also finds that large areas of land become profitable for carbon plantings once payment levels reach $40/tCO$_2$e, implying a peak in land-use change, if this land immediately changes use. In order to illustrate a range of alternative approaches to delivering land sector carbon credits, the carbon-focused scenario also assumes a constraint on the rate of new plantings of 0.725Mha per year in the raw (unscaled) scenario, selecting the most profitable potential plantings each year.

This analysis represents projections for the most profitable land use. Because the scenarios require only a fraction of the most profitable potential plantings, the analysis assumes these plantings occur immediately and so land use matches most profitable use over time for the plantings required to achieve the required sequestration volume

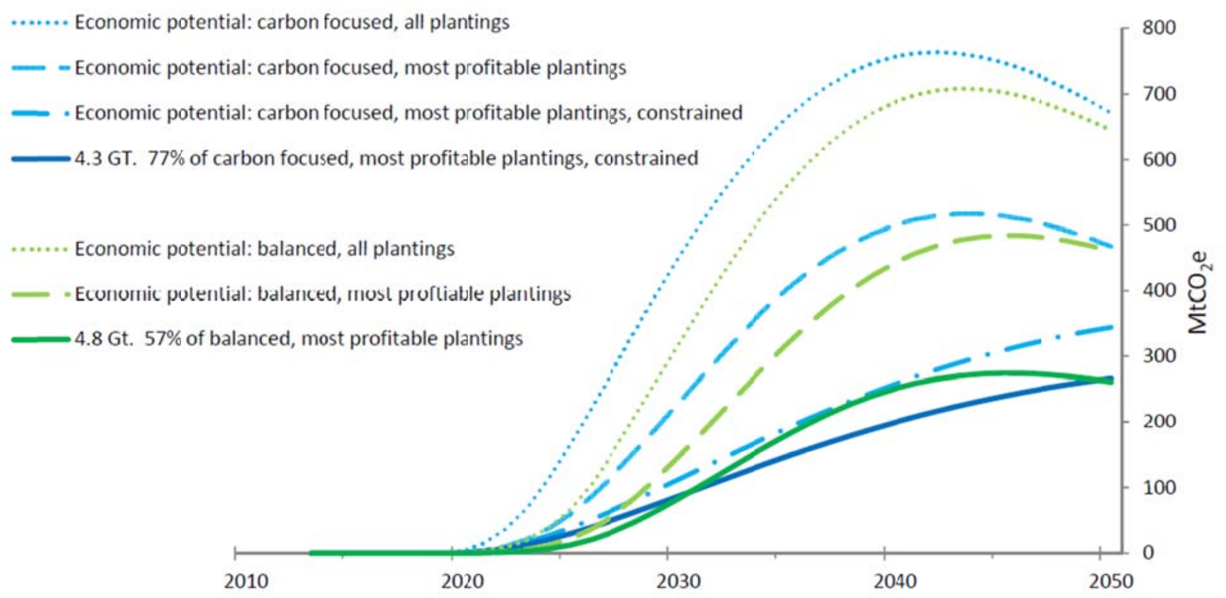
6.2 Results

The methods described above have been used to generate raw results for nine scenario variants: carbon-focused (constrained and unconstrained) and 'balanced' (unconstrained), each for three profitability levels (all profitable plantings, at least twice as profitable and most profitable).

The illustrative carbon-focused scenario delivers 4.3GtCO$_2$e of sequestration, requiring 74 percent of the cumulative carbon from most profitable plantings, assuming a constraint on the uptake of plantings. (In the unconstrained carbon-focused scenario, 43 percent of the most profitable plantings would be required.) The illustrative balanced scenario delivers 4.8GtCO$_2$e of sequestration, requiring 57 percent of the cumulative carbon from most profitable plantings. The time profile of carbon sequestration for the main results is shown in Figure 6.3, with details for the nine variants in Table 6.2.

The same scaling approach was applied to the area of major types of land use, as shown in Figure 6.4.

Figure 6.3 – Assumed supply of carbon sequestration relative to profitable potential (MtCO2e), 2010–2050



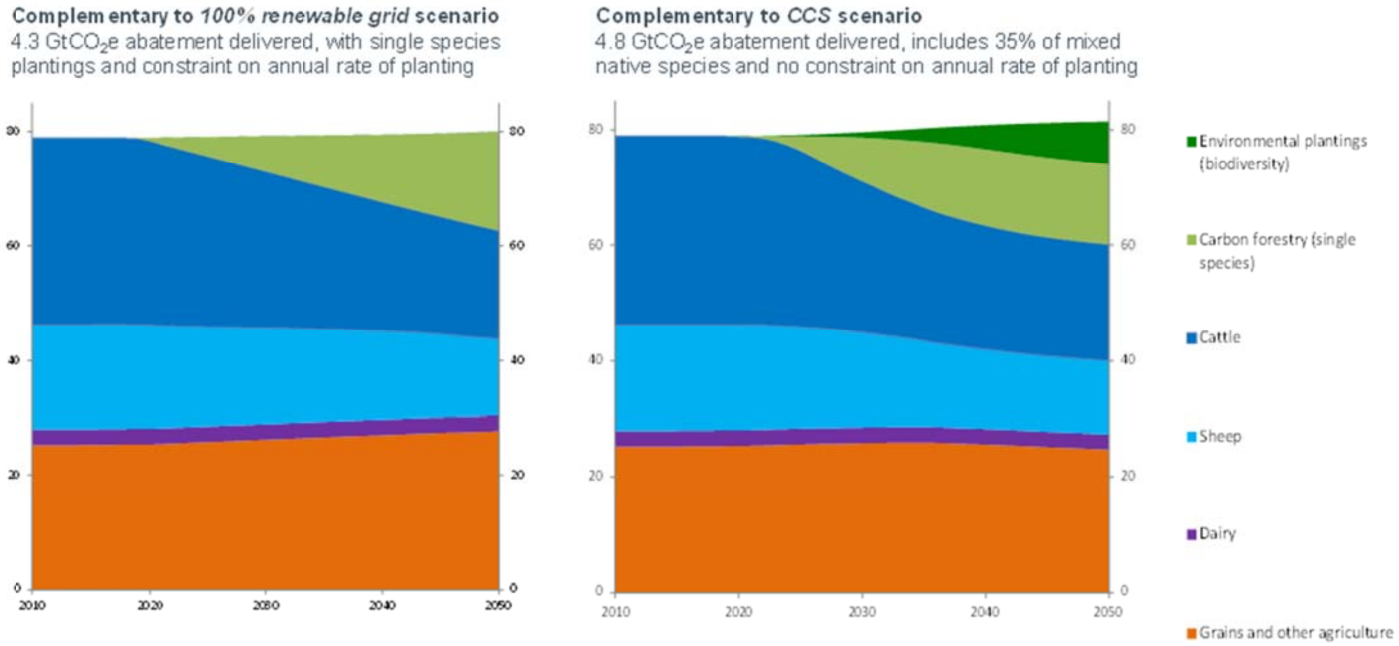
Source: LUTO

Table 6.2 – Raw sequestration potential relative to required sequestration volumes

	Carbon-focused, unconstrained			Carbon-focused, constrained			Balanced, unconstrained		
Profitability threshold (a)	1x	2x	5x	1x	2x	5x	1x	2x	5x
	Cumulative sequestration to 2050 (GT CO2e)								
Sequestration requirement	4.3	4.3	**4.3**	4.3	4.3	**4.3**	4.8	4.8	**4.8**
Raw potential	16.0	13.4	**10.0**	6.1	5.9	**5.6**	13.7	11.5	**8.5**
Requirement as a share of potential (b)	27 %	32 %	**43 %**	70 %	73 %	**77 %**	35 %	42 %	**57 %**
	Annual sequestration in 2050 (Mt CO2e)								
Raw potential	671	581	**468**	371	358	**344**	645	569	**461**
Scaled sequestration	181	187	**202**	260	261	**266**	226	237	**261**

Notes: (a) 1x profitability threshold is referred to as 'all plantings' or 'all profitable plantings'. 2x threshold includes all plantings at least twice as profitable as the next most profitable land use. 5x threshold is referred to as 'most profitable plantings' and includes plantings that are at least five times as profitable as the next most profitable use, based on net present values. (b) Calculated for each profitability level (column) as the requirement (row 1) as a share of potential cumulative sequestration (row 2). Source: LUTO

Figure 6.4– Projected change in land use, Australian intensive use zone, 2010–2050

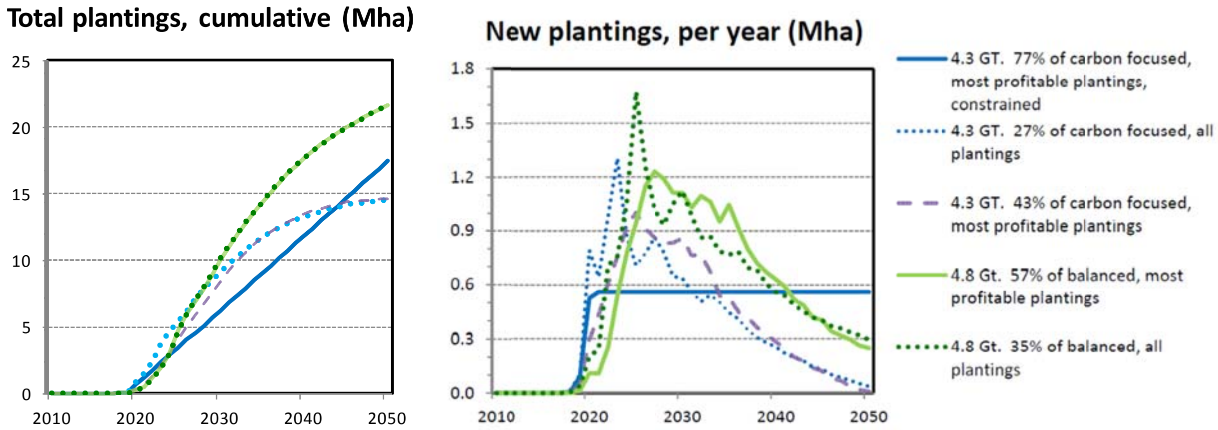


Source: Scaled LUTO results

We find that the constraint on the rate of land-use change is binding from 2020 and limits the area of new plantings to 0.56Mha per year in the scaled scenarios. Without this constraint, the scaled area of most profitable plantings would peak at 1.00Mha per year in 2025 and involve more than 0.75Mha of new profitable plantings per year from 2024–2037, as shown in Figure 6.5 below.

The constraint results in significantly lower area of plantings (and carbon sequestration) in the raw scenarios, with 23.6Mha of plantings projected with the constraint versus 33.9Mha without the constraint in raw (unscaled) results for the most profitable scenarios. The scaled results appear higher for the constrained approach, however, because achieving the required volume of 4.3GtCO2e requires 74 percent of the raw potential of the constrained scenario compared to 43 percent of the raw potential of the unconstrained scenario.

Figure 6.5 – Scaled area of plantings, cumulative and per year, 2010–2050

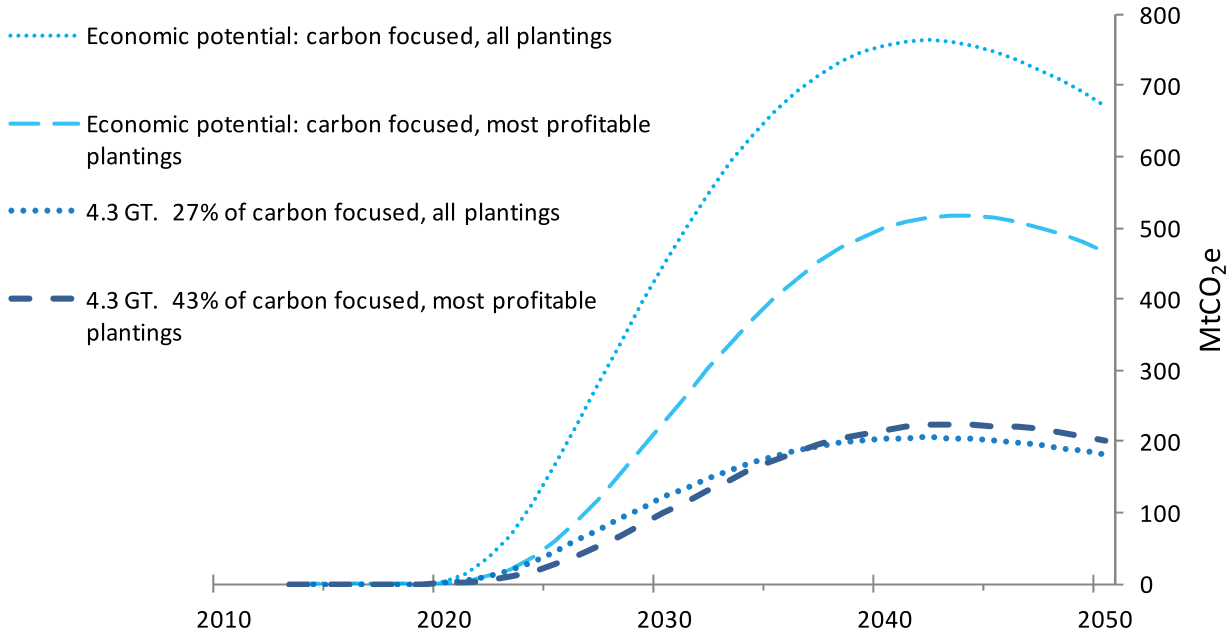


Source: Scaled LUTO results

The shift of land out of agricultural production reduces projected output volume of sheep and beef in the intensive use zone by around 20 percent by 2050, with grains and other agricultural products by less than five percent by 2050 in the scaled illustrative scenarios, relative to scenarios with no land-use change. Under modest productivity assumptions this implies wool and sheep meat volumes would peak and then decline to around current levels in 2050, while national beef output volumes would increase by around 10 percent (as around half national beef production occurs outside the intensive use zone) and grains output volumes would increase by around 20 percent. The gross value of output would grow strongly across all commodities, due to projected price increases of around 50 percent for grains and more than 75 percent for livestock.

