CLIMATE ANALYTICS

A 1.5°C COMPATIBLE CARBON BUDGET FOR QUEENSLAND

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Cover photo: Aerial view of the Great Barrier Reef. Photo by Edward Haylan

EXECUTIVE SUMMARY

This report provides key carbon budget benchmarks for the energy and industry sectors for Queensland that are consistent with the state playing its role in national and global efforts to limit global mean warming to 1.5°C above pre-industrial. The 1.5°C warming limit in the Paris Agreement is particularly important as it provides the best chance of survival for the Great Barrier Reef (GBR), a critical natural and economic asset for Queensland and World Heritage site.

Current national commitments under the Paris Agreement – Nationally determined contributions (NDC) - are projected to result in a global mean warming of 2.9°C above pre-industrial by 2100. Current national policies when aggregated globally do not match the present inadequate level of NDC commitments, and are projected to result in median warming of 3.2°C above pre-industrial by 2100.

The Intergovernmental Panel on Climate Change (IPCC) in its Special Report on 1.5°C has established a rapidly escalating risk for coral reefs with warming with a 70-90% loss at 1.5°C warming, and virtually complete losses of more than 99% by 2°C global mean warming above pre-industrial. With global average warming now at around 1°C above pre-industrial, increasingly frequent major coral bleaching events are occurring. The projected higher frequency of marine heatwaves and high intensity tropical cyclones as well as ocean acidification will lead to rapidly escalating damages to coral reefs with every increment of global mean warming.

Limiting warming to 1.5°C, and ultimately below, will substantially reduce the exposure of the Great Barrier Reef to extreme marine heatwaves, including those related to extreme El Nino events, more frequent intense tropical cyclones and accelerating sea level rise. The reductions in CO_2 emissions required to limit warming to this level, will lead to ocean acidification peaking and declining. The reduction in exposure to the drivers of coral reef mortality and loss under a 1.5°C compatible pathway is substantial and highly significant, and a significant share of coral reef cover could be saved, even though substantial risks remain for the reef even with a peak warming of 1.5°C. Exceeding 1.5°C would virtually guarantee the extinction of most of the Great Barrier Reef based on present scientific knowledge, even if warming were limited to 2°C.

The carbon budget for Queensland estimated in this report focuses on what the state's domestic fossil (energy and industry) CO_2 emission limits need to be, in order to be compatible with Australia's national emissions contribution to meeting the Paris Agreement's 1.5°C limit. To estimate this budget, we make use of state-of-the-art analysis of technically and economically feasible and plausible emissions pathways taking into account sustainability considerations (for example limits to the use of negative emissions technologies) and economic considerations (we aim to minimise costs). The 1.5°C pathways require global fossil (energy and industry) CO_2 emissions to peak in 2020, reduce by 45% by 2030 compared to 2010, and reach net zero CO_2 emissions around 2060, with a global phase out of coal in the power sector by 2040 globally (2030 in OECD countries). It is generally understood that developed countries will need to reach net zero CO_2 emissions earlier than many developing countries.

The requirement for deep carbon dioxide reductions and zero emissions means that all emitters - both large and small - will need to take part, as achieving zero CO_2 emissions, or even very deep reductions, cannot be achieved without comparable action by all smaller emitters. In this study we have adopted the assumption that for Paris Agreement compatibility, and to be consistent with the Queensland Governments' zero net GHG emissions by 2050, that Queensland's fossil fuel (energy and industry) CO_2 emissions will need to reach at least net zero by 2050.

We calculate the carbon budget for Queensland's fossil fuel (energy and industry) CO_2 emissions for the period 2018-2050 to be about 1.2 $GtCO_2$, which is about 0.20% of the remaining global carbon budget until zero emissions. This is consistent with earlier estimates at national level, taking into account that Queensland has a 24% share of Australia's fossil (energy and industry) CO_2 emissions, and Australia has an estimated share of 1.1% of respective global emissions in 2017.

At 2017 energy and industry CO_2 emission rates in Queensland of about 101 $MtCO_2$ per year this budget would be consumed in 12 years, by 2031. Emissions have exhibited a sharply increasing trend in all sectors in recent years between 2014 and 2017, which means that there is greater pressure on policy and action if Queensland is to stay within a 1.5°C Great Barrier Reef compatible budget.

Results for the carbon budget for each sector and for all energy/industry emissions are shown below in Table 1, as well as necessary reductions by 2030 compared to 2005 to get on to a path that can stay within this budget.

The power sector in Queensland accounted for about 50% of energy and industry CO_2 emissions in 2017 and needs to and can be decarbonised fastest with zero emissions by 2040 reducing reliance on negative emissions. By 2030, emissions will need to be around 74% lower than in 2005, and reach zero between 2035 and 2040, with limited deployment of negative emission technology from around 2040 based on sustainable biomass limits. A carbon budget of 415 $MtCO_2$ is estimated for the power sector, which is equivalent to 8 years at 2017 emission rates.

Fast decarbonisation of the transport sector, which was 22% of 2017 energy and industry emissions, is also needed. By 2030 emissions will need to be 22% lower than in 2005 and zero by 2050. Rapid electrification of both light-duty and heavy-duty vehicles is key to this with a mix of battery (EV) and renewable hydrogen fuel cell electric vehicles (FCEV). Air transport will be more difficult and likely slower to decarbonise, however zero emissions fuels are available and can be deployed over time. A carbon budget of about 364 $MtCO_2$ is estimated for this sector, which is equivalent to about 16 years at 2017 emission rates.

There needs to be a similarly fast decarbonisation of the building sector, which was 1.4% of 2017 emissions, largely through electrification. Therefore, the building sector will decarbonise with power generation shifting to renewable energy. The buildings need a 67% reduction in 2030 compared to 2005 baseline and a 100% decarbonisation by 2050. The building sector has an estimated carbon budget of 13 $MtCO_2$.

Industry and energy related agriculture CO_2 emissions accounted for about 26.4% of CO_2 emissions in 2017 and these sectors decarbonise slower than the power sector with 23% reductions by 2030 from 2005 levels and achieving zero emissions by around 2050. The industry sector includes manufacturing and construction, mining, energy industries such as gas extraction and LNG processing (including fugitive CO_2 emissions), and process emissions (e.g. from cement production). A carbon budget of about 391 $MtCO_2$ is estimated for industry and agriculture sector, which is equivalent to about 15 years at 2017 emission rates. Agriculture energy related emissions include emission from fuel combustion in agriculture, fisheries, and forestry relating to stationary and off-road vehicles and machinery.

Overall, a 58% reduction in energy and industry CO_2 emissions are needed by 2030 compared to 2005 (55% below 2010 levels), and slightly greater than a 100% reduction by 2050, with some negative CO_2 emissions technology deployed in the power sector. The fastest reductions are in the power sector, a common feature of all decarbonisation studies. The 55% reduction by 2030 from 2010 levels is faster that the global 2030 reductions required reported by the IPCC of 45%, however this is to be expected as developed countries can be expected to reduce emissions faster than developing countries.

As the Queensland government (2017) has an economy-wide net zero emissions target for 2050, the Land use, land-use change and forestry sector will need to be a net emissions sink to compensate for the remaining emissions from other greenhouse gases such as methane and from other sectors such as agriculture in 2050.

Table 1: Paris Agreement compatible energy carbon budget for Queensland 2018-2050

Sector	**Paris Agreement compatible carbon budget** 2018-2050 $MtCO_2$*	2030 reduction (compared to 2005 baseline)	2005 Baseline $MtCO_2$	Remaining years at 2017 emissions rates
Electricity generation	415	74%	47.42	8
Transport	364	22%	17.31	16
Industry	362	23%	17.61	15
Buildings	13	67%	1.08	10
Agriculture (energy related)	28	22%	1.35	14
Total energy/industry emissions	**1182**	**58%**	**84.77**	**12**

INTRODUCTION

This report provides key carbon budget benchmarks for the energy system for Queensland that are consistent with the state playing its role in national and global efforts to limit global mean warming to 1.5°C above pre-industrial. The Paris Agreement's long-term temperature goal (LTTG) aims to limit global average warming to 1.5°C above pre-industrial levels[1], which is particularly important as it provides the best and perhaps only chance for survival of the Great Barrier Reef (GBR). Recent scientific reports, including the Intergovernmental Panel on Climate Change 1.5°C Special Report (IPCC SR15) have found by the time global average warming reaches 2°C, the GBR is unlikely to survive, with losses exceeding 99% (IPCC 2018a)[2]. Limiting warming to 1.5°C will still entail very serious damage to the Great Barrier Reef, and indeed all warm water coral reef systems, with 70-90% losses projected.

With the present level of warming at about 1°C above preindustrial levels, limiting warming to 1.5°C will require urgent and rapid action globally. The IPCC Special Report has shown that this remains feasible provided action is initiated very soon. Main messages from the IPCC (2018a) SR15 include:

- Climate Change poses a severe threat, with risks being lower at 1.5°C than at 2°C or higher temperature increases above pre-industrial levels.
- Avoiding these severe risks is still feasible, but requires cutting global greenhouse gas (GHG) emissions by about half by 2030, and reaching zero CO_2 emissions from all sources by 2050 globally.

The carbon budget for Queensland will focus on what the state's fossil (energy and industry) CO_2 emission limits need to be, in order to be compatible with Australia's national emissions contribution to meeting the Paris Agreement's 1.5°C limit.

To estimate this budget, we use multiple lines of evidence from the scientific and technical literature, making use of state-of-the-art analysis of technically and economically feasible and plausible emissions pathways and technologies. We also consider sustainability constraints (for example limits to the use of biomass and negative emissions technologies) and economic considerations (we aim to minimise costs). As a starting point we look at fossil fuel and industry related CO_2 emissions by down-scaling the results of complex energy system models of how the world's energy system needs to transform to reduce emissions to stay within the Paris Agreement 1.5°C limit at the broad regional level. However, as individual countries like Australia, or subnational regions such as the state of Queensland, are not modelled, and as the available models have not yet accounted for the rapid reductions in the costs of range of technologies including renewable energy and storage (batteries, pumped storage), electric vehicles, and renewable hydrogen, we also need to make further assumptions which are explained in the report. In addition, we account for Queensland's own policies such as its 50% by 2030 renewable electricity goal and net zero GHG emissions by 2050 goal. The results are consistent with the state's

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[1] Article 2.1 of the Paris Agreement (PA) defines its long-term temperature goal (LTTG) as "[h]olding the increase in the global average temperature to well below 2 °C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 °C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change" (UNFCCC 2015).

[2] IPCC (2018c) Summary for Policy Makers B4.2 states "The risks of climate-induced impacts are projected to be higher at 2°C than those at global warming of 1.5°C (high confidence). Coral reefs, for example, are projected to decline by a further 70–90% at 1.5°C (high confidence) with larger losses (>99%) at 2ºC (very high confidence). The risk of irreversible loss of many marine and coastal ecosystems increases with global warming, especially at 2°C or more (high confidence). {3.4.4, Box 3.4}"

economic structure, population and present emission profile. These techniques generate a Queensland Paris Agreement compatible carbon budget range that is consistent with global and national efforts to limit warming to 1.5°C.

The requirement for deep carbon dioxide reductions and zero emissions means that all emitters - both large and small - will need to take part. It is argued by some in Australia that because it is a small global emitter - about 1.1% to 1.4% of global emissions - then its actions are irrelevant and not necessary. However, small emitters, under 2% of global emissions of CO_2, add up to close to 30% of global CO_2 emissions in 2017, showing that achieving zero CO_2 emissions, or even very deep reductions, cannot be achieved without comparable action by all smaller emitters.

In order to meet the Paris Agreement commitments, Australia needs to make both domestic emission reductions and contributions to assisting poorer countries[3] in reducing theirs. An estimate of what reasonable domestic emission reductions Australia needs to make to play its role in meeting the Paris Agreement goals, and 1.5°C global warming limit, can be derived from global integrated assessment and energy model scenarios of 1.5°C compatible energy transformations. Based on these results it is possible to then evaluate what individual states, such as Queensland need to do as part of the Australian energy system transformation. The carbon budget exercise for Queensland will focus on what the state emission limits need to be, in order to be compatible in overall terms with Australia's national emissions contribution to meeting the Paris Agreement’s 1.5°C limit.

WHY FOCUS ON CO_2 FROM THE ENERGY SYSTEM?

Carbon dioxide is the main driver of human induced climate change and ocean acidification, and CO_2 from fossil fuel is the largest source, about 66%, of total GHG emissions globally (and 63% in Queensland[4]). Ocean acidification itself is a major risk factor for the Great Barrier Reef (Mongin et al. 2016), exacerbated by warming (Prada et al. 2017), and reducing CO_2 emissions is the only way of ameliorating and reducing this.

[3] This study will not examine this issue. As further background, in addition to Australia's own domestic emission reductions, Australia, and other wealthier countries, also needs to contribute to assisting poorer countries and reduce their emissions, which gives rise to what is called a "fair share" contribution to global emission reductions. For wealthier countries such as Australia this almost always means that a fair share contribution (measured in terms of national emission reduction targets) is larger than least-cost domestic emission reductions. For example, a domestic emissions reduction target for Australia could be 50% by 2030, but the “fair share” reduction would be larger, for example, 70%. This does not mean that Australia has to make 70% emission reductions physically by 2030, but Australia would need to consider how to contribute to other poorer countries reduce their emissions equivalent to about 20% of Australia's base year emissions (2005). Countries are typically making these contributions to, for example the Green Climate Fund, along with bilateral activities to assist with climate action, all of which are agreed to be scaled up under the Paris Agreement.

[4] Queensland Inventory 2017: CO_2 from energy and industry: 101 Mt CO_2; total GHG emissions: 161 $MtCO_2eq$ (Department of the Environment and Energy 2019).

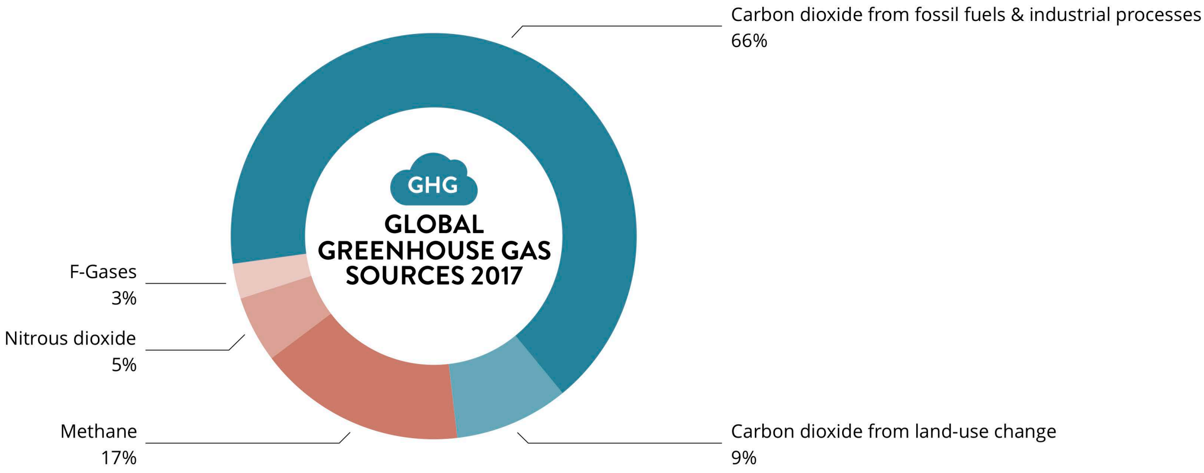

Figure 1: Global GHG emissions by gas. Source: (PBL 2018; Le Quéré et al. 2018)

PARIS AGREEMENT LONG TERM TEMPERATURE GOAL AND 1.5°C WARMING LIMIT

The long term temperature goal (LTTG) of the Paris Agreement (PA) is "[h]olding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 °C above pre-industrial levels, recognising that this would significantly reduce the risks and impacts of climate change" (UNFCCC 2015, Art. 2.1 PA). The legally binding long-term temperature goal is, by design, both a substantive and legal strengthening of the previous international goal of holding warming below 2°C, agreed in Cancun at UNFCCC COP16 in 2010[5]. This goal is to be operationalized through the Agreement's different enabling elements, in particular Article 4.1 which establishes a timetable for peaking global GHG emissions as soon as possible, rapidly reducing these, with zero GHG emissions to be achieved globally in the second half of this century. The timetable for these global reductions and timing of achieving zero GHG emissions is to be based on the best available science.

KEY SCIENTIFIC ASPECTS OF THE PARIS AGREEMENT'S LONG TERM TEMPERATURE GOAL

The Paris Agreement LTTG requires a substantially lower level of warming be achieved than the former 2°C Cancun goal, which is still often referred to in Australia. Scientifically, the 2°C Cancun goal is interpreted as emission pathways that have a likely (66% or higher probability) of holding warming below 2°C. Peak 21st century warming in the published mitigation pathways consistent with the 2°C Cancun goal is 1.7-1.8°C and generally these pathways have less than a 50% probability of warming below 1.5°C by 2100[6].

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5 UNFCCC 1/CP.16 The Cancun Agreements, Paragraph 4: "Further recognizes that deep cuts in global greenhouse gas emissions are required according to science, and as documented in the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, with a view to reducing global greenhouse gas emissions so as to hold the increase in global average temperature below 2 °C above preindustrial levels, and that Parties should take urgent action to meet this long-term goal, consistent with science and on the basis of equity; also recognizes the need to consider, in the context of the first review, as referred to in paragraph 138 below, strengthening the long-term global goal on the basis of the best available scientific knowledge, including in relation to a global average temperature rise of 1.5 °C"

6 Note that in the underlying scientific literature, probabilities of holding warming below a certain level for a particular emissions pathway consider uncertainties in the global carbon cycle and climate system. In this context, for example a "median" warming level associated with a particular global emissions pathway means that 50% of a large collection of climate/carbon-cycle models shows warming above, and 50% shows warming below, the specified warming level, for that particular emissions pathway.

The specific language of the Paris Agreement LTTG means warming should not rise above a level well below 2°C – which means peak 21st century warming needs to be lower than 1.7-1.8°C achieved in pathways consistent 2°C Cancun goal with a likely probability (66% or higher probability). The Paris Agreement LTTG excludes interpretations that would have warming rise above a level well below 2°C before declining to a level well below 2°C by, for example, 2100. The latter appears to be a common misunderstanding in the Australian policy debate. In addition, it is important to note that the only temperature limit referred to in the Paris Agreement is 1.5°C above preindustrial levels.

Given the strengthening of the long-term temperature goal in the PA, compared to the Cancun Agreements, emissions pathways compatible with the PA must increase substantially both the margin and likelihood by which warming is held below 2°C, and simultaneously satisfy the 1.5°C limit. To address this the IPCC (2018c) SR15 Summary for Policymakers (SPM) defined 1.5°C compatible mitigation pathways as those with no- or limited overshoot above 1.5°C warming:

- "no- overshoot"- limit median global warming to 1.5°C throughout the 21st century without exceeding that level
- "low-overshoot" - a brief and limited overshoot (<0.1°C) with median peak warming below 1.6°C around the 2060s and drop below 1.5°C by the end of the century (around 1.3°C warming by 2100).

We have stepped through the key scientific elements of Paris Agreement compatible pathways issues as they are fundamental for policy and in particular for the selection of mitigation pathways that can provide guidance for policies consistent with limiting warming to 1.5°C and provide the best chance of survival of the Great Barrier Reef.

