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A Resilient Australia: Technical Appendix

Minderoo Foundation

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Deloitte
Access Economics

1 D.CLIMATE modelling framework

1.1 Measuring the impact of change

Modelling the economic impacts of the physical risks from climate change, and the economic impacts of mitigation and adaptation pathways, can be fraught, but not insurmountable. The economics discipline has spent several decades debating the benefits and limitations of the established techniques to derive economic estimates. While there remains many uncertainties and technical limitations on what macroeconomic models can reasonably conclude, economic techniques have improved to integrate views of the physical climate and economies to provide important insights into the choices that can be made to drive prosperity.

In this report, Deloitte Access Economics models the economic impacts of adaptation and resilience building initiatives in the context of a changing climate and Australia's response to it.

The modelling provides a view of how this change impacts the growth trajectory for Australia – the macroeconomic implications of persistent global average warming and climate change in contrast to an effective system transformation, **with adaptation and resilience as a fundamental component to Australia's climate response** in pursuit of global near net-zero emissions by 2050.

This report is not a forecast, but a scenario analysis:

1. It compares the costs of clear and deliberate actions on adaptation and resilience as a component of broader action on climate to a future where the costs of climate change are accounted for
2. It provides an indication of the magnitude of the challenge and the opportunity available from investments in adaptation and resilience and of decarbonisation
3. It is grounded in a framework that accounts for dynamic effects and interactions that would otherwise be missing in static frameworks.

1.2 D.CLIMATE modelling framework

D.CLIMATE – which has been tested in Australian state jurisdictions as well as globally – is a modelling methodology and policy analysis technique that seeks to 'correct' the typical business as usual baseline assumed in most modelling.

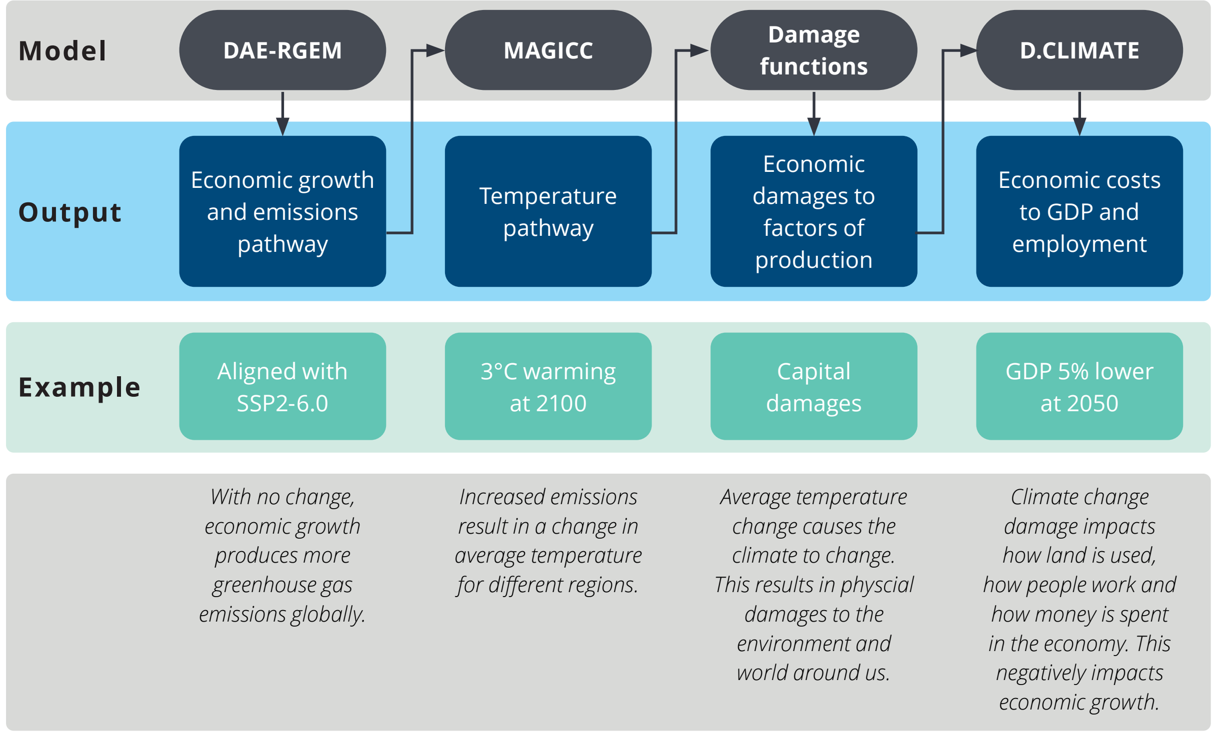
This model – that has been employed for this Report – is built on an economic modelling framework that accounts for the economic impacts of climate change and establishes a reference case that has been modelled to the year 2050.

The key innovation of this Report is the incorporation of climate adaptation and resilience in the context of decarbonisation.

The D.CLIMATE process and logic is as follows:

1. The modelling produces a baseline economic growth path which draws on short to medium-term Australian and global forecasts in combination with long run assumptions of contraction and convergence
2. The baseline economic growth path has an associated emissions growth path – derived from the established link between economic flows and emissions – and this corresponds to an evolution in atmospheric greenhouse gas concentration which rise in line with a Representative Concentrative Pathway (RCP)
3. Rising atmospheric concentrations of greenhouse gases causes global warming above pre industrial levels
4. Warming causes shifts in global climate patterns and natural disasters, resulting in damages to the factors of production (principally through affecting their productivity). Adaptation and resilience initiatives can help 'soften' some of these impacts
5. Damages to factors of production are distributed across the economy, impacting Gross Domestic Product (GDP)
6. These feedbacks become inputs back into the model to determine the associated deviation in economic activity associated with a given level of warming (i.e. the economic costs).

Figure 1.1 D.CLIMATE modelling process under the baseline



Source: Deloitte Economics Institute, Meinhausen et al.

Translating this concept into a modelling process involves three models which are linked through three key outputs. Deloitte Access Economics' approach extends methods adopted by the Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES), the International Panel on Climate Change (IPCC) and other research organisations.

The application of the D.CLIMATE methodology can also be extended by necessity for public policy purposes where additional specificity of regions is required. For example, the model allows results to be produced at the regional level – thereby capturing insights across specific geographic regions (e.g., Asia-Pacific), countries and even more granular statistical areas (e.g., local government areas).

For this study, the Australian geography was captured as a single model region in addition to several other global model regions used to capture trade flows. Throughout this paper, the terms geography and region are considered interchangeable.