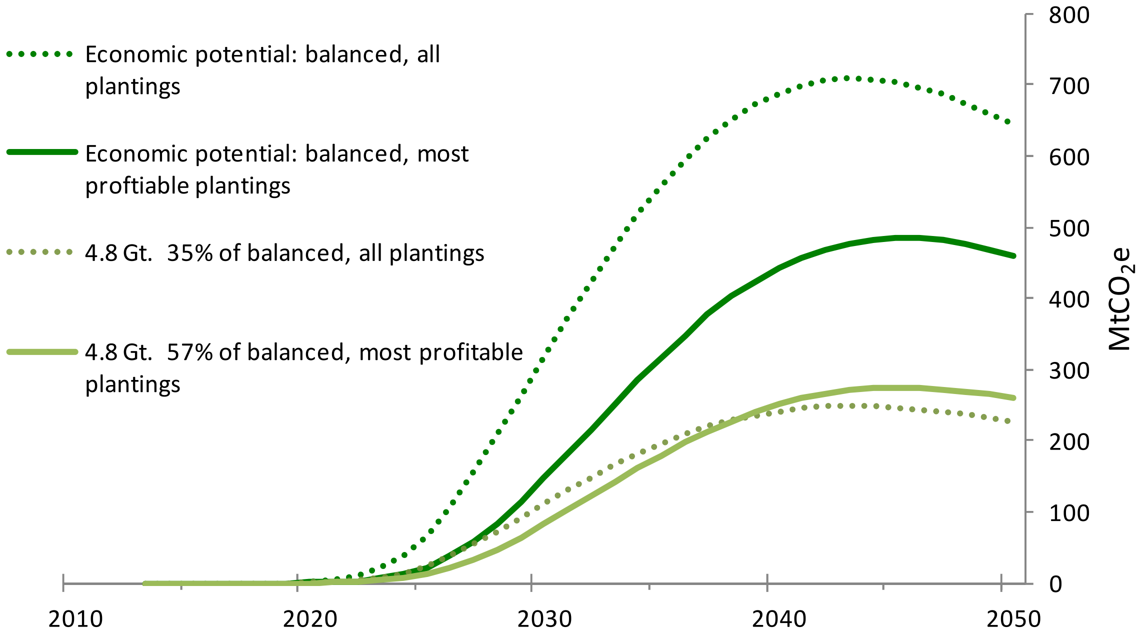
Figure 6.6 and Figure 6.7 show scaled sequestration potential for all plantings relative to most profitable plantings for the carbon-focused and balanced approaches, in the absence of an uptake constraint. These charts show that carbon sequestration scales up slightly more gradually, with a more gradual decline after peak sequestration is achieved.

Figure 6.6 – Potential scaled carbon supply relative to potential (MtCO2e), carbon-focused, 2010–2050



Source: Scale LUTO results

Figure 6.7.– Potential scaled carbon supply relative to potential (MtCO2e), balanced approach, 2010–2050



Source: Scale LUTO results

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MMRF Model

P. Adams, COPS

7. MMRF model

Executive summary

In this chapter, a CGE model of the Australian economy is used to project forward the Australian economy with the effects of deep decarbonisation action in place. Deep decarbonisation requirements for Australia are based on the emissions budget recommended by the Climate Change Authority (2014) in the context of a global 2°C pathway. In this project's modelling, Australia is on a deep decarbonisation pathway by virtue of domestic abatement from a broad range of sources, without relying on international permits.

A number of key findings emerge from the modelling.

- Domestic abatement (with allowance for land-use credits) achieves targeted abatement, with no need for imported permits.
- Despite the requirement for deep cuts in emissions the Australian economy continues to grow strongly in terms of production (real GDP) and employment.
- There are a number of industries for which deep decarbonisation significantly cuts output, leading to declines in production over the projection period. A good example is the industry generating electricity from coal. On the other hand, deep decarbonisation provides an impetus to some sectors, especially industries producing electricity from renewable generation.
- Overall, electricity use grows roughly in line with real GDP. Electricity maintains its share of GDP, even with a very high abatement incentive, because of two key factors: a modal shift in transport away from internal combustion and towards electric motors; and increased electrification of buildings and industry technologies.
- Forestry has a high-growth ranking because the abatement incentive is effectively a production subsidy on biosequestration. The additional forestry activity leads to higher sales to export and to downstream manufacturing.
- Another standout manufacturing industry with poor growth prospects is petroleum product, based on industry information that the Australian refinery industry will close down within the next 20 years. Plant closures will also impact the Australian motor vehicle assembly industry. However this is just one part of a broader industry, which is expected to remain roughly unchanged in size, reflecting continued strong growth in demand for parts and repairs.

7.1 Introduction

The key distinguishing characteristic of Computable General Equilibrium (CGE) modelling in Australia is its orientation to providing *detailed* inputs to the policy-formation process. This characteristic is ably demonstrated in this chapter in the analysis of ClimateWork's deep decarbonisation scenario for Australia.

The analysis relies on an application of the Monash Multi-Regional Forecasting model (MMRF). MMRF is a single-country multi-regional model of Australia and its six states and two territories. The current version of the model distinguishes 58 industries, 63 products produced by the 58 industries and eight states/territories. At the state/territory level, it is a fully specified bottom-up system of interacting regional economies, with a summary of the model's main features given in section 2. More detail is provided in Appendix A and in Adams and Parmenter (2013) and Adams et al. (2014).

Much of the modelling of the global aspects of deep decarbonisation has been undertaken by CSIRO, using, in part, their version of the Global Trade and Environment Model (GTEM) (Pant, 2007). This modelling was supplemented by global assumptions provided by the DDPP secretariat based on information from the International Energy Agency (IEA). This information was then used to inform simulations of MMRF. The role of MMRF is to supply estimates of the effects of deep decarbonisation action in Australia on the Australian economy at the level of detail that we think is required by policymakers.

A key dimension is detail about the electricity and transport systems. To cover this, MMRF is linked to specialised bottom-up models of Australia's electricity and transport systems. This modelling is provided by CSIRO.

The rest of the chapter is organised as follows. A brief general description of MMRF is given in section 7.2. Enhancements of the general form of the model that are necessary for the modelling of deep decarbonisation are discussed in detail in Appendix 0. Aspects of simulation design are given in section 7.3. Economic trends in Australia with deep decarbonisation action in place are discussed in section 7.4. The discussion of results focuses on explaining outcomes in a sequential way. National outcomes are dealt with first, then results for national industry output.

7.2 Overview of MMRF's modelling framework

Agents in MMRF operate in competitive markets. Optimising behaviour determines industry demands for labour and capital. Labour supply at the national level is determined by demographic factors, while national capital supply responds to rates of return.

Demand for goods and services equals supply in all markets. Governments intervene in markets by imposing *ad valorem* sales taxes on commodities. This places wedges between the prices paid by purchasers and the basic prices received by producers. Other wedges are imposed via the use of retail trade and transport services, which are required for the movement of commodities from producers to the purchasers.

MMRF recognises two broad categories of inputs into production: intermediate inputs and primary factors. Firms in each regional sector are assumed to choose the mix of inputs (intermediate and primary) that minimises the costs of production. In each region, the household buys bundles of goods to maximise a utility function subject to an expenditure constraint. The bundles are combinations of imported and domestic goods. A consumption function is used to determine aggregate household expenditure as a function of household disposable income.

Capital creators for each regional sector combine inputs to form units of capital. In choosing these inputs, they minimise costs subject to a technology similar to that used for current production. Industry overall investment is determined via relationships that link desired capital growth with expected rate of return. State/territory governments and the federal government demand commodities from each region. Such demand is set outside of the model (i.e. exogenously).

Each export-oriented sector in each state or territory faces its own downward-sloping foreign demand curve. Thus, a shock that reduces the unit costs of an export sector will increase the quantity exported, but reduce the foreign-currency price. By assuming that the foreign demand schedules are specific to product and region of production, the model allows for differential movements in foreign currency prices across domestic regions.

In addition to its economic core, MMRF contains a number of enhancements to facilitate the modelling of environmental issues, including:

- an accounting module for energy and greenhouse gas emissions that covers each emitting agent, fuel and region recognised in the model
- quantity-specific carbon taxes or prices
- equations for inter-fuel substitution in transport and stationary energy
- a representation of Australia's National Electricity Market (NEM)
- equations that allow for the adoption of abatement measures (for combustion and non-combustion emissions) as functions of the price of CO_2.

7.3 Assumptions and input

7.3.1 Introduction

Using MMRF to project forward the Australian economy, with allowance for domestic action directed at deep decarbonisation, the projections start in 2012 and end in 2050. In the remainder of this section, key inputs to the projections and the main assumptions regarding the behaviour of the macroeconomy in the MMRF modelling are discussed.

7.3.2 Inputs

The main inputs to the MMRF forecast include:

- the abatement incentive and Australia's target for emissions as specified by ClimateWorks and CSIRO
- various aspects of electricity supply, as modelled by CSIRO's Energy Sector Model (CESM)
- vehicle use by vehicle type, as modelled by CSIRO
- land-use (forestry) credits from CSIRO
- foreign currency import prices and the positions of foreign export-demand schedules from CSIRO
- assumptions for autonomous energy efficiency, electrification and use of bioenergy from ClimateWorks
- assumptions for the potential to reduce non-energy emissions in the industry sector from ClimateWorks.

EMISSIONS PRICE AND AUSTRALIA'S EMISSIONS TARGET

The abatement incentive (per tonne of CO_2-e) applied to Australian emissions is described in section 1.3.

It is represented in the model as a permit price and modelled as a tax imposed per unit of CO_2-e produced in Australia. It is imposed on all sources of emissions, including agriculture and transport. Initially, the price applied in some sectors is less than the full price to avoid modelling outcomes that are unrealistically large. But, from 2015, all emissions are priced at the same rate.

Figure 2 shows the target emissions path (including allowance for land-use credits) for Australia and is based on the emissions budget recommended by the Climate Change Authority (2014) in the context of a global 2°C pathway. Without action, Australia's emissions would continue to rise after 2013. In modelling, Australia is on a deep decarbonisation pathway by virtue of domestic abatement from a broad range of sources (including land sector offsets) and does not need to rely on international permits.

ELECTRICITY INPUTS FROM CESM

CESM provides projections for electricity generation, energy use, generation capacity, emissions and electricity prices. These projections are accommodated in the MMRF modelling *via* a series of changes that essentially replace the existing modelling of electricity supply with CESM results.

In CESM, the electricity sector responds to the abatement incentive by switching technologies, changing the utilisation of existing capacity and replacing old plants with new more-efficient plants. The modelling also includes changes in overall electricity usage projected in MMRF's modelling of demand. These factors underlie the decarbonisation-projections summarised in Table 7.1.