With the focus of this work on levels of warming and carbon budgets that provide a chance of survival of the Great Barrier Reef, the IPCC (2018a) SR15 1.5°C compatible mitigation pathways are particularly important. The IPCC (2018a) SR15 has shown that a 0.5°C overshoot of 1.5°C substantially increases climate impacts, and quite dramatically for coral reefs. The IPCC (2018a) SR15 is very clear about the increases in climate risks between 1.5°C and 2°C, which reinforces the clause of the LTTG that limiting warming to 1.5°C "would significantly reduce the risks and impacts of climate change".

It is important to note that the 2°C Cancun goal ("hold below 2°C") pathways discussed in much of the literature and in the IPCC reports predating the Paris Agreement do not provide a perspective on limiting the temperature increase to 1.5°C nor are they consistent with the survival of coral reef systems. An example of this problem can be found in the Queensland Government commissioned report from Ernst and Young (EY) which refers to a 2°C scenario ("2DS") as a Paris Agreement consistent scenario. Oddly enough the EY report also recognises that 2°C warming would catastrophically impact the Great Barrier Reef.[7]

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[7] IEA (2017) in its ETP qualified the 2DS scenario as having a 50% chance to stay below 2°C and as such it would not even meet the Cancun "hold below 2°C" goal. We verified that with specific assumptions on substantial negative emissions in the second half of the century comparable to typical Cancun "hold below 2°C" scenarios, warming would be limited to 1.7-1.8°C in this IEA scenario. Hence, if such assumptions are applied, this scenario (2DS) provides an analogue to a 2°C Cancun goal pathway. The IEA SDS scenario, with comparable emissions and energy system characteristics until 2040, would qualify as such as well, applying the same assumptions. Both are not consistent with achieving the Paris Agreement long term temperature goal. As is shown Climate Action Tracker (2018b), the IEA's (2017) "Beyond 2 Degrees Scenario" (B2DS) can be used as a proxy for 1.5° compatible pathways, with certain caveats.

In policy terms, if the 2°C goal were to be used as a guide, the resulting 2030 emissions levels would be far above those in 1.5°C-compatible pathways, as shown in IPCC SR15, so that 1.5°C limit would be out of reach, unless extreme carbon dioxide removal levels are achieved by 2050, which the Special Report does not deem feasible for technical, economic and sustainability reasons (Wachsmuth, Schaeffer, and Hare 2018).

KEY FINDINGS IPCC SPECIAL REPORT ON 1.5°C ON IMPACTS

The IPCC (2018a) Special Report on Global Warming of 1.5°C (IPCC SR15) has assessed the impacts of global mean temperature increase of 1.5°C above pre-industrial levels, as well as the impacts avoided compared to higher levels of warming including 2°C. The report details the extent of global warming so far and the risks and impacts for both natural and human systems.

The impacts of climate change from pre-industrial levels to the present day are evident. The global mean surface temperature (GMST) from 1850-1900 compared to 2006–2015 increased by 0.9°C (IPCC 2018a). There has been an increase in temperature for land and ocean (IPCC 2018a). There has been a higher frequency of heatwaves over land in most regions (IPCC 2018a). Marine heatwaves are more frequent and are of a longer duration (IPCC 2018a). The frequency, intensity and quantity of rainfall has increased in a number of regions (IPCC 2018a).

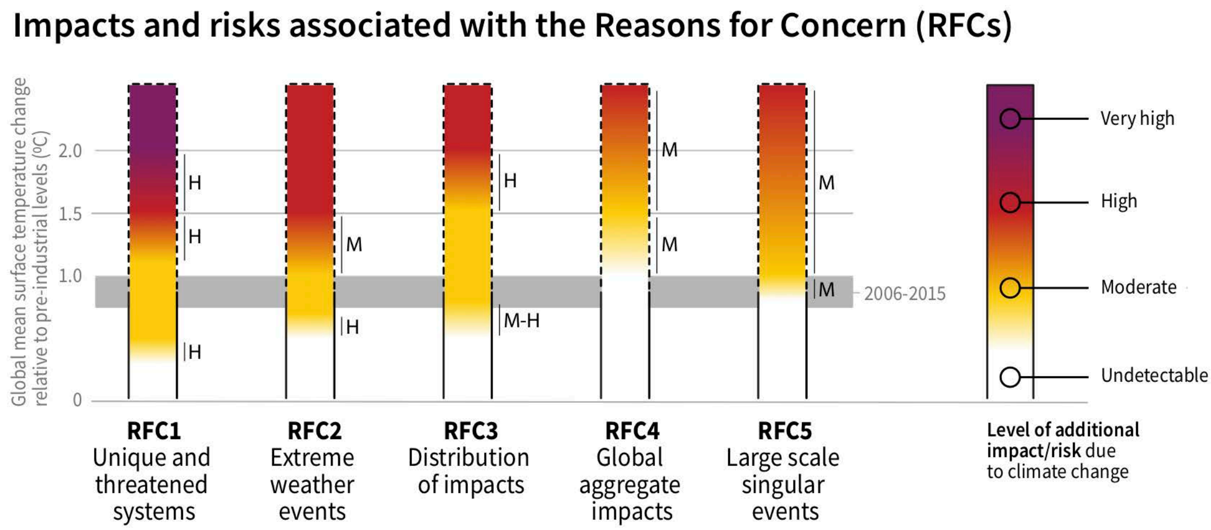

Figure 2: Impacts and risks associated with the Reasons for Concern (RFCs). Source: (IPCC 2018c)

The IPCC summarises its findings on the increase of the risks and impacts of climate change with global mean temperature in five 'Reasons for Concern' (RFCs): the risks to unique and threatened systems; the risks of extreme weather events; the distribution of impacts and vulnerabilities; global aggregated impacts; and risks of large scale singularities such as tipping points. The 'reasons for concern' are compared to different global warming levels (see figure 2). Purple indicates the highest severity of impacts and risks, signalling irreversible or persistent climate hazards, and the inability for adaptation (IPCC 2018c). 'High' risks marked by the transition to red colour indicate that impacts and risks will be severe and widespread (IPCC 2018c). Risks for all five "reasons for concern" identified by the IPCC will transition to 'high' risks if warming of 1.5°C is exceeded. Due to improved understanding on risks and impacts on all RFCs, the RFC risk transition levels to high risks have been corrected downwards since the IPCC's Fifth' Assessment Report published in 2014.

Figure 3 highlights selected examples of natural and human systems affected by climate change, and provides an insight into the diversity and severity of selected impacts. One of the more vulnerable natural systems are the coral reefs, which are already "in the red" with severe and widespread impacts detected. A 2°C rise will devastate coral reefs, whereas a 1.5°C rise may allow some coral reefs to survive.

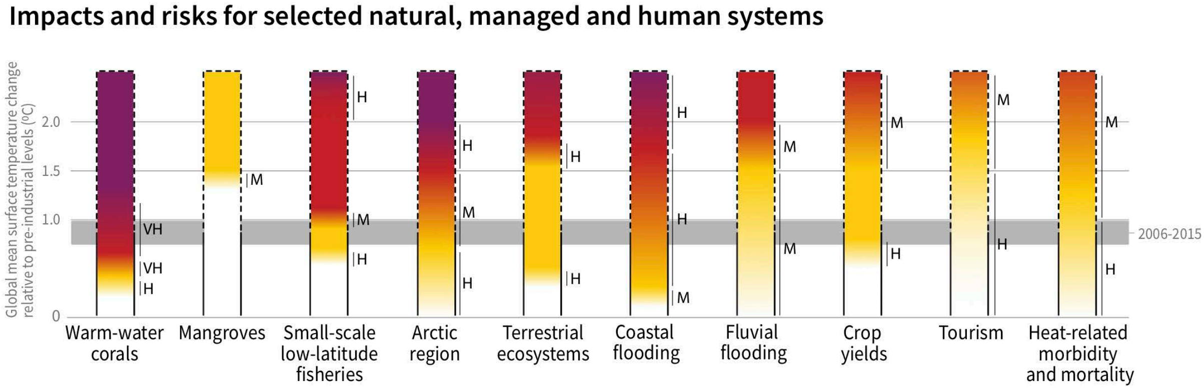

Figure 3: Impacts and risks for selected natural, managed and human systems. Source: (IPCC 2018c)

The projected risks on these human and natural systems are vast, and the risk levels take a massive leap between 1.5°C to 2°C warming above pre-industrial levels. One example, is that limiting warming to 1.5°C degrees could mean 420 million fewer people would be exposed to exceptional heatwaves in contrast to 2°C global warming (IPCC 2018a). Risks of species losses and extinction are less likely in 1.5°C scenario compared to a warmer climate of 2°C (IPCC 2018a). Keeping warming well below 1.5°C is essential to prevent these adverse impacts.

LIMITING WARMING TO 1.5°C AND THE FUTURE OF THE GREAT BARRIER REEF

Australia's Great Barrier Reef (GBR) is the largest coral reef system in the world and has been listed on the World Heritage list since 1981 for its outstanding universal natural values. It hosts a number of species threatened with extinction (UNESCO n.d.). Apart from its intrinsic and amenity values, the GBR is a major contributor the Australian economy with $6.4 billion and 64,000 jobs nationally (Deloitte 2017). The Reef was saved from mining and oil drilling in the 1970s (ABC News 2017) and one third is protected in marine national parks under the management of the Great Barrier Reef Marine Park Authority. Sections are under pressure from land-based pollution (GBRMPA n.d.), which has been the subject of decades of (not highly successful) management efforts.

For the State of Queensland, it is a critical natural and economic asset. The Queensland Climate Transition Strategy identifies the Great Barrier Reef as already impacted by climate change, "placing at risk the $6 billion and 69,000 jobs it contributes to our economy" (Queensland Government 2017). The Australian and Queensland governments' "Reef 2050 Long-term Sustainability Plan" lacks any action on climate change, identified by scientists and the government as the key threat to the GBR, owing to the impact of global warming and ocean acidification (Hughes, Day, and Brodie 2015).

BRIEF HISTORY OF SCIENTIFIC CONCERN OVER CLIMATE CHANGE AND CORAL REEFS

For at least twenty years the scientific community has flagged an existential risk to the GBR from unmitigated climate change (Hoegh-Guldberg 1999). Twenty years on it is worth recalling the conclusions of this seminal 1999 paper and its key projections:

> *"Events as severe as the 1998 event, the worst on record, are likely to become commonplace within 20 years. Most information suggests that the capacity for acclimation by corals has already been exceeded, and that adaptation will be too slow to avert a decline in the quality of the world's reefs. The rapidity of the changes that are predicted indicates a major problem for tropical marine ecosystems and suggests that unrestrained warming cannot occur without the loss and degradation of coral reefs on a global scale."*

In 2001, the IPCC Third Assessment Report (2001) flagged, for the first-time in an IPCC report, substantial risks to coral reefs for a warming of water temperature by 1°C:

> *"Sustained increases in water temperatures of as little as 1° C, alone or in combination with any of several stresses (e.g., excessive pollution and siltation), can lead to corals ejecting their algae (coral bleaching) and the eventual death of some corals"*

In 2009 key coral reef scientists flagged a clear existential risk for coral reefs from increase CO_2 concentration and warming, linking the effects of warming, increasing ocean acidification and local pressures (Veron et al. 2009), warning that:

> *"Damage to shallow reef communities will become extensive with consequent reduction of biodiversity followed by extinctions. Reefs will cease to be large-scale nursery grounds for fish and will cease to have most of their current value to humanity."*

Increasingly frequent bleaching events globally, as well as the growth of scientific understanding of the effects of climate change and ocean acidification on coral reefs has reinforced and sharpened scientific assessment of the risks to coral reefs. By 2018 overwhelming scientific evidence led to conclusions in the Summary for Policy Makers of the IPCC (2018c) Special Report on Global Warming of 1.5°C which states that:

> *"Coral reefs, for example, are projected to decline by a further 70–90% at 1.5°C (high confidence) with larger losses (>99%) at 2°C (very high confidence). The risk of irreversible loss of many marine and coastal ecosystems increases with global warming, especially at 2°C or more (high confidence)." (IPCC 2018c, B.4.2)*

GREAT BARRIER REEF EXPERIENCES MAJOR BLEACHING EVENTS CONSISTENT WITH PROJECTIONS

Consistent with the projections made in 1999 the Great Barrier Reef experienced major bleaching events in 2016 and 2017, exceeding in severity the events of 1998, with two thirds of the GBR area affected over 1,500km of coastline (ARC COE Coral Reef Studies n.d.) (Figure 4). This unprecedented bleaching has resulted in widespread coral mortality and a very slow recovery. The density of new corals has declined massively before and after the back-to-back bleaching events (Hughes et al. 2019). Due to mass mortality of adult brood stock in 2016 and 2017 owing to heat stress, the amount of larval recruitment declined in 2018 by up to 89% compared to historical levels in damaged areas.

The extent to which the Great Barrier Reef (GBR) will be able to recover from this collapse in stock-recruitment remains uncertain (Hughes et al. 2019). A long term reef monitoring program by the Australian Institute of Marine Science (AIMS 2019) report found the Central GBR declined to 12% in 2019 and the Northern GBR increased slightly to 14%, the latter close to the lowest levels since 1985 (AIMS 2019). The coral in the northern GBR could be overestimated as some reefs were not surveyed due to safety concerns (AIMS 2019).

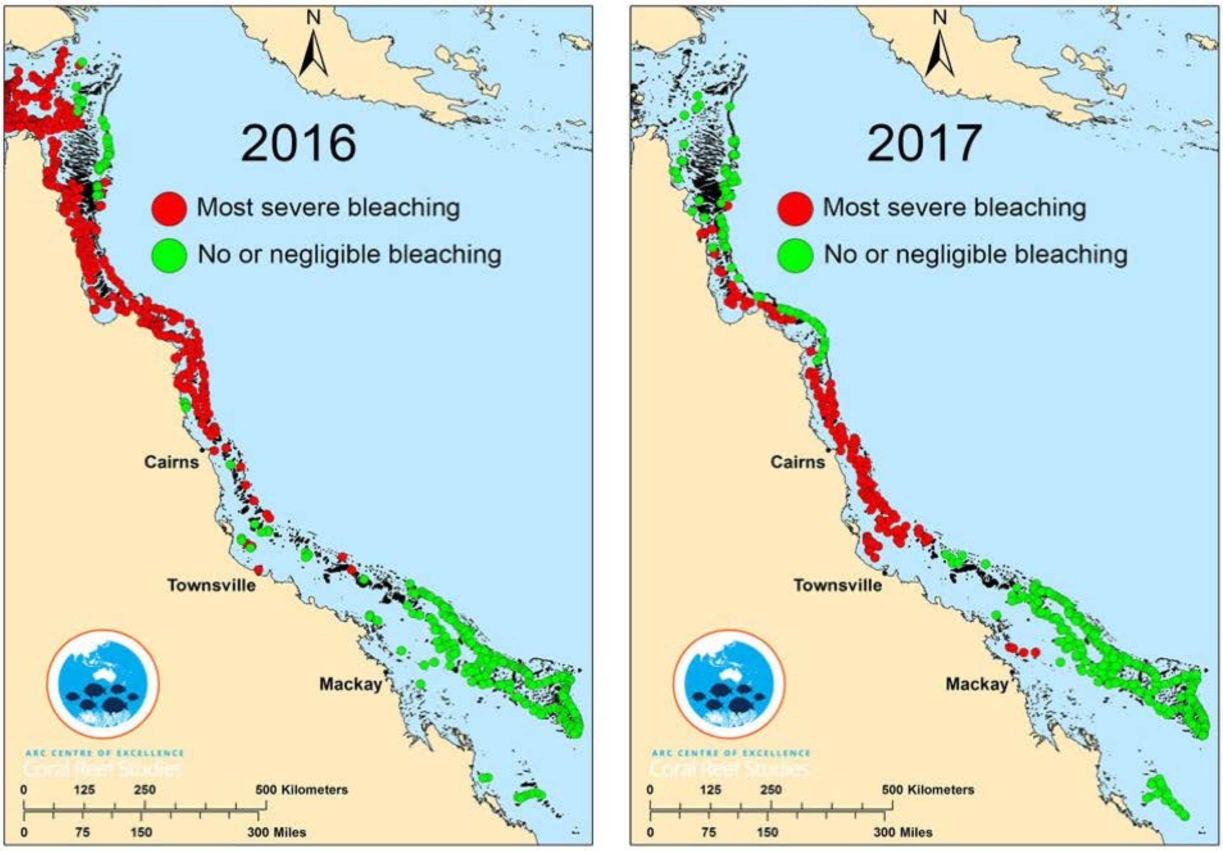

Figure 4: Extent of most severe bleaching in 2016 and 2017. Source: (ARC COE n.d.)

Recent research indicates that the "bleaching events of the past three decades have been mitigated by induced thermal tolerance of reef-building corals" and that a warming of only 0.5°C will cause corals to lose their sub-bleaching protection mechanism leading to faster Great Barrier Reef (GBR) degradation (Ainsworth et al. 2016).

This situation led the Great Barrier Reef Marine Park Authority to issue an unprecedented statement on the future of the reef:

> *"Climate change is the greatest threat to the Great Barrier Reef. Only the strongest and fastest possible actions to decrease global greenhouse gas emissions will reduce the risks and limit the impacts of climate change on the Reef. Further impacts can be minimised by limiting global*

temperature increase to the maximum extent possible and fast-tracking actions to build Reef resilience."[8]

CLIMATE CHANGE RISKS AND THE FUTURE OF THE GREAT BARRIER REEF

The Great Barrier Reef is subject to a range of climate change related threats resulting from the emission of carbon dioxide and other greenhouse gases. Whilst warming of the atmosphere is perhaps the best-known climate system change due to increasing CO_2 concentrations, there are other important effects such as ocean acidification and deoxygenation, compounding effects with more intense tropical cyclones and accelerated sea level rise interacting with the other factors. In the following, those different drivers of damage to the Great Barrier Reef and how they are affected by mitigation pathways, in particular limiting warming to 1.5°C, will be summarised.

Global mean temperature projections based on current mitigation policies

The present generation of national commitments made under the Paris agreement - Nationally determined contributions or NDCs - are calculated to result in median estimates of 2.9°C warming by 2100. The ambition of current policies globally does not yet match even this inadequate level of NDC commitment, and is estimated to lead to a median warming of 3.2°C.[9] It is important to note that these are median warming estimates (50% likelihood) based on probabilistic estimates of likely future warming for these emission pathways based on uncertainties in our knowledge of the climate system response. From a risk perspective it is important to know that there is about a 10% chance of warming exceeding 4°C by 2100 from current commitments and policies.

At the global mean level, it can be expected that warming would continue to accelerate unless emissions are reduced, with global mean warming above preindustrial exceeding 1.5°C by around 2035, and 2°C warming by around 2053[10]. A 1.5° pathway could peak globally average warming at about 1.5°C in the 2040s, with global mean surface temperature slowly declining thereafter under 1.5°C compatible mitigation pathways.

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[8] A draft of the Great Barrier Reef Marine Park Authority position in circulation and reported in the press stated this in slightly stronger terms: "Climate change is the greatest threat to the Great Barrier Reef. Immediate action to reduce greenhouse gas emissions is critical. Limiting global temperature increase to the Paris Agreement target of 1.5 degrees Celsius, or below, is critical to maintain the ecological function of the Great Barrier Reef."