The modelling process is summarised in the prior figure and in the points below:

1. Deloitte's in-house regional Computable General Equilibrium model (DAE-RGEM) is used to produce a projected path for economic output and emissions that aligns with a chosen RCP (refer to Figure 1.1, for a stylised representation of this model).
2. For each RCP scenario, the associated climate data (such as annual temperature increases and atmospheric concentrations) are sourced from a synthesis of the models available through the Coupled Modelling Intercomparison Project (CMIP6).[i]
3. This climate data becomes inputs into damage functions to inform how shifts in temperature may play out in terms of impacts on the stock and productivity of factors of production in each sector/region. Unlike most other models, a broad range of damages are modelled in D.CLIMATE, including capital damages, sea level rise damages to land stock, heat stress damages on labour productivity, human health damages to labour productivity, agricultural damages from changes in crop yields and tourism damages to net inflow of foreign currency.
4. Through a literature review, the potential ability of various adaptation strategies are characterised and applied to these economic damages where sensible and relevant to do so. These assumptions around adaptation benefits are listed in Section 3.

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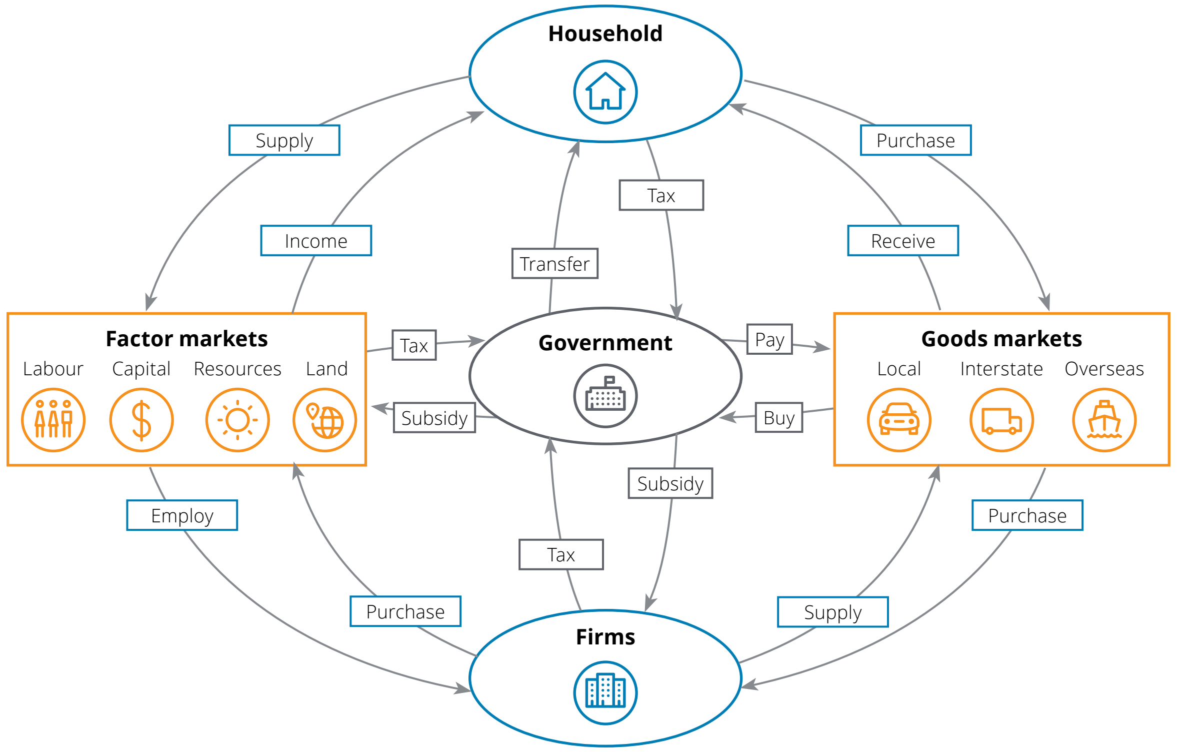
[i] Only models that permit commercial use are used.

Figure 1.2 Stylised representation of DAE-RGEM



Source: Deloitte Access Economics

1.3 Baseline economic assumptions

In the baseline, a set of assumptions have been applied for macroeconomic growth rates and technological improvements over the period 2015 to 2050. These key variables have been calibrated drawing on historical and forecast timeseries from various sources, detailed below.

1.3.1 Macroeconomic variables

Macroeconomic variables including GDP, population, labour supply and unemployment rate are calibrated for each year over the model period, 2015 to 2050.

Growth rates for GDP are calibrated drawing on the latest ABS and Deloitte Macroeconomic forecasts for Australia with data for global regions from the International Monetary Fund's (IMF) World Economic Outlook Database that provides historical and forecast GDP growth over the period 1980 to 2025. These growth rates are extrapolated using historical growth rates and assuming a degree of convergence over the long run.

Population growth rates are calibrated using a combination of data from the ABS, Deloitte,, and the IMF in the short-term and medium-term forecasts developed by the United Nations over the medium- to long-term. Labour supply is calibrated employing a similar approach and is assumed to broadly reflect trends in population growth.

Unemployment rates are calibrated using short-term forecasts developed by the ABS, Deloitte and the IMF. These are short-term forecasts and are extrapolated using a moving average. This approach implicitly assumes a steady state unemployment rate over the medium- to long-term.

1.3.2 Emissions, energy efficiency and productivity improvements

In the base year, once-off shocks are used to calibrate the energy mix for each region to ensure an accurate reflection of the current state of the energy mix between renewable and traditional sources. These shocks are calibrated drawing on data from the Department of Industry, Science, Energy and Resources (DISER) and drawing on data from Our World in Data for global regions.

The emissions trajectory for the baseline is calibrated to align broadly with an RCP6.0 emissions profile, developed by the Intergovernmental Panel on Climate Change (IPCC). RCP6.0 is chosen as an intermediate baseline scenario as it includes no specific or significant policy effort to mitigate, acting as an appropriate baseline for reference. Emissions are calibrated via uniform shocks to emissions efficiencies for all regions. Emissions for the Australian region are calibrated at the beginning of the model to reflect the level of emissions reported in the National Greenhouse Gas Inventory as published by DISER.

In addition to these specific calibrations, uniform energy productivity shocks are applied to clean energy sectors reflecting a continuation of the long-run improvement that has been observed to date and that is likely to occur in the future, even in the absence of further actions on climate.

1.4 Database: regions and sectors

The core economic data underpinning DAE-RGEM – the social account matrix (SAM) – is sourced from the Global Trade Analysis Project (GTAP) database.[1] In this instance, that economic data is supplemented with specific data on electricity differentiated by power generation type (i.e. coal, gas, solar, etc.) from the GTAP satellite database GTAP-Power as well as CO2 and non-CO2 emissions data. The behavioural parameters are also sourced from GTAP for the most part with some exceptions as discussed below.

This data is transformed in two key processes.

1.4.1 Regional aggregations

D.CLIMATE is a global model and can be tailored to a specified regional concordance in line with the Global Trade Analysis Project (GTAP) database.

