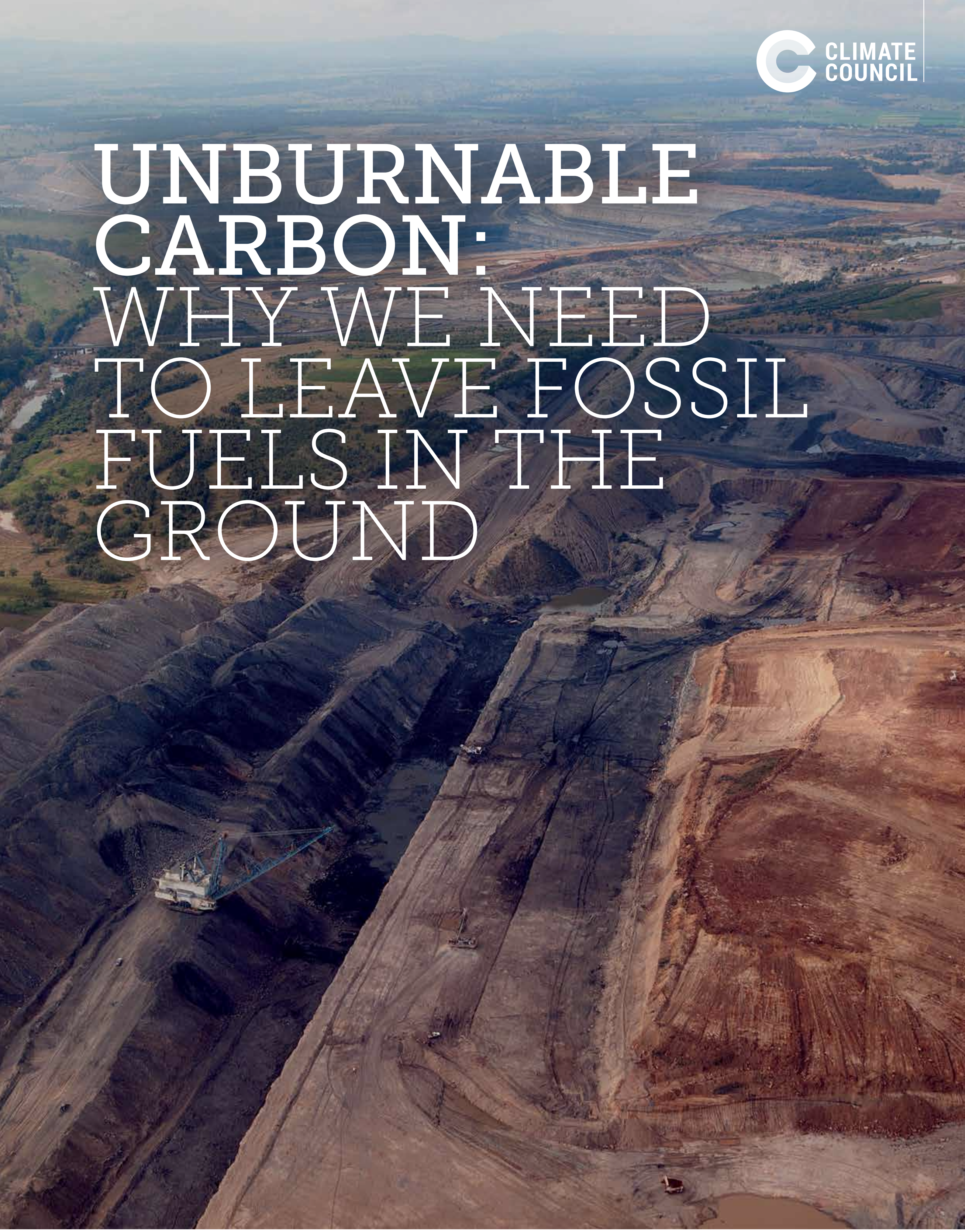

UNBURNABLE CARBON: WHY WE NEED TO LEAVE FOSSIL FUELS IN THE GROUND

The Climate Council is an independent, crowd-funded organisation providing quality information on climate change to the Australian public.

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Unburnable Carbon: why we need to leave fossil fuels in the ground by Will Steffen (Climate Council of Australia).

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Preface

The Climate Council is an independent, non-profit organisation, funded by donations from the public. Our mission is to provide authoritative, expert information to the Australian public on climate change.

The international community has agreed to limit an increase in global average temperature to no more than 2°C. If we are to have any chance of meeting this target, we need to rapidly reduce our carbon emissions and transition towards a decarbonised society. This report describes an approach - the carbon budget – to track progress against this goal. The carbon budget is a simple, scientifically-based method to determine how much carbon humanity can "spend". The higher the probability of meeting the warming limit, the more stringent the budget. That is, the less carbon we can spend.

The carbon budget has important implications for Australia, a major fossil fuel producer and exporter. The report explores the challenges and opportunities for Australia in a carbon-constrained world before concluding how, with the carbon budget rapidly running out, the opportunities that an energy system based on renewables offers a bright future for Australia.

The Climate Council is extremely grateful to our team of reviewers whose comments and suggestions improved the report. The reviewers were: Tim Buckley (Institute for Energy Economics and Financial Analysis), James Leaton (Carbon Tracker Initiative) and Ian Dunlop (Independent commentator & Member, the Club of Rome. Former Chair of the Australian Coal Association, CEO of the Australian Institute of Company Directors and senior oil, gas & coal industry executive). We thank CSIRO for reviewing the accuracy and relevance of the science underpinning this report. Their review is not an endorsement of the conclusions drawn.

The author retains the sole responsibility for the content of this report.

Will Steffen

Professor Will Steffen
Climate Councillor

Introduction

Scientists have been warning for decades that rising global temperatures, driven by carbon emissions, will have very harmful, and perhaps catastrophic, consequences for humanity. In response, governments the world over have agreed to keep global temperature rise to no more than 2°C above pre-industrial. While 2°C may not sound like much, it is a very substantial change to the Earth System and will have serious impacts on the lives and livelihoods of people world-wide. A good analogy is to the human body, where a 2°C rise in temperature is the difference between health and hospitalisation.

With just 0.85°C of warming we have already witnessed adverse consequences. In Australia hot days have doubled in the last 50 years, while heatwaves have become hotter, last longer and occur more often. Heatwaves are the most significant natural hazard in Australia in terms of loss of life and the elderly, the very young, and those with chronic disease are most at risk. Similarly, extreme fire weather has increased over the last 35 years in southeast Australia, putting people and property at risk. Property and infrastructure across Australia has been built for previous climatic conditions and much of it is ill-prepared to cope with increasingly frequent and/or intense extreme weather. For instance, over $226 billion in commercial, industrial, road and rail and residential assets around Australian coasts are potentially exposed to rising sea levels over the next 85 years.

A 2°C rise in temperature has long been considered a threshold that should not be crossed given the potential for catastrophic consequences. For instance, the threshold to trigger the melting of the Greenland ice-sheet, which would eventually raise sea level by about 7 metres, inundating major cities world-wide, lies between a 1 and 4°C rise, with the risk increasing through that temperature range. Moreover, as scientific knowledge has improved, it is clear that other risks previously anticipated to lie only above 2°C may well occur at lower temperatures.

> “With the carbon budget rapidly running out, it is urgent that global emissions begin to track downward in the next few years.”

Rising greenhouse gas emissions, primarily from the burning of coal, oil and gas, drive climate change. The most important gas is carbon dioxide, denoted in this report as CO_2. To tackle climate change the solution is simple: we need to reduce CO_2 emissions to virtually zero by the middle of the century, requiring a rapid rate of reduction from now. Furthermore, investment needs to switch rapidly and decisively away from fossil fuels to renewable energy systems.

This report considers the consequences of a 2°C rise in temperature and how much CO_2 we can emit and still have a good chance of staying below that limit.

To help governments create robust climate change policies based on science, the “carbon budget approach” has been developed. Analogous to a household budget, the budget tells us how much CO_2 can we “spend” and not exceed a 2°C rise in temperature.

How big the budget is depends on how determined we are to stay below a 2°C rise in temperature. Section 2 details a number of different scenarios based on the probability of avoiding a 2°C rise in global temperature. The bigger the budget, the greater the likelihood of crossing the 2°C threshold. The more stringent the budget, the higher the probability of avoiding crossing that threshold.

Section 3 explores what the carbon budget means for the use of fossil fuels, the primary contributor to climate change.

The inevitable conclusion from the commitment by the world’s governments to protect humanity from climate change is that the vast bulk of fossil fuel reserves cannot be burned. To have just a 50:50 chance of preventing a 2°C rise in global temperature: 88% of global coal reserves, 52% of gas reserves and 35% of oil reserves are unburnable and must be left in the ground. Put simply, tackling climate change requires that most of the world’s fossil fuels be left in the ground, unburned.

What does this mean for large-scale new fossil fuel developments? Developments like the Galilee Basin in Australia, the tar sands in Canada and new resources in the Arctic cannot be developed if we are to prevent a 2°C rise in temperature.

What does this mean for governments? Energy policies that continue to support substantial fossil fuel use are inconsistent with tackling climate change.

What does this mean for Australia? If all of Australia’s coal resources were burned, it would consume two-thirds of the global carbon budget based on a 75% chance of meeting the 2°C warming limit. For Australia to play its role in preventing a 2°C rise in temperature requires over 90% of Australia's coal reserves to be left in the ground, unburned. Similarly, the development of new coal mines, particularly the Galilee Basin, is incompatible with tackling climate change. Instead, if developed, they could well become stranded assets in a world that is rapidly cutting carbon emissions.

The international community has agreed to limit an increase in global average temperature to no more than 2°C. And if we are to have any chance of meeting this target, then we need to rapidly reduce our carbon emissions and transition towards a decarbonised society. This year in the lead up to the Paris climate talks, countries will announce their emission reduction targets for 2020 and beyond. The carbon budget will be an important tool in ensuring these targets are grounded in science.

While it is certainly a big challenge to reduce our fossil fuel dependency, there are also economic opportunities in moving to new sources of power. For example, many of Australia's coal-fired power plants are nearing the end of their lifetimes and are inefficient. Simultaneously, the costs of renewable energy technologies such as solar PV and wind continue to fall.

With the carbon budget rapidly running out, it is urgent that global emissions begin to track downward in the next few years. To have any chance of preventing a temperature rise of no more than 2°C, it is clear that new investment in fossil fuels, especially in coal, needs to be reduced to zero as soon as possible. There is no time to lose; now is the time to get on with the job.

Contents

Key Findings

1. To tackle climate change, 195 countries around the world, including Australia, have agreed to keep global temperature rise to no more than 2°C.

- Already at a global temperature rise of less than 1°C, climate change is making many extreme weather events in Australia significantly worse. For instance, hot days have doubled in the last 50 years, while heatwaves have become hotter, last longer and occur more often.