[9] CAT 2019 Warming update https://climateactiontracker.org/documents/644/CAT_2019-09-19_BriefingUNSG_WarmingProjectionsGlobalUpdate_Sept2019.pdf

[10] Climate Action Tracker (CAT) September 2019: Warming Projections Global Update. briefing https://climateactiontracker.org/documents/644/CAT_2019-09-19_BriefingUNSG_WarmingProjectionsGlobalUpdate_Sept2019.pdf

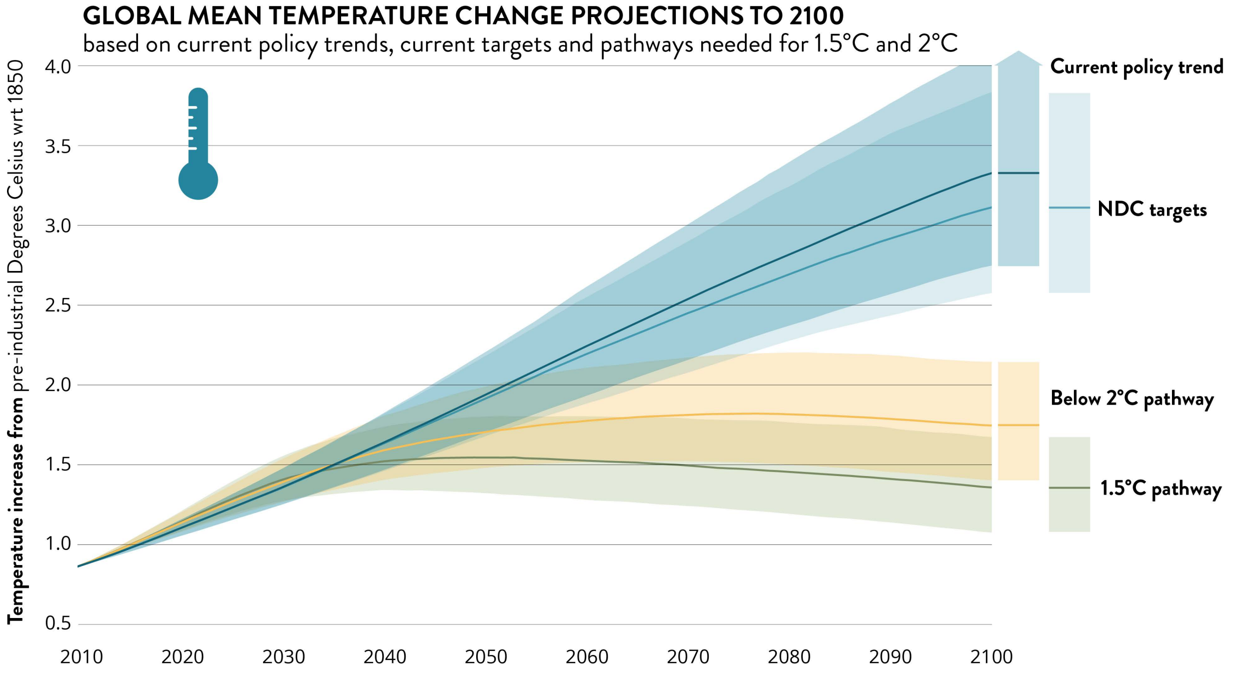

Figure 5: Projected global mean warmings for Paris Agreement 1.5°C compatible scenarios, Cancun 2°C goal scenarios, and projections under Current Policy Trends and assuming current NDC targets are met. (Source: own calculation, based on Climate Action Tracker (CAT) (2018a) data).

Increasing temperatures and marine heatwaves

Oceans are absorbing about 93% of the additional energy brought into the earth system by anthropogenic greenhouse gas emissions (Rhein et al. 2013). As a consequence, rapid ocean warming and temperatures outside the range of natural variability, including Marine Heat Waves, are observed at present levels of warming of 1°C global mean temperature increase above pre-industrial levels. Due to the larger share of energy being absorbed and the comparably smaller natural variability, observed changes in ocean systems generally happen at a rate much faster than atmospheric changes in the climate system.

The occurrence probability of Marine Heat Waves has already been made much more likely due to climate change (Frölicher and Laufkötter 2018). For some cases, the occurrence of Marine Heat Waves can be fully attributed to climate change, meaning that they would not have occurred without anthropogenic global warming (Frölicher and Laufkötter 2018). Today, about 87 per cent of Marine Heat Waves are attributable to human-induced warming, with this ratio increasing to nearly 100 per cent under any global warming scenario exceeding 2°C (Frölicher, Fischer, and Gruber 2018).

The probabilities of Marine Heat Wave occurrence are projected to increase rapidly with ongoing warming (see Figure 6). A recent global analysis by Frölicher et al. (2018) has found that:

> *"…a doubling in the number of MHW days, and this number is projected to further increase on average by a factor of 16 for global warming of 1.5 degrees Celsius relative to preindustrial levels and by a factor of 23 for global warming of 2.0 degrees Celsius. However, current national policies for the reduction of global carbon emissions are predicted to result in global warming of about 3.5 degrees Celsius by the end of the twenty-first century, for which models project an average increase*

in the probability of MHWs by a factor of 41. At this level of warming, MHWs have an average spatial extent that is 21 times bigger than in preindustrial times, last on average 112 days and reach maximum sea surface temperature anomaly intensities of 2.5 degrees Celsius. The largest changes are projected to occur in the western tropical Pacific and Arctic oceans."

While the risks associated with Marine Heat Wave occurrence are increasing rapidly with warming, only limiting to 1.5°C will prevent marine temperatures to shift to a complete new regime outside natural variability with potentially devastating consequences for marine ecosystems including coral reefs (Frölicher et al. 2018).

More frequent, intense and longer-lasting marine heatwaves will result in more frequent and severe bleaching events on coral reefs like the Great Barrier Reef, with the potential extinction of many coral species and co-dependent systems and species. Reducing the likelihood and intensity of marine heatwaves creates a much greater probability that the Great Barrier Reef system will be able to survive in the longer term.

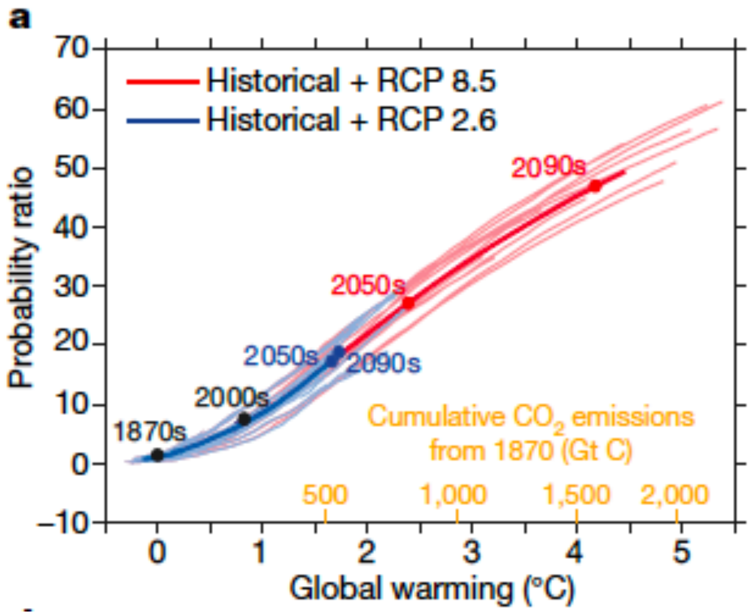

Figure 6: Increase in the probability of occurrence of extreme marine heatwaves globally with global warming. A probability ratio of 10 implies that an event that would have constituted a marine heatwave in pre-industrial times (at zero global warming) will occur 10 times more frequently. The ranges for a >4°C (RCP 8.5, red) and a <2°C Cancun goal pathway (RCP 2.6, blue) are highlighted. Source: (Frölicher et al. 2018).

Increasing sea surface temperatures beyond local reef tolerance levels are now well-established as a cause of coral reef bleaching. See surface temperatures do not increase smoothly and increase in response to other variations in the climate system such as El Niño. Global warming to date has led to episodic exposure to temperatures in excess of reef tolerance levels resulting in the unprecedented mass coral bleaching on the Great Barrier Reef. The rate of exceedances of bleaching temperature thresholds are known to increase rapidly with global mean warming but it also known that the rate of exceedance can be lowered by reducing greenhouse gas emissions and future warming.

Historically, coral reefs have recovered from bleaching events however it is known that bleaching events that are too frequent, more than once or twice per decade, are likely to result in a lack of recovery or very limited recovery (Frieler et al. 2013; Heron, Eakin, and Douvere 2017; Hoegh-Guldberg 1999).

Recent work by King et al (2017) has shown how the probability of extreme heat such as that which affected the Coral Sea in 2016 and caused the worst mass bleaching episode ever recorded, is affected significantly by different levels of global warming. They show in an unchanged climate unaffected by the addition of greenhouse gases there would be virtually no chance of such a warming event occurring, but that the addition of greenhouse gases to the atmosphere to date has given us a 31% chance of occurrence, or effectively every 3 to 4 years. At 1.5ºC global mean warming this increases to about 64%, or effectively two out of every three years in occurrence. By the time 2°C of global warming is reached, there will be an occurrence of about 87%, meaning that around 8 to 9 out of every 10 years would be experiencing Coral Sea warming, such as that led to their worst coral bleaching on record in 2016. Warming beyond 2°C would increase this probability substantially. In other words, warm ocean water associated with bleaching of the GBR in 2016 would be substantially less likely, by about 25%, if 21st century warming is kept to 1.5°C instead of 2°C (King et al. 2017).

Event		Associated impacts	Natural	Current	1.5 °C	2 °C
Angry summer 2012–2013		Severe heatwaves, Power blackouts, Bushfires	**3%** (1–5%)	**44%** (36–52%)	**57%** (50–65%)	**77%** (70–84%)
Coral Sea heat JFM 2016		Worst coral bleaching event on record	**0%** (0%)	**31%** (22–40%)	**64%** (53–76%)	**87%** (79–93%)
NE Australia rain December 2010		Widespread floods, Dozens of deaths	**1%** (0–2%)	**2%** (0–2%)	**1%** (1–1%)	**1%** (1–2%)
SE Australia drought 2006	Low rainfall	Water restrictions, Reduced crop yields	**1%** (1–2%)	**2%** (1–3%)	**3%** (1–4%)	**3%** (1–4%)
	High temperatures		**1%** (0–1%)	**35%** (28–42%)	**52%** (45–59%)	**74%** (67–81%)

Figure 7: Increasing likelihood of Australian extreme temperatures and rainfall events at 1.5°C and 2°C global mean warming. [11] *Source: (King et al. 2017)*

Unfortunately, experience with the recent global coral reef mortality events has shown that large, intense marine heat waves can also result in the direct destruction of coral reefs (Leggat et al. 2019). These effects go beyond and are significantly faster than the processes associated with coral reef bleaching and resulting in immediate mortality and loss of three-dimensional reef structure.

[11] Original figure caption "Examples of the likelihoods in a given year of similar events to four recent Australian extremes in a natural world, the current world, a 1.5C world and a 2 C world. For the Australian drought case, changes in the likelihood of both precipitation deficits and high temperatures are considered due to their relevance. The best estimate is shown with the 5th–95th percentile confidence intervals in parentheses. Several of the impacts of each extreme event are highlighted."

Increasing frequency of extreme El Niño Events

The most extreme marine heat waves at the GBR are associated with extreme El Niño events. The frequency of such extreme El Niño events is projected to increase rapidly with future warming (Cai et al. 2015). Even under a 1.5°C warming, the frequency of such extreme El Niño events is projected to more than double. Limiting warming to 1.5°C will nevertheless still avoid substantial risks, as for a 2°C warming extreme El Niño occurrence will almost triple in occurrence probability relative to pre-industrial levels (Wang et al. 2017).

Ocean acidification

Increasing concentrations of carbon dioxide in the atmosphere results in acidification of the oceans. CO_2 emissions to date have already resulted in the highest atmospheric CO_2 concentrations, and resulting ocean acidification, in 3 million years (Willeit et al. 2019).

Negative consequences of this were first acknowledged in the Synthesis Report of the IPCC Fourth Assessment in 2007 IPCC AR4)[12] which stated:

> *"The uptake of anthropogenic carbon since 1750 has led to the ocean becoming more acidic with an average decrease in pH of 0.1 units. Increasing atmospheric CO_2 concentrations lead to further acidification. Projections based on SRES scenarios give a reduction in average global surface ocean pH of between 0.14 and 0.35 units over the 21st century. While the effects of observed ocean acidification on the marine biosphere are as yet undocumented, the progressive acidification of oceans is expected to have negative impacts on marine shell-forming organisms (e.g. corals) and their dependent species." (IPCC 2007:9)*

Scientific literature at the time noted the need for urgent action to reduce CO_2 emissions if this threat were to be avoided and/or minimized with decisive action on global CO_2 emissions required if the loss of coral-dominated ecosystems were to be avoided (Hoegh-Guldberg et al. 2007). The need for an integrated strategy to deal with the combined threat of warming and ocean acidification on coral reefs and other marine systems has long been recognised (Rau, McLeod, and Hoegh-Guldberg 2012).

The IPCC 1.5°C Special Report contained a much stronger and broader high confidence finding of adverse effects than in the IPCC AR4:

> *"The level of ocean acidification due to increasing CO_2 concentrations associated with global warming of 1.5°C is projected to amplify the adverse effects of warming, and even further at 2°C, impacting the growth, development, calcification, survival, and thus abundance of a broad range of species, e.g., from algae to fish (IPCC 2018c, Para B4.3)*

The addition of CO_2 into the atmosphere since industrialisation has resulted in about 26% increase in the acidity of the ocean globally (IGBP IOC 2013). Observations around Australia confirm the global picture with acidification occurring generally in the oceans around the continent (Lenton et al. 2016).

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12 See The Royal Society (2005) for an early assessment of potentially adverse effects.

The GBR is very sensitive to CO_2 induced ocean acidification (Mongin et al. 2016) and this interacts synergistically with warming to increase coral mortality (Prada et al. 2017). Increasing ocean acidification reduces calcification rates for many marine organisms including corals, crabs and molluscs and as well affects the biology of organisms often adversely (Pörtner et al. 2014). Reduced calcification rates for coral reefs ultimately reduces the ability of reefs to adjust and survive in the longer term (Albright et al. 2016).

Recent work modelling the effects of ocean acidification on the net precipitation of calcium carbonate sediment which is essential for reef structures, lagoons and cays indicates a transition to net dissolution of the settlements under a 2°C warming by mid-century, with this accelerating by 2100 (Eyre et al. 2018). Some reefs are already exhibiting net dissolution, or loss of calcium carbonate sediment structures. The net dissolution of calcium carbonate sediment is significantly more sensitive to increasing ocean acidification than is calcification itself. The study shows that two coral reef locations on the Great Barrier Reef would move into net dissolution of carbonate sediment by the 2050s under an unmitigated warming scenario.

Reducing ocean acidification is only possible if CO_2 concentrations, and hence emissions, are reduced. Figure 8: below shows CO_2 concentrations continuing to increase under the Paris Agreement NDC's and current policies, reaching 550 ppm CO_2 by the 2050s and approaching 650-750 ppm CO_2 by 2100. It is only under 1.5°C pathways that CO_2 concentration actually begins to drop significantly, peaking at or below 450 ppm by 2040 and dropping to about 400 ppm by 2100. Under 2°C pathways CO_2 concentration peaks at or above 450 ppm CO_2 and declines only slowly, being around 450 ppm CO_2 still in 2100.

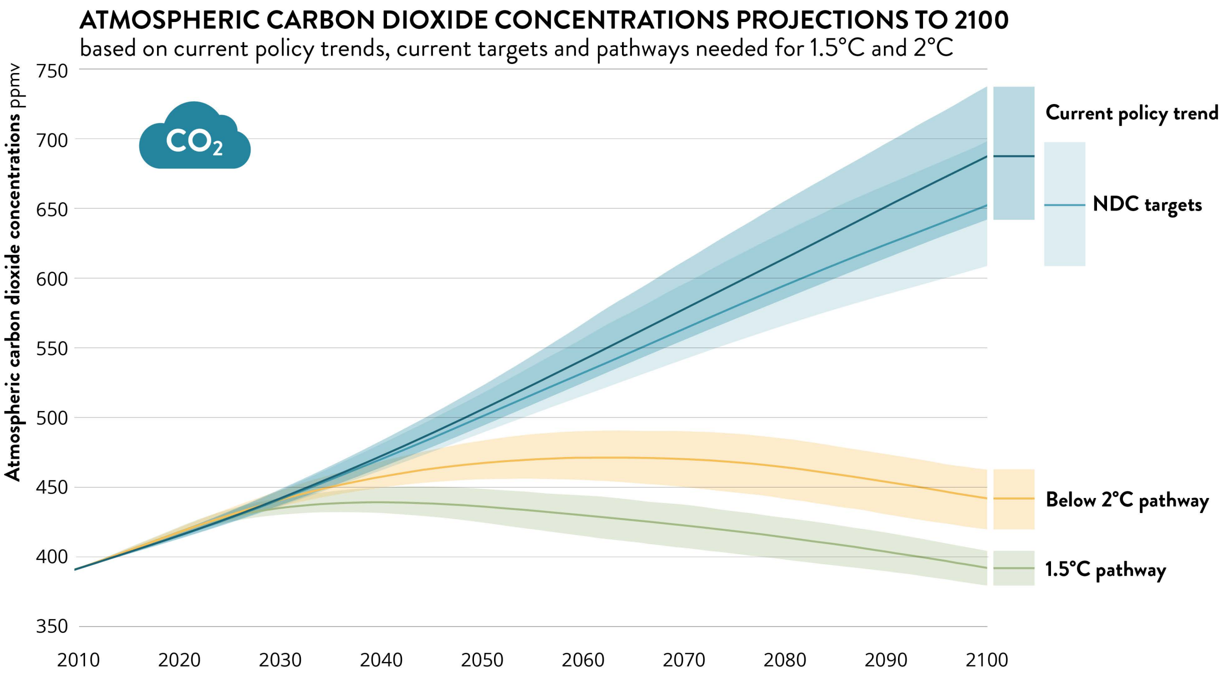

Figure 8: Projected atmospheric carbon dioxide concentrations for Paris Agreement 1.5°C compatible scenarios, Cancun 2°C goal scenarios, and projections under current policy trends and assuming current NDC targets are met. Source: own calculation, based on Climate Action Tracker (CAT) (2018a) data).