Deloitte Access Economics has undertaken several climate studies in recent years and with each study, continually seeks to improve the granularity and specificity of the underlying database. For this project, the most recent and advanced version of the D.CLIMATE database was chosen that incorporates recent innovations and refinements to key model parameters reflective of recent scientific and economic research on emissions responses and industry abatement tasks. This database identifies several global regions in addition to Australia, with most of these located in the Europe geography. These global regions interact with Australia in an international trade flow capacity but do not materially impact results if specified differently.

1.4.2 Sectoral aggregations

D.CLIMATE can also be tailored to a specified sectoral concordance in line with the Global Trade Analysis Project (GTAP) database.[2] For this project, a sectoral aggregation was chosen that provides a broad view of the impacts on various key sectors of the Australian economy.

The sectoral concordance for this study is presented in Table 1.1, below.

Table 1.1 Sectoral concordance

Aggregate sector	Sector name	GTAP sector(s)
Agriculture, forestry & fishing	Agriculture & fishing	Paddy rice
		Wheat
		Cereal grains nec
		Vegetables, fruit, nuts
		Oil seeds
		Sugar cane, sugar beet
		Plant-based fibers
		Crops nec
		Bovine cattle, sheep and goats, horses
		Animal products nec
		Raw milk
		Wool, silk-worm cocoons
		Fishing
	Forestry	Forestry

Aggregate sector	Sector name	GTAP sector(s)
Mining & Gas	Coal	Coal
	Oil	Oil
	Gas	Gas
	Other mining	Other Extraction (formerly Minerals nec)
Manufacturing	Food manufacturing	Bovine meat products
		Meat products nec
		Vegetable oils and fats
		Dairy products
		Processed rice
		Sugar
		Food products nec
		Beverages and tobacco products
	Light manufacturing	Textiles
		Wearing apparel
		Leather products
		Wood products
		Paper products, publishing
	Heavy manufacturing	Chemical products
		Basic pharmaceutical products
		Rubber and plastic products
		Mineral products nec
		Ferrous metals
		Metals nec
		Metal products
		Computer, electronic and optical products
		Electrical equipment
		Machinery and equipment nec
		Motor vehicles and parts
		Transport equipment nec
		Manufactures nec
Clean energy	Hydrogen	Petroleum, coal products*
	Bio-energy (carbon-neutral)	Petroleum, coal products*
	New energy sector	Nuclear base load
		Wind base load
		Hydro base load
		Hydro peak load
		Solar peak load
Conventional energy	Petroleum, coal products	Petroleum, coal products
	Electricity transmission and distribution	Electricity: Transmission and distribution
	Fossil fuels	Coal base load
		Gas base load
		Oil base load
		Other base load
		Gas peak load
		Oil peak load
	Gas manufacture and distribution	Gas manufacture, distribution
Water & utilities	Water	Water
Construction	Construction	Construction
Retail trade & tourism	Retail trade & tourism	Trade
		Accommodation, Food and service activities
Transport	Transport	Transport nec
		Water transport
		Air transport
		Warehousing and support activities
Services	Other services	Communication
		Financial services nec
		Insurance (formerly isr)
		Real estate activities
		Business services nec
		Recreational and other services
		Dwellings
	Government services	Public Administration and defense
		Education
		Human health and social work activities

Notes: ‘nec’ is not elsewhere classified. The Hydrogen and Bio-energy sectors are not identified as individual sectors in the GTAP database but have instead been distinctly separated from the petroleum, coal products sector.

2 Estimating the physical damages

The future of climate change is inherently uncertain. The rate at which CO2 and other pollutants accumulate in the earth's atmosphere could follow any number of trajectories, with each leading to a wide range of physical climate effects varying in both scope and scale. What is certain, however, is that the average global temperature has been rising and will likely continue to rise until a sustained and concerted effort is made to decarbonise globally. In the IPCC's Fifth Assessment Report, four Representative Concentration Pathways (RCPs) were selected as plausible future GHG emissions and atmospheric concentration trajectories extending out to 2100. These emissions pathways are as follows:

- RCP2.6 (assumes stringent decarbonisation),
- RCP4.5 and RCP6.0 (two central scenarios), and
- RCP8.5 (a high GHG emission scenario).

In the IPCC's Sixth Assessment report, these purely climatic scenarios based on emissions trajectories, radiative forcing and temperature change have been combined with a consistent set of socioeconomic 'narratives' known as Shared Socioeconomic Pathways. These provide further assumptions around population and economic growth, energy use and land use among others.

Data from the RCP6.0 climate scenario has been integrated in D.CLIMATE, representing the baseline state. RCP6.0 represents an economic future with a relatively high rate of GHG emissions and no further actions to constrain emissions beyond those already taken. The economic and emissions profile consistent with RCP6.0 has the potential to result in an increase to global average temperature in excess of 3°C.[3]

2.1 MAGICC and temperature as the fundamental driver of damages

The fundamental 'driver' of economic damages is rising temperature. As rising temperature induces climate change and extreme weather events, economic output (as measured by GDP) is impacted through the physical damages that affect productivity and/or the stock of productive factors Figure 2.1 below.

This study includes six regionalised damages to Australia:

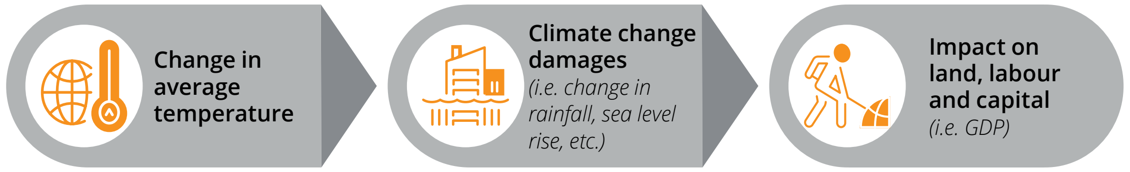
1. Heat stress damages to labour productivity
2. Human health damages to labour productivity, including loss of lives associated with natural disasters
3. Sea level rise damages to land and capital stock
4. Damages to capital stock from climate disasters
5. Agricultural damages from changes in crop yields
6. Tourism damages to net inflow of foreign currency

These regionalised damage functions are outlined in the following sections and draw on outputs from a global climate model – MAGICC (refer next section).

2.2 Climate model

Emissions produced by Deloitte's DAE-RGEM model are translated into global mean surface air temperature (GSAT) relative to pre-industrial (1750) period based on these emissions trajectories using a reduced complexity climate model. Specifically, the D.CLIMATE framework utilises outputs from the Model for the Assessment of Greenhouse Gas Induced Climate Change (MAGICC) as described in Meinshausen et al. (2011) and Meinshausen et al. (2020), and configured by Nicholls et al (2021).[4] This climate model was used as part of the IPCC's Sixth Assessment report.

Figure 2.1 'Two-stage' economic damages relationship



Source: Deloitte Economics Institute.

2.2.1 Heat stress damages to labour productivity

A working environment which is "too hot" can negatively affect the health and safety of workers, as well as restrict their ability to perform tasks and limit their productive capacity. For jobs where tasks are performed outdoors, it can be difficult for workers to moderate their heat exposure. The same can be true for indoor jobs where air-conditioning is not readily accessible.