One of the most notable features of the numbers in Table 7.1 is the increase in electricity usage, even with deep decarbonisation action. This increase reflects changes in the relative price of energy products. In response to the abatement incentive, electricity supply quickly adjusts by replacing fossil fuel generation with renewable generation. This allows the price of electricity to fall, relative to the price of coal, gas and petroleum products. As electricity becomes relatively cheaper, end-users of energy, especially in the industrial, commercial and transport sectors, shift their demand away from coal, gas and petroleum products and towards electricity.

In CESM, less CO_2-e intensive technologies for generating electricity from coal are adopted when the abatement incentive makes it economical to do so. Steadily, the use of coal falls away as the abatement incentive rises. By 2030 coal generation has all but disappeared. Renewable generation takes nearly coal's entire share.

Table 7.1 – Generation Sent Out by Generator Type with Deep Decarbonistion (PJ)

	Generation (PJ)
2015	
Electricity generation – coal	588.9
Electricity generation – gas	167.9
Electricity generation – oil products	4.1
Electricity generation – hydro	56.8
Electricity generation – other	143.0
Total	960.7
2030	
Electricity generation – coal	87.8
Electricity generation – gas	471.5
Electricity generation – oil products	4.1
Electricity generation – hydro	63.4
Electricity generation – other	591.4
Total	1218.2
2050	
Electricity generation – coal	4.2
Electricity generation – gas	373.0
Electricity generation – oil products	4.1
Electricity generation – hydro	120.0
Electricity generation – other	1666.4
Total	2167.7

ROAD TRANSPORT INPUTS FROM CSIRO

CSIRO provides data for growth in fuel use and emissions for road transport (private vehicles and commercial freight and passenger) by region. Fuels covered include LPG, gasoline, diesel, electricity and 'other', with other including CNG and biofuel. Blendings of ethanol and oil-based fuels are counted under the primary oil-based fuel. Projections for the use of each fuel type are accommodated in MMRF by endogenous shifts in fuel-usage coefficients in industries' production functions.

The CSIRO inputs computed as fuel shares are summarised in Table 7.2. The CSIRO numbers show electric-powered vehicles taking significant market share away from vehicles relying on internal combustion technologies. The share of electric vehicles at the start of the period is negligible, but rises rapidly to around 36 percent. This is a major factor explaining the increase in electricity usage overall, discussed above.

Table 7.2 – Road Transport Fuel Shares with Deep Decarbonisation (percentage)

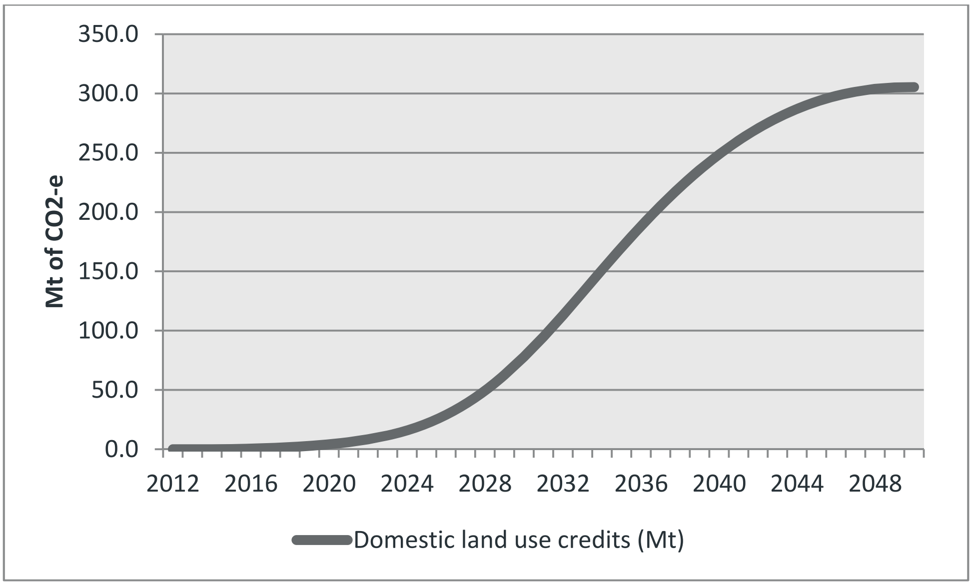
	Share (percentage)
2015	
LPG	5.7
Electricity	0.0
Petrol	51.9
Diesel	40.1
Other	2.2
Total	100.0
2030	
LPG	2.3
Electricity	11.6
Petrol	28.7
Diesel	46.7
Other	10.8
Total	100.0
2050	
LPG	0.0
Electricity	36.0
Petrol	21.6
Diesel	14.1
Other	28.3
Total	100.0

FORESTRY LAND AND BIO-SEQUESTRATION INPUTS FROM CSIRO

According to CSIRO, domestic action will have a significant impact on forestry production and forest biosequestration. CSIRO's estimates of land credits are accommodated in the MMRF modelling via a combination of increased forestry production and endogenous shifts in sequestration per unit of forestry output. Corresponding changes in land under forestry are also imposed, and total land availability by region fixed, land available for agriculture falls.

Figure 7.1 shows the amount of land-use credits allowed for in the deep decarbonisation scenario (expressed as Mt of CO_2-e). The current level of forestry sequestration is around 24Mt. By 2050, in the deep decarbonisation scenario, forestry sequestration is estimated to be around 300Mt.

Figure 7.1 – Domestic land-use credits (Mt) allowed for in the deep decarbonisation scenario



This level of sequestration is slightly higher than the final estimates of land sector credits from LUTO, which are used to calculate the national emissions trajectory. The volume of land sector credits in the central scenario is 266 $MtCO_2e$ in 2050. GNP results have been adjusted to be consistent with the final LUTO volume.

TRADE VARIABLES BASED ON INFORMATION FROM CSIRO

Projections for changes in the positions of foreign export-demand schedules for Australia are sourced from CSIRO.

ASSUMPTIONS FOR AUTONOMOUS ENERGY EFFICIENCY, ELECTRIFICATION AND USE OF BIOENERGY FROM CLIMATEWORKS

MMRF has a range of variables that allow for exogenous changes in overall energy usage and fuel shares by industry. For the simulations reported in this paper, we use inputs from ClimateWorks to impose changes in:

- autonomous rates of energy efficiency improvement in mining and manufacturing and in residential and commercial building
- rates of electrification of non-transport industry technologies – commercial, residential and industrial[21]
- rates of uptake of new forms of energy (notably, bioenergy).

The assumptions differ across time, energy source and industry for each scenario, making it difficult to summarise in a single table. Broadly, relative to reference case trends, in the deep decarbonisation scenario, there is enhanced rates of autonomous energy improvement, increased rates of electrification and faster uptake of bioenergy.

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[21] Electrification means the replacement of fossil fuel energy with electricity energy, especially for process heat. In many applications, 1Pj of electricity is equivalent to around 2Pj from fossil fuel.

The economy-wide autonomous rate of energy efficiency improvement in the reference case is, on average, 0.55 percent per annum. In the deep decarbonisation scenario, the overall rate is 0.92 percent per annum.

In the deep decarbonisation scenario, two factors encourage industries to further substitute fossil fuels for electricity in their production processes. First, due to the abatement incentive the price of electricity relative to the prices of natural gas and petroleum products drops. This puts in place an endogenous shift towards electricity by all users of energy. But more profound, are exogenous changes to technologies directly imposed using inputs from ClimateWorks. For example, two different processes can be used to produce steel, namely blast furnace (coke, oven-coal), using iron ore, and electric arc furnace (electricity), using scrap iron and steel. The second process consumes two to three times less energy than the first one. According to ClimateWorks' inputs for the deep decarbonisation scenario the Australian steel-making industry will shift from coal-based blast furnace operation to electric arc-furnace technologies and be fully electrified by 2030. Similarly, alumina production will be significantly less reliant on gas and more reliant on electricity by around 2030.

Electrification and increased use of bioenergy involve a cost – the cost of investing in the new technologies. In MMRF the investment costs per unit of output are imposed as an all-input using technological deterioration in the production functions of the investing industries.

7.3.3 Assumptions for the macroeconomy

The following assumptions are made for key aspects of the macroeconomy to incorporate deep decarbonisation action into the forecasts.

LABOUR MARKETS

At the national level, lagged adjustment of the real-wage rate to changes in employment is assumed. Deep decarbonisation is allowed to cause employment to change, but thereafter, real-wage adjustment steadily eliminates the short-run employment consequences of the abatement incentive. In the long run, the costs of reducing emissions are realised almost entirely as a fall in the national real-wage rate, rather than as a fall in national employment. This labour market assumption reflects the idea that in the long run national employment is determined by demographic factors, which are unaffected by the adoption of an abatement incentive.

At the regional level, labour is assumed to be mobile between state economies. Labour is assumed to move between regions so as to maintain interstate unemployment rate differentials. Accordingly, regions that are relatively favourably affected by emissions reductions will experience increases in their labour forces, as well as in employment, at the expense of regions that are relatively less favourably affected.

PRIVATE CONSUMPTION AND INVESTMENT

Private consumption expenditure is determined *via* a consumption function that links nominal consumption to household disposable income (HDI). HDI includes the lump-sum return of income raised by the abatement incentive, which is part of the deep decarbonisation simulation. For the current projections, the average propensity to consume (APC) is an endogenous variable that moves to ensure that the balance on current account in the balance of payments remains unchanged through the projection period. Thus any change in aggregate investment brought about by the abatement incentive is accommodated by a change in domestic saving, leaving Australia's call on foreign savings unchanged.

GOVERNMENT CONSUMPTION AND FISCAL BALANCES

MMRF contains no theory to explain changes in real public consumption. In the projection, public consumption is simply indexed to nominal GDP. The fiscal balances of each jurisdiction (federal, state and territory) as a share of nominal GDP are fixed at their values in 2012. Budget balance constraints are accommodated by endogenous movements in lump-sum payments to households.

PRODUCTION TECHNOLOGIES AND HOUSEHOLD TASTES

MMRF contains many variables to allow for shifts in technology and household preferences. In the deep decarbonisation scenario, most of these variables are exogenous. The exceptions are technology variables that are made endogenous to allow for:

- changes in the fuel intensity of electricity generation, based on data from CESM
- the new production technology required to achieve the reductions in emissions intensity implied, required by the model's emissions response functions
- the replacement of gasoline and diesel with cleaner (but more expensive) biofuels and electricity in the provision of private transport services. This is based on information from the detailed road transport modelling.

7.4 The Australian economy with deep decarbonisation

7.4.1 Introduction

This section contains a discussion of forecasts for the Australian economy with deep decarbonisation. Forecasts are given in Table 7.3 (national industry output), with a series of charts providing time profiles for key variables.

7.4.2 Macroeconomic variables

- Real GDP (Figure 7.2) grows at an average annual rate of 2.68 percent between 2012 and 2020, slowing to an average rate of 2.46 percent between 2021 and 2030. Average annual growth between 2012 and 2050 is 2.41 percent, which is consistent with the historical norm for Australia. GDP growth is projected to decline slowly in line with demographic projections from the IGR, which point to a gradual reduction in population growth over the projection period.
- Though not shown in Figure 7.2, but in line with recent history, the export-oriented states – QLD and WA – are projected to be the fastest-growing state economies, followed by NSW and VIC. SA and TAS are the slowest-growing, though the gap between the slowest and fastest growing states and territories is a little less than in recent times.
- Real national private consumption (Figure 7.2) grows at an average annual rate of 2.24 percent over the full projection period. The time profile of growth is similar to that for real GDP: initially strong, then stabilising and eventually declining slowly. Real consumption falls relative to real GDP because of a reduction in the terms of trade (see below).
- The regional pattern of growth for consumption is also similar to that for GDP: fastest growth occurs in QLD and WA and slowest growth in TAS and SA.
- Over the 15 years leading up to 2012, the volumes of international exports and imports grew rapidly relative to real GDP. This reflects several factors – strong growth in local economies (particularly China), declining transport costs, improvements in communications, reductions in protection in Australia and overseas and technological changes, favouring the use of import-intensive goods such as computers and communication equipment. The influence of this factor has weakened considerably over the past two years and this is expected to continue through the projection period (see Figure 7.3). On average, export volumes grow relative to GDP by about 1.1 percent per year. However import growth is projected to be less than export growth, implying some improvement in the current imbalance between export and import volumes. Relatively weak import growth is due to two factors: real devaluation of the currency from its present very high level; and slow growth in import-intensive investment spending.
- Australia's terms of trade is assumed to decline significantly in the first decade of the projection period (Figure 7.4), continuing the trend of the past two years. After 2020, the rate of decline moderates, until the terms of trade reaches its historically normal level in 2030.