- A 2°C rise in global temperature will have serious impacts on the lives and livelihoods of many people world-wide, and could trigger major changes in the Earth System. For instance, a 2°C rise could trigger the melting of the Greenland ice-sheet, which would eventually raise sea level by about 7 metres, inundating major cities world-wide.

2. Most of the world's fossil fuel reserves must be left in the ground, unburned, to keep global temperature rise to no more than 2°C.

- The carbon budget is a scientifically based method to determine how much carbon humanity can "spend". The higher the probability of limiting warming to no more than 2°C, the more stringent the budget.

- To have a 50% chance of meeting the 2°C warming limit at least 62% of the world's fossil fuel (oil, gas, coal) reserves must be left in the ground, unburned. To have a 75% chance of meeting the 2°C warming limit, at least 77% of the world's fossil fuels cannot be burned.

- Coal is the fossil fuel with the greatest proportion that cannot be used; 88% of global reserves are unburnable.

3. Australia is potentially a huge contributor to global CO_2 emissions through domestic use and exports. Use of our coal must be severely constrained to tackle climate change effectively.

- If all of Australia's coal resources were burned, it would consume two-thirds of the global carbon budget (based on a 75% chance to meet the 2°C warming limit).
- It is likely that over 90% of Australian coal reserves are unburnable under even the most generous carbon budget.
- Exploitation of Australia's Galilee Basin coal deposits is incompatible with effective action on climate change.

4. The remaining carbon budget is decreasing rapidly. This is the critical decade to get emissions tracking downwards and to move investment away from fossil fuels.

- Energy policies that support substantial fossil fuel use are inconsistent with tackling climate change. Huge new fossil fuel developments, like the Galilee Basin in Australia, the tar sands in Canada and new resources in the Arctic, cannot be developed.
- To have any chance of meeting the 2°C policy target, new investment in fossil fuels, particularly in coal, needs to be reduced to zero as soon as possible.
- To be consistent with the carbon budget approach, Australia needs to move to an emissions reduction target of 15% below 2000 levels by 2020, and to a 40-60% reduction below 2000 levels by 2030.
- Meeting the carbon budget also presents opportunities for the Australian economy by replacing its ageing, inefficient fleet of power stations with modern, clean renewables and by shifting our export industries to low-carbon primary products and minerals.

1.

RISKS OF A 2°C RISE IN TEMPERATURE

1.1 Setting a limit to the level of climate change

The imperative to avoid a level of climate change that would have "dangerous" impacts on human society has been recognised by the 195 countries, including Australia, that are signatories to the United Nations Framework Convention on Climate Change (UNFCCC 2008). The UNFCCC has proposed that the collective global aim should be to limit the human-driven increase in average temperature to no more than 2°C above pre-industrial levels (UNFCCC 2010).

There is now, however, an enormous body of evidence that climate change is already having increasingly negative impacts on almost every aspect of human society, as well as the environment that supports us (IPCC 2014). In Australia, annual average temperature over the continent has risen by 0.9°C since 1910 - not quite halfway to the 2°C warming limit - yet even at this seemingly modest increase in average temperature, climate change is already making many extreme weather events significantly worse (CSIRO and BoM 2015).

Since 1971 heatwaves in Australia are occurring more often and are lasting longer, and the hottest day in a heatwave is becoming even hotter (Perkins et al. 2012; Perkins and Alexander 2013). In southeast Australia the bushfire season is becoming longer, and the area burned by bushfires has increased over the past 35 years (Bradstock et al. 2013; Figure 1). An increase in heavy rainfall events across the continent has been observed (CSIRO and BoM 2015). A long-term drying trend in the cooler months of the year is affecting southwest Western Australia and the southeast of the continent (CSIRO and BoM 2015). Coastal flooding from extreme sea-level events has increased three-fold at Sydney and Fremantle since the mid-20th century (Church et al. 2006). The risks that this worsening of extreme weather events creates for our health, communities, infrastructure, economy and livelihoods, and natural ecosystems is well documented (e.g., Field el al. 2014).

> "The world's countries have agreed to keep global temperature rise to no more than 2°C."

Observations in Australia and around the world of significant impacts already at less than a 1°C rise in global average temperature (Field et al. 2014) means that the scientific underpinning for the 2°C warming limit as a "safe" level of climate change is now weaker than it was a decade ago. In fact, the scientific case for

Figure 1: Forest bushfire damage in Matlock, Victoria.

“Climate change is already making many extreme weather events significantly worse.”

a limit below 1.5°C, as proposed by the small island states (UN-OHRLLS 2014), is more consistent with our current level of understanding.

Many small island states are extremely low-lying and are vulnerable to even modest changes in climate. For example, even small sea-level rises in the future will threaten many Pacific and Indian Ocean island communities, as well as Torres Strait island communities within Australia (Figure 2). Inundation from rising sea levels affects houses, roads, water supply, power stations, sewage and stormwater systems, cultural sites, cemeteries, gardens, community facilities and ecosystems, and is often accompanied by severe erosion. Even at a 1.5°C rise in global average temperature, climate change threatens the lives, livelihoods, and unique cultures of many small island communities (Green et al. 2010; Suppiah et al. 2010; Climate Council 2014). Therefore, at the UNFCCC Conference of the Parties (COP16) in Cancun in 2010, the Alliance of Small Island States (AOSIS) felt that any target other than to limit global average temperature rise to below 1.5°C would undermine the survival of these vulnerable communities (Tschakert 2015).

Figure 2: Coastal flooding in Saibai Island in the Torres Strait.

Nonetheless, the 2°C "warming limit" provides an agreed and clearly defined policy target that would prevent even more serious impacts affecting most people and countries around the globe. This has given nations and policymakers the capacity to craft a response to climate change. However, as scientific understanding has improved, it is increasingly clear that the risk of very significant changes to the climate system - some of them catastrophic for some communities, regions and countries - may occur at lower temperatures than previously thought.

To synthesise and communicate the observed and projected impacts of climate change at various levels of temperature rise, the Intergovernmental Panel on Climate Change (IPCC) has developed the "reasons for concern" approach (Smith et al. 2001). This approach, described graphically in what has been called the "burning embers diagram", is based on a small number of broad areas where climate change is either already driving observable impacts or is projected to pose major risks for human well-being (Figure 3).

The reasons for concern include (i) extreme weather events, where the influence of climate change is already apparent (IPCC 2012, 2013), (ii) the risks to unique and threatened ecosystems, (iii) the local and regional distribution of

"As science improves, it is clear that the risks previously anticipated above 2°C may well occur at lower temperatures."

impacts (e.g., showing relatively larger impacts on disadvantaged communities and countries), (iv) the aggregation of impacts to the scale of the global economy and Earth's biodiversity, and (v) the risk of crossing thresholds or tipping points in large-scale features of the climate system, called "large-scale discontinuities" in the figure. These tipping points, or "large-scale discontinuities", are described in more detail below. The figure is coloured from white through yellow to red, where increasing red tones denote increasing risk of damaging impacts.

Figure 3 consists of three panels, representing assessment of impacts or risk at three different times – 2001 (IPCC Third Assessment Report; Smith et al. 2001), 2007 (IPCC Fourth Assessment Report; Smith et al. 2009) and 2014 (IPCC Fifth Assessment Report 2014). The 2°C policy target is shown as a horizontal line, referenced to the pre-industrial estimate of global average temperature. Three features stand out in a comparison of the three panels.

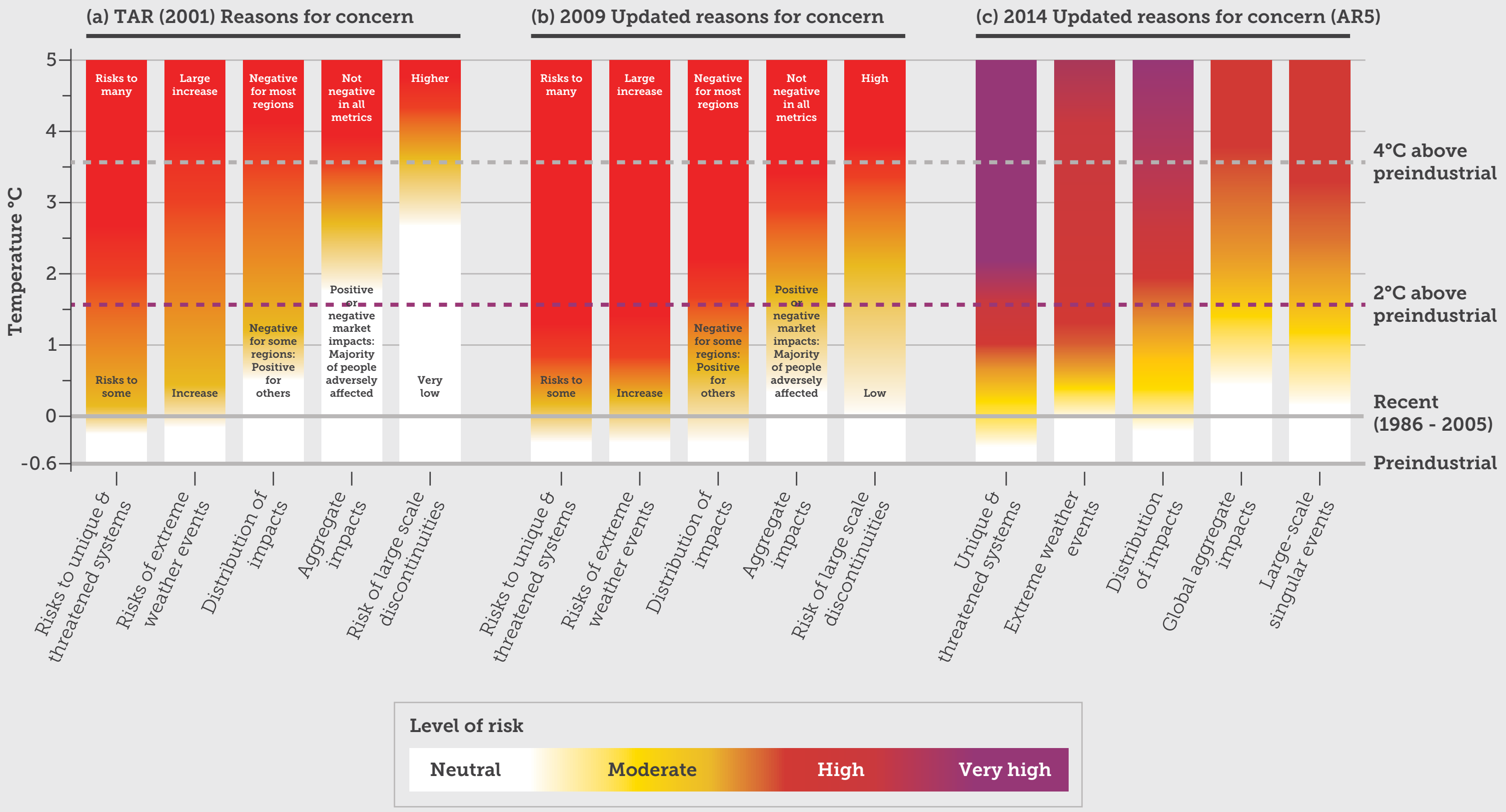


Figure 3: Risks from climate change by reason for concern (RFC) for 2001 compared with the updated data for 2009 and for 2014. Climate change consequences are plotted against increases in global mean temperature (GMT) (°C) after 1990. Each column corresponds to a specific RFC and represents additional outcomes associated with increasing global mean temperature. The colour scheme represents progressively increasing levels of risk. The historic period 1900 to 2000 warmed by about 0.6°C, which led to some impacts. (A) RFCs adapted from the IPCC Third Assessment Report as described in Smith et al. (2001); (B) Updated RFCs adapted from IPCC Fourth Assessment Report as discussed in Smith et al. (2009); (C) Updated RFCs adapted from the IPCC Fifth Assessment Report (IPCC 2014).