Climate change is expected to see average global temperatures continue to rise, leading to shifts in the distribution of daily peak temperatures and relative humidity. Altogether, this means that heat waves are likely to become more frequent and increasingly extreme for many countries.

When workers exert energy to perform physical tasks, their bodies produce thermal energy and begin to heat up internally. For body temperature to be maintained at a healthy level, thermal energy needs to be transferred to a cooler external environment. If body temperature exceeds 39°C, heatstroke can develop, and temperatures exceeding 40.6°C can be fatal. However, before these serious health effects occur, at lower levels of heat exposure, workers can experience diminished "work capacity", mental task ability, and increased accident risk.

To continue functioning at elevated body temperatures, workers can take instinctive actions to reduce their work intensity or increase the frequency of short breaks. This "slowing down" of activity (whether it occurs through self-instinct or occupational health management interventions) results in reduced "work capacity" and lower labour productivity.

This analysis estimates the effect of rising temperatures and changing relative humidity levels on labour productivity using wet bulb globe temperature (WBGT) as a measure of heat stress. For this project, analysis is conducted at an Australian geography level. It is assumed that changes in labour productivity (economic concept) are equal to changes in estimated work capacity (physiological concept).

The methodology follows an approach proposed by Kjellstrom et. al. (2017). This approach utilises a series of functions describing the relationship between WBGT and labour productivity across three different work intensities: 200W (equivalent to light manual labour, such as office work), 300W (equivalent to moderate manual labour, such as manufacturing) and 400W (equivalent to high intensity manual labour, such as farming). Relationships have been determined by Kjellstom et al. (2017), based on a review of epidemiological datasets.

Workers in each GTAP sector are assumed to perform tasks at one of the three work intensities specified above. GTAP sectors have been allocated to specific work intensities based on internal advice from Deloitte subject matter experts. The significance of the heat stress damage function is sensitive to the allocation of these work intensities across sectors.

Consistent with the approach proposed by Kjellstrom et. al. (2017), it is assumed that a region's WBGT varies over three 4-hour intervals comprising the approximate 12 hours in a working day:

1. Early morning and early evening: 4-hours at WBGT mean (calculated using average monthly temperature)
2. Middle of the day: 4-hours at WBGT max (calculated using average monthly maximum temperature)
3. Hours in between: 4-hours at WBGT half (calculated as the mid-point between WBGT mean and WBGT max)

TThese three variants of WBGT have been projected at monthly intervals using the simplified WBGT index, sWBGT, based on surface temperature and water vapour pressure (developed by the Australian Bureau of Meteorology). Water vapor pressure was derived using estimates of relative humidity and the corresponding surface temperature.

Labour productivity is then estimated for each region at monthly intervals, across each of the three 4-hour intervals assumed to comprise the working day. The mean of these three estimates is then taken to represent the average labour productivity for workers throughout the working day. Workers are assumed to maintain the same level of productivity for all days contained within each month. Monthly labour productivity estimates are then averaged to give an aggregate measure of labour productivity for each year in the modelling period.

2.2.2 Human health damages to labour productivity

The impacts of climate change on human health are many and complex. Increasing temperatures can increase heat-related health problems, particularly those with pre-established cardiovascular and respiratory disorders. Increasing temperatures can also reduce cold-related health problems, again most prevalent in people with cardiovascular disorders.

Climate change can impact the range, abundance and dispersion of species carrying diseases. Studies generally agree that the prevalence of Malaria increases alongside temperature increases. Other vector-borne diseases may increase or decrease. Climate change would allow diseases to invade immunologically naïve populations with unprepared medical systems and would affect food- and waterborne diseases, with cholera and diarrhoea being potentially most problematic.

As extreme weather events become more severe and frequent, so too does the threat they present to human populations also rise. Climate change can affect air quality, leading to greater incidence of diseases caused by air pollution – the 2020 summer of bushfires in Australia are a stark reminder of this. Climate change may also affect human health indirectly, through changes in food production, water resources, migration and economic development.

Human health is therefore prominent in estimates of future climate change impacts. The welfare costs (or benefits) of health impacts contribute substantially to the total costs of climate change. Many estimates of economic damages rely on direct cost methodologies (i.e., price times quantity). With regards to human health, the price is typically equal to the value of a statistical life, based on estimates of willingness to pay to reduce the risk of death or diseases, or the willingness to accept compensation for increased risk. However, these methods ignore the human health impacts on labour productivity and the demand for health services.

The approach adopted for this analysis is an adaption of work undertaken by Roson & Sartori (2015), which is based on Bosello et al. (2006), by considering some vector-borne diseases (malaria, dengue, schistomiasis), heat and cold related diseases, and diarrhoea. It does not consider other diseases and impacts mentioned in the IPCC AR5 (2014), such as, heat exposure effects on labour productivity (separately considered), haemorrhagic fever with renal syndrome, plague, chikungunya fever, Japanese and tick-borne encephalitis, cholera and other (non-diarrhoea) enteric infections, air quality and nutrition related diseases, allergic diseases, and mental health.

The starting point of the analysis presented in Bosello et al. (2006) is a meta-analysis of the epidemiological, medical and interdisciplinary literature to achieve the best estimates for the additional number of extra cases of mortality and morbidity associated with a given increase in average temperature. The information obtained in this research has been combined with data on the structure of the working population, to infer the number of lost working days. The changes in morbidity and mortality are interpreted as changes in labour productivity.

Roson & Sartori (2015) update the work of Bosello et al. (2006) to account for recent literature on health impacts and studies mentioned in IPCC (2014, scaling up or down the variations in labour productivity.

The results of these studies are expressed as changes in average labour productivity for a +1°C increase in temperature (implicitly assuming that the relationship is approximately linear). For the purposes of this analysis, and to understand the relationship between human health impacts, an increase in average temperature and time, we regressed the variables to find an equation with a satisfactory fit for the relationship.

The analysis estimates the flow-on economic effects (or indirect costs) of human health impacts, variations in labour productivity. It is important to note that this methodology excludes induced demand for health care that could have ambiguous impacts on the economy – i.e., while greater sickness and strain on health resources would undoubtedly be a negative for the cost of healthcare provision, this would be correlated with increased economic activity in the health sector and may reflect a positive impact to GDP.

A key innovation for this project included augmenting the existing human health damages to capture the loss of life associated with the occurrence of extreme heatwaves. This process involved drawing on a study of heatwave deaths under climate change scenarios, specifically estimates of the historical deaths due to heatwaves in Australia and the mean percent change of heatwave-related excess deaths estimated as part of this study. Only those deaths estimated to occur in working age people were captured in the CGE framework as a loss in the stock of labour. This represents a key addition to the D. CLIMATE modelling framework and fills a gap that till now was not covered by other damage functions and is particularly relevant in the Australian context.