Figure 7.2 – Real GDP and real private consumption with deep decarbonisation (index 2012=100)

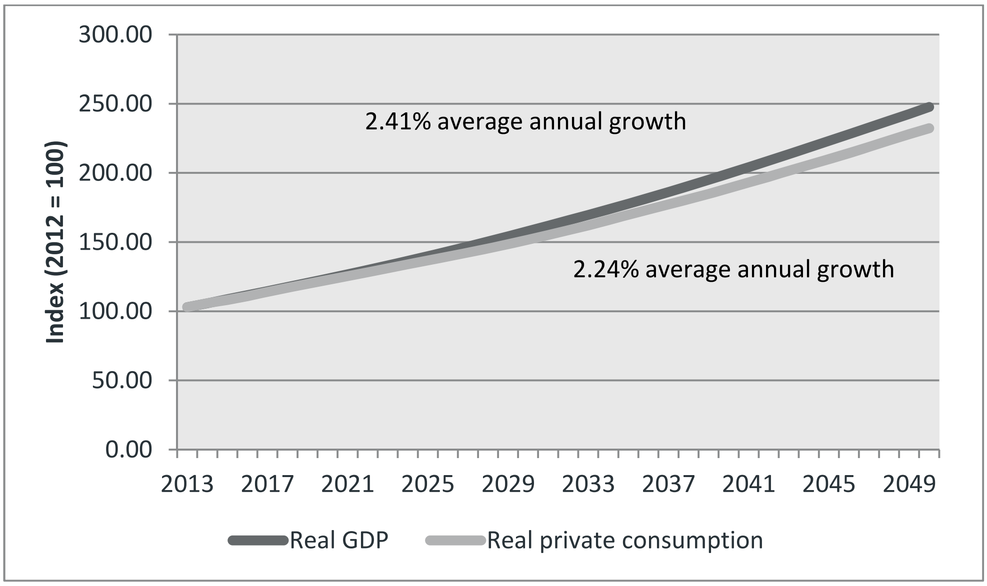


Figure 7.3 – Export and import volumes with deep decarbonisation (index 2012 = 100)

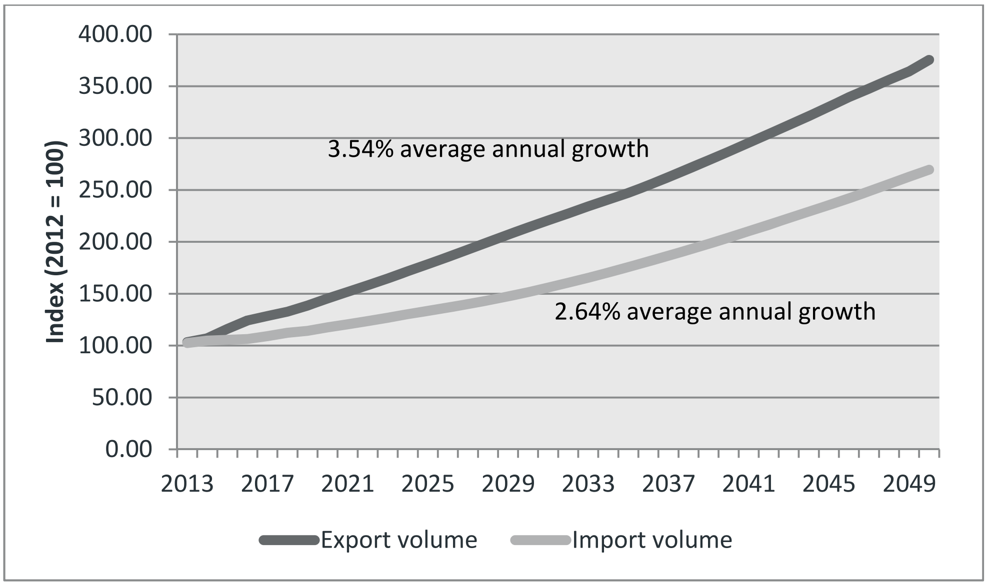
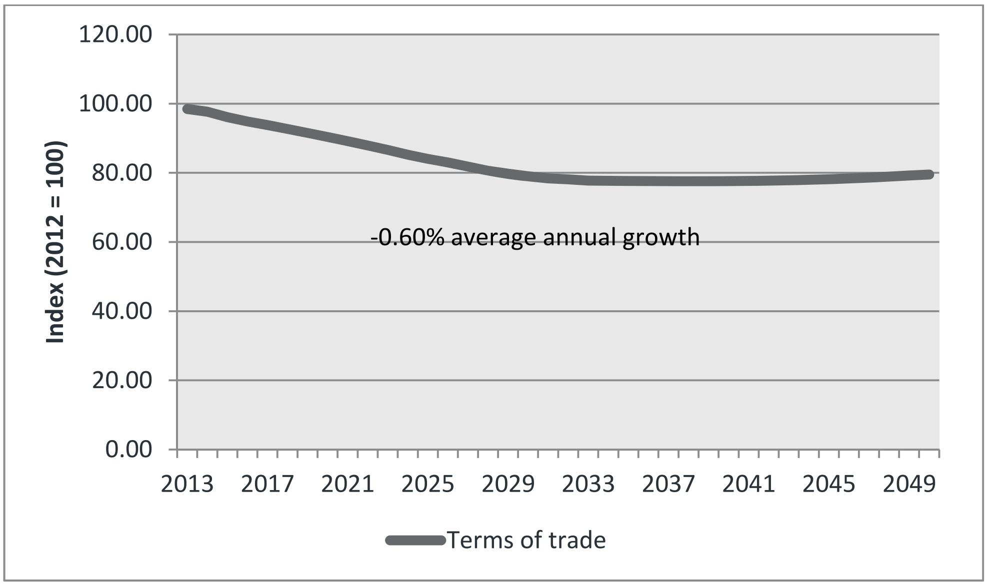


Figure 7.4 – Terms of trade with deep decarbonisation (index 2012 = 100)



7.4.3 Industry production

Table 7.3 shows projections for industry output with deep decarbonisation. Industries are listed in order of projected production growth between 2012 and 2050, fastest to slowest.

Electricity generation – other (industry 37) has the strongest growth prospects, with average annual growth of 7.6 percent, compared to projected real GDP growth of 2.4 percent (Figure 4). This is a good example of an industry for which deep decarbonisation raises output significantly. Other favourably impacted sectors include the non-coal electricity generation sectors: *Electricity generation – gas* (industry 33, rank 11) and *Electricity generation – hydro* (industry 36, rank 33). The abatement incentive causes substitution in favour of these industries at the expense of high-emissions *Electricity generation – coal* (industry 32, rank 58). Another positive factor for the non-coal generation industries is the increase in overall electricity demand, which shows up in the high ranking of *Electricity supply* (industry 38, rank 13). Electricity demand increases because of two key factors:

- a modal shift in transport away from internal combustion and towards electric motors (section 7.3.2)
- increased electrification of buildings and industry technologies (section 7.3.2).

Forestry (industry 7, rank 2) has a high-growth ranking because the abatement incentive is effectively a production subsidy on biosequestration. The additional forestry activity leads to higher sales to export and to downstream manufacturing. This imparts a modest increase to the production of *Wood products* (industry 17, rank 14).

Table 7.3 shows that *Gas mining* (industry 10, rank 3) has strong growth prospects, with average annual growth of 4.1 percent. This reflects the assumption of very strong growth in exports, particularly of Liquefied Natural Gas (LNG). *Other mining* (13, rank 4) also has strong growth prospects due to strong export growth. The remaining mining industries have mixed prospects. *Non-ferrous ore mining* (12) and *Iron ore mining* (11) have average rankings of 19 and 23. This is due to relatively strong export growth. However oil (9) and coal (8) production falls over the projected period. The oil industry is ranked 55, with production falling at an average annual rate of 0.9 percent. The coal industry is ranked 56, with production falling at an average annual rate of 2.4 per ent. Oil is restrained by local supply constraints and by mild contractions in export demand. Coal mining shrinks because demand (foreign and domestic) for all types of coal (thermal and metallurgical) is projected to fall due to global measures to reduce greenhouse emissions.

The growth prospects of the metal manufacturing industries are generally poor. *Aluminium* (industry 27, rank 50) and *Iron and steel* (industry 24, rank 49) are both forecast to expand at an average annual rate of 0.8 percent. In both cases, existing capital is nearing the end of its economic life. We forecast that most of the capacity will be renewed, but only if deep decarbonisation efforts in Australia allow. The fortunes of *Alumina* (industry 26, rank 45) reflects two factors operating in the same direction. The first is weak growth in local demand from the aluminium industry, which is alumina's only local downstream customer. The second is reduced exports. For alumina there is some limited scope to switch away from its major fuel, gas, but this does not prevent the abatement incentive from increasing significantly the unit cost of alumina production. As the cost rises, the industry is less competitive in its major markets overseas.

Another standout manufacturing industry with poor growth prospects is *Petroleum products* (industry 20, rank 57), which is expected to contract at an average annual rate of 6.6 percent. This reflects an assumption based on industry information that the Australian refinery industry will close down within the next 20 years. Plant closures will also affect the Australian motor vehicle assembly industry however this is just one part of the broader industry, *Motor vehicles and parts* (industry 30, rank 54). Despite the closure of vehicle manufacturing and assembly, the overall industry is expected to contract only at an average annual rate of 0.1 percent per annum, reflecting continued strong growth in demand for parts and repairs. Other adversely affected industries are *Private transport services* (industry 56, rank 49), *Private electricity equipment services* (industry 57, rank 56) and *Private heating services* (industry 58, rank 53). All three are affected by increases in the price of energy: automotive fuels for transport services, electricity for electrical equipment services and gas for heating services. Increased energy costs shift their supply schedules up, leading to adverse substitution in residential demand.

Residential use of electricity equipment and electricity is supplied by *Private electricity equipment services* (industry 57, rank 42) and residential use of heating equipment and fuels is supplied by *Private heating services* (industry 58, rank 48). Both industries have below-average growth ranks due to adverse substitution effects in household demand.

Table 7.3 – Industry Output with Deep Decarbonistion(average annual percentage growth rates, 2012 to 2050, ranked)

Rank	Industry	Growth (percent)
1	37. Electricity generation – other	7.6
2	7. Forestry	7.4
3	10. Gas mining	4.1
4	13. Other mining	3.9
5	52. Business services	3.5
6	50. Communication services	3.5
7	46. Rail passenger transport	3.3
8	51. Financial services	3.0
9	54. Public services	2.9
10	49. Air transport	2.7
11	33. Electricity generation – gas	2.7
12	28. Other non-ferrous metals	2.7
13	38. Electricity supply	2.7
14	17. Wood products	2.6
15	47. Rail freight transport	2.6
16	6. Agricultural services, fishing and hunting	2.6
17	48. Water, pipeline and transport services	2.6
18	42. Trade services	2.5
19	12. Non-ferrous ore mining	2.4
20	55. Other services	2.4
21	3. Other livestock	2.4
22	53. Dwelling services	2.3
23	11. Iron ore mining	2.3
24	14. Meat and meat products	2.3
25	5. Other agriculture	2.2
26	16. Textiles, clothing and footwear	2.2
27	19. Printing and publishing	2.2
28	41. Construction services	2.2
29	4. Grains	2.1
30	43. Accommodation, hotels and cafes	2.1
31	15. Other food, beverages and tobacco	2.1
32	21. Basic chemicals	2.0
33	36. Electricity generation – hydro	2.0
34	18. Paper products	1.9
35	40. Water supply	1.9
36	22. Rubber and plastic products	1.9
37	2. Dairy cattle	1.8
38	31. Other manufacturing	1.8
39	24. Cement	1.8
40	45. Road freight transport	1.8
41	44. Road passenger transport	1.7
42	57. Private electricity equipment services	1.7
43	1. Sheep and beef cattle	1.7
44	23. Non-metal construction products	1.5
45	26. Alumina	1.5
46	29. Metal products	1.3
47	56. Private transport services	1.2
48	58. Private heating services	1.0
49	25. Iron and steel	0.8
50	27. Aluminum	0.8
51	34. Electricity generation – oil products	0.0
52	35. Electricity generation – nuclear	0.0
53	39. Gas supply	0.0
54	30. Motor vehicles and parts	-0.1
55	9. Oil mining	-0.9
56	8. Coal mining	-2.4
57	20. Petroleum products	-6.6
58	32. Electricity generation – coal	-12.4

Forecasts for the agricultural sector are, in the main, determined by the prospects of downstream food and beverage industries. *Meat and meat products* (industry 14, rank 24) has average good growth prospects, reflecting fairly strong growth in exports, offset by increased import penetration on local markets. As a consequence, the growth prospects of *Other livestock* (industry 3, rank 21) is relatively good. *Sheep and beef cattle* (industry 1, rank 43) and *Grains* (industry 4, rank 29) have below-average growth prospects, due mainly to a relatively weak export-demand growth forecast. *Agricultural services, fishing and hunting* (industry 6, rank 16) is projected to grow relatively strongly, despite resource constraints on fishing stocks.