First, as the science improves, our assessment of risk changes. The enhanced knowledge base includes observations of actual impacts at the current temperature rise of about 0.85°C above pre-industrial, as well as improved modelling capability to project future impacts. For example, as the science has improved between 2001 and 2014, the scientific assessment of the risks of global warming between 1 and 2°C have been elevated (Figure 3). For example, in 2001 the expected risk of increasing extreme weather with a rise of between 1 and 2°C in global temperature was considered moderate. Today the risk is considered high. Risks to unique and threatened ecosystems, like coral reefs, at 1 to 2°C of warming were considered moderate in 2001. Today the risk is high. Globally aggregated impacts were estimated at the low end of the risk scale in 2001 whereas they are now assessed as the moderate risk level.

Second, as discussed above, the scientific underpinning for the 2°C policy target as a "safe" level of climate change is now weaker than it was a decade ago, and the scientific case for the 1.5°C limit is more consistent with our current level of understanding.

Third, at a 2°C temperature rise, we are now closer to the risk of crossing thresholds or tipping points, or "large-scale discontinuities" as they are called in Figure 3. These refer to large features of the climate system that are prone to abrupt and/or irreversible change when a critical threshold level of temperature rise is reached. Examples include loss of the Greenland ice-sheet, the partial conversion of the Amazon rainforest to a savanna or grassland, and the large-scale emission of CO_2 and methane from thawing permafrost. Each of these examples would cause further disruptions to the climate system, with knock-on effects for human societies. For instance, melting of the Greenland ice-sheet would eventually raise sea level by approximately 7 metres (Church et al. 2013), committing humanity to continuously rising sea levels for centuries or millennia, devastating major coastal cities world-wide as their limits to adapt to coastal flooding were exceeded. While large uncertainties surround the position of many of these tipping points, a few are becoming better

> "In 2001 the expected risk of increasing extreme weather with a rise of between 1 and 2°C in global temperature was considered moderate. Today the risk is considered high."

Figure 4: Northwest Greenland sea ice.

understood. For example, the tipping point for the Greenland ice-sheet (Figure 4) is estimated to lie within a temperature rise of 1°C and 4°C above pre-industrial (Church et al. 2013). Potential emissions of CO_2 and methane from melting permafrost in the northern high latitudes (e.g., Siberia, Alaska), which can accelerate climate change, are assessed to be in the range of 50 to 250 billion tonnes of carbon over the 21st century under the highest emissions scenario (Ciais et al. 2013). By comparison, current human emissions of carbon averaged about 10 billion tonnes per year (or about 36 billion tonnes if measured as CO_2) over the most recent decade (Le Quéré et al. 2014).

This recent knowledge is now included in the 2014 burning embers diagram, where a moderate risk of crossing large-scale tipping points exists in the 1.5-2°C range and very high risk in the 3-4°C range. In contrast, in 2001 there was negligible risk of crossing tipping points up to a temperature rise of 3°C and a high risk did not appear until above 4°C.

In summary, the more we know about climate change, the riskier it looks, including at a temperature rise of 2°C above pre-industrial. This observation (i) underscores the urgency in stabilising the climate system as soon as possible to minimise the high-end risks; and (ii) emphasises the need to dramatically reduce CO_2 emissions from fossil fuel combustion.

> “It is clear that a 2°C rise in global temperature will have serious impacts on the lives and livelihoods of many people world-wide.”

1.2 Measuring progress towards meeting the 2°C warming limit

To track emissions against the warming limit, the most commonly used method in the policy world is the "targets and timetables" approach, which is based on a target reduction in greenhouse gas emissions by a certain date or over a specified period. Examples of targets and timetables include China's target of peaking its total greenhouse gas emissions by 2030 (The White House 2014), the United States target of reducing emissions by 26-28% by 2025 against a 2005 baseline (UNFCCC 2015), and Australia's target of reducing emissions by 5% by 2020 against a 2000 baseline (Commonwealth of Australia 2013).

The scientific rationale for this approach is based on achieving the level of greenhouse gas concentrations in the atmosphere that correspond to the 2°C warming limit, and from that, determining the amount of emission reductions that are required to stabilise the atmospheric concentration at the desired level.

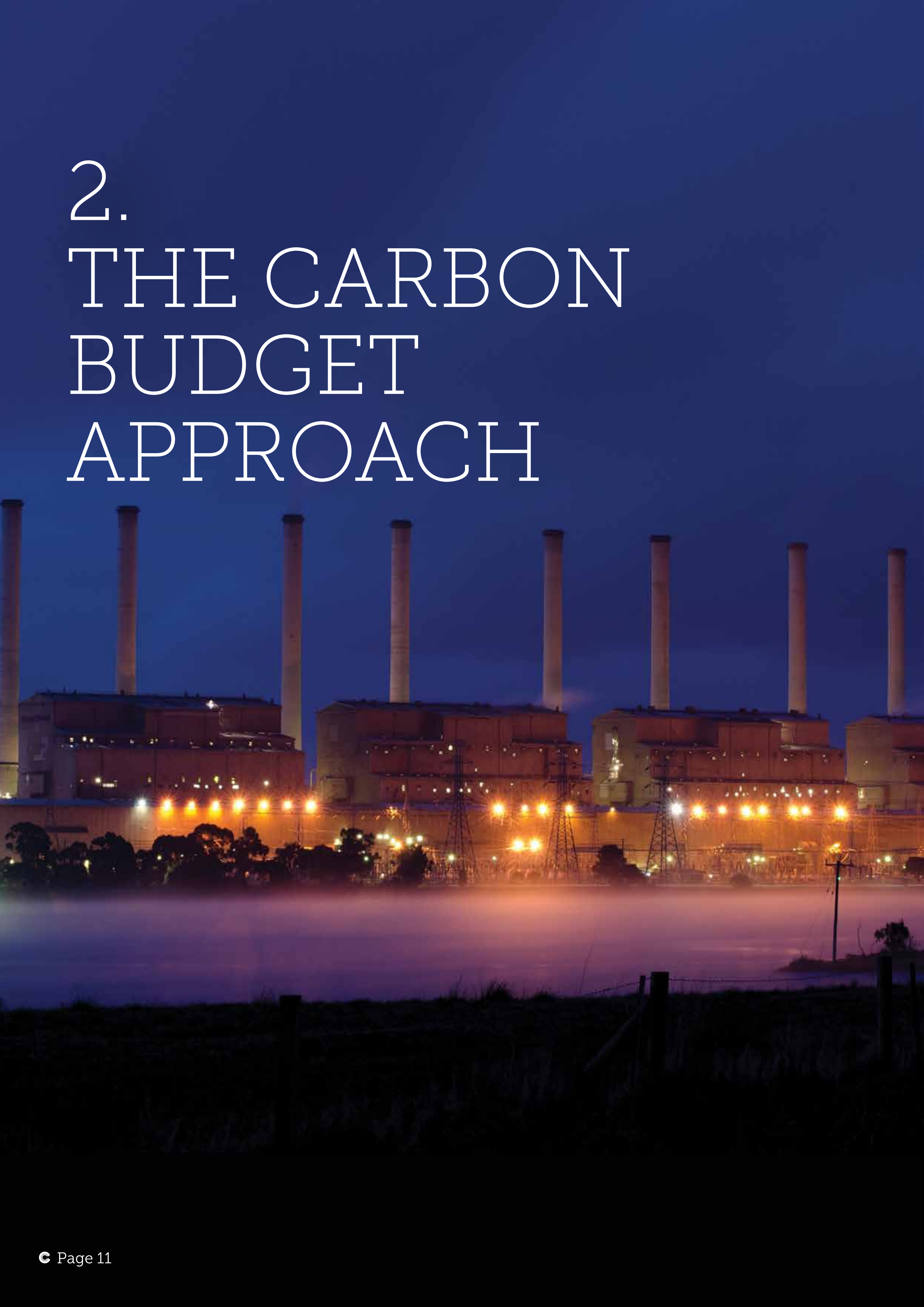
In practice, this approach is far more complex than it appears on the surface because national commitments can vary in many ways. These include:

- the greenhouse gases included in the commitment.
- whether the promised emission reduction is expressed in absolute amounts (e.g., tonnes) of greenhouse gases or expressed as a percentage reduction.
- the baseline year against which the reduction is to be applied.
- whether a percentage reduction applies to actual emissions or to the 'emission intensity' of the economy, that is, the amount of emissions per unit economic activity.
- whether the reductions are applied against a business-as-usual (high emissions) scenario or against some other future scenario.

The complexity of the targets-and-timetables approach, especially the number of variations, makes it difficult to compare the level of effort of one country against another and to assess the aggregated effect of all countries' efforts in terms of their effectiveness in stabilising the climate system. For example, it is not easy to compare the "level of effort" of China, the United States and Australia based on their individual policy approaches.

2.

THE CARBON BUDGET APPROACH



The carbon budget approach was developed by scientists to build a clearer picture of the level of global effort required to stabilise the climate system. It is a conceptually simple approach based on the observation that the level of temperature rise is directly related to the cumulative amount of CO_2 that is emitted to the atmosphere (Figure 5; IPCC 2013; Meinshausen et al. 2009).

The carbon budget is defined as the maximum amount of CO_2 from human sources that can be released into the atmosphere to limit warming to no more than 2°C above pre-industrial levels. That is, the carbon budget is the amount of CO_2 that humanity can "spend". Once the carbon budget is spent, global emissions of CO_2 must be zero; the global economy must be completely decarbonised.