While the addition of heatwave deaths represents an important addition to the human health damage function, there are still several omissions not captured in this modelling. These omissions represent human health impacts that are difficult to quantify due to a lack of data that links prevalence to disease/death/injuries with temperature pathways. Examples include the health effects of bushfire smoke on respiratory diseases, mental health impacts, lives lost, and injuries associated with other types of extreme weather events (not heatwaves).

2.2.3 Sea level rise damages to land and capital stock

As average global temperatures continue to rise, land-based glaciers are melting, and water bodies are experiencing thermal expansion. Together, these factors cause the phenomenon of sea level rise (SLR).

SLR can impact a geography's total stock of land (an economic factor of production) through a combination of erosion, inundation, and salt intrusion along the coastline. As the global stock of land declines due to SLR, productive activity that would otherwise occur on that land is also foregone.

The extent of land lost to SLR will depend on several geography-specific characteristics, including (i) the composition of the shoreline (cliffs and rocky coasts are less subject to erosion than sandy coasts and wetlands), (ii) the total length of the coastline, (iii) the share of the coast which is suitable for productive purposes (i.e., in agriculture or urban land), and (iv) the vertical land movement (VLM).[iii]

This report estimates land area lost due to SLR using a methodology proposed by Roson & Sartori (2016), who estimated the mean SLR (in metres) associated with global mean surface temperature change from a series of regressions based on data within the IPCC AR5 Report, while also accounting for vertical land movement.

The proportion of agricultural land lost per metre of SLR is then estimated based on the findings of Roson & Sartori (2016), as well World Bank data describing the extent of Low Elevation Coastal Zones (LECZ) for each region. The proportion of LECZ used for agricultural production in each geography is assumed to be equal to the proportion of total land area used for agriculture in that same geography.

This analysis extends the Roson & Sartori (2016) methodology to also capture urban land area lost due SLR, again leveraging World Bank data describing the extent of urban area in LECZ. In low lying and seacoast urban areas, residential and commercial properties may incur physical damages and require significant capital investment to repair. Economic activity that would otherwise occur in these urban areas will also need to transition to other geographies.

The process for estimating both components is as follows:

- The percentage of effective land area lost per metre of SLR is calculated by multiplying the following factors: the percentage loss in coastal wetland (a proxy for loss of land due to SLR, estimated by HadCM3 climate model under the A1b SRES scenario),[5] the LECZ area, the percentage of erodible coast and relevant coastline.
- Considering which proportion of total coast is suitable for agricultural(productive)/urban purposes, the percentage of effective land change is adjusted by agricultural land area/urban land area.
- The percentage change in agricultural and urban land stock is computed by multiplying the percentage of effective land change by metre of SLR and the estimated SLR.

[iii] VLM is a general term for all processes affecting the elevation at a given location (tectonic movement, subsidence, ground water extraction), causing the land to move up or down. Local VLM is relevant when looking at local effects of SLR.

2.2.4 Capital damages

This study captures climate induced capital damages as a function of increasing global mean average temperature. Capital damages in this context, consider the impact of riverine flooding, coastal inundation, forest fires, subsidence, high wind speeds (including cyclone), storms and hail climate events on physical capital, including dwellings, infrastructure and machinery and equipment.

Accounting for capital damages in this way represents a departure from existing economic impact modelling and integrated assessments of climate change. In some cases, capital damages are included but at a highly aggregated level that limits regional analysis. Often, reports discuss the exposure or risk of countries and regions to capital damages but do not attempt to monetise an impact.

The methodology used in this report employs data produced by XDI modelling of climate change impacts on Australia's physical capital stock. Global databases monetising climate induced capital damages are uncommon and those that exist are difficult to integrate into an IAM framework. As a result, Australia specific data is used to infer capital damages in other regions through a process of climate matching, controlling for key regional differences such as physical capital density and distribution.

This XDI data only captures a subset of the full climatic events that were of interest for this project and so estimates of economic damages from the Australian Business Roundtable Deloitte report were also used to adjust the XDI data to reflect a more complete suite of capital damages.[6] Specifically, the XDI database captures damages to the physical built environment due to riverine flooding, coastal inundation, forest fires, subsidence and high wind speeds (excluding cyclones). Data from the Australian Business Roundtable report was used to capture the impacts of cyclones, storms and hail events.

The XDI data provides estimates for total technical insurance premiums at the LGA level – akin to a monetised capital damage by LGA. These LGAs are subsequently categorised by key climatic characteristics including temperature and precipitation to form several sub-groupings. The categorisation of LGAs is largely informed by climate maps produced by the Australian Building Codes Board and are derived from climate data published by the Australian Bureau of Meteorology.

Data on climate characteristics (average temperature, precipitation, etc.) are then gathered for Australia and other model regions (country level). Drawing on this data and an updated Köppen-Geiger climate classification map (a concept frequently applied in climate research), each of the countries and regions are categorised into comparable climate groups based on the Australian LGAs.

A natural log-log model is produced for each country drawing on data for Australian LGAs with similar climatic characteristics and predicted global mean average temperature increases under an RCP 6.0 emissions pathway. This regression controls for differences in physical capital density across LGAs. The estimated damages produced by this research can be interpreted as a percentage of annual capital investment that is diverted to repair and replace damages assets due to an associated rise in average temperature in a region.

Estimated capital damages are produced at a country level and are aggregated to focus regions using regional shares of capital stock, proxied by population distribution.

2.2.5 Agriculture

Climate change will see rising temperatures, higher concentrations of carbon dioxide (CO2) in the atmosphere and different regional patterns of precipitation. These factors all affect crop yields and agricultural productivity.

The effects of climate change on agricultural productivity are one of the most studied areas of climate change impacts. Yet, despite the many existing studies and the extensive empirical evidence, it is still difficult to identify some sort of "consensus" for the impacts of climate change on agricultural productivity. There are many factors at play, including the role of adaptation behaviour by farmers, firms and organisations, including variety selection, crop rotation, sowing times, the amount of fertilisation due to higher CO2 concentration, and the actual level of water available for irrigation, and irrigation techniques.

Modelling the economic consequences of yield changes to understand the consequences of climate change impacts on agriculture is important for two main reasons. Firstly, varying capacities for agronomic and economic adaptation exist in the agricultural sector; farmers can adjust how they grow a particular crop, the location and timing of crop growth will shift in response to climate change impacts, trade in agricultural commodities will adjust and consumers are able to substitute goods as prices adjust. Each of these adaptive responses will mediate the impacts of yield changes. Secondly, climate change impacts will vary by crop and by region, changing the comparative advantage of countries, leading to highly place-based outcomes across global agricultural markets.

The approach undertaken in this analysis is one which provides an estimate of productivity changes for the whole agricultural sector across the modelled regions. The methodology is based on the Mendelsohn and Schlesinger (1999) reduced form Agricultural Response Functions in the formulation proposed by Cline (2007), where the variation in output per hectare is expressed as a function of temperature, precipitation, and CO2 concentration.