The response of ocean acidification to the CO_2 scenarios is shown in Figure 9. Under the 1.5°C compatible pathways global average ocean acidification peaks in the 2030s and begins to decline close to present levels by 2100, whereas under the 2°C pathway peak ocean acidification is delayed by about 30 years and is still well above present levels by 2100.[13]

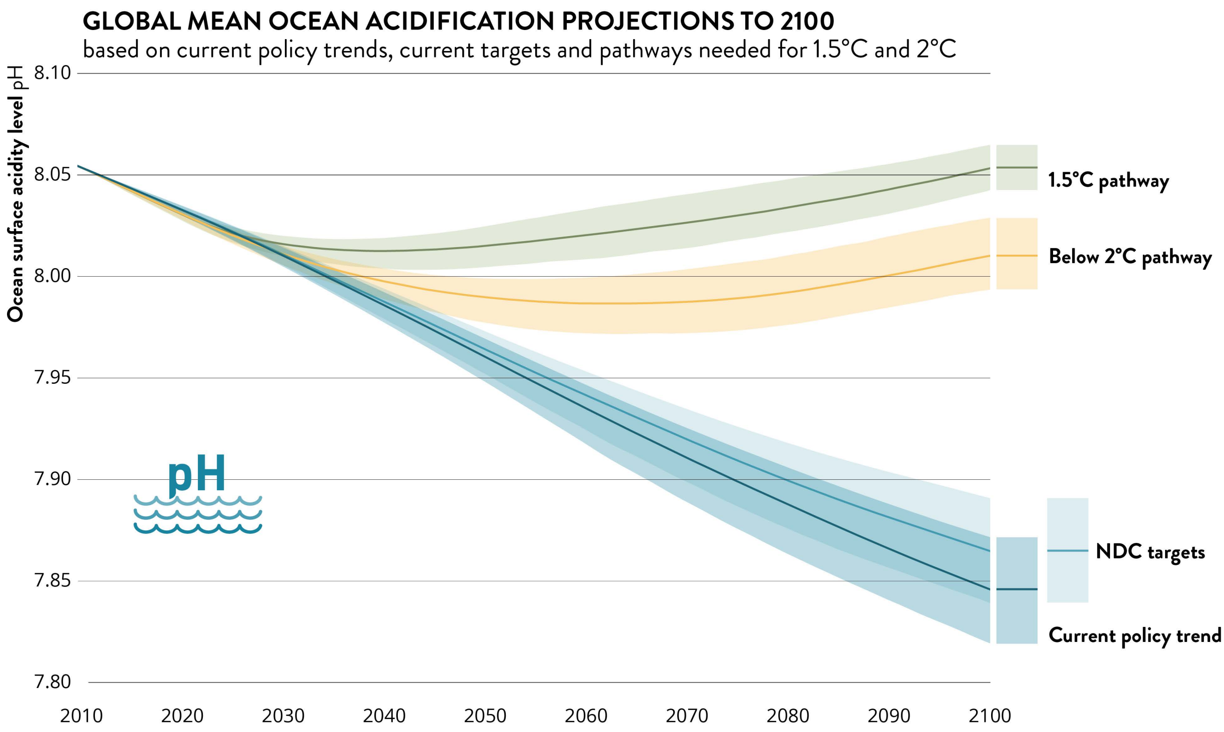

Figure 9: Projected global mean acidification for Paris Agreement 1.5°C compatible scenarios, Cancun 2°C goal scenarios, and projections under current policy trends and assuming current NDC targets are met. (Source: own calculation of ocean acidification, based on Climate Action Tracker (CAT) (2018a) data and method of Bernie et al. (2010). Note these calculations are based on a single model and reflect global mean surface pH, which does not reflect highly variable regional patterns, in particular for coastal regions, not changes in pH at depth.

Reduction of ocean acidification under 1.5°C compatible mitigation scenarios can be expected to result in increased calcification rates for coral reefs and other marine organisms (Albright et al. 2016) and potentially avoidance of the onset of net calcium carbonate dissolution of reef building sediments on the Great Barrier Reef. These improvements in outlook appear unlikely to be achieved under 2°C pathways, and certainly not under present Paris Agreement NDC and current policy trajectories.

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13 See also scenarios of Mathesius et al. (2015).

Tropical cyclone intensity

The frequency of high intensity large tropical cyclones is projected to grow as global mean warming intensifies, and is likely to have a significant adverse effect on the Great Barrier Reef. Observed severe ecological impacts of three unusually intense storms in the Great Barrier Reef are thought to have exacerbated the effects of major warming events that contributed to the unprecedented coral mortality of 2016 and 2017. Projections by Cheal et al. (2017) indicate that the increased intensity of tropical cyclones under a business as usual warming scenario is likely to cause substantial damage to the Great Barrier Reef over the coming century. The effects of tropical cyclones are likely to interact adversely with warming, reduced calcification driven by increasing ocean acidification and other factors. With increasing warming, the number of total storms as well as major tropical cyclones are projected to increase in Australian waters. Recent state of the art high-resolution modelling suggests an increase in the total number of major cyclones (Category 4 and 5) of 80-120% by the end of the century at >4°C warming (Bhatia et al. 2018). Limiting warming to 1.5°C would reduce the anticipated increase in intensity of tropical cyclones substantially.

Sea-level rise

Whilst healthy coral reefs can keep up with projected rates of sea level rise at least over the next century, there remains a risk that the degraded state of coral reefs, reduced calcification and a move towards net dissolution of calcium carbonate sediments could lead to the ultimate drowning of reef systems. Sea level rise is a critical long-term problem and Figure 10 below shows the likely projections from 1.5°C compatible pathways, 2°C pathways and present Paris Agreement NDC and current policy pathways.

In addition to the absolute rise, the rate of sea level rise is critical for the ability of coral reefs to adapt. Under a 2°C scenario, future rates of sea level rise will exceed current rates over the full 21st century with no sign of slow-down. Under a 1.5°C scenario, however, the rate of sea level rise is declining towards 2100 and the end-of-century rate of sea level rise is already about 30% lower than in a 2°C scenario (Schleussner et al. 2016).

Sea level rise will continue for centuries after emissions are stopped and there will be a thousand-year legacy of the present level of action and from the warming this century (Clark et al. 2018).

Delaying emission reduction effort in line with the Paris Agreement by 5 years would result in an additional 20 cm of long-term sea level rise in 2300 (Mengel et al. 2018).

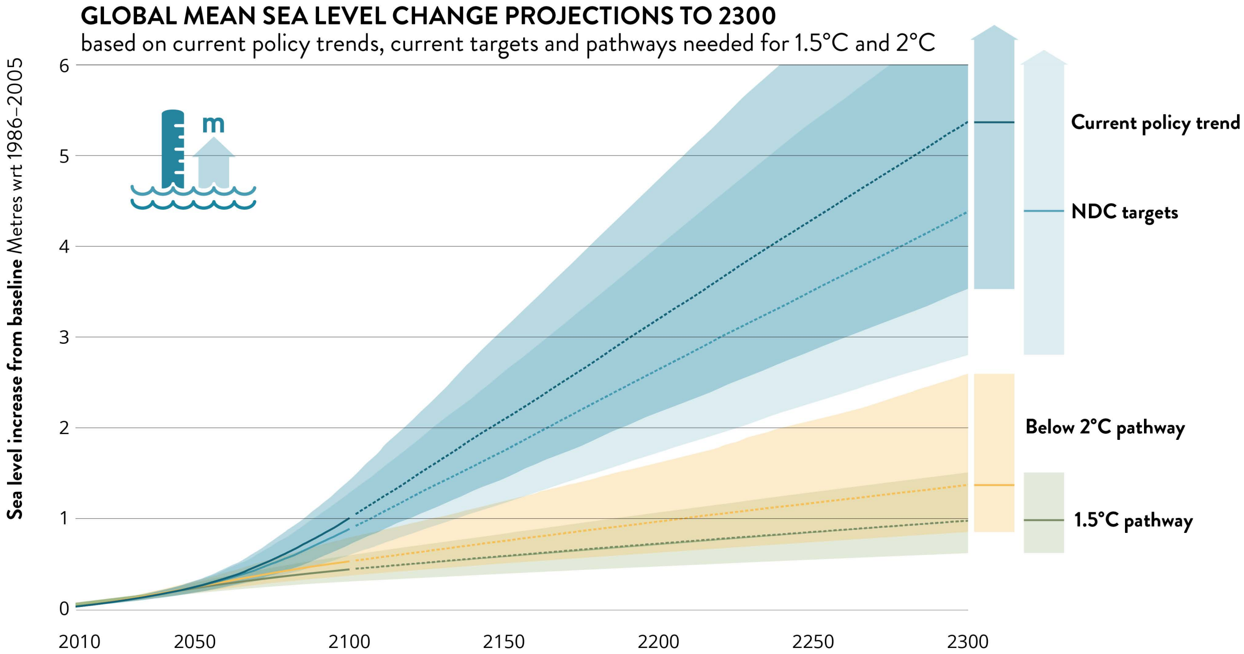

Figure 10: Projected global mean sea level rise for Paris Agreement 1.5°C compatible scenarios, Cancun 2°C goal scenarios, and projections under current policy trends and assuming current NDC targets are met. (Source: own calculations, based on Climate Action Tracker (CAT) data). The projections are based on a methodology developed by Nauels et al. (2017). Projections for scenarios exceeding 1.5°C warming are subject to considerable uncertainty in relation to the contribution of potential ice sheet instabilities in Greenland and Antarctica.

Other anthropogenic stressors

The Great Barrier Reef is subject to a range of additional stresses beyond those due to climate change and related phenomenon, including water quality and pollution. These often-chronic stresses, if not managed, exacerbate the major threats brought about by climate change. It will be necessary to manage water quality, pollution and non-climate related stresses aggressively to provide the maximum opportunities for the Great Barrier Reef to recover from the effects of climate change and ocean acidification (Ortiz et al. 2018).

WHAT WILL LIMITING WARMING TO 1.5°C MEAN FOR THE REEF?

Limiting warming to 1.5°C will substantially reduce the exposure of the reef to extreme marine heatwaves including those related to extreme El Niño events, ocean acidification, more frequent tropical cyclones, as well as reduce longer-term exposure to accelerating sea level rise.

The reduction in exposure to the drivers of coral reef mortality and loss under 1.5°C compatible pathways are substantial and highly significant, nevertheless even with a peak warming of 1.5°C very substantial risks remain for the reef. Exceeding the 1.5°C limit would virtually guarantee the extinction of most of the Great Barrier Reef based on present scientific knowledge.

Mid-century projections from the only available study (Wolff et al. 2018) of the likely trajectory of the Great Barrier Reef indicate some recovery potential for coral in the near-term, followed by climate-driven decline. Under unmitigated emissions (RCP8.5), relatively close to the present Paris Agreement

NDC and current policy trajectories, and business-as-usual management of local stressors, mean coral cover on the GBR is predicted to recover over the next decade and then rapidly decline to only 3% by 2050. In other words under present Paris Agreement NDC and current policy trajectories the reef would be virtually extinct by 2050.

Under a Cancun 2°C goal type scenario (RCP2.6) and with improved water quality, however, significant coral recovery is projected over the next two decades, followed by a climate-driven decline that sustains coral cover above 26% by 2050 (Wolff et al. 2018).

A 1.5° compatible pathway with lower peak warming, reduced exposure to heat extremes and marine heatwaves would likely lead to much better outcomes. Thus there are grounds for optimism that limiting warming to 1.5°C globally provides the best available chance of maintaining a healthy Great Barrier Reef into the future, with high levels of warming rapidly reducing those prospects.

GLOBAL MITIGATION PATHWAYS FOR THE 1.5°C LIMIT

To limit warming to the 1.5°C limit of the Paris Agreement global CO_2 and GHG emissions will need to be reduced rapidly and substantially, with zero emissions achieved in a matter of decades. This is recognised in Article 4.1[14] of the Paris Agreement which is designed to operationalize the LTTG ("in order to achieve the long-term temperature goal set out in Art. 2.1") with global emission goals: to peak global emissions "as soon as possible", followed by "rapid reductions thereafter", and to reach a "balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century" (UNFCCC 2015). The reductions are to be determined "according to best available science" so as to be consistent with the LTTG.

1.5°C COMPATIBLE MITIGATION PATHWAYS AND GLOBAL EMISSIONS

The IPCC (2018a) Special Report on 1.5°C (SR15) adopted and published in October 2018 has assessed a new generation of mitigation pathways based on Integrated Assessment Models that examine the technical and economic feasibility of holding warming below 2°C and in particular limiting warming to 1.5°C, simultaneously considering many dimensions of sustainable development. The IPCC (2018a) SR15 currently provides the "best available science" for operationalising the LTTG and defining key elements of the emission pathway in Article 4.1, because it provides the most comprehensive and up-to-date assessment of mitigation.

The IPCC (2018c) SR15 Summary for Policy Makers (SPM) focuses on 1.5°C compatible pathways - pathways that hold global warming to 1.5°C or below throughout the 21st century and involve no- or limited overshoot (<0.1°C) – thereby reducing the risk of dangerous and potentially irreversible climate change impacts that would result from high overshoot of 1.5°C. These impacts are identified in the IPCC (2018a) SR15. In addition, the IPCC (2018a) SR15 also assessed a broader range of pathways that hold warming below 2°C, but include peak 21st century warming of up to 1.9°C above pre-industrial levels, which is substantially above the 1.5°C limit.

The IPCC (2018a) SR15 clearly shows that rapidly reducing global GHG emissions by 2030 – by around 45% compared to 2010 (see Figure 11) – is a key milestone towards limiting warming to 1.5°C and avoiding the risks of escalating costs and institutional and economic lock-ins with carbon intensive infrastructure, which will then be costly or more difficult to phase out later. Delaying emissions reductions would reduce the flexibility of future response options and increase the reliance on negative CO_2 emissions - taking CO_2 from the atmosphere – using Carbon Dioxide Removal (CDR) technologies. All pathways require a rapid decarbonisation of energy systems by 2050, with global anthropogenic CO_2 emissions at net zero by around 2050, and total GHG emissions zero globally by around 2070. Figure 11 below provides an illustration of these pathways.

A 45% reduction in global GHG emissions by 2030 compared to 2010 corresponds to an emissions level of 25-30 GtCO2eq/year by 2030. Full implementation of the current Nationally Determined Contributions (NDCs) corresponds to an emissions level of 52-58 $GtCO_2eq$/year, nearly twice as much as the 1.5°C compatible pathways imply. The IPCC (2018a) SR15 therefore concludes that the ambition

[14] Article 4.1 states, inter alia, "In order to achieve the long-term temperature goal set out in Article 2, Parties aim to reach a global peaking as soon as possible …, and to undertake rapid reductions thereafter in accordance with best available science, so as to achieve a balance between anthropogenic emissions by sources and removals by sinks of [GHGs] in the second half of this century"

level of the current Paris Agreement national emission commitments – NDCs - are not consistent with limiting global warming to 1.5°C, even if supplemented by very challenging increases in the scale and ambition of emissions reductions after 2030. The Climate Action Tracker (2018c) shows this pathway reflecting the ambition level of current NDCs leads to warming reaching 3°C by 2100. It should also be noted, the Climate Action Tracker estimates that with current policies (as of December 2018), the median warming is projected to result in a rise of 3.3°C by 2100 (Climate Action Tracker 2018c). Whilst 3°C warming is itself likely to be extremely damaging, and catastrophic to some systems, there is at least a one in 10 chance (10%) that the current policy pathway could lead to global warming reaching, or exceeding, 4.5°C by 2100 (Climate Action Tracker 2018c).

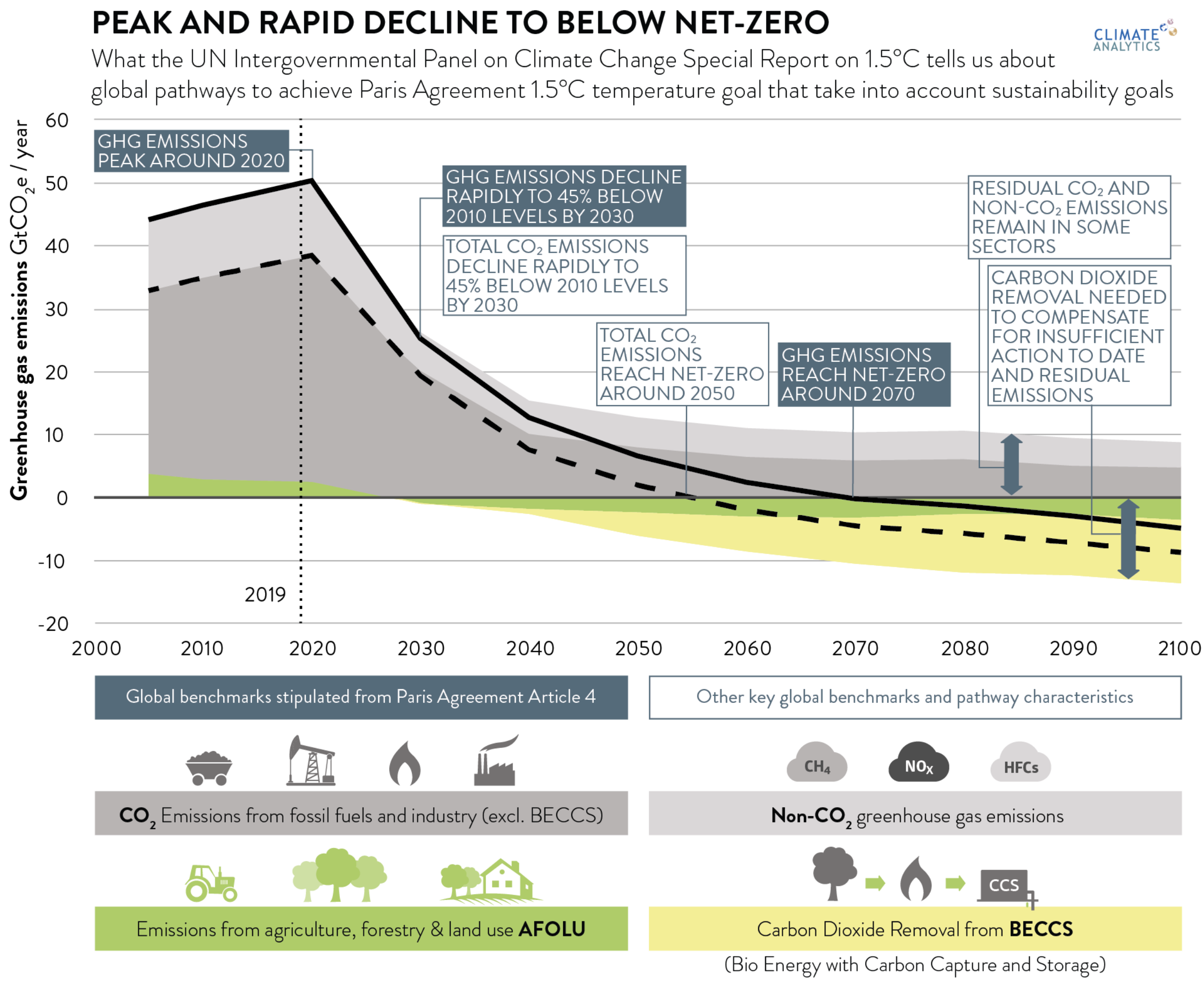

Figure 11: Illustration of the three benchmarks in Paris Agreement Article 4.1 for operationalisation of Article 2.1 (dark blue boxes) and global decarbonisation benchmarks (white box). This representative pathway is the median across all 1.5°C-compatible pathways from the IPCC (2018a) SR15 that reach levels of Carbon Dioxide Removal (CDR) below the upper end of estimates for sustainable, technical and economic potential around 2050 from SR15 in the sector of Agriculture, Forestry and Land-Use (AFOLU), as well as via Bioenergy combined with Carbon Capture and Storage (BECCS)[15]. Source: (Climate Analytics 2019a)

[15] All emissions and removals where calculated from the median emissions levels across the 46 pathways in the SR15 scenario database that are 1.5°C compatible, that satisfied the limits to CDR mentioned, and that reported data for all variables included here Source: SR15 scenario database (IIASA 2018) https://data.ene.iiasa.ac.at/iamc-1.5c-explorer

MAIN ENERGY TRANSFORMATION FEATURES OF 1.5°C COMPATIBLE PATHWAYS

Rapid reductions in energy demand across all sectors are fundamental for 1.5°C compatible pathways that also limit negative emissions through carbon capture technologies. The 1.5°C compatible transformation will require significant additional investment worldwide in low-emission infrastructure as well as redirection of financial resources from carbon-intensive investments toward low-emissions infrastructure.

A rapid and almost complete global phase-out of coal by 2040 in the power sector is a universal message from the new scenario results with many regions in particular OECD phasing out coal much earlier (around 2030). The share of coal for electricity generation (without CCS) shows a steep reduction in 1.5°C compatible pathways to 80% below 2010 levels in 2030 (Climate Analytics, 2019b).