Air transport (industry 49, rank 10) has a projected average annual growth rate of 2.7 percent. Prospects for this industry are above average because of expected strong growth in inbound tourism and a taste shift in household spending away from local travel and towards travel interstate and overseas.

Rapid growth in *Business services* (industry 52, rank 5), *Communication services* (industry 50, rank 6) and *Financial services* (industry 51, rank 8) reflects the assumption that changes in technology through the projection period will favour intermediate usage of these services strongly and that comparatively rapid productivity growth will reduce their prices relative to consumer prices in general.

Most of the remaining industries have forecast growth rates close to average. General local economic conditions are particularly influential for the service industries, which have relatively low exposure to international trade.

Rail passenger transport (industry 46) is the seventh ranked industry, with a projected average annual growth rate of 3.3 percent. Prospects for this industry are good, because it is assumed that road congestion in urban areas will intensify through the projection period, inducing commuters to substitute rail for road travel. As a consequence, the road passenger industry (44, rank 41) and *Private transport services* (industry 56, rank 47) have relatively poor prospects. Like its passenger counterpart, *Rail freight transport* (industry 47, rank 15) has a reasonably high ranking. Just as urban road congestion boosts demand for rail passenger transport, so congestion on the major arterial roads within and between cities on the east coast is projected to increase demand for rail freight at the expense of road freight (industry 45, rank 41).

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Appendices

Appendix A: P. Graham, CSIRO

Appendices B and C: P. Adams, COPS

Appendix A: ESM description

This appendix provides summary information about the Energy Sector Model (ESM).

Structure and theoretical underpinnings

Energy Sector Model (ESM) is solved as a linear program, where the objective function to be maximised is welfare, which is calculated as the discounted sum of consumer and producer surplus over time. The sum of consumer and producer surplus is calculated as the integral of the demand functions minus the integral of the supply functions, each of which are disaggregated into many components across the electricity and transport markets. The objective function is maximised subject to constraints that control for the physical limitations of fuel resources, the stock of electricity plant and transport vehicles, greenhouse gas emissions as prescribed by legislation and various market and technology specific constraints, such as the need to maintain a minimum number of peaking plants to meet rapid changes in the electricity load.

Main components

The main components of ESM include:

- coverage of all states and the Northern Territory (Australian Capital Territory is modelled as part of New South Wales)
- 22 centralised generation (CG) electricity plant types: black coal pulverised fuel; black coal integrated gasification combined cycle (IGCC); black coal with CO2 capture and sequestration (CCS) (90 percent capture rate); brown coal pulverised fuel; brown coal (IGCC); brown coal direct injection coal engine; brown coal with CCS (90 percent capture rate); natural gas combined cycle; natural gas peaking plant; natural gas with CCS (90 percent capture rate); biomass; hydro; onshore wind; offshore wind; large-scale photovoltaic (PV); solar thermal; solar thermal with six hours storage; integrated solar and gas; hot fractured rocks (geothermal), wave, ocean current and nuclear
- 17 distributed generation (DG) electricity plant types: internal combustion diesel; gas reciprocating engine; gas turbine; gas micro turbine; gas combined heat and power (CHP); gas micro turbine CHP; gas micro turbine with combined cooling, heat and power (CCHP); gas reciprocating engine (CCHP); gas reciprocating engine (CHP); solar photovoltaic; bagasse (CHP); biomass steam; biogas reciprocating engine; landfill gas reciprocating engine; wind; natural gas fuel cell (CHP); and hydrogen fuel cell (CHP)
- trade in electricity between National Electricity Market (NEM) regions
- four electricity end-use sectors: industrial; commercial and services; rural and residential
- nine road transport modes: small, medium and large passenger cars; small, medium and large commercial vehicles; rigid trucks; articulated trucks and buses
- five engine types: internal combustion; hybrid electric/internal combustion; hybrid plug-in electric/internal combustion; fully electric and fuel cell
- 14 road transport fuels: petrol; diesel; liquefied petroleum gas (LPG); natural gas (compressed (CNG) or liquefied (LNG)); petrol with 10 percent ethanol blend; diesel with 20 percent biodiesel blend; ethanol and biodiesel at high concentrations; biomass to liquids diesel; gas to liquids diesel; coal to liquids diesel with upstream CO2 capture; shale to liquids diesel with upstream CO2 capture, hydrogen (from renewables) and electricity
- all vehicles and centralised electricity generation plants are assigned a vintage based on when they were first purchased or installed in annual increments

- time is represented in annual frequency.

All technologies are assessed on the basis of their relative costs, subject to constraints such as the turnover of capital stock, existing or new policies such as subsidies and taxes. The model aims to mirror real-world investment decisions by simultaneously taking into account:

- the requirement to earn a reasonable return on investment over the life of a plant or vehicle
- that the actions of one investor or user impacts the financial viability of all other investors or users simultaneously and dynamically
- that consumers react to price signals (price elastic demand)
- that the consumption of energy resources by one user affects the price and availability of that resource for other users and the overall cost of energy and transport services
- energy and transport market policies and regulations.

The model projects uptake on the basis of cost-competitiveness, but at the same time takes into account constraints on the operation of energy and transport markets, current excise and mandated fuel mix legislation, GHG emission limits, existing plant and vehicle stock in each state, as well as lead times in the availability of new vehicles or plant. It does not take into account issues such as community acceptance of technologies, but these can be controlled by imposing various scenario assumptions, constraining the solution to user-provided limits.

ESM model inputs

ESM requires both economic and biophysical data in order to support the selection of a least-cost solution that is within biophysical limits of the technologies and energy resources that are employed. Key economic data include:

- national carbon price or emissions limit
- electricity generation technology cost changes
- fuel prices to electricity generators
- road vehicle costs
- transport fuel prices
- net excise, charges, registration and insurance fees by state.

Key biophysical data includes:

- existing stock and age of generators by state
- road vehicle fuel efficiencies and emission factors by mode
- state resource or technology constraints
- electricity technology capacity factor and supply constraints
- transmission losses or premiums
- air, marine, road and rail transport demand
- state electricity energy consumption and peak demand growth.

Some social considerations include:

- road vehicle size preferences
- social constraints on land use
- number of houses with two vehicles.

ESM model outputs

For given time paths of the exogenous (or input) variables that define the economic environment, ESM determines the time paths of the endogenous (output) variables. Key output variables include:

- fuel, engine and electricity generation technology uptake
- fuel consumption
- price of fuels
- greenhouse gas and criteria air pollutant emissions
- wholesale and retail electricity prices, and
- demand for transport and electricity services.

Some of these outputs can also be defined as fixed inputs depending upon the design of the scenario.

The endogenous variables are determined using demand and production relationships, commodity balance definitions and assumptions of competitive markets at each time step for fuels, electricity and transport services and, over time, for assets such as vehicles and plant capacities. With respect to asset markets, the assumption is used that market participants know future outcomes of their joint actions over the entire time horizon of the model.

Appendix B: MMRF modelling

B1 Industries

The 58 industries identified in MMRF are shown in Table 0.1.

Table 0.1 – Industries in MMRF[22]

Name	Description of major activity
1. Sheep and beef cattle	Primary agricultural activities related to sheep and cattle production
2. Dairy cattle	Primary agricultural activities associated with dairy cattle
3. Other livestock	Primary agricultural activities associated with other animals
4. Grains	Grains production
5. Other agriculture	Other primary agricultural production
6. Agricultural services, fishing and hunting	Provision of agricultural services, fishing and hunting
7. Forestry	Logging and forestry services
8. Coal mining	Mining of coal
9. Oil mining	Mining of oil
10. Gas mining	Production of natural gas at well
11. Iron ore mining	Mining of iron ore
12. Non-ferrous ore mining	Mining of ore other than iron
13. Other mining	Other mining activity
14. Meat and meat products	Processed food related to animal
15. Other food, beverages and tobacco	Other food and drink products
16. Textiles, clothing and footwear	Textiles, clothing and footwear
17. Wood products	Manufacture of wood (including pulp) products
18. Paper products	Manufacture of paper products
19. Printing and publishing	Printing and publishing
20. Petroleum products	Manufacture of petroleum (refinery) products
21. Basic chemicals	Manufacture of basic chemicals and paints
22. Rubber and plastic products	Manufacture of plastic and rubber products
23. Non-metal construction products	Manufacture of non-metallic building products excl. cement
24. Cement	Manufacture of cement
25. Iron and steel	Manufacture of primary iron and steel.
26. Alumina	Manufacture of alumina
27. Aluminum	Manufacture of aluminum
28. Other non-ferrous metals	Manufacture of other non-ferrous metals
29. Metal products	Manufacture of metal products
30. Motor vehicles and parts	Manufacture of motor vehicles and parts
31. Other manufacturing	Manufacturing non elsewhere classified
32. Electricity generation - coal	Electricity generation from coal (black and brown) thermal plants
33. Electricity generation - gas	Electricity generation from natural gas thermal plants
34. Electricity generation – oil products	Electricity generation from oil products thermal plants
35. Electricity generation - nuclear	Electricity generation from nuclear plants
36. Electricity generation – hydro	Electricity generation from renewable sources – hydro
37. Electricity generation – other	Electricity generation from all other renewable sources
38. Electricity supply	Distribution of electricity from generator to user
39. Gas supply	Urban distribution of natural gas
40. Water supply	Provision of water and sewerage services
41. Construction services	Residential building and other construction services
42. Trade services	Provision of wholesale and retail trade services
43. Accommodation, hotels and cafes	Provisions of services relating to accommodation, meals and drinks
44. Road passenger transport	Provision of road transport services – passenger
45. Road freight transport	Provision of road transport services – freight
46. Rail passenger transport	Provision of rail transport services – passenger
47. Rail freight transport	Provision of rail transport services – freight
48. Water, pipeline and transport services	Provision of water transport services
49. Air transport	Provision of air transport services
50. Communication services	Provision of communication services
51. Financial services	Provision of financial services
52. Business services	Provision of business services

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[22] * For most of the industries identified in this table there is an obvious correspondence to one or more standard categories in the Australian and New Zealand Standard Industrial Classification (ANZSIC), 2006 version. The exceptions are: industries 32 to 38, which together comprise ANZSIC 26 Electricity Supply; industry 53, which is equivalent to the ownership of dwellings industry in the industrial classification of the official input/output statistics; and industries 56 to 58, which relate to the provision of services from the private stocks of motor vehicles, electrical equipment (not heating) and heating equipment.

53. Dwelling services	Provision of dwelling services
54. Public services	Provision of government and community services
55. Other services	Provision of services not elsewhere classified
56. Private transport services	Provision of services to households from the stock of motor vehicles
57. Private electricity equipment services	Provision of services to households from the stock of electrical equipment
58. Private heating services	Provision of services to households from the stock of heating equipment

Three produce primary fuels (coal, oil and gas), one produces refined fuel (petroleum products), six generate electricity and one supplies electricity to final customers. The six generation industries are defined according to primary source of fuel: *Electricity-coal* includes all coal-fired generation technologies; *Electricity-gas* includes all plants using turbines, cogeneration and combined cycle technologies driven by burning gas; *Electricity-oil products* covers all liquid-fuel generators; *Electricity-hydro* covers hydro-generation; and *Electricity-other* covers the remaining forms of renewable generation from biomass, biogas, wind etc. Nuclear power generation is not currently used in Australia but *Electricity-nuclear* is included and could be triggered, if desired, at a specified abatement incentive.

Apart from *Grains* (industry 4) and *Petroleum products* (industry 20), industries produce single products. *Grains* produces grains for animal and human consumption and biofuel used as feedstock by *Petroleum products*. *Petroleum products* produces gasoline (including gasoline-based biofuel blends), diesel (including diesel-based biofuel blends), LPG, aviation fuel and other refinery products (mainly heating oil).

B2 General equilibrium core

B2.1 The nature of markets

MMRF determines regional supplies and demands of commodities through optimising behaviour of agents in competitive markets. Optimising behaviour also determines industry demands for labour and capital. Labour supply at the national level is determined by demographic factors, while national capital supply responds to rates of return. Labour and capital can cross regional borders in response to relative regional employment opportunities and relative rates of return.