This method has been augmented as a key innovation for this project to incorporate the acute instances of drought impacts on agriculture. This process involved drawing on a study from the Centre of Policy Studies that estimated the regional economic impacts of droughts in Australia and estimated changes in the frequency of drought occurrences.[7]

2.2.6 Tourism damages to net inflow of foreign currency

Climate induced tourism damages are driven by changes in net visitor flows and expenditure. In D.CLIMATE, changes to net visitor flows and expenditure are fundamentally driven by the exposure of each region to climate change. As such, regions with a greater exposure to adverse climate change – in terms of average temperature – experience relatively more severe tourism damages.

To estimate tourism damages in D.CLIMATE, functions that relate visitor arrivals and departures to average temperature are employed. These functions are consistent with those employed by Roson & Satori and are derived from econometric models expressed in terms of land area, average temperature, length of coastline, per capita income and the number of countries with shared land borders. This approach yields global parameters that are assumed consistent with Australia. Forecast average temperatures are used as inputs to these functions to determine a resulting net flow of foreign currency.

The magnitude and persistence of tourism damages are also a function of the economic structure of each region's economy.

3 Estimating the benefits of actions on climate change

The climate response scenario reflects a world of global decarbonisation with specific investment in adaptation and resilience initiatives incorporated. In this world, the economy shifts away from emissions-intensive production and invests in new energy sectors.

3.1 Estimating the benefits of mitigation

Efforts to reduce global emissions of greenhouse gases in the scenario reflect coordinated global action towards deep decarbonisation and near net-zero by 2050. Reductions in greenhouse gas emissions have a direct impact on the future increase in global average temperature and a reduction in the burden of climate on economic activity – as reflected in D.CLIMATE through damage functions.

These benefits of mitigation are achieved and realised in D.CLIMATE through three key mechanisms that facilitate a transition away from the emissions-intensive economic activity of today to a decarbonised low-emissions economy of tomorrow. These three mechanisms reflect a combination of industry innovation and government policy that enable and facilitate a smooth transition for Australian industry and are explored in greater detail in the following sub-sections.

3.1.1 Emissions constraint

The transition to a low-carbon economy has been modelled as one in which policy makers set clear and ambitious targets. These are implemented as constraints on the total level of emissions in each region such that global and regional emissions are reduced at a rapid rate over the next 30 years broadly consistent with the budget prescribed in the RCP2.6 scenario.

The emissions constraint forms a shadow price on carbon such that processes which have associated emissions – like the combustion of coal to produce electricity – become more expensive. Those processes which don't have associated emissions – like the generation of electricity from renewables – don't face this price increase.

Relative price changes such as these lead to changes in behaviour – like the switching from fossil fuel-based electricity generation to renewables. As these changes aren't seamless, the combined effect of them is to impose an aggregate cost on each economy which is known as the shadow price of carbon. This isn't the same as a legislated carbon tax, or a traded emissions price, but it is analogous in that it represents the projected price at which a given reduction in emissions can be achieved.

3.1.2 Clean electricity productivity improvements

The scenario also involves the introduction of learning rate-based productivity improvements for renewables, hydrogen and bio-energy. It also involves the introduction of gradual reductions in emissions which are not a function of fuel choice (like fugitive emissions in agriculture).

The case for cost reductions in zero emission fuel sources is based on the concept of learning by doing articulated first by Kenneth Arrow in 1962. The first step of the simulation provides a guide to the potential uptake of each technology which is then used in determining the appropriate rate of productivity-induced cost reduction to impose.

There is a significant portion of the global and regional emissions inventory which can not be reduced through the kind of price-based switching described above. Examples include fugitive emissions from mining, industrial process emissions from the production of cement and factor-based emissions from livestock farming. These emissions will need to be removed through changes in production processes like, for example, the adoption of methane-reducing feed additives for livestock. These changes will not be costless, but there is inherent uncertainty regarding how these processes will be developed and what each will cost.

3.1.3 Transition assistance

The scenario involves coordinated government investment to offset structural adjustment costs in industries and regions as decarbonisation accelerates. The investment is targeted at industries which are neither emissions-intensive nor in high demand as the world decarbonises. For example, coordinated government effort does not go to emission intensive conventional energy or emerging clean energy as they primarily respond to price and changing demand.

Coordinated government transition assistance does, however, reflect economic and regulatory settings that create new economic activity for economies to transition into. This smooths the structural disruption to economies and their workforces, resulting in increased job creation earlier in the phases of decarbonisation.

This exists both in current policy commitments, such as the European Green Deal and the Regenerate EU programs and is likely to feature prominently in fiscal policies of national governments throughout a transition to 2050.

A failure to provide coordinated transition assistance increases the cost of the transition for industry, and most significantly for those employed in those industries.

3.2 Estimating the benefits of adaptation

The focus of this project and a key innovation from prior Deloitte modelling has been the incorporation of adaptation and resilience in consideration of climate damages. The integration of these initiatives into the scenario results in 'softened' climate damages – reflecting the greater resilience and fortification of Australian industries in response to natural disasters and chronic impacts from climate change.

Adaptation and resilience initiatives are, by nature, diverse and range from potentially low-cost and relatively fast-to-implement initiatives such as early warning systems or community outreach programs to potentially higher-cost or longer-term initiatives such as changes to building codes and construction requirements.

To incorporate the benefits of adaptation and resilience, a three-stage process was taken that included a review of the available evidence-base for adaptation to ascertain the proportion of economic damages from various types of climatic events that could plausibly be negated as a direct result of adaptation and resilience initiatives (refer Figure 3.1).

Figure 3.1 Adaptation and resilience modelling framework

STAGE 1 – Literature scan

- A review of the available evidence-base for adaptation provided a basis for estimating the potential benefits of adaptation strategies in reducing the negative impacts of natural disasters on the economy
- This review of the available evidence-base was conducted through the lens of the IPCC's adaptation framework and considered various adaptation strategies including those structural / physical, social and institutional in nature

STAGE 2 – Mapping of adaptative strategies

- Of those adaptation strategies with quantified reductions in cost, a mapping process was undertaken to tie each adaptation strategy to the six damage functions in D.CLIMATE
- This matching process was largely driven by an understanding of the climate events / natural disasters captured under each of the D.CLIMATE damage functions and those covered by the adaptation strategy considered

STAGE 3 – Incorporated into modelling

- An adoption pathway was assumed for each of the adaptation strategies that reflects the time required for a strategy to become 'proliferated' or 'widespread'
- Importantly this pathway reflects one of many possible futures but was chosen to reflect collective and deliberate actions by government and businesses, today
- The potential reductions in the cost of climate events is then applied to the relevant climate damage function identified in Stage 2

Source: Deloitte Access Economics

3.2.2 Literature scan and mapping

There is a breadth of adaptation strategies that can be utilised by businesses, governments and individuals to build a more resilient Australia at the national, regional and local community level. A detailed literature review on a variety of adaptation strategies was undertaken to assess the potential reduction to damages from implementing a strategy. This evaluation was done through the lens of the IPCC's adaptation framework, which identifies three 'types' of adaptation - structural, social and institutional. This IPCC framework enables various types of adaptation strategies to be categorised into distinct groupings.