Substantial reductions in oil use by 2050 are also projected, coming in at around 30-80% lower than 2010 levels. By 2030 oil would need to decline by up to 35% below 2010 levels, but some models show an *increase* of up to a 5%, reflecting assumptions about a lower and slower uptake of electric vehicles and transport than in other models.

For natural gas, scenarios show a large range of changes by 2030, up to 20% increase and a 25% decrease, and up to a 55% reduction by 2050 with some models showing about the present levels (5% above 2010). It should be noted that the lower reductions in coal and natural gas correspond to those scenarios where it is assumed there is a high level of carbon capture and storage deployment, which at present seems quite unlikely given the reducing costs of renewable energy and storage technologies.

Table 2: Changes in fossil fuels in global primary energy supply compared to 2010 in global mitigation pathways consistent with the Paris Agreement 1.5°C limit (see text).

	Change compared to 2010	
	2030	2050
Coal	-80% to -60%	-95% to -75%
Natural gas	-25% to +20%	-55% to +5%
Oil	-35 to 5%	-0% to -30%

In all scenarios that limit warming to 1.5°C, renewable energy (excl. biomass) has to be ramped up quickly to supply 50-65% of total primary energy by 2050[16], displacing fossil fuels from traditional markets for power generation, mobility and heating. Renewables reach a particularly high share in electricity supply of 45-65% in 2030 and 70-85% in 2050.

The decrease in use of fossil-fuels and increase in renewables is associated with a major shift in investments, where global annual investments in low-carbon energy technologies overtake fossil investments by around 2025 in 1.5°C pathways (IPCC 2018b). The IPCC (2018a) Special Report shows

[16] Information on this was included by IPCC authors in the final draft of the SPM , but was not included in the final government-approved SPM. This data can however be extracted from the publicly available scenario data in IPCC's online scenario database: (IIASA 2018) https://data.ene.iiasa.ac.at/iamc-1.5c-explorer/

that annual investment in low-carbon energy technologies and energy efficiency increase rapidly by a factor of 4-5 by 2050 compared to 2015. Compared to 2°C pathways, total energy-related investments in both supply and demand side increase by 12%.

GLOBAL CARBON BUDGET FOR 1.5°C

There is a limited amount of carbon that can be emitted to the atmosphere if warming is to be limited to 1.5°C. The figure below gives a global perspective on this, showing that the remaining carbon budget over this century from 2018 is only about 470 $GtCO_2$. With present CO_2 emissions at about 37-41 $GtCO_2$/year this leaves only 11-13 years at the present rates of emissions. Most 1.5°C compatible scenarios keep within this budget by also deploying negative emission technologies, with a budget of around 610 $GtCO_2$ of emissions until the point of zero CO_2 emissions globally and about 140 $GtCO_2$ of negative CO_2 emissions overall. The need for negative CO_2 emissions technology can be reduced significantly by bringing forward the time at which CO_2 emissions reach zero globally, and also increasing the rate of reductions of other greenhouse gases. In effect, this means the earlier that fossil fuel emissions are phased out, the faster renewable energy is phased in and the higher the level of efficiency achieved in energy use, transport, industry and agriculture, the lower will be the need for negative CO_2 emissions technology.

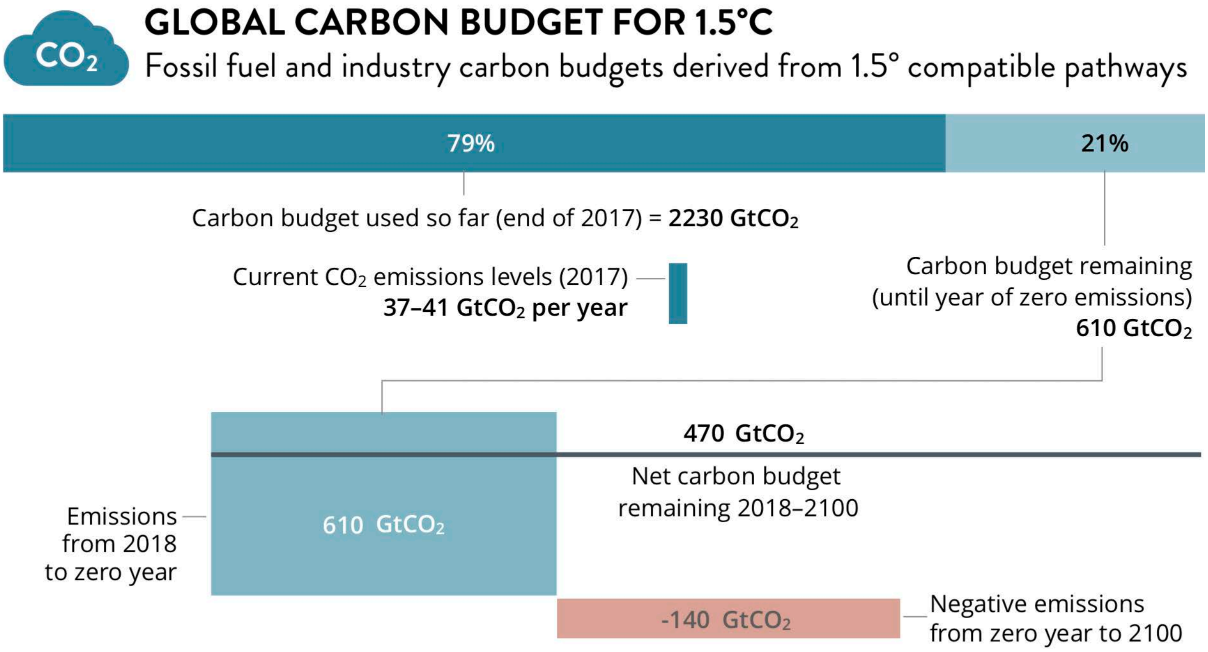

Figure 12: Energy system carbon budgets derived from 1.5° compatible pathways (no and limited overshoot of 1.5° from IPCC SR1.5). Source: Own calculation.

We estimate a global budget for fossil fuel and industry related CO_2 emissions by calculating the cumulative CO_2 emissions from 2018 to the year of zero net global (fossil fuel and industry related) CO_2 emissions resulting from socioeconomic pathways assessed by the IPCC to be 1.5ºC compatible. These pathways reach global net zero total CO_2 emissions from all sources around 2050, i.e. a total net zero sum of:

- Positive CO_2 emissions from fossil fuel and industry

- Negative CO_2 emissions from these sectors via Bio Energy combined with Carbon Capture and Storage (BECCS), and
- Negative CO_2 emissions from land use and land-use change emissions.

Excluding the land sector, the net total of positive and negative CO_2 emissions from fossil fuel and industry emissions reach zero some 10 years later[17]. The resulting net cumulative fossil fuel and industry CO_2 emissions (incl. BECCS) from 2018 to the year of (net) zero emissions for these 1.5°C compatible pathways (around 2060) is about 610 $GtCO_2$, after accounting for historical emissions (Le Quéré et al. 2018). The cumulative CO_2 emissions until 2100 are somewhat lower (and uncertainty is larger), because of negative CO_2 emissions increasingly required in the second half of the century to compensate for emissions that cannot be reduced to zero (such as some of the agriculture and industry process related emissions) as well as for excessive emissions in the past.[18]

Table 3 shows the comparison of these results for 1.5°C pathways and for those pathways that are consistent with the old "hold below 2°C" goal agreed by the international community in Cancun in 2010. All pathways analysed here are from the IPCC SR database.[19]

Table 3: Cumulative fossil-fuel and industry emissions of CO_2 for PA 1.5°C-compatible pathways compared with cumulative emissions for pathways compatible with the "hold below 2°C" goal.

Warming limit	2016 - to year of zero emissions	2018 - to year of zero emissions	2016 - 2100	2018 - 2100
Paris Agreement 1.5°C pathways	680 (625-800)	610 (555-730)	540 (395-775)	470 (320-700)
Cancun Agreement 2°C pathways	1020 (902-1199)	950 (830-1128)	925 (846-1196)	855 (776-1124)

Note: Values represent median (and 50% ranges) across all 1.5°C-compatible and Cancun pathways from the IPCC SR15 database (IIASA 2018) that reach levels of carbon dioxide removal (CDR) below the upper end of estimates for sustainable, technical and economic potential around 2050 from SR15 in the agriculture, forestry and land use (AFOLU) sector, as well as via bioenergy combined with carbon capture and storage (BECCS).

17 Fossil fuel and industry CO_2 emissions reach net zero later because they do not include Land use change emissions, which include negative emissions from afforestation/reforestation.

18 Note that if CO_2 emissions from land use, land-use change and forestry, are included, the resulting total cumulative CO_2 emissions from 2016 until end-of-century – including the land-use sector - are substantially lower (370 $GtCO_2$, range 250-620 $GtCO_2$ not shown in table 1), because of the carbon dioxide removals that the models typically show in the land-use sector in 1.5°C (and 2°C) compatible pathways from time of zero total CO_2 emissions to end of century.

QUEENSLAND'S ENERGY SYSTEM AND 1.5°C

QUEENSLAND IN NATIONAL CONTEXT AND PRESENT TRENDS

The Queensland Government has set a state target to reach zero net GHG emissions by 2050, and an interim target of at least 30% reduction in emissions on 2005 levels by 2030. With energy related CO_2 emissions in 2010 some 6% above 2005 levels, this translates into about 34% reduction in energy related CO_2 emissions below 2010 levels, which is far from the benchmark from the IPCC (2018a) SR15 of a 45% reduction by 2030. The zero net GHG emissions by 2050 is consistent with the IPCC (2018a) SR15 benchmarks for a 1.5°C pathway considering that developed economies would need to achieve zero emissions earlier than the global average.

The Queensland Government (2017) has also has set a target of 50% renewable energy share in power generation in 2030.

Queensland is the largest emitting state in Australia (with a 30% share of total GHG emissions in 2017 (Australian Government 2019). While total GHG emissions have decreased between 2005 and 2017, this is due to a decrease in land use, land-use change and forestry emissions (according to the national inventory), as energy related emissions have increased strongly in this period. Table 4 provides an overview of Queensland's energy and industry sector emissions in 2005, 2010 and 2017.

Table 4: Queensland energy and industry sector carbon dioxide emissions ($MtCO_2$) and total Queensland greenhouse gas emissions ($MtCO_2e$). Total QLD emissions includes other sectors beyond the main sectors listed here. Industry emissions include manufacturing, energy industries excluding electricity, fugitive emissions, and process emissions.

	2005		2010		2017	
Sector	**$MtCO_2$**	**$MtCO_2$ e**	**$MtCO_2$**	**$MtCO_2$ e**	**$MtCO_2$**	**$MtCO_2e$**
Power	47.42	47.56	48.94	49.19	50.80	51.15
Transport	17.31	17.85	19.31	19.82	22.13	22.51
Industry	17.61	29.60	18.93	34.13	24.72	43.57
Buildings	1.08	1.20	1.16	1.23	1.38	1.46
Agriculture (energy)	1.35	1.37	1.46	1.49	1.95	1.98
Total energy and industry	84.77	97.58	89.8	105.86	100.98	120.67
Other sectors[20]	62.75	90.09	38.11	63.97	15.7	40.53
Total QLD emissions	**147.52**	**187.67**	**127.91**	**169.83**	**116.68**	**161.20**

[20] Other sectors: agriculture; waste; land use, land-use change and forestry (LULUCF)

Queensland has the highest proportion of solar households (33%) in Australia, and the largest number of renewable energy projects under construction (Climate Council 2019), however the share of renewable energy in the electricity sector is presently still relatively low (7.1% in 2017) (Climate Council 2018). Queensland has experienced a dramatic expansion of renewable energy project development activity in a short period of time, with the share of renewable energy in electricity consumption potentially rising to a share of up to 25.6% in 2020 if all projects under construction, expected uptake of rooftop solar and the successful conclusion of a 400 MW renewable energy tender are taken into account (Green Energy Markets 2018). If all projects in the pipeline considered for investment were realized this share could rise up to more than 90% of Queensland's forecasted electricity consumption in 2030 (Green Energy Markets 2018), however it is not expected that these would all actually be implemented without additional policies to provide incentives for these investments (RenewEconomy 2019).

DOWNSCALING GLOBAL SCENARIOS TO QUEENSLAND

We have used as the starting point for developing the 1.5°C compatible energy system pathway for Queensland global and regional data from the "Beyond 2°C Scenario" (B2DS) in the "Energy Technology Perspective" (ETP 2017) report of the International Energy Agency (IEA 2017). The ETP model enables a technology-rich, bottom-up analysis of the global energy system. We recently analysed the B2DS and this analysis (Climate Action Tracker 2018b) is reproduced in the next paragraphs.

The IEA (2017) estimated that the B2DS pathway has a peak global warming of 1.75°C above pre-industrial with a 50% likelihood meaning that its warming exceeds that of a 1.5°C compatible scenario. In its estimation of the peak warming level associated with the B2DS scenario, the IEA assumed that non-CO_2 GHG would add about 0.35°C to the CO_2-only warming. We however have evaluated the IEA B2DS pathway applying the same climate model approach to warming levels as was used in the IPCC Special Report on 1.5°C and earlier IPCC Fifth Assessment Report, enabling a comparison of "like with like" with the IPCC 1.5°C compatible scenario set. As the IEA provides only energy-related CO_2 emissions, land-use and non-CO_2 GHG emissions need to be estimated. When we assume comparable non-CO_2 GHG emissions pathways to the ones analysed by the IPCC, and allow for negative emissions also comparable to the IPCC 1.5 pathways, we find that the B2DS scenario until 2050 is a close analogue climatically to the more recent 1.5°C compatible pathways.

There are however significant caveats, some related to the limitations of downscaling (see below) and others to the faster than expected cost reductions in key technologies for decarbonisation in particular renewable energy, storage (battery and pumped storage), electric vehicles and renewable hydrogen.

Since the IEA (and in general scenarios in the scientific literature) does not provide scenario data at sub-national state levels, nor at national level for Australia, in this report we first downscale the results of the B2DS scenario for the OECD region to Queensland, by using a model-based approach: SIAMESE (**S**implified **I**ntegrated **A**ssessment **M**odel with **E**nergy **S**ystem **E**mulator) (Sferra et al. 2019).

SIAMESE is a reduced complexity IAM (Integrated Assessment Model), which provides cost-optimal emission pathways at the country, or state level, taking into account the complex interactions between economic growth, energy consumption and carbon emissions. While downscaling the energy-sector results from a given model (e.g. the IEA/ETP 2017), SIAMESE takes into account a coherent set of assumptions in line with a "middle of the road" socio-economic storyline (Dellink et al. 2017; Fricko et al. 2017). This storyline relies on a continuation of historical trends regarding technological developments and GDP growth at the country (or state) level. At the same time, SIAMESE has a cost optimisation perspective when allocating how much a country or a region would need to contribute to global emissions reductions in line with the Paris Agreement long term goal.

The SIAMESE downscaling approach can be applied to the overall economy (e.g. scaling down the overall primary energy consumption and emissions), or to individual sectors (e.g. transport, power and others). SIAMESE takes as input the original IEA B2DS (pathways for the OECD region, which start in 2014 in this scenario) and the observed energy consumption and emissions data for Queensland. Based on the SIAMESE simulation we calculate the B2DS compatible carbon budget for Queensland as the cumulative emissions remaining from 2018 to 2050 considering historical emissions until 2017.

Limitations of the downscaling are embedded in the driving scenario, which in this case is weak in several areas including decarbonization in industry, electrification of transport, and costs of renewable hydrogen as an energy carrier. We therefore use the SIAMESE simulation and estimate of a B2DS compatible carbon budget as an initial estimate which provides an upper bound on the carbon budget, and then examine the output from each sector to evaluate against the Paris Agreement benchmark of achieving zero CO_2 emissions by around 2050 for developed economies. These leads to Paris Agreement benchmark budgets for each sector.

To develop sectoral energy related (fossil fuel and industry) CO_2 emissions pathways and corresponding Paris Agreement benchmark budgets we adjust the IEA ETP B2DS scenario based on the national and state level context, as well as other sectoral benchmarks identified in earlier studies. This is consistent with the approach taken in an earlier state-based analysis by Climate Analytics (Hare et al. 2018) estimating a national carbon budget for energy related emission of about 5.5 $GtCO_2$ based on a proxy scenario for a Paris Agreement consistent national pathway, with a decarbonised energy system by 2050[21].

In making these adjustments we take into account:

- A decarbonised energy system by 2050, including decarbonised passenger and freight land transport[22] (consistent with the objective of the Queensland government to achieve net zero greenhouse gas emissions by 2050);
- The need to phase out coal for power generation by 2030 in OECD countries, and therefore also in Australia and Queensland (Climate Analytics, 2016);
- A benchmark of a fully decarbonised, that is fossil fuel free power sector in Australia by 2040 (See: Hare et al. 2017, 2018)
- The Queensland goal of achieving 50% renewable energy share in power generation in 2030.
- Sustainability constraints on biomass for energy use.
- More recent developments in the costs and availability of renewable energy, storage technologies, electrical vehicle cost reductions, greater availability of decarbonisation options for industry and the projected rapid cost reductions for producing renewable hydrogen as an energy carrier.

[21] The IPCC SR15 Glossary defines "Decarbonisation" as the "the process by which countries, individuals or other entities aim to achieve zero fossil carbon existence. Typically refers to a reduction of the carbon emissions associated with electricity, industry and transport".

[22] See the Climate Action Tracker Decarbonisation Memo Series (Climate Action Tracker n.d.) https://climateactiontracker.org/publications/decarbonisation-memo-series/

Power sector

This section provides a pathway for the Queensland's power sector, under a Paris Agreement compatible emissions pathway, and considering the national and state context and previously analysed national and sectoral scenarios for fossil fuel and renewable energy benchmarks. In addition, we have considered a limit to the sustainable use of biomass. This assumes that biomass only includes residues left over from agriculture or forestry industry. A conservative estimate of sustainable biomass use has been taken to exclude native forests and in particular any clearing of native vegetation.[23] Specifically, it includes current data on residues from cropping; and harvest residues or wood processing residues from softwood plantations, sourced from the Queensland Biomass Data Mapping Tool (Queensland Government 2018). The conversion of biomass (residue dry tonnes) to electricity (MWh) uses the assumptions made by Crawford et al. (2012).

Table 5: Fuel mix for: electricity generation in Queensland, under a Paris Agreement compatible scenario with coal phase out in 2030, decarbonised (fossil fuel free) power generation by 2040, and limited sustainable biomass use. Historical shares for 2014, 2015, 2016: From (Department of the Environment and Energy, Australian Energy Statistics n.d., table O). Renewables includes biomass. The temporary increase in natural gas use in 2030 does not imply the need for investment in new capacity for gas use in the power sector. Given recent technology developments, and earlier estimates about the existing investment pipeline, the share of renewable energy could be considerably higher than 64% in 2030 (and natural gas correspondingly lower than 35%).

	HISTORICAL			PARIS COMPATIBLE BENCHMARK SCENARIO		
	2014	2015	2016	2030	2040	2050
Coal	66.0%	68.3%	72.6%	0%	0%	0%
Natural gas	26.2%	23.7%	19.1%	35%	0%	0%
Oil	1.7%	1.8%	1.8%	1%	0%	0%
Renewables	6.2%	6.3%	6.5%	64%	100%	100%
All fuels	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**

With the benchmark of coal phasing out by 2030, and decarbonised – that is, fossil fuel free - power by 2040, the share of renewable energy (including biomass) increases to more than 60% in 2030 and to 100% in 2040, consistent with a range of national scenarios or studies for the National Electricity Market (NEM) showing the feasibility of 100% renewable power generation (Blakers, Lu, and Stocks 2017; Gulagi et al. 2017; Teske et al. 2016). The temporary increase in use of natural gas in 2030 would not imply the need for investment into new capacity for gas use in the power sector. Given recent technology developments, and earlier estimates about the existing investment pipeline, the share of renewable energy could be considerably higher than 64% in 2030 (and natural gas correspondingly lower than 35%).