The assumption of competitive markets implies equality between the basic price (i.e. the price received by the producer) and marginal cost in each regional sector. Demand is assumed to equal supply in all markets other than the labour market (where excess-supply conditions can hold). The government intervenes in markets by imposing *ad valorem* sales taxes on commodities. This places wedges between the prices paid by purchasers and the basic prices received by producers. The model recognises margin commodities (e.g. retail trade and road transport), which are required for the movement of commodities from producers to the purchasers. The costs of the margins are included in purchasers' prices of goods and services.

B2.2 Demands for inputs to be used in the production of commodities

MMRF recognises two broad categories of inputs: intermediate inputs and primary factors. Firms in each regional sector are assumed to choose the mix of inputs that minimises the costs of production for their levels of output. They are constrained in their choices by a three-level nested production technology. At the first level, intermediate-input bundles and a primary-factor bundle are used in fixed proportions to output.[23] These bundles are formed at the second level. Intermediate-input bundles are combinations of domestic goods and goods imported from overseas. The primary-factor bundle is a combination of labour, capital and land. At the third level, inputs of domestic goods are formed as combinations of goods sourced from each of the eight domestic regions and the input of labour is formed as a combination of inputs from nine occupational categories.

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[23] A miscellaneous input category, *Other costs*, is also included and required in fixed proportion to output. The price of O*ther costs* is indexed to the price of private consumption. It is assumed that the income from O*ther costs* accrues to the government.

B2.3 Domestic final demand: household, investment and government

In each region, the household buys bundles of goods to maximise a utility function, subject to an expenditure constraint. The bundles are combinations of imported and domestic goods, with domestic goods being combinations of goods from each domestic region. A Keynesian consumption function is usually used to determine aggregate household expenditure as a function of household disposable income.

Capital creators for each regional sector combine inputs to form units of capital. In choosing these inputs, they minimise costs subject to a technology similar to that used for current production, with the main difference being that they do not use primary factors directly.

State/territory governments and the federal government demand commodities from each region. In MMRF, there are several ways of handling these government demands, including:

- by a rule, such as moving government expenditures with aggregate household expenditure, domestic absorption or GDP
- as an instrument to accommodate an exogenously determined target, such as a required level of government budget deficit
- exogenous determination.

B2.4 Foreign demand (international exports)

MMRF adopts the ORANI[24] specification of foreign demand. Each export-oriented sector in each state or territory faces its own downward-sloping foreign demand curve. Thus, a shock that reduces the unit costs of an export sector will increase the quantity exported, but reduce the foreign currency price. By assuming that the foreign demand schedules are specific to product and region of production, the model allows for differential movements in foreign currency prices across domestic regions.

B2.5 Regional labour markets

The response of regional labour markets to policy shocks depends on the treatment of three key variables – regional labour supplies, regional unemployment rates and regional wage differentials. The main alternative treatments are:

- to set regional labor supplies and unemployment rates exogenously and determine regional wage differentials endogenously
- to set regional wage differentials and regional unemployment rates exogenously and determine regional labour supplies endogenously (*via* interstate migration or changes in regional participation rates)
- to set regional labor supplies and wage differentials exogenously and determine regional unemployment rates endogenously.

The second treatment is the one adopted for the simulations reported in this paper, with regional participation rates exogenous. Under this treatment, workers move freely (and instantaneously) across state borders in response to changes in relative regional unemployment rates. With regional wage rates indexed to the national wage rate, regional employment is demand determined.

B2.6 Physical capital accumulation

Investment undertaken in year t is assumed to become operational at the start of year t+1. Under this assumption, capital in industry i in region q accumulates according to a typical accumulation equation, with gestation lag for new investment of one year.

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[24] MMRF and MONASH (Dixon and Rimmer, 2002) have evolved from the Australian ORANI model (Dixon et al. (1977) and Dixon et al. (1982)).

New investment in industry i in region q is modelled as a positive function of expected rate of return. In the current version of MMRF, it is assumed that investors take account only of current rentals and asset prices when forming expectations about rates of return (static expectations).

B2.7 Lagged adjustment process in the national labour market

The simulations in this paper are year-to-year recursive-dynamic simulations, in which it is assumed that deviations in the national real wage rate from its base-case level increase through time in inverse proportion to deviations in the national unemployment rate. That is, in response to a shock-induced increase (decrease) in the unemployment rate, the real wage rate declines (increases), stimulating (reducing) employment growth. The coefficient of adjustment is chosen so that effects of a shock on the unemployment rate are largely eliminated after about 10 years.

Given the treatment of regional labour markets outlined above, if the national real wage rate rises (falls) in response to a fall (rise) in the national unemployment rate, then wage rates in all regions rise (fall) by the same percentage amount and regional employment adjusts immediately, with regional labour supplies adjusting to stabilise relative regional unemployment rates.

B3 Environmental enhancements

In this section, the key environmental enhancements of MMRF are described. These are:

- an accounting module for energy and greenhouse gas emissions that covers each emitting agent, fuel and region recognised in the model
- quantity-specific carbon taxes or prices
- equations for inter-fuel substitution in transport and stationary energy
- a representation of Australia's National Electricity Market (NEM)
- the treatment of energy-using equipment in private household demand
- linking MMRF to a global model to enhance MMRF's handling of global aspects of environmental policies and of changes to Australia's trading conditions
- linking MMRF to a detailed electricity-supply model
- modelling abatement of non-combustion emissions
- modelling carbon sequestration in forest industries.

B3.1 Energy and emissions accounting

MMRF tracks emissions of greenhouse gases according to: emitting agent (58 industries and the household sector); emitting state or territory (8); and emitting activity (9). Most of the emitting activities are the burning of fuels (coal, natural gas and five types of petroleum products). A residual category, named *Activity*, covers non-combustion emissions, such as emissions from mines and agricultural emissions not arising from fuel burning. *Activity* emissions are assumed to be proportional to the level of activity in the relevant industries (animal-related agriculture, gas mining, cement manufacture, etc.).

The resulting 59 × 8 × 9 array of emissions is designed to include all emissions except those arising from land clearing. Emissions are measured in terms of carbon dioxide equivalents, $C0_2$-e. Table 0.2 summarises MMRF's emission data for the starting year of the simulations, 2012. Note that MMRF accounts for domestic emissions only; emissions from combustion of Australian coal exports, say, are not included, but fugitive emissions from the mining of the coal are included.

Based on the raw numbers in Table 0.2, the burning of coal, gas and refinery products account for around 36, 11 and 24 percent of Australia's total greenhouse emissions. The residual, about 29 percent, comes from non-combustion sources. The largest emitting industry is electricity generation, which contributes around 35 percent of total emissions. The next largest is animal agriculture, which contributes 14 percent; agriculture in total contributes nearly 20 percent. Other large emitters include transport (including private transport services), with about 10 percent of total emissions; coal mining with around six percent; and other services (including waste dumps) with nearly three percent.

Table 0.2 – Summary of MMRF Emissions Data for Australia in 2012 (Kt of CO_2-e)

	Source of Emissions (fuel and non-fuel)				
Fuel user	Coal	Gas	Refinery	Non-fuel	Total
1. Sheep and beef cattle	0	1	877	72,216	73,094
2. Dairy cattle	0	0	332	6,633	6,965
3. Other livestock	0	1	139	2,132	2,271
4. Grains	0	1	1,582	2,252	3,835
5. Other agriculture	0	0	942	2,931	3,874
6. Agricultural services, fishing and hunting	0	1	1,361	12	1,374
7. Forestry	0	0	430	-24,978	-24,548
8. Coal mining	0	0	3,005	26,032	29,037
9. Oil mining	0	0	147	979	1,126
10. Gas mining	0	12,017	219	7,845	20,082
11. Iron ore mining	0	0	1,049	0	1,049
12. Non-ferrous ore mining	0	0	7,173	0	7,173
13. Other mining	0	0	1,113	0	1,113
14. Meat and meat products	169	52	14	0	235
15. Other food, beverages and tobacco	842	1,326	80	0	2,249
16. Textiles, clothing and footwear	0	181	7	0	188
17. Wood products	122	59	9	0	190
18. Paper products	241	852	11	0	1,104
19. Printing and publishing	0	106	20	0	126
20. Petroleum products	0	712	2,912	477	4,101
21. Basic chemicals	3,130	816	1,307	6,062	11,316
22. Rubber and plastic products	0	592	248	0	840
23. Non-metal construction products	499	1,229	104	3,440	5,271
24. Cement	2,084	787	322	5,488	8,681
25. Iron and steel	19,204	609	78	7,604	27,495
26. Alumina	0	6,863	389	0	7,252
27. Aluminum	0	0	183	4,688	4,871
28. Other non-ferrous metals	3,431	536	468	0	4,434
29. Metal products	0	48	17	0	65
30. Motor vehicles and parts	0	29	10	0	39
31. Other manufacturing	3	134	45	784	965
32. Electricity generation – coal	165,551	0	0	0	165,551
33. Electricity generation – gas	0	20,063	0	0	20,063
34. Electricity generation – oil products	0	0	1,843	0	1,843
35. Electricity generation – nuclear	0	0	0	0	0
36. Electricity generation – hydro	0	0	0	0	0
37. Electricity generation – other	0	0	0	0	0
38. Electricity supply	0	0	481	0	481
39. Gas supply	0	0	12	6,664	6,676
40. Water supply	0	0	243	0	243
41. Construction services	0	127	1,884	0	2,011
42. Trade services	0	1,063	4,132	530	5,724
43. Accommodation, hotels and cafes	0	150	494	399	1,044
44. Road passenger transport	0	6	2,669	1,029	3,704
45. Road freight transport	0	78	26,603	0	26,681
46. Rail passenger transport	0	0	345	0	345
47. Rail freight transport	0	0	2,499	0	2,499
48. Water, pipeline and transport services	0	4	3,046	0	3,050
49. Air transport	0	0	6,138	0	6,138
50. Communication services	0	77	1,302	0	1,379
51. Financial services	0	1	2	85	88
52. Business services	0	202	1,369	0	1,571
53. Dwelling services	0	4	13	0	17
54. Public services	0	133	1,439	85	1,657
55. Other services	0	31	1,261	12,855	14,146
56. Private transport services	0	0	40,918	0	40,918
57. Private electricity equipment services	0	0	0	3,664	3,664
58. Private heating services	0	5,645	0	0	5,645
Residential	20	0	385	0	405
Total	195,296	54,538	121,670	149,907	521,411

B3.2 Carbon taxes and prices

MMRF treats the price on emissions as a specific tax on emissions of CO_2-e. On emissions from fuel combustion, the tax is imposed as a sales tax on the use of fuel. On *Activity* emissions, it is imposed as a tax on production of the relevant industries.

In MMRF, sales taxes are generally assumed to be *ad valorem*, levied on the basic value of the underlying flow. Carbon taxes, however, are specific, levied on the quantity (CO_2-e) emitted by the associated flow. Hence, equations are required to translate a carbon tax, expressed per unit of CO_2-e, into *ad valorem* taxes, expressed as percentages of basic values. The CO_2-e taxes are specific but coupled to a single price index (typically the national price of consumption) to preserve the nominal homogeneity of the system. Suppressing indices, an item of CO_2-e tax revenue can be written as:

$$TAX = S \times E \times I \tag{1}$$

where:

S is the specific rate ($A per tonne of CO_2-e)

E is the emission quantity (tonne of CO_2-e)

I is a price index (base year = 1) used to preserve nominal homogeneity.

Ad valorem taxes in MMRF raise revenue

$$TAX = \frac{V \times P \times Q}{100} \tag{2}$$

where:

V is the percentage *ad valorem* rate

P is the basic price of the underlying taxed flow

Q is the quantity of the underlying taxed flow.

To translate from specific to *ad valorem* the RHSs of equations (1) and (2) are set equal to each other, yielding:

$$V = \frac{S \times E \times I \times 100}{P \times Q} \tag{3}$$

As can be seen from equation (3), to convert specific CO_2-e taxes to *ad valorem* taxes frequent use is made of the ratio of the indexed value of emissions ($E \times I$) to the value of the *ad valorem* tax base ($P \times Q$). Indeed, values for the ratio across all fuels and users and the matrix of specific tax rates are the primary additional data items added to MMRF for carbon-tax/ETS modelling.

Production taxes in MMRF are also assumed to be *ad valorem* and levied on the basic value of production. Accordingly, the linking equation for a CO_2-e tax on *Activity* emissions is:

$$V = \frac{S \times E \times I \times 100}{P \times Z} \tag{4}$$

where:

Z is the volume of production for which P is the basic price.