While a detailed scan of adaptation strategies and their associated damage reduction was undertaken for each natural disaster type, some strategies are inherently better researched than others. This meant there was a limited number of studies that quantified the reduction in damages resulting specifically from the adaptation strategy, and of those studies that did, only those with a strong evidence base were used for modelling purposes. Consequently, of the list of possible adaptation strategies identifiable under an IPCC framework, only a subset has been modelled.

To allow the damage functions to be reduced in the model, each data point is matched to a damage function/s where relevant. The relevant damage function for each adaptation strategy considered is detailed in Table 3.1. In cases where there are multiple data points for each damage function, a weighted average based on the cost of natural disasters/climate events was used to ensure that the reduction applied to each damage function represented the range of strategies that could be implemented and the range of climate events that each damage function captures.

Consideration of alternative approaches

There are a range of economic techniques that could be used to explore the benefits of adaptation strategies. For instance, cost benefit analysis could be used to evaluate the benefit-cost-ratio (BCR) or net present value (NPV) from investments in adaptation. However, these alternative techniques would require greater detail in the estimation of the costs to implement adaptation strategies and as such were not considered.

The advantage of the D.CLIMATE and CGE framework in this context is the ability to capture dynamic effects. Namely, the impact of climate change and transition policy on the supply and demand of productive inputs and prices as well as the long-term nature of the modelling with consideration for changing preferences and pricing incentives across time, allowing for a more nuanced reflection of the complexities associated with climate change and climate policy.

Table 3.1: Damage reduction from various adaptation strategies

Climatic event	Adaptation category	Adaptation strategy	Potential reduction to damages	Damage function
Drought	Structural: Technological	Applying water saving technologies such as rainwater harvesting and the use of water efficient appliances to increase water-use productivity	15% reduction in damages to capital[8] 17.5% reduction in losses due to drought[9]	Agriculture, capital
	Institutional: Laws and regulations	Establishment of water regulations such as interregional water markets	20% - 30% reduction in losses due to drought[10]	
Heatwave	Social: Informational	Establishing an early warning system of a coming heatwave	30% reduction in damages to assets and the loss of lives[11]	Heat stress
Bush fires	Structural: Ecosystem based	Establishment of a prescribed burning regime	67% - 97% reduction in damages to capital[12]	Capital
Storm	Structural: Engineered and built environment	Implementation of wind design standards for all new housing	50% - 80% reduction in damages to capital[13]	
	Structural: Engineered and built environment	Introduction of building codes requiring houses to be structurally designed to resist wind loads	67% reduction in damages to capital[14]	
	Social: Informational	Establishing an early warning system of a coming storm	30% reduction in damages to assets and the loss of lives[15]	
Hail	Structural: Engineered and built environment	Placement of a hail net above an orchard	60% reduction in damages to capital[16]	
Cyclone	Structural: Engineered and built environment	Implementation of wind design standards for all new housing	50% - 80% reduction in damages to capital[17]	
	Structural: Engineered and built environment	Introduction of building codes requiring houses to be structurally designed to resist wind loads	67% reduction in damages to capital[18]	
Flood	Structural: Engineered and built environment	Introduction of flood proofing measures to commercial properties	50% reduction in damages to capital[19]	
	Structural: Technological	Introduction of effective flood warning system	15% reduction in damages[20]	
	Social: Behavioural	Establishment of a comprehensive flood action plans	80% reduction in damages to stock and equipment[21]	
Sea level rise	Structural: Engineered and built environment	Instalment of coastal protection structures such as dikes	99.5% reduction in impacts to GDP[22]	Sea level rise
	Institutional: Government policies and programs	Investment in urban greening such as lining, irrigating, public open space with water and restoring wetlands	74% reduction in damages to productivity[23]	

Source: Deloitte Access Economics

3.2.3 Mapping

Drawing on the available evidence-base for adaptation strategies outlined in Section 3.2.2, a damage reduction potential was applied to each of the six damage functions in D.CLIMATE. Detail on the specific reductions applied and the adaptation strategies considered for each is provided below with timing discussed separately in Section 3.2.4.

3.2.3.1 Agriculture

Economic damages to agriculture are assumed to be reduced by up to 21% by 2050. This reduction reflects research into the potential benefits of technological adaptation (water saving technologies) and regulation adaptation (water regulation) to reduce the annual costs (capital and operational) that can accrue to the agricultural industry because of drought.

3.2.3.2 Health

Economic damages associated with health comprise of impacts from the prevalence of vector-borne disease and the loss of life impacts associated with heatwaves. The prevalence of disease in this context dominates the contribution of impacts from heatwaves.

While the research supporting the link between adaptation strategies such as early warning systems for heatwaves and the ability to save lives, the nexus between adaptation strategies and the ability to reduce the prevalence of disease is less well researched.

It is possible that investments in adaptation could lead to reductions in disease (e.g. land works or flood barriers could help reduce the persistent presence of floodwater and potentially the breeding and spread of mosquito-borne disease near populous regions); however, a causal link is not well defined in the available literature.

As such, only the reduction in loss of life available through the utilisation of early warning systems was captured. These are assumed to reduce loss of life by up to 30% by 2050. The result is that the economic damages associated with health are reduced by around 2% at 2050 (weighted by significance of heatwave deaths in terms of total health damages).

3.2.3.3 Capital

Economic damages to capital are assumed to be reduced by up to 56% by 2050. This reduction represents a weighted average (by cost of natural disasters / climate events covered) of several adaptation strategies reflecting the broad nature of the capital damage function and the natural disasters that are covered. Specific adaptation strategies considered include infrastructure adaptation (flood proofing measures, wind design, building codes, hail nets for agriculture), technological adaptation (early warning systems), behavioural adaptation (flood action plans) and ecosystem-based adaptation such as prescribed burns for bushfires.

3.2.3.4 Sea level rise

Economic damages to capital and productive land arising from sea level rise are chronic in nature and are assumed to be reduced by up to 87% by 2050. This reduction in economic damages reflects infrastructure adaptation (coastal protection structures) and government policies and program adaptation (e.g. urban upgrading, large trees, irrigation, public spaces, restoring wetlands etc.). They also reflect behavioural changes and the availability of alternative productive land. Whilst being the most effective adaptation strategy in terms of absolute reduction, sea level rise remains the smallest of the economic damages captured in the D.CLIMATE framework and consequently, the impact of adaptation specific to sea level rise remains marginal in terms of its impact on economic activity despite the effectiveness of adaptation strategies in reducing negative impacts.