23 Our conservative stance has been taken to ensure that only sustainable biomass is considered. Biomass use from native forests has been excluded despite claims of a high potential for biomass from sustainably managed private native forests (Ngugi et al. 2018). Other sources of biomass such as urban waste, livestock and food processing have been excluded due to a lack of data.

Under our assumptions, biomass has a share of around 3-4% from 2030 onwards (from around 2% today), some of it used with carbon capture and storage to create negative emissions, in order to compensate for high historical emissions and emissions from other sectors that are not as easy to decarbonise. While the original IEA scenario achieves decarbonisation partly including fossil fuel use with CCS, this can also be achieved through 100% renewable energy and therefore completely fossil fuel free electricity generation, given renewable energy is the lowest cost option for energy in Australia. A study by the CSIRO and the AEMO (Australian Energy Market Operator) found that for any further new build option, renewables offers the lowest cost option for electricity generation when including storage, compared to coal power (Graham et al. 2018).

Under our assumptions and overall decarbonisation benchmarks, electricity related emissions (Figure 13) would be around 12 $MtCO_2$ by 2030, 74% below 2005 levels, and drop to zero by 2040 and below afterwards with an average of up to -1.9 $MtCO_2$ of negative emissions using biomass with CCS. The carbon budget for this scenario is estimated at 415 $MtCO_2$. This confirms what is found consistently in decarbonisation scenarios: The power sector needs to and can decarbonise faster than other sectors. Slower decarbonisation (such as in the IEA ETP B2DS scenario) would imply higher reliance on negative emissions (Figure 13).

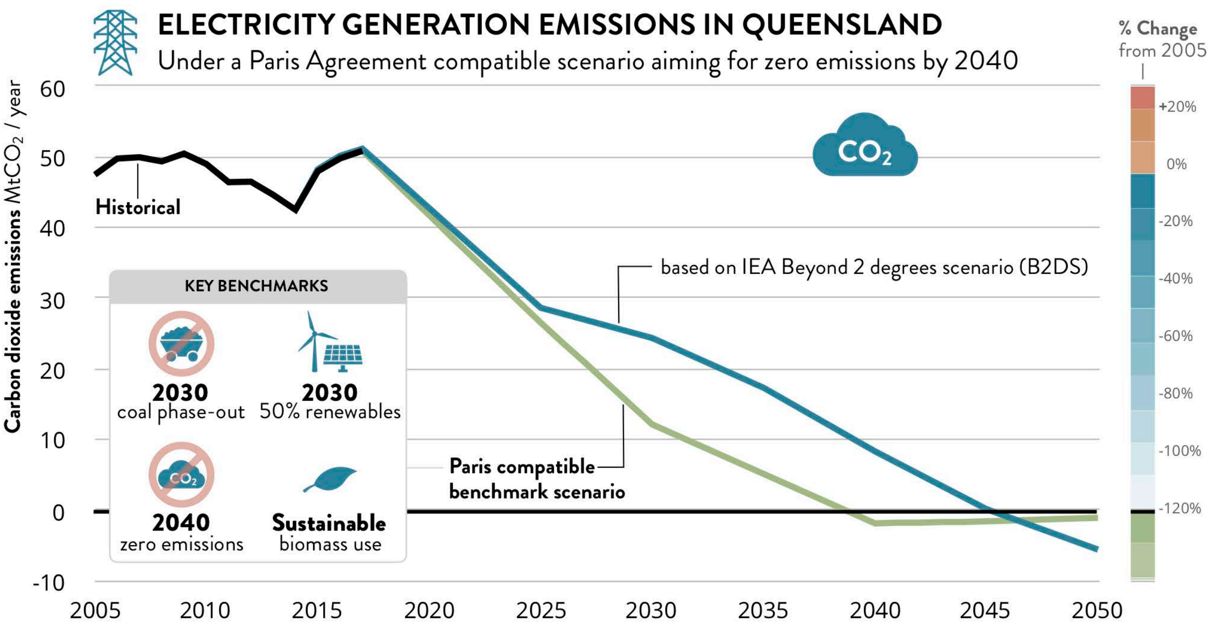

Figure 13: Electricity related CO_2 emissions in Queensland, for IEA B2DS scenario and a Paris Agreement compatible benchmark scenario: a) (blue) based on original IEA B2DS scenario, scaled down to Queensland, and adjusted taking into account historical emissions until 2017 and b) (green) emissions corresponding to Paris Agreement decarbonisation benchmarks, state Renewable energy target, and limited sustainable use of biomass, adjusted to take into account historical emissions (2014-2017) Because of increasing emissions 2014-2017, these need to be compensated with faster reductions to stay within the same budget. Source: Own calculation, historical emissions: AGEIS inventory data: (Department of the Environment and Energy 2019) See Annex II.

In all 1.5°C compatible pathways fast decarbonisation of the power sector paves the way for deeper emissions reduction in other sectors by means of increasing electrification. This is also the case in the transport sector, where internal combustion engine (ICE) cars should be replaced by electric vehicles.

Transport sector

This section focuses on the energy transformation that needs to happen in Queensland in line with the Paris Agreement long term goal.

Table 6: Fuel mix for Queensland's transport sector under a Paris Agreement compatible pathway based on technology assumptions in IEA (2017) ETP B2DS.

		PARIS COMPATIBLE BENCHMARK SCENARIO		
	2014	2030	2040	2050
Oil	97%	77%	51%	0%
Natural gas	1%	2%	0%	0%
Electricity	2%	16%	39%	65%
Biomass	0%	1%	2%	2%
Hydrogen	0%	4%	8%	33%
All fuels	100%	100%	100%	100%

Based on the technology assumptions of the IEA B2D scenario, oil consumption is expected to decline over time mainly due to increasing reliance on clean electricity generation powering electric vehicles but also due to some hydrogen developments, for example for freight transportation. The downscaled B2DS scenario does not fully decarbonise by 2050, with about a 73% reduction from 2005 emissions levels and a carbon budget of around 383 $MtCO_2$. Intermediate reductions in 2030 are about 23% from 2005 levels.

From today's perspective, the IEA B2DS scenario appears very conservative in its assumptions about the mitigation options in the transport sector, both for passenger and freight transport. In particular, in the B2DS scenario the transport sector is not yet fully decarbonised by 2050 in the OECD region, even though it does show a transition towards technological options that allow full decarbonisation through electrification or use of biofuels. The IEA B2DS scenario does not envisage a prominent role for hydrogen in the transport sector. However, recent studies see a more viable future in green hydrogen-powered vehicles especially for fuel cell trucks to cover long range freight transport, which might happen already in the next few years, given the rapid decrease in the cost of generating electricity from renewable energy.

In a national energy system scenario analysed earlier by Climate Analytics, the transport sector (like other energy sectors) is fully decarbonised by 2050 (Hare et al. 2018; Teske et al. 2016). This is also more in line with recent technological developments. Based on recent analysis of mitigation potential in the transport sector, both for passenger and freight road emissions, including a faster electrification and introduction of renewable hydrogen or synthetic fuels generated with electricity from renewable energy, the benchmark for achieving a fully decarbonised passenger and freight land transport should be 2050 (Climate Action Tracker 2016, 2018d). This implies the last fossil fuel combustion engine car should be sold before 2035. For the Paris compatible benchmark scenario we follow the B2DS until the mid 2030s and then progress towards zero CO_2 emissions by 2050, giving a total carbon budget of about 364 $MtCO_2$.

For aviation, technologies are also emerging zero emissions fuels and/or propulsion systems. The International Renewable Energy Agency (IRENA) (2018) has reported on a variety of pathways to produce renewable jet fuel, short range electric aircraft, and hybrid electric propulsion systems. Here we assume full decarbonisation by 2050, which in the case of aviation might imply the need for negative emissions to compensate for remaining fossil fuel use if decarbonisation is not achieved by 2050.

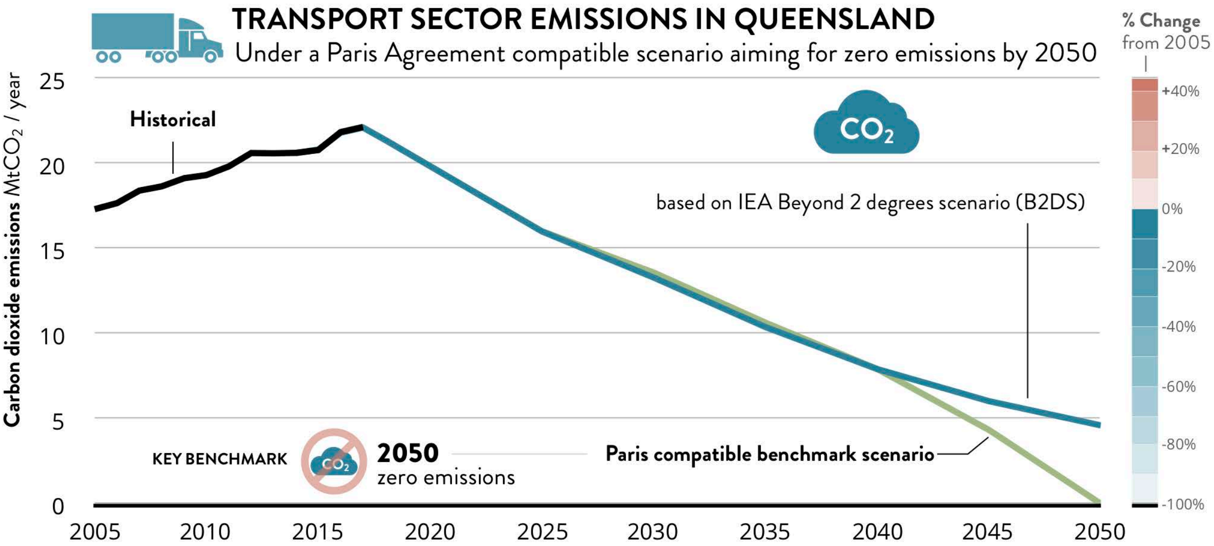

Figure 14: Carbon emissions from the transport sector in Queensland for IEA B2DS scenario and a Paris Agreement compatible pathways (a) based on the IEA ETP B2DS and (b) with the benchmark of full decarbonisation by 2050. Shown adjusted pathways taking into account the increase in historical emissions from 2014 to 2017. The IEA pathway relies on more negative emissions to compensate for more fossil fuel emissions still occurring in 2050.

Electric car sales are increasing worldwide, especially in countries like Norway or sub national states like California. Those countries and states have successfully introduced incentives and policies to accelerate the adoption of electric vehicles and other e-mobility options including metros, trams etc., and an increasing number of countries are introducing targets to ban internal combustion cars, ending the sale of fossil-fuel dependent internal-combustion engines. For example, the UK plans to stop the production of petrol and diesel cars by 2040, Scotland stepped up this target to phase out combustion cars by 2032, France by 2040, and Netherlands by 2030 (World Economic Forum 2017).

Industry, buildings, agriculture and fishery

The IEA B2DS Scenario is conservative regarding the potential for decarbonising the industry sector. The B2DS Scenario is based on older technology assumptions and is therefore very conservative as the use of coal, oil and natural gas can be replaced in industry processes by electricity or fuels generated from electricity such as green hydrogen, with more recent cost estimates, with CSIRO in the National Hydrogen Roadmap estimating that in or around 2025, clean hydrogen could be cost-competitive with existing industrial feedstocks such as natural gas, and energy carriers such as batteries in many applications[24], making it much more likely for these to become least cost options in particular with adequate policies in place at federal and state level.

[24] See also https://www.bloomberg.com/news/articles/2019-08-29/how-hydrogen-could-solve-steel-s-climate-test-and-hobble-coal and

The IEA B2DS scenario has a carbon budget of about 542 $MtCO_2$, with emission still at 2005 levels in 2030 and only 39% below these levels in 2050.

An increasing number of pathways are being developed internationally and nationally that show the potential for a faster decarbonisation.

In a national energy system scenario analysed earlier by Climate Analytics, the industry sector (like other energy sectors) is fully decarbonised by 2050 (Hare et al. 2018; Teske et al. 2016). We have analysed how existing gas demand in industry and mining can be eventually replaced by renewables, (as was also shown in a study by Teske et al (2016)).

Hydrogen can also serve as an additional renewable fuel option for high-temperature applications in the industry sector, together with biomass. Gas can also be replaced by renewably-produced hydrogen as feedstock for ammonia production. Queensland has a Hydrogen Industry Strategy and has had its first export of green hydrogen to Japan (Queensland Government 2019). The IEA has, already in 2017, pointed out the vast opportunities in Australia based on the "extreme abundance of solar and wind resources" to spur international trade in renewables-based, hydrogen-rich chemicals and fuels (IEA 2017b). Renewable energy alternatives exist for all applications of industrial natural gas use, not only for power generation but also for lower output temperatures and high temperature thermal processes as well as chemical feedstock, as studied by ARENA (2015). Recent interest internationally (IRENA) and nationally (ARENA, CSIRO) in the development of strategies for renewable hydrogen offer opportunities for a faster decarbonisation of industry sectors in Queensland.

An important strategy across all industry (and other end use) sectors is an increase in energy efficiency. Australia is lagging behind most other developed and even many developing countries with policies to incentivise energy efficiency (Climate Analytics 2018). Such policies can also be introduced at state level.

Taking these factors into account it is clear that industry should be able to achieve zero CO_2 emissions by 2050. The Paris compatible benchmark budget we estimate here is about 362 $MtCO_2$, with a reduction of about 23% from 2005 levels by 2030 and zero emission by 2050.

While the building sector (Figure 16) is already largely using electricity and therefore is decarbonised with power generation shifting to renewable energy, electrification is a key strategy to decarbonise either directly or indirectly through replacing fossil fuel combustion with "green" hydrogen (generated from renewable electricity), with some applications for biomass. The B2DS scenario has a budget of about 14 $MtCO_2$ and reaches a 92% reduction from 2005 emission levels by 2050, with about a 28% reduction in emissions by 2030. Full decarbonisation of this sector by 2050 reduces the carbon budget to about 13 $MtCO_2$.

In the energy use in agriculture sector the B2DS is slow to decarbonise for similar reasons to those discussed for industry. Reductions from 2005 levels by 2030 are only 3% and by 2050 58%, with a total carbon budget of about 38 $MtCO_2$. Energy used in this sector could also be fully decarbonized by 2050, based on the technology assumptions described above in relation to industry, with sustainable biomass as well as clean electricity replacing oil for energy and transport in the agriculture and fisheries sector (not shown). A Paris compatible carbon budget for this sector would be around 28 $MtCO_2$, with about a 22% reduction in emissions by 2030 from 2005 levels and reaching zero by 2050.

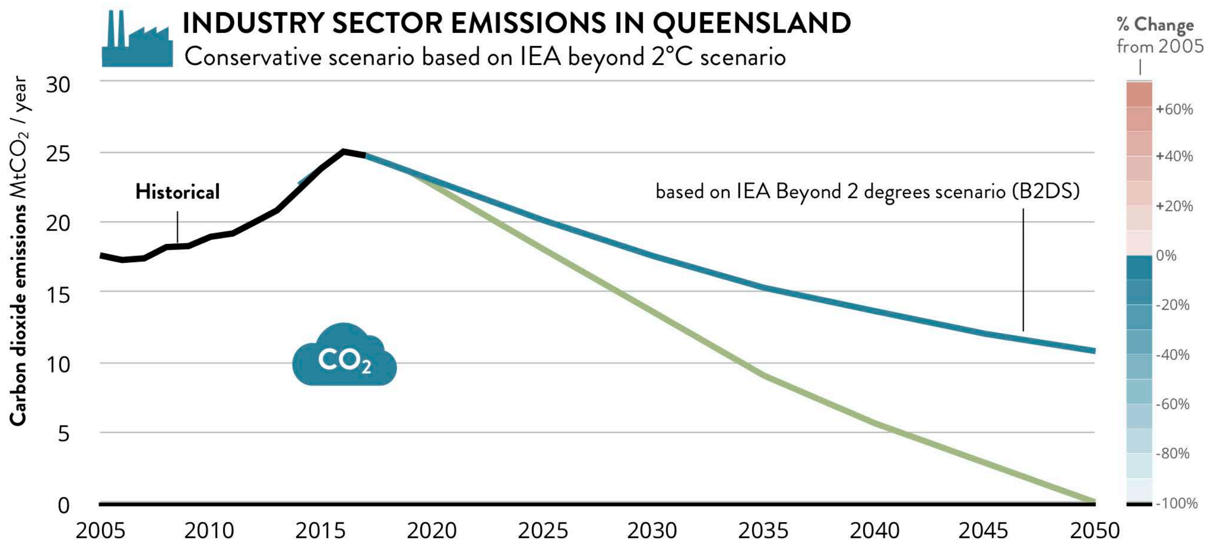

Figure 15: Carbon emissions from the industry sector in Queensland for a Paris Agreement compatible pathway (a) based on the IEA ETP B2DS and (b) with the benchmark of full decarbonisation by 2050. Both are adjusted to take into account historical emissions until 2017.

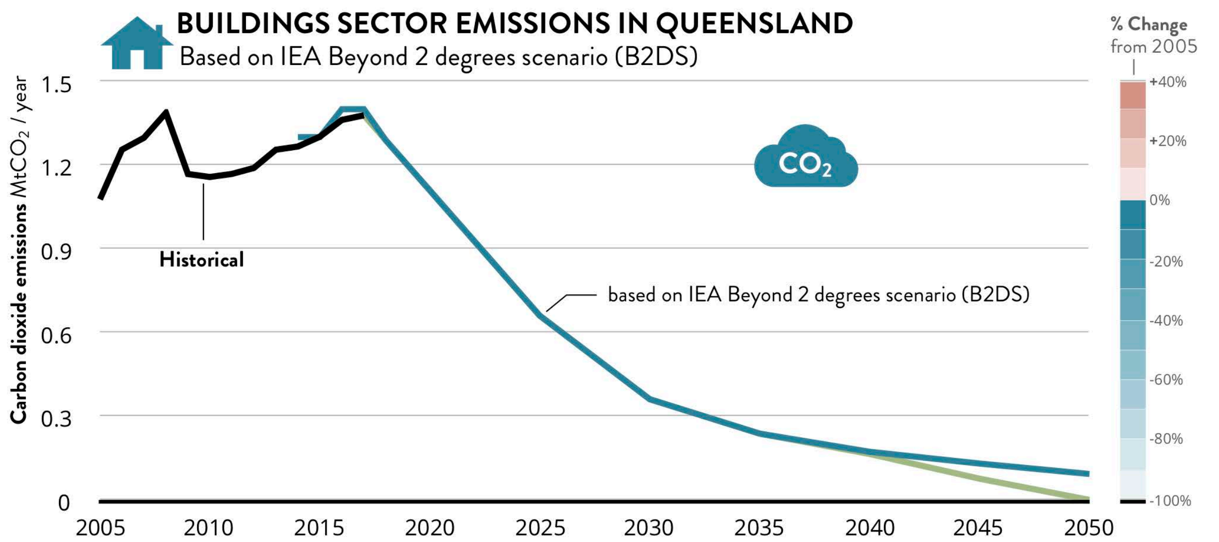

Figure 16: Carbon emissions from the buildings sector (residential and commercial) in Queensland,. for IEA B2DS scenario and a Paris Agreement compatible pathways (a) based on the IEA ETP B2DS and (b) with the benchmark of full decarbonisation by 2050 and adjusted to take into account historical emissions until 2017.