C3.3 Inter-fuel substitution

In the standard specification of MMRF, there is no price-responsive substitution between units of commodities or between commodities and primary factors. With fuel-fuel and fuel-factor substitution ruled out, CO_2-e taxes could induce abatement only through activity effects.

We correct this in two ways: firstly, by introducing inter-fuel substitution in electricity generation using a 'technology bundle' approach; and secondly, by introducing a weak form of input substitution in sectors other than electricity generation to mimic 'KLEM substitution'.

Electricity-generating industries are distinguished based on the type of fuel used. There is also an end-use supplier (*Electricity supply*) in each state and territory and a single dummy industry (*NEM*) covering the six regions that are included in Australia's National Electricity Market (New South Wales, Victoria, Queensland, South Australia the Australian Capital Territory and Tasmania). Electricity flows to the local end-use supplier either directly in the case of Western Australia and the Northern Territory or *via NEM* in the remaining regions.

Purchasers of electricity from the generation industries (*NEM* in NEM regions or the *Electricity supply* industries in the non-NEM regions) can substitute between the different generation technologies in response to changes in generation costs. Such substitution is price-induced, with the elasticity of substitution between the technologies typically set at around five.

For other energy-intensive commodities used by industries, MMRF allows for a weak form of input substitution. If the price of cement (say) rises by 10 percent relative to the average price of other inputs to construction, the construction industry will use one percent less cement and a little more labour, capital and other materials. In most cases, as in the cement example, a substitution elasticity of 0.1 is imposed. For important energy goods (petroleum products, electricity supply and gas), the substitution elasticity in industrial use is 0.25.

B3.4 The National Electricity Market (NEM)

The NEM is a wholesale market covering nearly all of the supply of electricity to retailers and large end-users in NEM regions. MMRF's represents the NEM as follows.

Final demand for electricity in each NEM region is determined within the CGE-core of the model in the same manner as demand for all other goods and services. All end-users of electricity in NEM regions purchase their supplies from their own state *Electricity supply* industry. Each of the *Electricity supply* industries in the NEM regions sources its electricity from a dummy industry called *NEM*, which does not have a regional dimension; in effect *NEM* is a single industry that sells a single product (electricity) to the *Electricity supply* industry in each NEM region. *NEM* sources its electricity from generation industries in each NEM region. Its demand for electricity is price-sensitive. For example, if the price of hydro-generation from Tasmania rises relative to the price of gas-generation from NSW, then *NEM* demand will shift towards NSW gas-generation and away from TAS hydro-generation.

The explicit modelling of the NEM enables substitution between generation types in different NEM regions. It also allows for interstate trade in electricity, without having to trace explicitly the bilateral flows. Note that WA and NT are not part of the NEM and electricity supply and generation in these regions is determined on a state-of-location basis.

B3.5 Services of energy-using equipment in private household demand

The final three industries shown in Table 0.1 are dummy industries that provide services of energy-using equipment to private households. These dummy industries enable households to treat energy and energy-using equipment as complementary, which is not possible in MMRF's standard budget-allocation specification based on the Linear Expenditure System (LES).

Industry 56 provides private transport services to the household sector, using inputs of capital (private motor vehicles), automotive fuel and other inputs required for the day-to-day servicing and running of vehicles. Industry 57 provides the services of electrical equipment (including air conditioners) to households, using inputs of capital (electrical equipment) and electricity. Industry 58 provides the services of appliances used for heating and cooking, using inputs of capital (heating and cooking appliances), gas and electricity. Energy used by these three dummy industries accounts for all of the energy consumption of the residential sector.

Including these dummy industries improves the model's treatment of price-induced energy substitution and its treatment of the relationship between energy and energy equipment in household demand. For example, in the LES-based specification of household demand, if the price of electricity fell relative to the price of other goods and services, electricity would be substituted for other commodities, including electrical and heating appliances. But under the dummy-industry specification, a change in the price of electricity induces substitution only through its effect on the prices of electrical equipment services and private heating services. If the change in the electricity price reduces the price of electrical equipment services relative to the price of other products, then electrical equipment services (including its inputs of appliances and energy) will be substituted for other items in the household budget.

B3.6 Linking with a global model of energy and trade – GTEM

Much of the global modelling undertaken for this project was undertaken using the Global Trade and Environment Model (GTEM) (Pant, 2007). Information from GTEM was used to inform simulations of MMRF and MMRF supplied estimates of the effects of the global abatement scheme on the Australian economy.

Linking economic models with different economic structures is not straightforward. For example, MMRF and GTEM have similar production structures, but their industrial classifications are not the same. Also, the elasticities of supply and demand associated with comparable industries are not necessarily consistent across the two models.

In general, the degree of linking required will vary depending on the number and nature of variables that are common between the two models. For example, if the only common variables are exogenous in the primary model (MMRF), then a relatively simple top-down linking from the secondary model (GTEM) is sufficient. On the other hand, if there are many common variables with some endogenous to both systems, a more complex linking with two-way transmission of results may be necessary.

The abatement scenario reported for this project involves a global permit price GTEM was used to model the effects of the global price on Australia's trading conditions. These are as represented in MMRF as changes in the positions of foreign export-demand and import-supply schedules. In MMRF, import supply is assumed to be perfectly elastic and foreign-currency import prices are naturally exogenous, once again allowing for one-way transmission from GTEM to MMRF.

For exports, however, foreign demand schedules are assumed to be downward sloping. In this case, one-way transmission is problematic because export prices and quantities are endogenous in both models. Despite the potential for feedback, the linking between GTEM and MMRF for export variables was done *via* one-way transmission from GTEM to MMRF.

B3.7 Linking with a detailed electricity supply model – CSIRO's ESM

The idea that environmental issues could be tackled effectively by linking a CGE model with a detailed bottom-up energy model has a long history with Australian modellers. For this report, MMRF uses information from CSIRO's Electricity Supply Model (CESM) to obtain very detailed projections for the structure of electricity supply.

CESM simulates the least-cost expansion and operation of generation and transmission capacity in the Australian electricity system. In linking MMRF to CESM, the electricity sector in MMRF is effectively replaced with CESM's specification. MMRF provides information on fuel prices and other electricity sector costs and on electricity demand from industrial, commercial and residential users. This is fed into *CESM*, which generates a detailed description of supply, covering generation by generation type, capacity by generation type, fuel use, emissions and wholesale and retail electricity prices. Retail electricity prices are a key endogenous variable in both systems. Information is passed back and forth between the two models in a series of iterations that stop when the average retail price in the electricity model has stabilised. Experience suggests that up to three iterations for each year are necessary to achieve convergence.

There are a number of reasons to prefer linking to a detailed electricity model over the use of MMRF's standard treatment of electricity.

- *Technological detail*. MMRF recognises six generation technologies (Table 0.1). CESM recognises many hundreds, some of which are not fully proved and/or are not in operation. For example, MMRF recognises one form of coal generation. CESM recognises many forms, including cleaner gasification technologies and generation in combination with carbon capture and storage (CCS). Having all known technologies available for production now or in the future allows for greater realism in simulating the technological changes available in electricity generation in response to a price on emissions. CESM also captures details of the interrelationships between generation types. A good example is the reliance by hydro-generation on base-load power in off-peak periods to pump water utilised during peak periods back to the reservoir.

- *Changes in capacity*. MMRF treats investment in generation like all other forms of investment. Capital supply is assumed to be a smooth increasing function of expected rates of return, which are set equal to current rates of return. Changes in generation capacity, however, are generally lumpy, not smooth, and investment decisions are forward-looking, given long asset lives. CESM allows for lumpy investments and for realistic lead times between investment and capacity change. It also allows for forward-looking expectations, which aligns more with real-world experience than does MMRF's standard static assumption. The demand for electricity is exogenous in CESM but when demand is endogenised by running CESM linked to MMRF, investment in the electricity sector is essentially driven by model-consistent expectations.

- *Policy detail*. Currently, in Australia there are around 100 policies at the state, territory and commonwealth levels affecting electricity generation and supply. These include: market-based instruments to encourage increased use of renewable generation; regulations affecting the prices paid by final residential customers; and regional policies that offer subsidies to attract certain generator types. Associated interactions and policy details are handled well in CESM but are generally outside the scope of standalone modelling in MMRF.

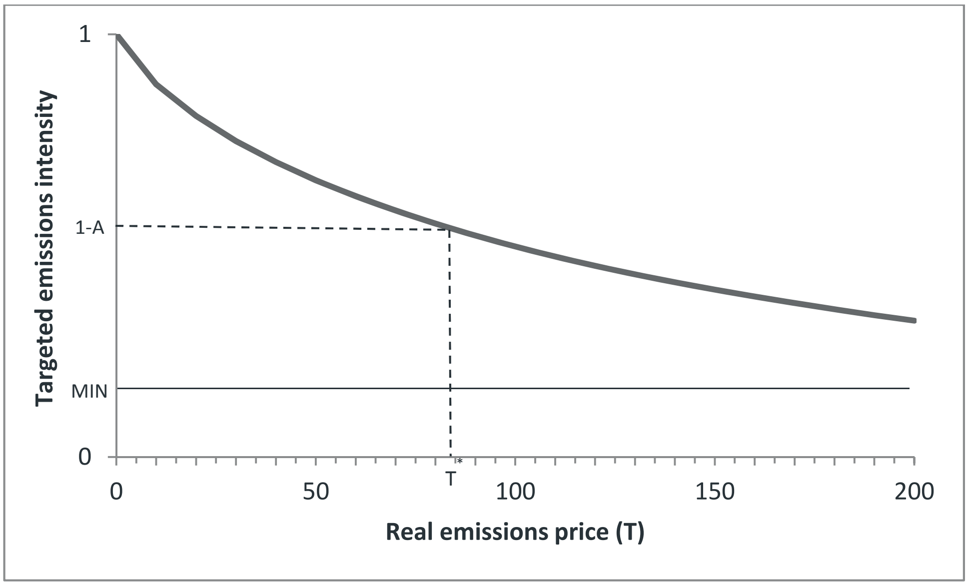
- *Sector detail*. In MMRF, electricity production is undertaken by symbolic industries – Electricity-coal Victoria, Electricity-gas NSW etc. In CESM, actual generation units are recognised – unit x in power station y located in region z. Thus results from the detailed electricity model can be reported at a much finer level and in a way which industry experts fully understand. This adds to credibility in result reporting.

B3.8 Abatement of non-combustion emissions

Non-combustion (or *Activity*) emissions include: agricultural emissions (largely from animals); emissions from land clearing or forestry; fugitive emissions (e.g. gas flaring); emissions from industrial processes (e.g. cement manufacture); and emissions from landfill rubbish dumps. In modelling with MMRF, it is assumed that in the absence of an emissions price, non-combustion emissions move with industry output, so that non-combustion emissions intensity (emissions per unit of output) is fixed.

MMRF's theory of abatement of non-combustion emissions in the presence of an emissions price is similar to that developed for GTEM. It assumes that as the price of CO_2-e rises, *targeted* non-combustion emissions intensity (emissions per unit of output) falls (abatement per unit increases) through the planned introduction of less emission-intensive technologies. More specifically, for *Activity* emitter i in region q it is assumed that abatement per unit of output can be achieved at an increasing marginal cost according to a curve such as that shown in Figure 0.1.