3.2.3.5 Heat stress

The economic damages that arise due to warming temperatures and heat stress are assumed to be reduced by up to 30% by 2050. This reduction represents largely behavioural changes in working patterns and informational adaptation such as early warning systems.

3.2.3.6 Tourism

The nexus between adaptative strategies and the impact on international tourism flows is an area in the literature that is not well researched. There are several factors that can influence a person's decision to visit a particular country (such as cost, attractions, climate, sights, perceptions). It is true that natural disasters such as the Australian bushfires can lead to marked declines in overseas visitor numbers.[24] It is also true that adaptation strategies can reduce the negative impact of natural disasters on the Australian economy including the built environment. However, the causal link between adaptation strategies and their ability to directly influence overseas tourist numbers is not well defined in the literature. Consequently, no benefits of adaptation have been accounted for through tourism damages.

3.2.4 Incorporating adaptation and resilience into D. CLIMATE

In practice, adaptation and resilience initiatives are incorporated into the D. CLIMATE model as a reduction in the economic burden of each damage function discussed in Section 2 of this Appendix. This requires a view on two aspects:

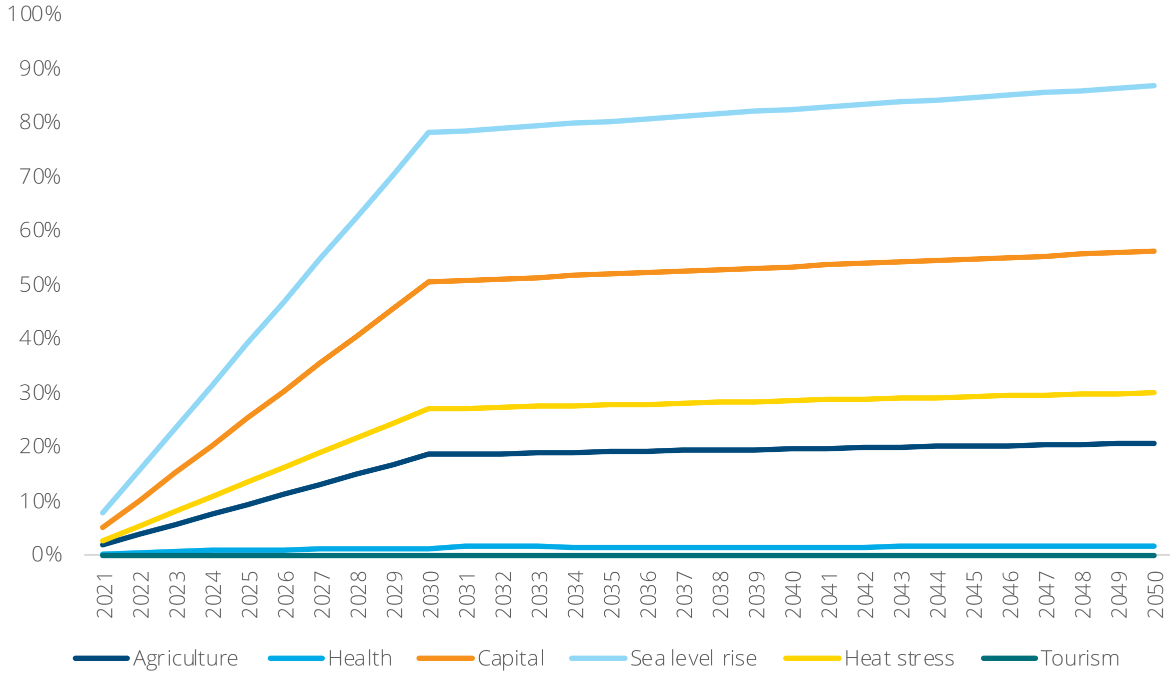
- The **maximum potential reduction** in each damage function achievable through relevant adaptation strategies as determined through the process described in Section 3.2.2
- The **timing** in which these reductions can reasonably be achieved across each damage function

Whilst the future is inherently uncertain, this scenario reflects one of many possible futures for adaptation and resilience that reflects coordinated efforts by government and business, from today.

Importantly, adaptation and resilience are assumed to yield benefits immediately but take time to proliferate across each damage function. In practical terms this could be interpreted like an adoption rate or market penetration rate. A tangible example could be a change to building codes that takes time to filter through new builds to the stock of housing. On the other hand, some forms of adaptation can be implemented early and lead to adaptation benefits that are experienced almost immediately (such as greater investment in early warning systems for various disasters).

The scenario modelling assumes that much of the total potential of adaptation in each context is achieved in the first decade. Benefits continue to grow over the proceeding decades to 2050 but at a much slower rate than that experienced in the first decade. The assumed magnitude and timing of the reductions in economic damages by damage function are detailed in Chart 3.1, below.

Chart 3.1 Assumed proportion of economic damages by damage function able to be avoided through adaptation and resilience initiatives



Source: Deloitte Access Economics

3.3 Discounting the future

It is inherently difficult to ‘discount’ the future, particularly concerning an issue as socially and economically complex as global climate change.

In considering this issue, it is important to recognise the intergenerational impact of climate change on society and in doing so, how to value ‘income’, ‘consumption’, ‘utility’ or ‘wellbeing’ at one point in time relative to another. In comparing these conditions across generations, the discount rate must reflect a preference for short-term consumption over the long-term and the opportunity cost of saving.

In determining the rate, the question becomes what rate is appropriate to embody these preferences in estimating the net present value of impacts to economies and societies from climate change and various climate change responses including adaptation.[25]

Greenhouse gas emissions have a long residence time in the atmosphere, which means that the value of the impacts of today’s emissions must be considered for future generations. Equally, policy responses regarding mitigation and adaptation to altered climatic conditions, impact future generations significantly. In this context:[26]

- The use of a *high discount rate* implies that society put less weight on future impacts and therefore less emphasis on guarding against such future costs.
- The use of a *low discount rate* highlights the importance of future generations’ wellbeing.[27] Society should act now to protect future generations from climate change impacts.

A discount rate of 2% has been used by Deloitte in this analysis, after considering the differing perspectives within literature, the economic framework adopted for analysis in D.CLIMATE and broader policy actions modelled.[28] This rate reflects a consistent view on social discounting in the economic analysis of climate change.

Further, the results of a survey of economists in the *American Economic Journal: Economic Policy* (the sample contains over 200 academics who are defined as experts on social discounting by virtue of their publications) indicates that most favour a low discount rate: with more than three-quarters comfortable with a median discount rate of 2%.[29]

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In the aftermath of the devastating Black Summer bushfires fires across Australia in 2019-2020, Minderoo Foundation established the Fire and Flood Resilience Initiative and committed AU$70 million to response, recovery and long-term resilience. Our vision is audacious. We want to reduce harm caused by fire and floods by harnessing the collective power of communities, industry, government, philanthropy and the research sector to lift Australia to be the global leader in disaster resilience by 2025.

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