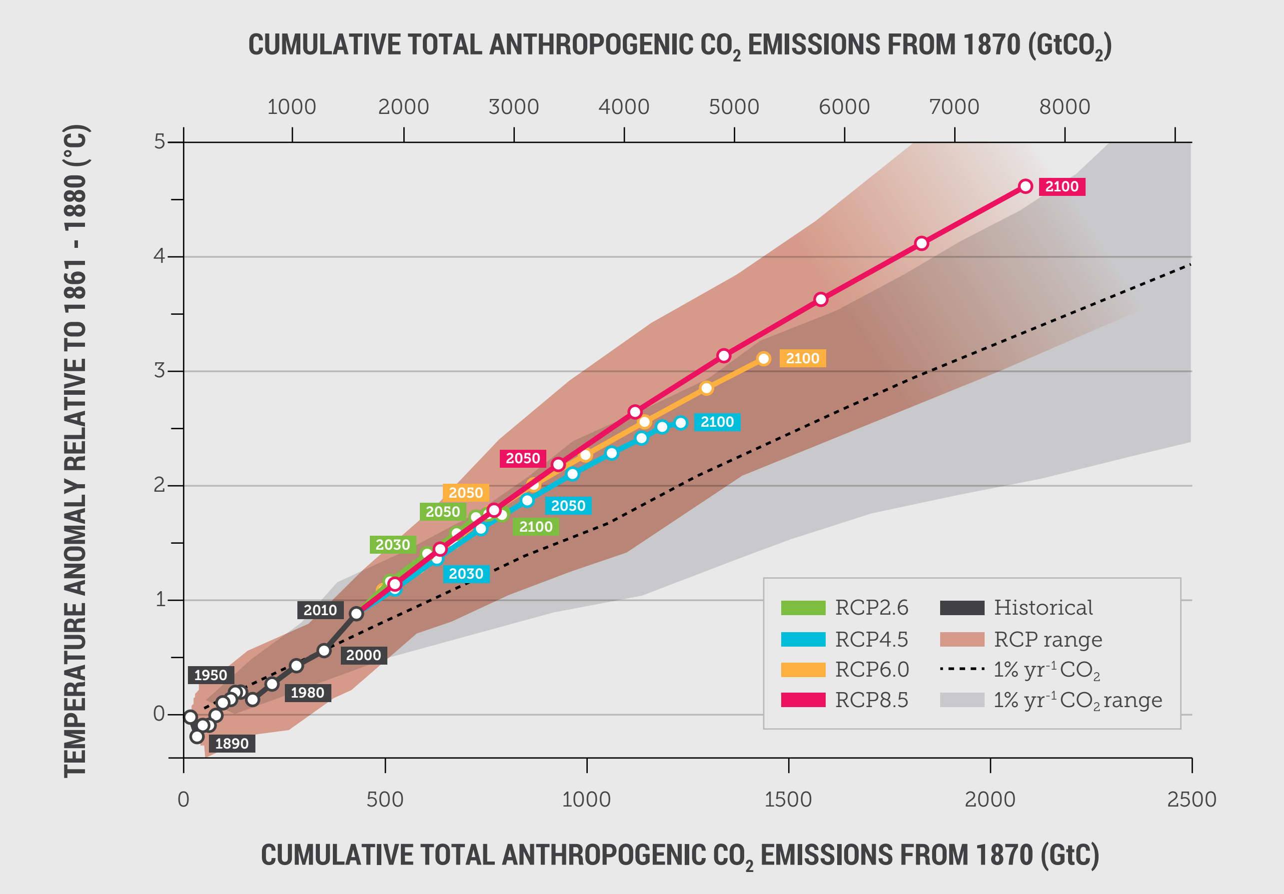


Figure 5: Global mean surface temperature increase as a function of cumulative total global CO_2 emissions from various lines of evidence. Multi-model results from a hierarchy of climate-carbon cycle models for each RCP (emission scenario) until 2100 are shown with coloured lines and decadal means (dots). Some decadal means are labeled for clarity (e.g., 2050 indicating the decade 2040-2049). Model results over the historical period (1860 to 2010) are indicated in black. The coloured plume illustrates the multi-model spread over the four RCP scenarios and fades with the decreasing number of available models in RCP 8.5. The multi-model mean and range simulated by CMIP5 models, forced by a CO_2 increase of 1% per year (1% yr^{-1} CO_2 simulations), is given by the thin black line and grey area. For a specific amount of cumulative CO_2 emissions, the 1% per year CO_2 simulations exhibit lower warming than those driven by RCPs, which include additional non-CO_2 forcings. Temperature values are given relative to the 1861-1880 base period, emissions relative to 1870. Decadal averages are connected by straight lines. **Source:** Adapted from IPCC (2013).

Figure 6: Coal loading at Korragang Island, NSW.

> “The carbon budget is the amount of CO_2 that humanity can “spend”.”

The Intergovernmental Panel on Climate Change (IPCC) summarised the carbon budget approach in its Fifth Assessment Report (IPCC 2013). Two critical features that affect the precise carbon budget are (i) the desired probability of meeting the 2°C warming limit, and (ii) the treatment of the non-CO_2 “forcing” factors that also contribute to the warming of the climate system.

The various carbon budgets are summarised in Table 1, showing two reference dates for the start of the budget (2000 and 2012) and three probabilities for meeting the budget. The budgets in Table 1 take into account the contribution of the non-CO_2 greenhouse gases to the warming of the climate. The budget constricts considerably when the probability of not exceeding the 2°C warming limit is increased from 50% (a toss of the coin) to 66% and 75%; from 2012 the carbon budgets based on these three probabilities are 1112, 1010 and 672 billion tonnes of CO_2, respectively. If a greater than 75% probability of not exceeding the 2°C warming limit is desired, the carbon budget drops sharply to values much lower than 672 Gt CO_2. For example, if a more risk-averse approach is taken (say, greater that 90% probability of not exceeding the 2°C policy target), then the carbon budget becomes very much smaller. As noted current human emissions of CO_2 are about 36 billion tonnes per year (Figure 5) (Le Quéré et al. 2014).

Two additional assumptions may also affect the budget. First, the approach assumes that the current strength of the

Table 1: The carbon budget for three probabilities of meeting the 2°C warming limit.

Probability of meeting 2°C policy target	Budget from 2000 Gt CO_2	Budget from 2012 Gt CO_2
50%	1440	1112
66%	1338	1010
75%	1000	672

Sources: IPCC (2013) and Meinshausen et al. (2009).

carbon "sinks" on land and in the ocean will remain the same as measured by the fraction of emissions. "Sinks" refer to the removal of CO_2 from the atmosphere by natural processes and its storage on land (vegetation and soils) and in the ocean. Sinks are important because the CO_2 is then not in the atmosphere trapping heat and contributing to global temperature rise.

The "strength" of a sink refers to how much CO_2 the land or ocean can remove and store. At present, these two sinks remove slightly more than half of the CO_2 that is emitted to the atmosphere from human activities (Le Quéré et al. 2014). There are concerns that these sinks could weaken. That is, as emissions continue to rise, the land and ocean sinks may remove proportionally less CO_2.

The future trajectory of these two sinks can be projected by Earth System models. As the CO_2 concentration rises in the atmosphere from human emissions, the strength of the land and ocean sinks will increase proportionally due to the effect of increasing CO_2 on its own. However, because the climate is also changing as atmospheric CO_2 concentration rises, it will affect the processes that underpin the land and ocean sinks. The likely net effect of climate change is to weaken these processes, thus partially offsetting the increases in land and ocean carbon sinks caused by the rising atmospheric CO_2 concentration alone (IPCC 2013). This possible weakening of carbon sinks would likely be small under the lowest of the IPCC emission pathways, which approximately corresponds to the budget required to have a 66% or better probability

"Land and ocean "sinks" remove about half the CO_2 emitted by human activities, slowing the rate of temperature rise."

of meeting the 2°C warming limit (Table 1), but will be larger if we do not meet this target, exacerbating the already serious risks of a temperature rise beyond 2°C.

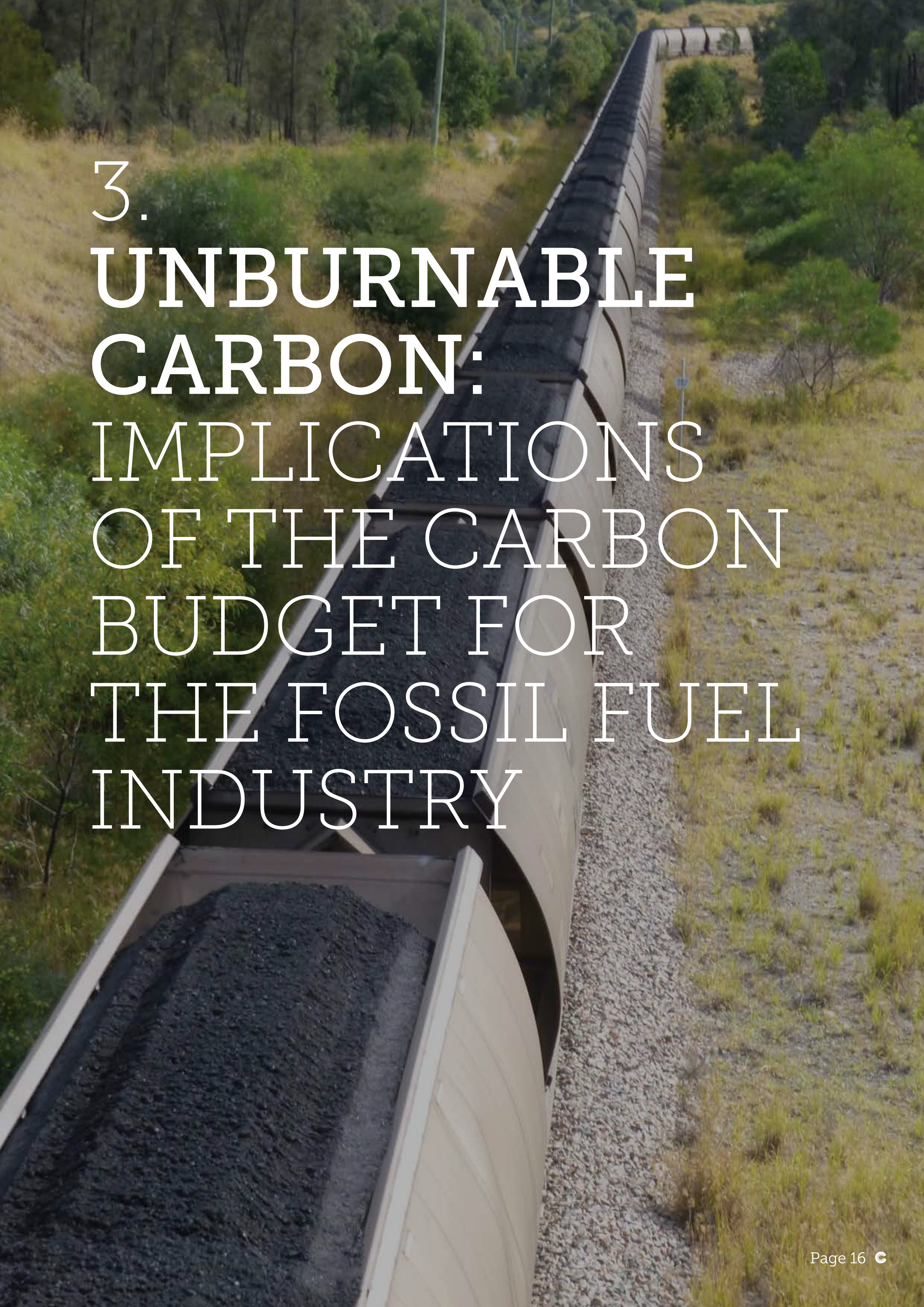
The second issue is feedback processes. A common feedback process in daily life is weight gain. As people gain weight, their appetite may increase and they become less inclined to exercise, and so they put on more weight, which in turn increases the appetite and reduces exercise even more, and so on. The climate system has a number of important feedback processes. For example, rising temperatures thaw permafrost, which releases CO_2 or methane to the atmosphere, which in turn, creates further warming, which then triggers even more emissions, and so on.