CARBON BUDGETS FOR QUEENSLAND ENERGY AND INDUSTRY SECTORS

In this concluding section of the report we consolidate the preceding analysis to produce a Queensland state Paris Agreement compatible budget and related sectoral carbon budgets for the period 2018-2050, and indicative emission reductions for 2030 compared to 2005 levels to establish both the state and its key sectors on 1.5°C compatible pathways.

The methodological approach here has been to begin the estimation of a Paris Agreement compatible budget by downscaling a driving global scenario, the IEA B2DS scenario to estimate an upper bound, before considering a range of additional factors. We have had to account for the initial conditions of the IEA B2DS scenario as well as the continuing growth of emissions from all of the covered sectors in Queensland. The IEA B2DS scenario assumes that action to transform sectors has already begun, whereas there is little evidence of this in Queensland, and from a carbon budget perspective this means that the carbon budget derived from the IEA scenarios for the period from 2018 needs to be adjusted downwards to take account of the sharp increase in emissions in all sectors between 2014 and 2017, compensating this with a sharper reduction to stay within the 1.5°C pathway.

We estimate a total Paris Agreement compatible budget for energy and industry fossil fuel CO_2 emissions for Queensland for 2018-2050 of about 1.2 $GtCO_2$. The IEA B2DS related budget we estimate as somewhat higher at 1.4 $GtCO_2$. Results for the carbon budget for each sector and for all energy/industry CO_2 emissions are shown below in Table 7, as well as necessary reductions by 2030 compared to 2005 to be established on a pathway to stay within this budget. The power sector needs to and can be decarbonised fastest with emissions in 2030 already 74% lower than in 2005 (and zero in 2040). This leads to a similarly fast decarbonisation of the building sector (relying largely on electricity). While electrification also leads to fast decarbonisation of the transport sector, other sectors are more difficult to decarbonise, with lower reductions by 2030.

At 2017 energy and industry CO_2 emission rates in Queensland of about 101 $MtCO_2$ per year, this budget would be consumed in less than 12 years, by 2031. Emissions have exhibited a sharply increasing trend in all sectors between 2014 and 2017, which means that there is greater pressure on policy and action if Queensland is to stay within a 1.5°C Great Barrier Reef compatible budget.

The power sector in Queensland accounted for about 50% of energy and industry CO_2 emissions in 2017 and needs to and can be decarbonised fastest with zero emissions by 2040 reducing reliance on negative emissions. By 2030, emissions will need to be 74% lower than in 2005. A carbon budget of about 415 $MtCO_2$ is estimated for the power sector, which is equivalent to about 8 years at 2017 emission rates.

Fast decarbonisation of the transport sector, which was 22% of 2017 energy and industry emissions, is also needed with 22% reductions from 2005 levels by 2030 and zero CO_2 emissions by 2050. Rapid electrification of both light-duty and heavy-duty vehicles is key to this with a mix of battery (EV) and renewable hydrogen fuel cell electric vehicles (FCEV). Air transport will be more difficult and likely slower to decarbonise, however, zero emissions fuels are available and can be deployed over time. A carbon budget of about 364 $MtCO_2$ is estimated for this sector, which is equivalent to about 16 years at 2017 emission rates.

There needs to be a similarly fast decarbonisation of the building sector, which was 1.4% of 2017 emissions, largely through electrification. Therefore, the building sector will decarbonise with power generation shifting to renewable energy. The buildings need a 67% reduction in 2030 compared to 2005 baseline. The building sector has an estimated carbon budget of 13 $MtCO_2$.

Industry and energy related agriculture CO_2 emissions accounted for about 26.4% of CO_2 emissions in 2017 and in the Paris Agreement benchmark pathway decarbonises slower than the power sector with 23% reductions by 2030 and achieves zero emissions by around 2050. A carbon budget of about 390 $MtCO_2$ is estimated for industry and agriculture sector, which is equivalent to about 15 years at 2017 emission rates. For the industry and energy related agriculture sectors, the IEA B2DS scenario decarbonises very slowly due to technology assumptions that we consider conservative based on current technology developments, with renewable hydrogen not yet taken up in the IEA modelling. It is to be noted that the industry sector includes manufacturing and construction, mining, energy industries such as gas extraction and LNG processing (including fugitive CO_2 emissions), and process emissions (e.g. from cement production). Coal, oil and gas used in this sector can be replaced earlier than in the IEA B2DS scenario, and in fact phased out by 2050 to be replaced by electricity or other fuels on a renewable energy basis such as green hydrogen, with emissions well below the IEA B2DS based budget of around 520 $MtCO_2$.

Overall, a 58% reduction in energy and industry CO_2 emissions across all sectors are needed by 2030 compared to 2005 (55% below 2010 levels), and slightly more than 100% by 2050, with limited deployment of negative emissions technology in the power sector in the 2040s. As the Queensland government (2017) has an economy-wide net zero emissions target for 2050 for all greenhouse gas emissions, other greenhouse gas emissions including from other sectors beyond energy and industry (for example agriculture not energy related, waste) will also need to be reduced and there may need to be a net emissions sink to compensate for remaining emissions for example from methane in agriculture. In the Paris Agreement compatible benchmark pathways developed here fossil fuel and industry CO_2 emissions are reduced by virtually 100% by 2050, some ten years earlier than in the B2DS scenario. The Paris Agreement benchmark pathways developed here are more optimistic than in the B2DS scenario due to more recent technological development that show that replacing oil, coal, and gas with electricity and fuels based on renewable energy such as green hydrogen will be cheaper than previously assumed.

Table 7: Paris Agreement compatible energy carbon budget for Queensland 2018-2050

Sector	**Paris Agreement compatible carbon budget** 2018-2050 $MtCO_2$*	2030 reduction (compared to 2005 baseline)
Electricity generation	415	74%
Transport	364	22%
Industry	362	23%
Buildings	13	67%
Agriculture (energy related)	28	22%
Total energy/industry emissions	**1,182**	**58%**

It is important to crosscheck the estimated carbon budget for Queensland for plausibility against other methodologies used to generate national carbon budgets:

- Based on a national scenario for decarbonising the entire energy system (Hare et al. 2018; Teske et al. 2016)[25], we have estimated a national budget for Australia of about 5.5 Gt CO_2. Assuming a share of 25% of this national budget for Queensland, corresponding to the share of energy CO_2 emissions in 2017 (Department of the Environment and Energy 2019), this would result in a similar, slightly higher budget for Queensland (1.4 $GtCO_2$) (without industry process emissions).
- If we apply Australia's share of current global emissions of about 1.1% of global fossil fuel (energy and industry) emissions[26] in 2017 (C. Le Quéré et al.2018) to the global carbon budget of 610 $GtCO_2$ (range 555 to 730 Gt) until the year of zero emissions, this results in a budget for Australia of 6.7 $GtCO_2$ (range 6.1-8.0 $GtCO_2$)[27]. With the current Australian share of 24% for Queensland of fossil energy and industry CO_2 emissions the Queensland budget would be 1.6 $GtCO_2$ (range 1.5- 1.9 $GtCO_2$).
- As a cross check for consistency against the global carbon budget derived from Integrated Assessment Modelling results outlined above, we have downscaled some of these scenarios[28] from the OECD90 region to the Australian level, producing an estimated budget for Australian energy related CO_2 emissions over 2018-2050 in the range of 4.8-6.6 $GtCO_2$ (Sferra et al. 2019)[29]. A 24% share for Queensland would correspond to 1.2 to 1.6 $GtCO_2$.

These consistency checks confirm that the carbon budget we have derived here for the period 2018-2050 based on sectoral pathways of 1.2 $GtCO_2$ is a robust estimate for a Paris Agreement, Great Barrier Reef compatible energy and industry carbon budget for Queensland. It is important to note that the budget to 2050 does not account for the negative emissions that will be needed after this time, which would be increased through inadequate action prior to 2050, or could be reduced through faster reductions in some sectors. Examining the implications for negative emissions and opportunities in Queensland is beyond the scope of the study. The energy system transformation in Queensland would need to consider the need for negative emission technologies and their deployment on a sustainable basis.

In this analysis we have examined CO_2 from energy and industry. To achieve zero GHG emissions by 2050 for Queensland as a whole action in the energy area will need to be complemented by a strategy for the land use sector to reduce emissions from land use change and forestry, in particular land clearing, in order to achieve the target of net zero emissions of all greenhouse gases by 2050.

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25 This did not include industry process emissions.

26 Assuming a share of 1.1% for Australia is comparable to the share recommended by the Climate Change Authority (2014, Figure C.3). However, here we derive a budget for domestic emissions consistent with socio-economic least cost pathways and national and state potentials and policies. An equity based share would be lower than this share.

27 However, it is important to note that the total global carbon budget until 2100 is considerably lower, (470 GtCO2; range 320-700 GtCO2) implying the need for negative emissions in order to allow for a higher budget until the year of zero emissions. Australia's share of this budget until 2100 would be, based on the current 1.1% share of global emissions, 5.2 GtCO2 (range 3.5-7.7 GtCO2), and Queensland's share would be 1.2 GtCO2 (range 0.8 – 1.8 GtCO2) based on a 24% share.

28 RCP1.9 marker scenarios (IMAGE SSP1, MESSAGE SSP2 – see (Rogelj et al., 2018))

29 Analogous to the methodology underlying the global carbon budgets above we have excluded scenarios that overshoot 1.5°C by more than 0.1°C, which would not be Paris-Agreement compatible.

CONCLUSION

This analysis has produced an energy and industry Paris Agreement, Great Barrier Reef compatible carbon budget for Queensland that is consistent with the global carbon budget and the global and national energy transformation across different regions required to limit warming to 1.5°C. It shows how the Queensland carbon budget relates to the global carbon budget and also provides information on the emissions pathway by which the budget needs to be met. It confirms the key strategy to decarbonise the power sector by a fast transition to renewable energy, taking advantage of the vast potentials and low and falling costs of renewable energy and storage technologies and the opportunities for a range of sectors.

For Queensland to take advantage of these potentials and opportunities it is of vital importance to develop a whole of the economy strategy as well as detailed sectoral strategies in line with the pathways and carbon budgets outlined in this study, and implement transformational policies that put Queensland on the right track of decarbonisation. This includes ambitious renewable energy targets and a clear and stable framework to encourage investment into renewable energy, policies to support infrastructure for electrification of transport, as well as modal shift to public transport, cycling and walking, and incentives for industry to enhance efficiency and shift towards zero emissions processes and fuels.

Beyond energy and industry, Queensland also needs to reduce emissions from agriculture as well as from Land use, land-use change and forestry and stop land clearing to achieve the net zero GHG emissions target by 2050.

The 1.5°C warming limit in the Paris Agreement is vital for the best chance of survival of the Great Barrier Reef. As a critical natural and economic asset for Queensland and Australia, the state must play its part in decarbonisation efforts to protect its future. The Reef is a world heritage site, harbouring species threatened with extinction (UNESCO n.d.), and is a major contributor to the Australian economy generating $6.4 billion and 64,000 jobs nationally (Deloitte 2017). It plays a vital part in representing Queensland and Australia's international reputation and identity.

ANNEX I: IEA BELOW 2 DEGREES (B2DS) SCENARIO AS A PROXY FOR A 1.5°C COMPATIBLE PATHWAY

For a full climate-model simulation one needs to assume pathways for non-CO_2 emissions and air pollutants. Rogelj et al (2015, 2018) showed that the key difference between 1.5°C compatible pathways and "likely below 2°C" scenarios is in CO_2 emissions, because the potential to reduce non-CO_2 emissions is seen as essentially the same as "likely below 2°C" scenarios. As non-CO_2 scenario information is available most extensively for "likely below 2°C" scenarios in the public database of IPCC SSP-RCP2.6 scenarios, we used the average of RCP2.6 scenarios (SSP2 representing middle-of-the-road socio-economic and technical developments) to characterize non-CO_2 emissions and to evaluate the IEA B2DS scenario. In addition, we assumed CO_2 emissions from the land sector also follow the average of these scenarios, reaching largest amounts of annual removals of about -2 Gt CO_2 /yr around 2060, which we note is within the sustainable potential estimated by IPCC SR1.5 at around -3.6 Gt CO_2 /yr by 2050. For energy related CO_2 emissions, the IEA (2017) adopted a pre-defined assumption that there would not global negative CO_2 from the energy sector, which is a feature of nearly all 1.5°C compatible pathways after 2050-2060. It is important to note that IEA B2DS energy sector CO_2 emissions reach net zero around 2060, supported by negative emissions through deployment of bioenergy with CCS, but are not allowed by assumption to lead to globally negative emissions.

We extended the B2DS post 2060 with negative CO_2 from the energy sector comparable with 1.5°C compatible pathways. To evaluate the global warming consequences of the B2DS scenario through 2100 we used the carbon-cycle/climate model MAGICC (Meinshausen, Raper, and Wigley 2011) in the same configuration used for IPCC's Fifth Assessment Report (IPCC 2014) and in the IPCC (2018a) SR1.5. The results of this evaluation show that after accounting for non-CO_2 GHGs as described above B2DS reaches a peak warming of 1.6°C above pre-industrial by 2060 and stays around that level afterwards. In contrast to 1.5°C compatible pathways in the IPCC SR1.5, warming does not drop to below 1.5°C after the peak. Extending the B2DS energy related CO_2 emissions beyond 2060 to include negative CO_2 emissions comparable to those in 1.5°C compatible pathways leads to peak warming dropping below 1.5°C after the peak at 1.6°C. It is clear that the IEA's predefined assumption of no global net negative CO_2 from the energy sector leads to warming not reducing after the peak at 1.6°C and that if this is relaxed the B2DS is consistent with the IPCC compatible 1.5°C pathways. The IPCC SR1.5 has also considered the utility of B2Ds for providing information on 1.5°C consistent pathways. In Chapter 2 of IPCC Special Report on 1.5°C, the B2DS scenario is shown to be consistent with 1.5°C pathways in terms of emissions up to 2060 (see section 2.4.3 and Figures 2.18, 2.19 and 2.20). While emissions intensity by 2050 in the power and industry sectors in the B2DS pathway are above those typical for 1.5°C pathways, B2DS emissions intensity is lower in the transport and buildings sectors. IPCC SR1.5 concludes that "… although its temperature rise in 2100 is below 1.75°C rather than below 1.5°C, this [B2DS] scenario can give information related to 1.5°C consistent overshoot pathway up to 2050." The IPCC did not conduct a like-for-like comparison of the full global warming consequences of the B2DS scenario, which as shown above results in a 1.6°C peak warming. With these considerations, it is clear that both the energy-related CO_2 emissions in the B2DS scenario up to 2060, and its peak warming at 1.6°C around 2060 are comparable to low-overshoot 1.5°C scenarios. The B2DS scenario until 2060 is confirmed to be a suitable analogue to 1.5°C compatible pathways.

ANNEX II: SCOPE OF EMISSIONS FROM THE AUSTRALIAN GREENHOUSE EMISSIONS INFORMATION SYSTEM (AGEIS).

Energy and Industry Emissions

Electricity generation emissions are from fuel combustion for public electricity and heat production (AGEIS 1.A.1.a).

Transport sector includes fuel combustion emissions from domestic aviation, road transportation (cars, light commercial vehicles, heavy duty trucks and buses, motorcycles, and other), railways, domestic navigation (pleasurecraft and domestic marine), and other transportation (AGEIS 1.A.3).

Industry emissions include:

- Energy industries (AGEIS 1.A.1) minus public electricity and heat production (AGESIS 1.a.1.a). This includes fuel combustion from petroleum refining, manufacture of solid fuels industries (i.e. coal mining, gas production and distribution) and other energy industries.
- Manufacturing industries and construction (AGEIS 1.A.2) includes fuel combustion emissions from iron and steel; non-ferrous metals; chemicals pulp, paper and print; food processing, beverages, and tobacco; non-metallic minerals; and other.
- Fugitive emissions from fuels (AGEIS 1.B) including from coal mining (underground and surface mines); oil (exploration, crude oil production, transport, refining and storage, and distribution); natural gas (exploration, production, transmission and storage, distribution and other); and venting and flaring.
- Industrial Processes (AGEIS 2) which includes the mineral, chemical, metal and electronic industries; plus non-energy products from fuels and solvent use; product uses as substitutes for ozone depleting substances, and other.

Building sector emissions include fuel combustion from commercial/ institutional (AGEIS 1.A.4.a) and residential buildings (AGEIS 1.A.4.b).

Agriculture energy sector emissions (AGEIS 1.A.4.c) include fuel combustion emissions from agriculture, forestry and fishing relating to stationary; off-road vehicle and machinery; and fishing.

Other sectors (non energy and industry related emissions) (not included in this study)

Agriculture emissions (AGEIS 3) from enteric fermentation, manure management, rice cultivation, agricultural soils, prescribed burning of savannas, field burning of agricultural residues, liming, urea application and other carbon-containing fertilisers.

Land use, Land use change and forestry KP sector (AGEIS 4) includes emissions from afforestation and reforestation (deforestation, forest management, cropland management, grazing land management and revegetation).

Waste emissions (AGEIS 5) include solid waste disposal, biological treatment of solid waste, incineration and open burning of waste, wastewater treatment and discharge, other.

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Climate Analytics is a non-profit climate science and policy institute based in Berlin, Germany with offices in New York, USA, Lomé, Togo and Perth, Australia, which brings together interdisciplinary expertise in the scientific and policy aspects of climate change. Our mission is to synthesise and advance scientific knowledge in the area of climate change and on this basis provide support and capacity building to stakeholders. By linking scientific and policy analysis, we provide state-of-the-art solutions to global and national climate change policy challenges.

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REFERENCES

ABC News. 2017. "Campaigners from 1960s Return to Fight for Great Barrier Reef." *ABC News*. Retrieved August 14, 2019 (https://www.abc.net.au/news/2017-10-15/great-barrier-reef-50-years-on-campaigners-return-ellison-reef/9050106).

AIMS. 2019. *Mixed Bill of Health for the Great Barrier Reef*.

Ainsworth, Tracy D., Scott F. Heron, Juan Carlos Ortiz, Peter J. Mumby, Alana Grech, Daisie Ogawa, C. Mark Eakin, and William Leggat. 2016. "Climate Change Disables Coral Bleaching Protection on the Great Barrier Reef." *Science* 352(6283):338 LP – 342.

Albright, Rebecca, Lilian Caldeira, Jessica Hosfelt, Lester Kwiatkowski, Jana K. Maclaren, Benjamin M. Mason, Yana Nebuchina, Aaron Ninokawa, Julia Pongratz, Katharine L. Ricke, Tanya Rivlin, Kenneth Schneider, Marine Sesboüé, Kathryn Shamberger, Jacob Silverman, Kennedy Wolfe, Kai Zhu, and Ken Caldeira. 2016. "Reversal of Ocean Acidification Enhances Net Coral Reef Calcification." *Nature* 531(7594):362–65.

ARC COE. n.d. "Coral Bleaching and the Great Barrier Reef." *– ARC Centre of Excellence for Coral Reef Studies*. Retrieved August 19, 2019 (https://www.coralcoe.org.au/for-managers/coral-bleaching-and-the-great-barrier-reef).

ARC COE Coral Reef Studies. n.d. "Two-Thirds of Great Barrier Reef Hit by Back-to-Back Mass Coral Bleaching." *ARC Centre of Excellence for Coral Reef Studies*. Retrieved August 14, 2019 (https://www.coralcoe.org.au/media-releases/two-thirds-of-great-barrier-reef-hit-by-back-to-back-mass-coral-bleaching).