Figure 0.1 – Marginal abatement curve for the hypothetical industry



In this figure, units are chosen so that complete elimination of non-combustion emissions corresponds to an abatement level of 1. However complete elimination is not possible. So, as shown in the figure, the marginal cost of abatement goes to infinity as the abatement level per unit of output reaches a maximum level, 1-MIN, where MIN is the proportion of non-combustion emissions that cannot be removed. From Figure 0.1, an intensity function for emissions can be derived of the form:

$$Intensity_{i,q} = MAX_{i,q}\left\{MIN_{i,q},\ F_{i,q}(T)\right\} \qquad (5),$$

where:

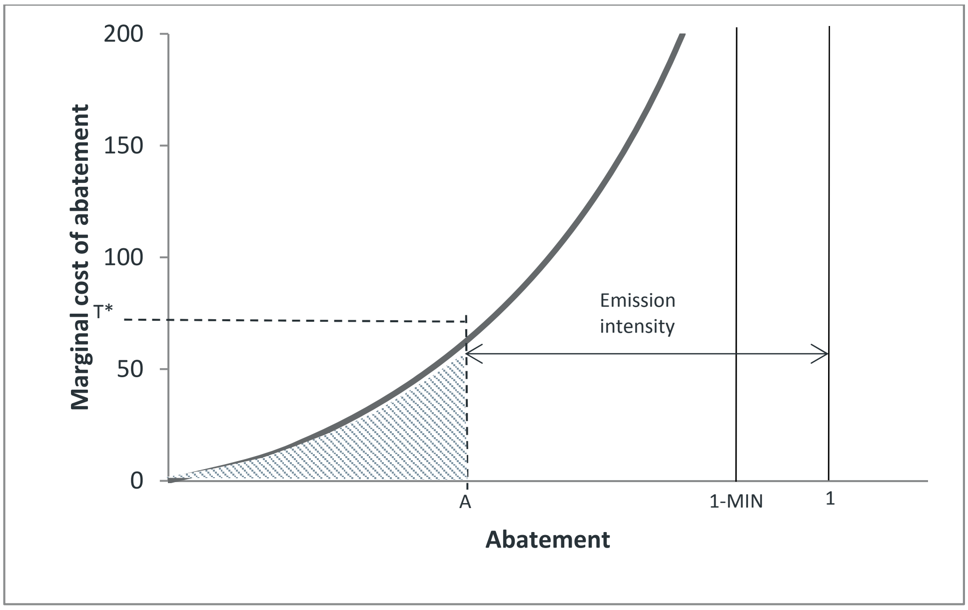
$Intensity_{i,q}$ is the target level of non-combustion emissions intensity

$MIN_{i,q}$ is the minimum possible level of emissions intensity

$F_{i,q}$ is a non-linear monotonic decreasing function of the real level of the emissions price, T ($ per tonne of CO_2-e in constant 2010 prices).

This is illustrated in Figure 0.2, which shows for a typical *Activity* abatement, the relationship between targeted emissions intensity and emissions price, with intensity indexed to 1 for T = 0.

Figure 0.2: Emissions intensity as a function of the real carbon price



To ensure that emissions intensities do not respond too vigorously to changes in the emissions price, especially at the start of a simulation in which the price of CO_2-e rises immediately from zero, a lagged adjustment mechanism is also put in place, allowing actual emissions intensity to adjust slowly towards targeted emissions intensity specified by (4).

In MMRF the abatement cost per unit of output (the shaded area in Figure 0.2) is imposed as an all-input, using technological deterioration in the production function of the abating industry.

B3.9 Land use in forestry

In MMRF, land is an input to production for the agricultural industries and forestry. For the projections in this report, land is considered region-specific but not industry-specific and there are regional supply constraints. This means that within a region, an industry can increase its land usage but that increase has to be met by reduced usage by other industries within the region. Land is assumed to be allocated between users to maximise the total return to land subject to a Constant Elasticity of Transformation (CET) constraint defining production possibilities across the various land-using sectors. This is the same treatment as adopted in GTAP and GTEM. With this mechanism in place, if demand for biosequestration offsets pushes up demand for land in the forestry sector, then forestry's use of land will increase, increasing the region-wide price of land and causing non-forestry industries to reduce their land usage and overall production.

Appendix C: Reference case

The reference case is the control projection against which the policy scenario, deep decarbonisation for Australia, is compared. In section C1 we describe the key assumptions underlying the reference case. Sections C2 to C4 contain reference-case projections for macroeconomic variables, industry outputs and greenhouse gas emissions.

C1 Key assumptions

The reference case incorporates a large amount of information from specialist forecasting agencies. MMRF traces out the implications of the specialists' forecasts at a fine level of industrial and regional detail. Information imposed on the model includes:

- macroeconomic forecasts based on information published by the Treasury (to 2015), private forecasting groups (to 2020) and extrapolations of medium-term trends (2021 onwards)
- national-level assumptions for changes in industry production technologies and in household preferences developed from MONASH and MMRF historical-decomposition modelling
- forecasts through to 2025 for the quantities of agricultural and mineral exports from a range of industry sources, ClimateWorks and CSIRO (all consistent with action outside of Australia directed at significant reductions in greenhouse emissions)
- estimates of changes in Australia's generation mix, generation capacity, fuel use, emissions and wholesale prices from CSIRO
- forecasts for state/territory populations and participation rates, drawing on projections in the Treasury's most recent Intergeneration Report
- forecasts for land-use change and for forestry sequestration from CSIRO
- forecasts for changes in Australia's aggregate terms of trade and for the foreign export and import prices for Australia's key traded goods in agriculture, mining and manufacturing drawn from information provided by CSIRO (from modelling with GTEM) and ClimateWorks
- projections for the production of ferrous and non-ferrous metals and ores, based on industry information and data provided by ClimateWorks.

To accommodate this information in MMRF, numerous naturally endogenous variables are made exogenous. To allow the naturally endogenous variables to be exogenous, an equal number of naturally exogenous variables are made endogenous. For example, to accommodate the exogenous setting of the aggregate terms of trade, an all-commodity and all-region shift variable, naturally exogenous in MMRF but endogenous in the reference case simulation, imparts an equi-proportionate change in the positions of foreign demand curves. Another example relates to real GDP. In the reference case, real GSP (a naturally endogenous variable) is set exogenously by allowing technological progress across all primary factor inputs and industries to adjust endogenously.

C2 Reference-case projections for selected macroeconomic variables

Error! Reference source not found. and Error! Reference source not found. show base case projections for selected national macroeconomic variables. The following are some key features.

- Real GDP (Error! Reference source not found.) grows at an average annual rate of 2.8 percent between 2012 and 2020, slowing to an average rate of 2.6 percent between 2021 and 2030. Average annual growth between 2012 and 2050 is 2.6 percent, which is consistent with the historical norm for Australia. GDP growth is projected to decline slowly in line with demographic projections from the IGR, which point to a gradual reduction in population growth over the projection period.

- Though not shown in Error! Reference source not found., but in line with recent history, the export-oriented states – QLD and WA – are projected to be the fastest-growing state economies, followed by NSW and VIC. SA and TAS are the slowest-growing, though the gap between the slowest and fastest-growing states and territories is a little less than in recent times.

- Real national private consumption (Error! Reference source not found.) grows at an average annual rate of 2.4 percent over the full projection period. The time profile is similar to that for real GDP: initially strong, then stabilising and eventually declining slowly.

- The regional pattern of growth for consumption is also similar to that for GDP: fastest growth occurs in QLD and WA, with slowest growth in TAS and SA.

- Over the 15 years leading up to 2012, the volumes of international exports and imports grew rapidly, relative to real GDP. This reflects several factors – strong growth in local economies (particularly China), declining transport costs, improvements in communications, reductions in protection in Australia and overseas and technological changes favouring the use of import-intensive goods, such as computers and communication equipment. The influence of this factor has weakened considerably over the past two years and this is expected to continue through the projection period (see Error! Reference source not found.). On average, export volumes grow relative to GDP by about 1.5 percent per year. However import growth is projected to be less than export growth, implying some improvement in the current imbalance between export and import volumes. Relatively weak import growth is due to two factors: real devaluation of the currency from its present very high level and slow growth in import-intensive investment spending.

- Australia's terms of trade is assumed to decline significantly in the first decade of the reference case (Error! Reference source not found.), continuing the trend of the past two years. After 2020, the rate of decline moderates, until the terms of trade reaches its historically normal level in 2035.

C3 Reference case projections: Emissions by source

Table 0.1 gives a picture of the level of emissions at the national and state/territory levels at the start of the projection period (2012) and at the end (2050). It covers all emissions except for emissions from land clearing in line with Kyoto accounting principles.

In aggregate, emissions are projected to grow at an average annual rate of 1.0 percent between 2012 and 2050. By 2050, emissions are projected to be 47.7 percent higher than in 2012.

The largest source of emissions is electricity generation, especially generation from coal combustion. In 2012 electricity contributed almost 36 percent to total emissions. But the detailed electricity modelling indicates that average annual growth in emissions from electricity will be -0.5 percent through the projection period. As a consequence, at the end of the period electricity contributes less than 20 percent of total emissions. The projected rate of growth in electricity demand over the period is, on average, 1.6 percent per annum (see Table B1 for *Electricity supply)*. Thus emissions per unit of generation are projected to fall by over 2 percent per annum. Nearly all of this comes from improved energy efficiency. Relatively little comes from replacement of fossil fuel generation by renewable generation. Other stationary energy sources contribute 18.0 percent to total emissions in 2012. These include residential, industrial and commercial space heating. Emissions from other stationary sources are projected to grow at an average annual rate of 1.5 percent. This is below the growth rate of real GDP, reflecting the relatively slow growth of *Private heating services* (1.5 percent per annum) and *Other manufacturing* (1.7 percent).

Transport contributes 17.3 percent to total emissions in 2012 and has projected emissions growth of 1.2 percent per annum. Around 60 percent of transport emissions come from *Private transport services*. This industry is projected to grow at an average annual rate of 1.4 percent (Table B1). Much of the remaining transport emissions come from *Road freight transport*, which grows at an average annual rate of 1.9 percent. Emissions grow by less than output in these two key industries because it is assumed that use of bioproducts will increase.

The next largest source of emissions in 2012 is agriculture, with a share of 16.7 percent. In the Kyoto accounting framework, most of Australia's agricultural emissions come from methane emitted by cattle and sheep. Reference case growth prospects for these livestock industries are well below GDP growth (Table B1): *Sheep and beef cattle* (2.3 percent per annum), *Dairy cattle* (2.0 percent) and *Other livestock* (2.5 percent). Average annual growth in emissions from agriculture overall is 2.2 percent. Of the remaining sources, growth in fugitive emissions is lowest, reflecting reductions in production of gas and coal. Industrial process emissions are projected to grow at an average annual rate of 1.2 percent, reflecting growth in output from *Cement* and the metals-manufacturing industries. Emissions of methane from landfill waste dumps are assumed to grow in line with recent history.

The final category is *Forestry*. The modelling ignores all emissions from land-use change except for sequestration from forestation and reforestation. For the reference case, data on forestry sequestration was supplied by CSIRO. The CSIRO projections take account of the lifecycle of individual forests established since 1990, accounting for carbon sequestered when the forest is planted and growing and for carbon released when the forest is harvested. Note that Forestry makes a negative contribution to emissions in 2012 and 2050.

Aggregate emissions per $ of real GDP (national emissions intensity) is projected to fall, on average, by 1.6 percent per year. Much of this has been explained in our discussion of growth rates in emissions by source. In addition, there is a structural effect. The service industries, *Communication services*, *Financial and business services*, *Dwelling ownership*, *Public services* and *Other services*, together contribute around 40 percent of GDP but emit relatively little (directly and indirectly *via* their use of electricity) per unit of real value added. In the reference case, they contribute significantly to growth in real GDP, but have little impact on growth in emissions, generating a fall in emissions per unit of GDP.

Table B2 shows that total emissions are projected to grow fastest in the states/territories with the highest projected growth rates – NT, WA and QLD. Total emissions are highest in NSW and VIC up until 2015. Beyond 2015, QLD surpasses VIC. Emissions in Western Australia increase by more than other states, reflecting the high economic growth rates and the increase in mining, natural gas and mineral processing activities in that state.

Table 0.1: CO_2-e Emissions by Major Source Category: Reference case

Average annual growth rates (percentage), 2012 to 2050	AUS
Energy sector, total	0.5
Fuel combustion	0.6
Stationary	0.4
Electricity generation	-0.5
Other	1.5
Transport	1.2
Fugitive emissions from fuels	0.1
Industrial processes	1.2
Agriculture	2.2
Waste	1.2
Forestry	-2.6
Total	1.0

Shares in Australia-wide total (percentage)	AUS
2012	
Energy sector, total	79.1
Fuel combustion	71.0
Stationary	53.8
Electricity generation	35.8
Other	18.0
Transport	17.3
Fugitive emissions from fuels	8.0
Industrial processes	6.6
Agriculture	16.7
Waste	2.5
Forestry	-4.8
Total	100.0
2050	
Energy sector, total	65.6
Fuel combustion	60.0
Stationary	41.6
Electricity generation	19.8
Other	21.8
Transport	18.4
Fugitive emissions from fuels	5.7
Industrial processes	7.0
Agriculture	25.9
Waste	2.7
Forestry	-1.2
Total	100.0

Total emissions (Mt of CO_2-e)	AUS
2012	515.9
2050	761.9

Contact

Amandine Denis

Head of Research

amandine.denis@climateworksaustralia.org

ClimateWorks Australia
Level 1, 31 Flinders Lane
Melbourne VIC 3000
PHONE +61 3 9902 0741
EMAIL info@climateworksaustralia.org