The budget approach cannot yet fully account for such feedback processes. As noted in Section 1, possible emissions from permafrost are assessed to be in the range of 50 to 250 billion tonnes as measured in carbon (not CO_2) over the 21st century under the highest emissions scenario (IPCC 2013). This corresponds to a range of five to 25 years of emissions from fossil fuel combustion at current rates. However, if the carbon budget is met, that is, the lowest of the IPCC emissions trajectories (an emission rate very much lower than the current one) is followed, loss of permafrost carbon is unlikely to become a significant problem.

In summary, if humanity exceeds the carbon budget for the 2°C warming limit, there is a strong risk of exacerbating the release of carbon from natural sources, causing further warming. On the other hand, if we cut our carbon emissions and stay within the 2°C warming limit, there is much less risk.

Finally, it is sometimes suggested that managing the land carbon cycle, through both avoided emissions from reducing deforestation and the sequestration of atmospheric CO_2 in soils and vegetation, could play a major role in climate stabilisation, offsetting a considerable amount of fossil fuel emissions. However, an analysis that includes the competing demands for land and its biomass – food production, wood products, biofuels for energy production, and biodiversity conservation – shows that land-based activities can play only a small role, accounting for only 3-8% of estimated energy consumption by 2050 (Canadell and Schulze 2014).

In summary, the carbon budget approach is a scientifically robust, conceptually simple way of estimating how much more CO_2 we can emit to the atmosphere before we raise global temperature above 2°C. It gives a single, globally aggregated amount of CO_2 that can be emitted before the world's economy must be decarbonised. The higher the probability we want of preventing a global temperature rise of 2°C, the more stringent the budget.



3.

UNBURNABLE CARBON: IMPLICATIONS OF THE CARBON BUDGET FOR THE FOSSIL FUEL INDUSTRY

3.1 Calculating the amount of carbon that can be burned

One hundred and ninety-five countries around the world have agreed to limit global temperature rise to no more than 2°C as a key climate change policy (UNFCCC 2010; Figure 7), and simultaneously some of these countries have energy policies that include the extensive use of fossil fuels. Are these climate and energy policies consistent? Similarly, are the activities and plans of the large, multinational energy companies consistent with the agreed 2°C policy objective? Checking these consistencies is difficult with the targets-and-timetables approach to emissions reductions, but is much more straightforward and transparent with the carbon budget approach.

Figure 7: UNFCCC Climate talks in Cancun, Mexico 2010.

"Carbon capture and storage technologies do little to extend the carbon budget."

An obvious way to test this consistency is to compare the world's fossil fuel reserves with the remaining carbon budget. In the analyses that follow, we use the least stringent of the three budgets from 2012 (Table 1), the budget of 1112 billion tonnes of CO_2 that gives a 50% probability of avoiding a greater than 2°C rise in global temperature. For better-than-even chances of meeting the policy target, more stringent carbon budgets will be required. Thus, the analyses described below are the most "optimistic" ones from the perspective of fossil fuel usage. Higher probabilities of meeting the 2°C warming limit, and hence lower risks of suffering damaging or catastrophic climate change impacts, will require much lower usage of fossil fuels than the numbers cited below.

An initial study in 2013 compared the known global fossil fuel reserves (coal, oil, gas) with the carbon budget (Carbon Tracker and Grantham Institute 2013). That study estimated that if all of the world's indicated reserves of fossil fuels were burned, 2,860 billion tonnes of CO_2 would be emitted to the atmosphere. This is more than 2.5 times greater than the allowed budget.

Some have suggested that carbon capture and storage (CCS) technologies, which capture CO_2 from the smokestacks of power plants and allow it to be buried underground, could alleviate the constraint on burning fossil fuels. However, CCS does little to extend the carbon budget. Even optimistic estimates of the deployment of CCS suggest that the carbon budget could be extended by, at most, about 125 Gt of CO_2 (Carbon Tracker and Grantham Institute 2013). This would still leave the amount of burnable carbon well under half of the known reserves.

A recent study has examined in much more detail the implications of the carbon budget for the use of fossil fuels (McGlade and Ekins 2015). Their carbon budget is also based on a 50% probability of meeting the 2°C policy target, and spans the time period from 2011 to 2050. Based on the IPCC budget approach, their proposed budget is about 1,100 billion tonnes of CO_2, very similar to the budget shown in Table 1.

Their analysis compares this budget to both fossil fuel "reserves" and fossil fuel "resources". Resources are defined as "…the remaining ultimately recoverable resources, that is, the quantity of oil, gas or coal remaining that is recoverable over all time with both current and future technology, irrespective of economic conditions". Reserves are defined as "…a subset of resources that are defined to be recoverable under current economic conditions and have a specific probability of being produced." (McGlade and Ekins 2015). In other words, "resources" are all of the fossil fuels that we know exist, and "reserves" are the subset of resources that are economically and technologically viable to exploit now.

Table 2: The carbon budget for three probabilities of meeting the 2°C warming limit, and the fraction of fossil fuel reserves and resources that can be burned within the budget. See text for definition of “reserves” and “resources”.

Probability of meeting 2°C policy target	Budget from 2000 Gt CO_2	Budget from 2012 Gt CO_2	% of fossil fuel reserves that can be burned from 2012	% of fossil fuel resources that can be burned from 2012
50%	1440	1112	38	10
66%	1338	1010	35	9.2
75%	1000	672	23	6.1

Sources: IPCC (2013), Meinshausen et al. (2009) and McGlade and Ekins (2015).

“Tackling climate change requires that most of the world’s fossil fuels be left in the ground, unburned.”

Current reserves consist of 1,294 billion barrels of oil, 192 trillion cubic metres of gas, 728 billion tonnes of hard coal, and 276 billion tonnes of lignite (McGlade and Ekins 2015). If all of these reserves were burned, nearly 2,900 billion tonnes of CO_2 would be emitted (virtually identical to the Carbon Tracker and Grantham Institute 2013 estimate), while combustion of all of the world’s fossil fuel resources would release nearly 11,000 billion tonnes of CO_2 to the atmosphere (McGlade and Ekins 2015). These estimates are combined in Table 2 with the range of carbon budgets that are based on the three different probabilities of meeting the 2°C policy target. For each probability the table shows the percentages of fossil fuel reserves and resources that can be exploited and still stabilise the climate system at no more than a 2°C temperature rise above pre-industrial levels.

The results confirm the earlier study (Carbon Tracker and Grantham Institute 2013), which estimated amounts of burnable carbon based on a number of assumptions. The most generous budget, which allowed (i) an additional 300 billion tonnes of CO_2 because of deeper cuts in the emissions of non-CO_2 greenhouse gases such as methane and nitrous oxide, and (ii) an additional 125 Gt CO_2 from the most optimistic roll-out of CCS technologies, estimated that only about 35% of the world’s known fossil fuel reserves could be exploited.

The McGlade and Ekins (2015) analysis, under the most generous assumptions for fossil fuel usage (which give only a 50:50 chance of meeting the 2°C target), estimates that 38%, at most, of the world's reserves can be burned (Table 2). The amount of fossil fuel reserves that can be burned is reduced if we want a better-than-even change of limiting the rise in global temperature to no more than 2°C.

For a 75% chance of meeting this target, this allowance reduces substantially to only 23% of reserves. That is, 77% of the world's fossil fuel reserves cannot be burned. To have an even greater chance of limiting the rise in global temperature to no more than 2°C, the allowance would shrink rapidly towards zero. The conclusion is clear: under any set of assumptions, effectively tackling climate change requires that most of the world's fossil fuels be left in the ground, unburned.

The inevitable conclusion from the commitment of the world's governments to protect humanity from climate change means the vast bulk of fossil fuel reserves and almost all fossil fuel resources cannot be burned. Many countries are now moving rapidly away from fossil fuels toward alternative sources of power, like wind and solar (Climate Council 2015). However, some countries, like Australia, are committed to both tackling climate change and maintaining a fossil fuel industry long-term rather than phasing it out and vigorously supporting the transition to a decarbonised energy system (Commonwealth of Australia 2015). Energy policies that continue to support substantial fossil fuel use are inconsistent with tackling climate change.

> "Energy policies that support substantial fossil fuel use are inconsistent with tackling climate change."

3.2 How does each type of fossil fuel fare?

The McGlade and Ekins (2015) analysis goes further than earlier studies by estimating the relative amounts of the three major types of fossil fuel – coal, oil and gas – that can be burned and stay within the carbon budget. The combustion CO_2 emissions embedded in the major types of fossil fuels are shown in Figure 8 for both reserves and non-reserve resources. Furthermore, the study also estimates the geographical distribution of the fossil fuels that can be burned from an economic efficiency perspective.

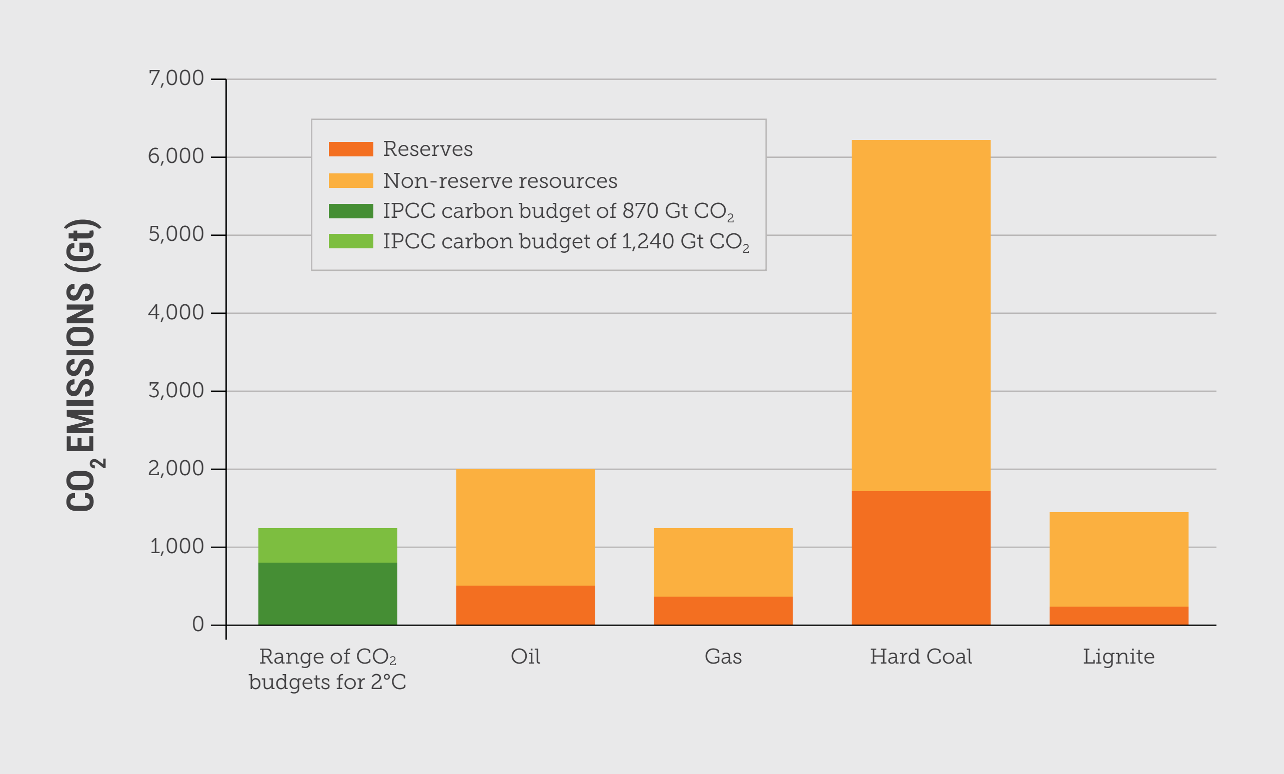


Figure 8: The combustion CO_2 emissions for oil, gas and coal (hard coal and lignite) resources and reserves. The range of carbon budgets between 2011 and 2050 that are approximately commensurate with limiting temperature rise to 2°C (870-1240 Gt CO_2) is also shown. **Source:** Adapted from McGlade and Ekins (2015).

"Coal is the fossil fuel with the greatest proportion that cannot be used; 88% of global reserves are unburnable."

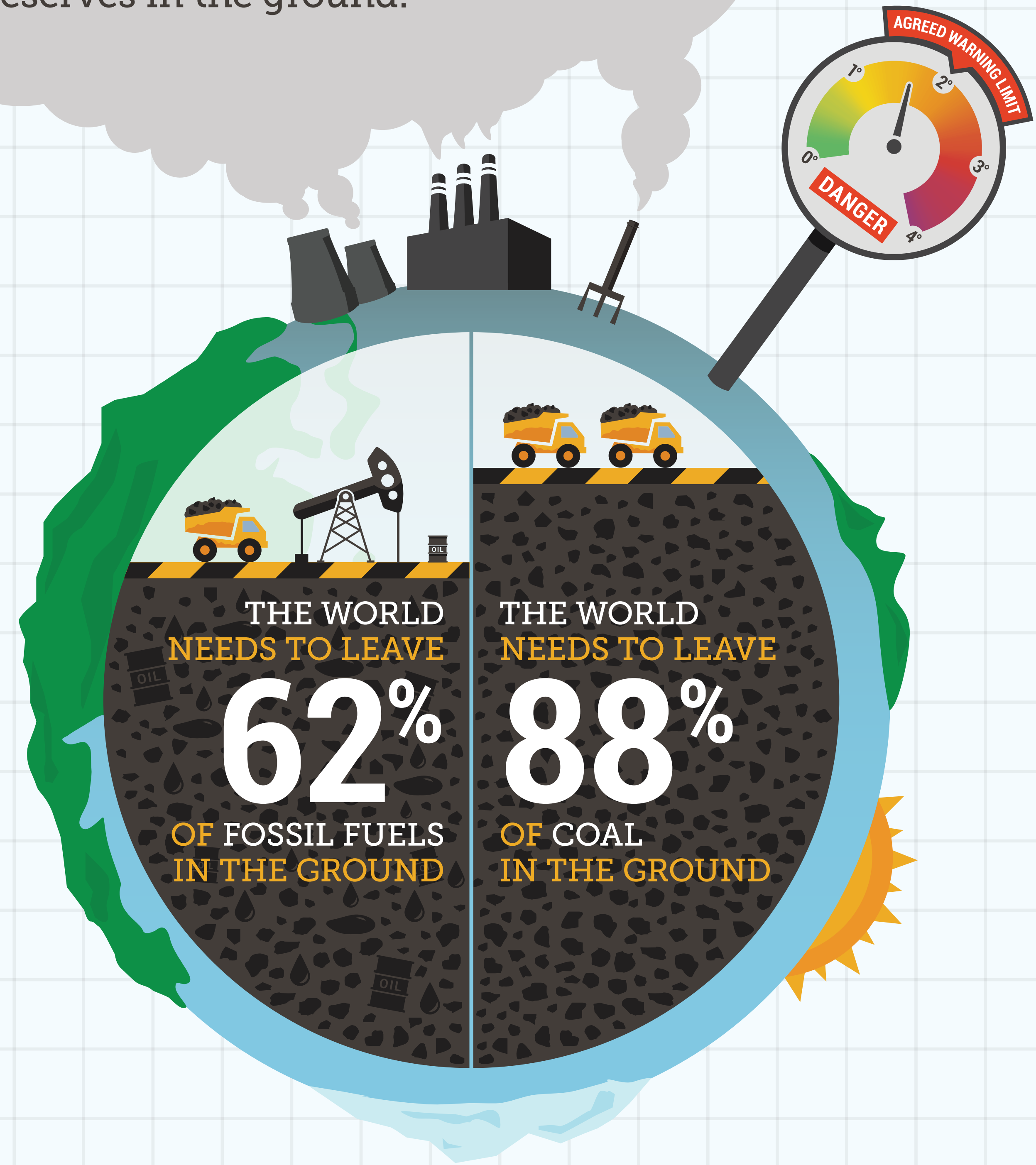
The analysis is based on the results of a sophisticated integrated assessment model that minimises whole-energy system costs for an assumed carbon budget (Anandarajah et al. 2011). The world's energy system is divided into 16 geographical regions, accounting for the various types of energy reserves and resources and where they are located. The minimisation of cost is based on the entire energy system, including the cost of resource extraction and production, conversion to products and use of those products by sectoral end-users. Infrastructure requirements are included in the analysis. Based on this approach, an economically-optimal (least cost) solution is generated by the model. The output gives the relative amounts of coal, oil and gas, and the geographical distribution, of the fossil fuels that can still be burned while avoiding a 2°C rise in global temperature. The remainder of the fossil fuels must then be left in the ground, unburned.

The results of the integrated assessment model show that to meet the budget, coal is the fossil fuel with the greatest proportion that cannot be used; 88% of global reserves are unburnable (Figure 9). Oil is the fossil fuel with the least proportion that cannot be used, with 35% of reserves unburnable. Just over half – about 52% - of the known reserves of gas are unburnable. Application of CCS technology does not alter the mix very much. The fraction of unburnable coal reserves reduces only slightly to 82%, while 33% of oil and 49% of gas reserves are unburnable. Of the coal that can be burned to stay within the budget, about three-quarters is hard coal (often called "black coal" in Australia) and only one-quarter is lignite ("brown coal") (McGlade and Ekins 2015).

"Over half of the known reserves of gas are unburnable."

WHAT IS OUR CARBON BUDGET?

To have just a break-even, 50:50 chance of staying **below 2°C** of global warming, we must keep most of the world's fossil fuel reserves in the ground.



THE WORLD NEEDS TO LEAVE **62%** OF FOSSIL FUELS IN THE GROUND

THE WORLD NEEDS TO LEAVE **88%** OF COAL IN THE GROUND

AT THE CURRENT RATE

We will blow our carbon budget within the next **two decades** or even sooner.

Figure 9: Carbon Budget Report 2015.

The analysis yields some interesting results regarding non-conventional fossil fuels. For example, to meet the carbon budget, the open-pit mining of natural bitumen (tar sands; Figure 10) in Canada must be reduced rapidly over the next five years to near zero. With or without CCS, 99% of the Canadian natural bitumen resources are unburnable if we are to keep global temperature rise below 2°C. Similarly, none of the Arctic Ocean oil and gas resources is exploitable in any of the scenarios that meet the policy target. This means that all Arctic resources are unburnable; any exploitation of any of the resources in that region is incompatible with effective action on climate change.

“Tar sands mining in Canada must be reduced rapidly to near zero over the next five years.”

Figure 10: Tar sands in Alberta, Canada.

“Any exploitation of Arctic fossil fuels resources is incompatible with effective action on climate change.”

4.

THE CHALLENGE FOR AUSTRALIA

The calculation of the world's unburnable fossil fuel reserves presents especially serious challenges for Australia, given our focus on coal both for domestic consumption and as an export commodity. To put the nature of this challenge into perspective, it is useful to compare Australia's known coal reserves and resources with the global carbon budget based on the 2°C warming limit.

Australia's coal reserves are estimated to be 76 billion tonnes, of which 39 billion tonnes are black (hard) coal and 37 billion tonnes are brown coal (lignite) (Geoscience Australia 2010). If all of the reserves were exploited and burned, 128 billion tonnes CO_2 would be emitted to the atmosphere (Department of Environment 2014). These emissions represent 11.5% the global carbon budget from 2012 for a 50% probability of meeting the 2°C warming limit and 19.0% of the budget for a 75% probability. Our total resources of coal are much higher (estimated to be 308 billion tonnes, with 114 billion tonnes of black coal and 194 billion tonnes of lignite (Geoscience Australia 2009), which is equivalent to 454 billion tonnes CO_2 if all of the resources were burned (Department of Environment 2014). These resources are very large in the context of the total global carbon budget from 2012, comprising 40.8% of the budget for a 50% probability of meeting the 2°C warming limit, and 67.6% of the budget for a 75% probability. In summary if all of Australia's coal was burned, it would consume two-thirds of the global carbon budget based on a 75% chance to meet the 2°C warming limit.

The McGlade and Ekins (2015) analysis breaks down the global estimates of unburnable fossil fuels into geographical regions, with Australia in the "OECD Pacific" group which also includes South Korea, Japan and New Zealand. The estimates for this group are essentially equivalent to the estimates for Australia alone because South Korea and Japan have negligible fossil fuel resources. Furthermore, Australia's fossil fuel resources are far greater than those of New Zealand.

"If all of Australia's coal was burned, it would consume two-thirds of the global carbon budget based on a 75% chance to meet the 2°C warming limit."

> "It is estimated that over 90% of Australian coal reserves cannot be burned."

Based on the McGlade and Ekins (2015) analysis, without CCS it is estimated that the unburnable fossil fuels for the OECD Pacific group (i.e., primarily Australia) are 46% of oil reserves, 51% of gas reserves and 95% of coal reserves. The most optimistic application of CCS technology from 2025 onwards does not diminish these daunting figures by much; 37% of oil reserves are unburnable; 56% of gas and 93% of coal. In summary, it is estimated that over 90% of Australia's coal reserves cannot be burned (for example, Figure 11), compared to the global average of 82% of coal reserves that cannot be burned.

These estimates, however, contain large uncertainties. The modelled geographical distribution of unburnable fossil fuels is based on several critical assumptions out to 2050, such as the total future demand for energy in different regions, the future costs of mining and energy extraction, the relative costs of different energy technologies, and the local costs of alternatives. All of these factors are difficult to predict into the future with a high degree of certainty. In addition, the analysis does not include factors such as regulation of local air pollution (e.g., in China), which would favour coal reserves with lower sulfur content and higher energy density (i.e., some Australian reserves).

Figure 11: Tarrawonga coal mine adjacent to Leard State Forest in NSW.

> "Tackling climate change makes it highly unlikely that any new Australian coal resources would ever be developed."

In terms of coal specifically, uncertainties include:

- the level of global demand given improvements in energy efficiency and the falling cost of alternative renewables;
- the impact on the global market of changes in energy policy in China (e.g., peaking thermal coal use) and perhaps India;
- potential restrictions on coal usage in a post-Paris climate agreement; and
- the cost of developing new coal resources that typically require expensive new rail and port facilities (Carbon Tracker 2014a, 2014b).

In summary, it is likely that the fraction of Australia's unburnable coal is larger than the global average, but it is not clear by how much, given the large uncertainties in the geographical distribution analysis and the future of the global coal market.

Effectively tackling climate change, that is, meeting the 2°C warming limit, makes it highly unlikely that any of Australia's potential coal resources beyond the reserves already being exploited would ever be developed. This includes the Galilee Basin deposits, which in general have high costs of development and contain relatively low-grade coal. Such resources, if developed, would very likely become stranded assets in a world that is rapidly cutting carbon emissions. These resources are in a similar category to the natural bitumen deposits in Canada or the oil and gas resources under the Arctic Sea. They are unburnable; any exploitation of them is almost certain to be incompatible with effective action on climate change.

In contrast to the challenges that the global carbon budget presents for Australia's coal industry, observing the 2°C warming limit opens up many opportunities for the Australian economy (ClimateWorks Australia and the ANU 2014). For example, many of Australia's coal-fired power plants are nearing the end of their lifetimes, and, simultaneously, the costs of renewable energy technologies such as solar PV (Figure 12) and wind continue to fall. Replacing our ageing coal stations with modern, clean renewables could help Australia meet its share of the carbon budget with little or no economic cost, or, more likely, with economic benefits (Climate Council 2014). Rapid innovation on energy efficiency and conservation technologies would also yield significant economic benefits (The Climate Institute 2013; ATSE 2014; ClimateWorks Australia 2015).

Figure 12: Solar Panels in Sydney.

"Exploitation of Australia's Galilee Basin coal deposits is incompatible with effective action on climate change."

As for export coal, the recent boom since the early 2000s was driven by inflated prices, largely in the Chinese market, and as coal prices continue to fall towards their long-term average, the coal export industry is much less profitable. In addition, scenarios of the future show that we can build an Australian economy that remains a large exporter of primary products and minerals but on a low-carbon basis. This scenario requires rapid change in the energy sector away from fossil fuels to 50% renewables by 2030 (ClimateWorks Australia and the ANU 2014).

5.

URGENCY: GETTING ON WITH THE JOB NOW

With the carbon budget rapidly running out, it is extremely urgent that global emissions track downward. The trajectory to 2050 needed to stay within budget for the 2°C policy target is highly sensitive to the year in which global emissions reach their maximum. If emissions peak this year, the maximum rate of emission reduction thereafter would be about 5.3% per year (Figure 13). That is already a daunting task. But if the peaking year does not occur until 2020, now only five years away and itself a formidable challenge, the maximum rate of emission reduction thereafter becomes 9.0% per year and the global economy needs to be essentially decarbonised by 2040-2045 (WBGU 2009). These are global average emission rates, and the rate of emission reduction by OECD (wealthy) countries such as Australia would need to be significantly higher to allow poorer countries to develop.

If there is any chance to meet the 2°C warming limit, it is clear that new investment in fossil fuels, especially in coal, needs to be reduced to zero as soon as possible. This is evident in the McGlade and Ekin (2015) analysis showing that only 12% of the world's coal reserves - and only 18% with the

"It is extremely urgent that global emissions start tracking downward this decade."

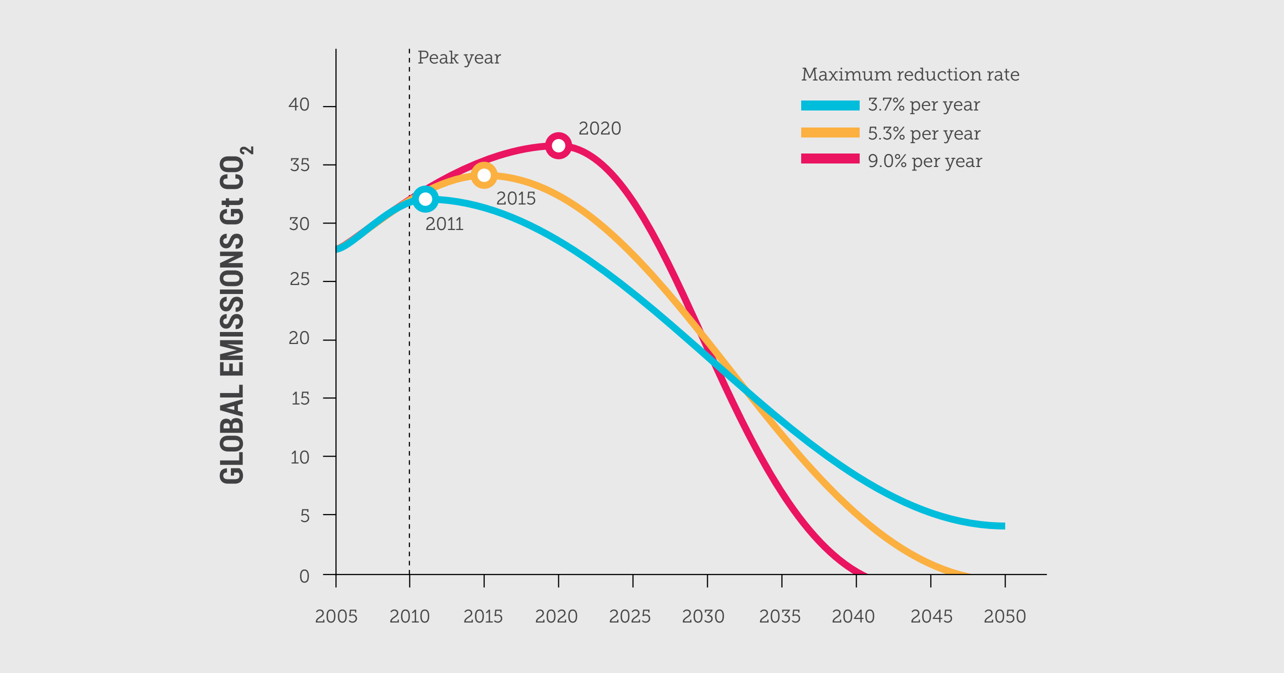


Figure 13: Three emission trajectories based on the budget approach and giving a 67% probability of meeting the 2°C guardrail. **Source:** Adapted from WBGU 2009.

> “There is no time to lose; now is the time to get on with the job.”

application of CCS technology - can be burned between now and 2050. It is likely that much, if not all, of the infrastructure needed to burn a rapidly diminishing allowable amount of coal already exists so any new investment in coal infrastructure is very likely to be incompatible with the climate policy target. In fact, some existing coal infrastructure may need to be retired before its planned lifetime is reached.

This year countries world-wide are setting emission reduction targets for the period after 2020. For instance, the United States government has said they will reduce emissions by 26%-28% by 2025 relative to 2005 levels (UNFCCC 2015), and they are on track to meet their reduction target of 17% by 2020. Australia’s bipartisan commitment is currently a 5% reduction by 2020 based on 2000 levels, and a commitment to move to 15-25% if certain factors exist (Climate Change Authority 2014). The Australian government has indicated they will make a post-2020 commitment by June this year.

While targets and timetables are not the best way of measuring future effort as noted above (and shown by the differing baselines and reduction targets used by the US and Australia), historically this is how major countries have made commitments. The Climate Change Authority (2014) recently assessed Australia’s commitments to determine what Australia’s target should be in light of the carbon budget and significant progress being made internationally. Australia’s current emission reduction target was found to be too low and out of step with our allies and trading partners. The Authority concluded that climate science, international action and economic factors all justify stronger action, and recommended Australia move to emissions reduction target of 15% below 2000 levels by 2020. They also recommended a 40-60% reduction below 2000 levels by 2030 (Climate Change Authority 2014). Both of these targets would be more in line with the carbon budget approach.

In summary, the carbon budget is a far more powerful approach to informing climate change policy than the more traditional targets-and-timetables method. The budget approach is simpler, and progress (or lack thereof) is easier to monitor. It focuses attention on the end game, that is, to decarbonise the global economy by around mid-century. This, in turn, emphasises the need for immediate investment decisions as well as strenuous mitigation actions. The carbon budget approach is consistent with a multitude of possible deep decarbonisation pathways, allowing for flexibility, ingenuity, innovation and rapid technological and institutional advances, but it does emphasise that fossil fuel usage must be phased out well before reserves, let alone resources, are exhausted. But most of all, the rapid decrease in the remaining carbon budget underscores the need for urgency. There is no time to lose; now is the time to get on with the job.

References

Anandarajah G, Pye S, Usher W, Kesicki F and McGlade, C (2011) TAIM-UCL Global Model Documentation. Accessed at http://www.ucl.ac.uk/energy-models/models/tiam-ucl/tiam-ucl-manual.

ATSE (Australian Academy of Technological Sciences and Engineering) (2014) Doubling Australia's Productivity. Accessed at http://www.atse.org.au/Documents/policy/doubling-australias-energy-productivity.pdf.

Bradstock RA, Penman T, Boer M, Price O, Clarke H (2013) Divergent responses of fire to recent warming and drying across south-eastern Australia. Global Change Biology doi:10.1111/gcb.12449.

Canadell JG and Schulze ED (2014) Global potential of biospheric carbon management for climate mitigation. *Nature Communications,* doi: 10.1038/ncomms6282.

Carbon Tracker and the Grantham Research Institute (2013) Unburnable carbon 2013: Wasted capital and stranded assets. Accessed at http://www2.lse.ac.uk/GranthamInstitute/publications/Policy/docs/PB-unburnable-carbon-2013-wasted-capitalstranded-assets.pdf.

Carbon Tracker (2014a) Carbon Supply Cost Curves: Evaluating Financial Risk to Coal Capital Expenditures. Accessed at http://www.carbontracker.org/report/carbon-supply-cost-curves-evaluating-financial-risk-to-coal-capital-expenditures/.

Carbon Tracker (2014b) ETA – Coal Supply Research Paper. Accessed at http://www.carbontracker.org/wp-content/uploads/2014/10/Carbon-Supply-Coal-ETA.pdf.

Church J, Hunter J, McInnes K and White N (2006) Sea-level rise around the Australian coastline and the changing frequency of extreme sea-level events. *Australian Meteorological Magazine,* 55:253-260.

Church JA, Clark PU, Cazenave A, Gregory JM, Jevrejeva S, Levermann A, Merrifield MA, Milne GA, Nerem RS, Nunn PD, Payne AJ, Pfeffer WT, Stammer D and Unnikrishnan AS (2013) Sea Level Change. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group Ito the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker TF, Qin D, Plattner GK, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V and Midgley PM (eds)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1137–1216, doi:10.1017/ CBO9781107415324.026.

Ciais P, Sabine C, Bala G, Bopp L, Brovkin V, Canadell J, Chhabra A, DeFries R, Galloway J, Heimann M, Jones C, Le Quéré C, Myneni RB, Piao S and Thornton P (2013) Carbon and Other Biogeochemical Cycles. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker TF, Qin D, Plattner GK, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V and Midgley PM (eds)]. Cambridge University Press, Cambridge,United Kingdom and New York, NY, pp. 465–570. doi:10.1017/CBO9781107415324.015.

Climate Change Authority (2014) Reducing Australia's Greenhouse Gas Emissions- targets and progress review-final report. Australian Government. Accessed at http://climatechangeauthority.gov.au/files/files/Target-Progress-Review/Targets%20and%20Progress%20Review%20Final%20Report.pdf.

Climate Council (2014) Report on Australia's Ageing Fleet of Electricity Generating Plants. Stock A. Accessed at www.climatecouncil.org.au/australia-s-electricity-sector-ageing-inefficient-and-unprepared.

Climate Council (2015) The Global Renewable Energy Boom. Stock A, Flannery T and Stock P. Accessed at https://www.climatecouncil.org.au/globalrenewablesreport.

ClimateWorks Australia and the ANU (2014) Pathways to Deep Decarbonisation in 2050. How Australia can Prosper in a Low Carbon World. Initial Project Report. ClimateWorks Australia and the Centre for Climate Economics and Policy, Crawford School, the Australian National University. September 2014, 47pp.

ClimateWorks Australia (2015) Australia's Energy Productivity Potential. Accessed at http://www.climateworksaustralia.org/sectors/energy-efficiency.

Commonwealth of Australia (2013) Australia's Sixth National Communication on Climate Change. A report under the United Nations Framework Convention on Climate Change. Published by the Department of Industry, Innovation, Climate Change, Science, Research and Tertiary Education. Accessed at http://www.dfat.gov.au/international-relations/themes/climate-change/Pages/australias-sixth-national-communication-on-climate-change.aspx.

Commonwealth of Australia (2015) 2015 Energy White Paper. Accessed at http://ewp.industry.gov.au/.

CSIRO and BoM (2015) Climate change in Australia: Projections for Australia's NRM regions. Technical Report, 216pp.

Department of Environment (2014) National Greenhouse Accounts Factors: Australian National Greenhouse Accounts. Accessed at http://www.environment.gov.au/system/files/resources/b24f8db4-e55a-4deb-a0b3-32cf763a5dab/files/national-greenhouse-accounts-factors-2014.pdf.

Field CB, Barros VR, Mach KJ, Mastrandrea MD, van Aalst M, Adger WN, Arent DJ, Barnett J, Betts R, Bilir TE, Birkmann J, Carmin J, Chadee DD, Challinor AJ, Chatterjee M, Cramer W, Davidson DJ, Estrada YO, Gattuso J-P, Hijioka Y, Hoegh-Guldberg O, Huang H-Q, Insarov GE, Jones RN, Kovats RS, Romero Lankao P, Larsen JN, Losada IJ, Marengo JA, McLean RF, Mearns LO, Mechler R, Morton JF, Niang I, Oki T, Olwoch JM, Opondo M, Poloczanska ES, Pörtner H-O, Redsteer MH, Reisinger A, Revi A, Schmidt DN, Shaw MR, Solecki W, Stone DA, Stone JMR, Strzepek KM, Suarez AG, Tschakert P, Valentini R, Vicuña S, Villamizar A, Vincent KE, Warren R, White LL, Wilbanks TJ, Wong PP and Yohe GW (2014) Technical Summary. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field CB, [Barros VR, Field CB, Dokken DJ, Mastrandrea MD, Mach KJ, Bilir TE, Chatterjee M, Ebi KL, Estrada YO, Genova RC, Girma B, Kissel ES, Levy AN, MacCracken S, Mastrandrea PR and White LL (eds.)] Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 35-94.

Geoscience Australia (2009) Australia's Identified Mineral Resources. Geoscience Australia, Canberra. Accessed at http://www.australianminesatlas.gov.au/aimr/index.jsp.

Geoscience Australia (2010) Australian Energy Resource Assessment. Commissioned by the Australian Government Department of Resources, Energy and Tourism (RET) and jointly undertaken by Geoscience Australia and ABARE. Accessed at http://www.ga.gov.au/corporate_data/70142/70142_complete.pdf.

Green D, Alexander L, McInnes K, Church J, Nicholls, N and White N (2010) An assessment of climate change impacts and adaptation for the Torres Strait Islands, Australia. Climatic Change 102: 405–433.

IPCC (Intergovernmental Panel for Climate Change) (2012) Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change. [Field CB, Barros V, Stocker TF, Qin D, Dokken D, Ebi KL, Mastrandrea MD, Mach KJ, Plattner G-K, Allen SK, Tignor M and Midgley PM (eds.)], Cambridge University Press, Cambridge and New York, 582 pp.

IPCC (2013) Summary for Policymakers. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker TF, Qin D, Plattner G-K, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V and Midgley PM (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1–30.

IPCC (2014) Summary for Policymakers. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field C, Barros V, Mach K, Mastrandrea M (eds)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Le Quéré C, Moriarty R, Andrew RM, Peters GP, Ciais P, Friedlingstein P, Jones SD, Sitch S, Tans P, Arneth A, Boden TA, Bopp L, Bozec Y, Canadell JG, Chevallier F, Cosca CE, Harris I, Hoppema M, Houghton RA, House JI, Johannessen T, Kato E, Jain AK, Keeling RF, Kitidis V, Klein Goldewijk K, Koven C, Landa C, Landschützer P, Lenton A, Lima I, Marland G, Mathis JT, Metzl N, Nojiri Y, Olsen A, Peters W, Ono T, Pfeil B, Poulter B, Raupach MR, Regnier P, Rödenbeck C, Saito S, Salisbury JE, Schuster U, Schwinger J, Séférian R, Segschneider J, Steinhoff T, Stocker BD, Sutton AJ, Takahashi T, Tilbrook B, Viovy N, Wang Y-P, Wanninkhof R, Van der Werf G, Wiltshire A and Zeng N (2014) Global Carbon Budget 2014. *Earth System Science Data Discussions,* doi:10.5194/essdd-7-521-2014, http://dx.doi.org/10.5194/essdd-7-521-2014.

McGlade C and Ekins P (2015) The geographical distribution of fossil fuels unused when limiting global warming to 2°C. *Nature,* 517(7533), 187-190.

Meinshausen M, Meinshausen N, Hare W, Raper SC, Frieler K, Knutti R, Frame DJ and Allen MR (2009) Greenhouse-gas emission targets for limiting global warming to 2°C. *Nature,* 458(7242): 1158–1162.

Perkins S and Alexander L (2013) On the measurement of heat waves. *Journal of Climate,* 26:4500-4517.

Perkins S, Alexander L and Nairn J (2012) Increasing frequency, intensity and duration of observed global heatwaves and warm spells. *Geophysical Research Letters* 39(20), doi: 10.1029/2012GL053361.

Smith JB, Schellnhuber H-J, Mirza MMQ, Fankhauser S, Leemans R, Erda L, Ogallo L, Pittock B, Richels R, Rosenzweig C, Safriel U, Tol RSJ, Weyant J and Yohe G (2001) Vulnerability to climate change and reasons for concern: A synthesis. In: Climate Change 2001: Impacts, Adaptation, and Vulnerability. [McCarthy J, Canziana O, Leary N, Dokken D and White K (eds.)] Cambridge University Press: New York.

Smith JB, Schneider SH, Oppenheimer M, Yohe GW, Hare W, Mastrandrea MD, Patwardhan A, Burton I, Corfee-Morlot J, Magadza CHD, Fussel H-M, Pittock AB, Rahman A, Suarez A and van Ypersele J-P (2009). Assessing dangerous climate change through an update of the Intergovernmental Panel on Climate Change (IPCC) “reasons for concern”. *Proceedings of the National Academy of Sciences (USA),* 106 doi/10.1073/pnas.0812355106.

Suppiah R, Bathols J, Collier M, Kent D and O’Grady J (2010) Observed and future climates of the Torres Strait Region. CSIRO, Marine and Atmospheric Research. Report to the Torres Strait Regional Authority, p.66.

The Climate Institute (2013) Energy efficiency and economic growth. Accessed at http://www.climateinstitute.org.au/verve/_resources/Vivid_Economics_-_Energy_efficiency_and_economic_growth_June_2013.pdf.

The White House (2014) Fact Sheet: US-China Joint Announcement on Climate Change and Clean Energy Cooperation. Accessed at https://www.whitehouse.gov/the-press-office/2014/11/11/fact-sheet-us-china-joint-announcement-climate-change-and-clean-energy-c.

Tschakert P (2015) 1.5°C or 2°C: a conduit’s view from the science-policy interface at COP20 in Lima, Peru. *Climate Change Responses,* 2(1):3.

UNFCCC (United Nations Framework Convention on Climate Change) (2008). Ad hoc working group on long-term cooperative action under the convention. Accessed at http://unfccc.int/resource/docs/2008/awglca4/eng/misc05a02p01.pdf.

UNFCCC (2010) The Cancun Agreements. Accessed at http://cancun.unfccc.int/cancun-agreements/significance-of-the-key-agreements-reached-at-cancun/.

UNFCCC (2015) INDCs as communicated by Parties. Accessed at http://www4.unfccc.int/submissions/indc/Submission%20Pages/submissions.aspx.

UN-OHRLLS (UN Office of the High Representative for the Least Developed Countries, Landlocked Developing Countries and Small Island Developing States) (2014) Urgent Action Needed Says Leader of the Least Developed Countries Group. Press release issued 3 June 2014. Accessed at http://unohrlls.org/news/3-june-2014-urgent-action-needed-says-leader-of-the-least-developed-countries-group/.

WBGU (German Advisory Council on Global Change) (2009) Solving the climate dilemma: The budget approach. Accessed at http://www.wbgu.de/fileadmin/templates/dateien/veroeffentlichungen/sondergutachten/sn2009/wbgu_sn2009_en.pdf.

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