Australian Government. 2019. *State and Territory Greenhouse Gas Inventories 2017 Australia's National Greenhouse Accounts*.

Bernie, D., J. Lowe, T. Tyrrell, and O. Legge. 2010. "Influence of Mitigation Policy on Ocean Acidification." *Geophysical Research Letters* 37(15):n/a-n/a.

Bhatia, Kieran, Gabriel Vecchi, Hiroyuki Murakami, Seth Underwood, and James Kossin. 2018. "Projected Response of Tropical Cyclone Intensity and Intensification in a Global Climate Model." *Journal of Climate* 31(20):8281–8303.

Blakers, Andrew, Bin Lu, and Matthew Stocks. 2017. "100% Renewable Electricity in Australia." *Energy* 133:471–82.

Cai, Wenju, Agus Santoso, Guojian Wang, Sang-Wook Yeh, Soon-Il An, Kim M. Cobb, Mat Collins, Eric Guilyardi, Fei-Fei Jin, Jong-Seong Kug, Matthieu Lengaigne, Michael J. McPhaden, Ken Takahashi, Axel Timmermann, Gabriel Vecchi, Masahiro Watanabe, and Lixin Wu. 2015. "ENSO and Greenhouse Warming." *Nature Climate Change* 5(9):849–59.

Cheal, Alistair J., M. Aaron MacNeil, Michael J. Emslie, and Hugh Sweatman. 2017. "The Threat to Coral Reefs from More Intense Cyclones under Climate Change." *Global Change Biology* 23(4):1511–24.

Clark, Peter U., Alan C. Mix, Michael Eby, Anders Levermann, Joeri Rogelj, Alexander Nauels, and David J. Wrathall. 2018. "Sea-Level Commitment as a Gauge for Climate Policy." *Nature Climate Change* 8(8):653–55.

Climate Action Tracker. 2016. *The Road Ahead: How Do We Move to Cleaner Car Fleets?*

Climate Action Tracker. 2018a. "Climate Action Tracker Data Portal." Retrieved (http://climateactiontracker.org/decarbonisation/intro [accessed on 31 October 2018]).

Climate Action Tracker. 2018b. *Scaling up Climate Action: European Union*.

Climate Action Tracker. 2018c. "The Climate Action Tracker (CAT) Thermometer." Global | CAT Thermometer. Retrieved June 18, 2019 (https://climateactiontracker.org/global/cat-thermometer/).

Climate Action Tracker. 2018d. *The Highway to Paris: Safeguarding the Climate by Decarbonising Freight Transport*.

Climate Action Tracker. n.d. "CAT Decarbonisation Memo Series." Retrieved August 7, 2019 (https://climateactiontracker.org/publications/decarbonisation-memo-series/).

Climate Analytics. 2018. "Australia Climate Factsheets - Industry." Retrieved May 23, 2019 (https://climateanalytics.org/publications/2018/australia-climate-factsheets-industry/).

Climate Analytics. 2019a. "Insights from the IPCC Special Report on 1.5°Cfor Preparation of Long-Term Strategies."

Climate Analytics, 2019b "Global and Regional Coal Phase out requirements of the Paris Agreement: Insights from the IPCC Special Report on .5°C"

Climate Change Authority. 2014. *Sharing the Global Emissions Budget, Appendix C1*.

Climate Council. 2018. *Powering Progress: States Renewable Energy Race*.

Climate Council. 2019. *Welcome to Queensland: Renewable One Day, and the next, and Next*.

Crawford, Debbie, Tom Jovanovic, Michael O'connor, Alexander Herr, John Raison, and Tim Baynes. 2012. *AEMO 100% Renewable Energy Study*.

Dellink, Rob, Jean Chateau, Elisa Lanzi, and Bertrand Magné. 2017. "Long-Term Economic Growth Projections in the Shared Socioeconomic Pathways." *Global Environmental Change* 42:200–214.

Deloitte. 2017. *At What Price? The Economic, Social and Icon Value of the Great Barrier Reef*.

Department of the Environment and Energy, Australian Energy Statistics. n.d. "Australian Energy Statistics, Table O, Australian Electricity Generation by Fuel Type."

Department of the Environment and Energy. 2019. "State Greenhouse Gas Inventory." *Australian Government*. Retrieved August 7, 2019 (http://ageis.climatechange.gov.au/SGGI.aspx).

Eyre, Bradley D., Tyler Cyronak, Patrick Drupp, Eric Heinen De Carlo, Julian P. Sachs, and Andreas J. Andersson. 2018. "Coral Reefs Will Transition to Net Dissolving before End of Century." *Science (New York, N.Y.)* 359(6378):908–11.

Fricko, Oliver, Petr Havlik, Joeri Rogelj, Zbigniew Klimont, and Mykola Gusti. 2017. "The Marker Quantification of the Shared Socioeconomic Pathway 2: A Middle-of-the-Road Scenario for the 21st Century." *Global Environmental Change* 42:251–67.

Frieler, K., M. Meinshausen, A. Golly, M. Mengel, K. Lebek, S. D. Donner, and O. Hoegh-Guldberg. 2013. "Limiting Global Warming to 2 °C Is Unlikely to Save Most Coral Reefs." *Nature Climate Change* 3(2):165–70.

Frölicher, Thomas L., Erich M. Fischer, and Nicolas Gruber. 2018. "Marine Heatwaves under Global Warming." *Nature* 560(7718):360–64.

Frölicher, Thomas L. and Charlotte Laufkötter. 2018. "Emerging Risks from Marine Heat Waves." *Nature Communications* 9(1):650.

GBRMPA. n.d. "Land-Based Run-Off." *Great Barrier Reef Marine Park Authority* . Retrieved August 14, 2019 (http://www.gbrmpa.gov.au/our-work/threats-to-the-reef/declining-water-quality).

Graham, Paul W., Jenny Hayward, James Foster, Oliver Story, and Lisa Havas. 2018. "GenCost 2018 Updated Projections of Electricity Generation Technology Costs." (December).

Green Energy Markets. 2018. *Renewable Energy across Queensland's Regions.*

Gulagi, Ashish, Dmitrii Bogdanov, Christian Breyer, Ashish Gulagi, Dmitrii Bogdanov, and Christian Breyer. 2017. "A Cost Optimized Fully Sustainable Power System for Southeast Asia and the Pacific Rim." *Energies* 10(5):583.

Hare, Bill, Ursula Fuentes Hutfilter, Fabio Sferra, Paola Parra, Jasmin Cantzler, and Matt Beer. 2017. *The Finkel Review and Scientific Consistency with the Paris Agreement*.

Hare, Bill, Niklas Roming, Ursula Fuentes Hutfilter, Michiel Schaeffer, and Matt Beer. 2018. "Western Australia's Gas Gamble." (March).

Heron, Scott F., C. Mark Eakin, and Fanny Douvere. 2017. *Impacts of Climate Change on World Heritage Coral Reefs: A First Global Scientific Assessment*.

Hoegh-Guldberg, O., P. J. Mumby, A. J. Hooten, R. S. Steneck, P. Greenfield, E. Gomez, C. D. Harvell, P. F. Sale, A. J. Edwards, K. Caldeira, N. Knowlton, C. M. Eakin, R. Iglesias-Prieto, N. Muthiga, R. H. Bradbury, A. Dubi, and M. E. Hatziolos. 2007. "Coral Reefs Under Rapid Climate Change and Ocean Acidification." *Science* 318(5857):1737–42.

Hoegh-Guldberg, Ove. 1999. "Climate Change, Coral Bleaching and the Future of the World's Coral Reefs." *Marine and Freshwater Research* 50(8):839.

Hughes, Terry P., Jon C. Day, and Jon Brodie. 2015. "Securing the Future of the Great Barrier Reef." *Nature Climate Change* 5:508.

Hughes, Terry P., James T. Kerry, Andrew H. Baird, Sean R. Connolly, Tory J. Chase, Andreas Dietzel, Tessa Hill, Andrew S. Hoey, Mia O. Hoogenboom, Mizue Jacobson, Ailsa Kerswell, Joshua S. Madin, Abbie Mieog, Allison S. Paley, Morgan S. Pratchett, Gergely Torda, and Rachael M. Woods. 2019. "Global Warming Impairs Stock–Recruitment Dynamics of Corals." *Nature* 568(7752):387–90.

IEA. 2017. *Energy Technology Perspectives 2017*.

IGBP IOC. 2013. *Ocean Acidification Summary for Policymakers – Third Symposium on the Ocean in a High-CO2 World*. Stockholm.

IIASA. 2018. "IAMC 1.5°C Scenario Explorer Hosted by IIASA." *International Institute for Applied Systems Analysis*. Retrieved October 22, 2018 (https://data.ene.iiasa.ac.at/iamc-1.5c-explorer/#/login?redirect=%2Fworkspaces).

IPCC. 2001. *TAR Climate Change 2001: The Scientific Basis*.

IPCC. 2007. *Climate Change 2007: Synthesis Report Summary for Policymakers An Assessment of the Intergovernmental Panel on Climate Change*.

IPCC. 2014. "Fifth Assessment Report." Retrieved August 7, 2019 (https://www.ipcc.ch/assessment-report/ar5/).

IPCC. 2018a. *Global Warming of 1.5 °C: An IPCC Special Report on the Impacts of Global Warming of 1.5 °C above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Chang*.

IPCC. 2018b. "Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development." in *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change*.

IPCC. 2018c. "Summary for Policy Makers. Global Warming of 1.5°C - IPCC Special Report on the Impact of 1.5°C." in *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change*.

IRENA. 2018. *Hydrogen from Renewable Power: Technology Outlook for the Energy Transition*.

King, Andrew D., David J. Karoly, and Benjamin J. Henley. 2017. "Australian Climate Extremes at 1.5 °C and 2 °C of Global Warming." *Nature Climate Change* 7(May).

Leggat, William P., Emma F. Camp, David J. Suggett, Scott F. Heron, Alexander J. Fordyce, Stephanie Gardner, Lachlan Deakin, Michael Turner, Levi J. Beeching, Unnikrishnan Kuzhiumparambil, C. Mark Eakin, and Tracy D. Ainsworth. 2019. "Rapid Coral Decay Is Associated with Marine Heatwave Mortality Events on Reefs." *Current Biology : CB* 0(0).

Lenton, Andrew, Bronte Tilbrook, Richard J. Matear, Tristan P. Sasse, and Yukihiro Nojiri. 2016. "Historical Reconstruction of Ocean Acidification in the Australian Region." *Biogeosciences* 13(6):1753–65.

Mathesius, Sabine, Matthias Hofmann, Ken Caldeira, and Hans Joachim Schellnhuber. 2015. "Long-Term Response of Oceans to CO2 Removal from the Atmosphere." *Nature Climate Change* 5(12):1107–13.

Meinshausen, M., S. C. B. Raper, and T. M. L. Wigley. 2011. "Emulating Coupled Atmosphere-Ocean and Carbon Cycle Models with a Simpler Model, MAGICC6 - Part 1: Model Description and Calibration." *Atmospheric Chemistry and Physics* 11(4):1417–56.

Mengel, Matthias, Alexander Nauels, Joeri Rogelj, and Carl-Friedrich Schleussner. 2018. "Committed Sea-Level Rise under the Paris Agreement and the Legacy of Delayed Mitigation Action." *Nature Communications* 9(1):601.

Mongin, Mathieu, Mark E. Baird, Bronte Tilbrook, Richard J. Matear, Andrew Lenton, Mike Herzfeld, Karen Wild-Allen, Jenny Skerratt, Nugzar Margvelashvili, Barbara J. Robson, Carlos M. Duarte, Malin S. M. Gustafsson, Peter J. Ralph, and Andrew D. L. Steven. 2016. "The Exposure of the Great Barrier Reef to Ocean Acidification." *Nature Communications* 7(1):10732.

Nauels, Alexander, Malte Meinshausen, Matthias Mengel, Katja Lorbacher, and Tom M. L. Wigley. 2017. "Synthesizing Long-Term Sea Level Rise Projections – the MAGICC Sea Level Model v2.0." *Geoscientific Model Development* 10(6):2495–2524.

Ngugi, Michael R., Victor J. Neldner, Sean Ryan, Tom Lewis, Jiaorong Li, Phillip Norman, and Michelle Mogilski. 2018. "Estimating Potential Harvestable Biomass for Bioenergy from Sustainably Managed Private Native Forests in Southeast Queensland, Australia." *Forest Ecosystems* 5(1):6.

Ortiz, Juan-Carlos, Nicholas H. Wolff, Kenneth R. N. Anthony, Michelle Devlin, Stephen Lewis, and Peter J. Mumby. 2018. "Impaired Recovery of the Great Barrier Reef under Cumulative Stress." *Science Advances* 4(7):eaar6127.

PBL. 2018. *Trends in Global CO2 and Total Greenhouse Gas Emissions: 2018 Report*.

Pörtner, H. O., D. M. Karl, P. W. Boyd, W. W. L. Cheung, S. E. Lluch-Cota, Y. Nojiri, D. N. Schmidt, and P. Zavialov. 2014. "Ocean Systems." in *Climate Change 2014: Impacts, Adaptation, and Vulnerability*, edited by C. B. Field, V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea, and L. L. White. Cambridge.

Prada, F., E. Caroselli, S. Mengoli, L. Brizi, P. Fantazzini, B. Capaccioni, L. Pasquini, K. E. Fabricius, Z. Dubinsky, G. Falini, and S. Goffredo. 2017. "Ocean Warming and Acidification Synergistically Increase Coral Mortality." *Scientific Reports* 7(1):40842.

Queensland Government. 2017. *Pathways to a Clean Growth Economy Queensland Climate Transition Strategy*.

Queensland Government. 2018. "Queensland Biomass Mapping and Data." Retrieved July 30, 2019 (https://www.statedevelopment.qld.gov.au/industry-development/queensland-biomass-mapping-and-data.html).

Queensland Government. 2019. *Queensland Hydrogen Industry Strategy*.

Le Quéré et al. 2018. "Global Carbon Budget 2018." *Earth System Science Data* 10:2141–94.

Rau, Greg H., Elizabeth L. McLeod, and Ove Hoegh-Guldberg. 2012. "The Need for New Ocean Conservation Strategies in a High-Carbon Dioxide World." *Nature Climate Change* 2(10):720–24.

RenewEconomy. 2019. "How Serious Is Queensland about Its 50 per Cent Renewable Energy Target?" *RenewEconomy*. Retrieved August 7, 2019 (https://reneweconomy.com.au/how-serious-is-queensland-about-its-50-per-cent-renewable-energy-target-94652/).

Rhein, M., S. R. Rintoul, S. Aoki, E. Campos, D. Chambers, R. A. Feely, S. Gulev, G. C. Johnson, S. A. Josey, A. Kostianoy, C. Mauritzen, D. Roemmich, L. D. Talley, and F. Wang. 2013. “Observations: Ocean Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.” 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*, edited by T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, and V. Midgley. Cambridge University Press.

Rogelj, Joeri, Gunnar Luderer, Robert C. Pietzcker, Elmar Kriegler, Michiel Schaeffer, Volker Krey, and Keywan Riahi. 2015. “Energy System Transformations for Limiting End-of-Century Warming to below 1.5 °C.” *Nature Climate Change* 5(6):519–27.

Rogelj, Joeri, Alexander Popp, Katherine V. Calvin, Gunnar Luderer, Johannes Emmerling, David Gernaat, Shinichiro Fujimori, Jessica Strefler, Tomoko Hasegawa, Giacomo Marangoni, Volker Krey, Elmar Kriegler, Keywan Riahi, Detlef P. van Vuuren, Jonathan Doelman, Laurent Drouet, Jae Edmonds, Oliver Fricko, Mathijs Harmsen, Petr Havlík, Florian Humpenöder, Elke Stehfest, and Massimo Tavoni. 2018. “Scenarios towards Limiting Global Mean Temperature Increase below 1.5 °C.” *Nature Climate Change*, 1–8.

Schleussner, Carl-Friedrich, Tabea K. Lissner, Erich M. Fischer, Jan Wohland, Mahé Perrette, Antonius Golly, Joeri Rogelj, Katelin Childers, Jacob Schewe, Katja Frieler, Matthias Mengel, William Hare, and Michiel Schaeffer. 2016. “Differential Climate Impacts for Policy Relevant Limits to Global Warming: The Case of 1.5°C and 2°C.” *Earth System Dynamics* 7(2):327–51.

Sferra, Fabio, Mario Krapp, Niklas Roming, Michiel Schaeffer, Aman Malik, Bill Hare, and Robert Brecha. 2019. “Towards Optimal 1.5° and 2 °C Emission Pathways for Individual Countries: A Finland Case Study.” *Energy Policy* 133:110705.

Teske, S., E. Dominish, N. Ison, and K. Maras. 2016. *100% Renewable Energy for Australia: Decarbonising Australia’s Energy Sector Within One Generation*. Sydney.

The Royal Society. 2005. *Ocean Acidification Due to Increasing Atmospheric Carbon Dioxide Policy Document 12/05*.

UNESCO. n.d. “Great Barrier Reef.” *UNESCO*. Retrieved August 14, 2019 (https://whc.unesco.org/en/list/154/).

UNFCCC. 2015. “Paris Agreement.” 1–16.

Veron, J. E. N., O. Hoegh-Guldberg, T. M. Lenton, J. M. Lough, D. O. Obura, P. Pearce-Kelly, C. R. C. Sheppard, M. Spalding, M. G. Stafford-Smith, and A. D. Rogers. 2009. “The Coral Reef Crisis: The Critical Importance of <350 Ppm CO2.” *Marine Pollution Bulletin* 58(10):1428–36.

Wachsmuth, Jakob, Michiel Schaeffer, and Bill Hare. 2018. *The EU Long-Term Strategy to Reduce GHG Emissions in Light of the Paris Agreement and the IPCC Special Report on 1.5°C.*

Wang, Guojian, Wenju Cai, Bolan Gan, Lixin Wu, Agus Santoso, Xiaopei Lin, Zhaohui Chen, and Michael J. McPhaden. 2017. “Continued Increase of Extreme El Niño Frequency Long after 1.5 °C Warming Stabilization.” *Nature Climate Change* 7(8):568–72.

Willeit, M., A. Ganopolski, R. Calov, and V. Brovkin. 2019. “Mid-Pleistocene Transition in Glacial Cycles Explained by Declining CO 2 and Regolith Removal.” *Science Advances* 5(4):eaav7337.

Wolff, Nicholas H., Peter J. Mumby, Michelle Devlin, and Kenneth R. N. Anthony. 2018. “Vulnerability of the Great Barrier Reef to Climate Change and Local Pressures.” *Global Change Biology* 24(5):1978–91.

World Economic Forum. 2017. “Countries Are Announcing Plans to Phase out Petrol and Diesel Cars. Is Yours on the List?” *World Economic Forum*. Retrieved September 5, 2019 (https://www.weforum.org/agenda/2017/09/countries-are-announcing-plans-to-phase-out-petrol-and-diesel-cars-is-yours-on-the-list/).

CLIMATE ANALYTICS

Climate Analytics is a non-profit organisation headquartered in Berlin, Germany, with regional offices in Lomé, Togo, Perth, Australia and New York, USA and with associates across Europe, South America, Asia, Africa, the Pacific and the Caribbean. The organisation's main mission is to synthesise and advance scientific knowledge in the area of climate change. The team is backed by its own and co-developed science-based models to assess and synthesise climate science and policy. By linking scientific and policy analysis, we provide state-of-the-art solutions to global and national challenges posed by climate change.

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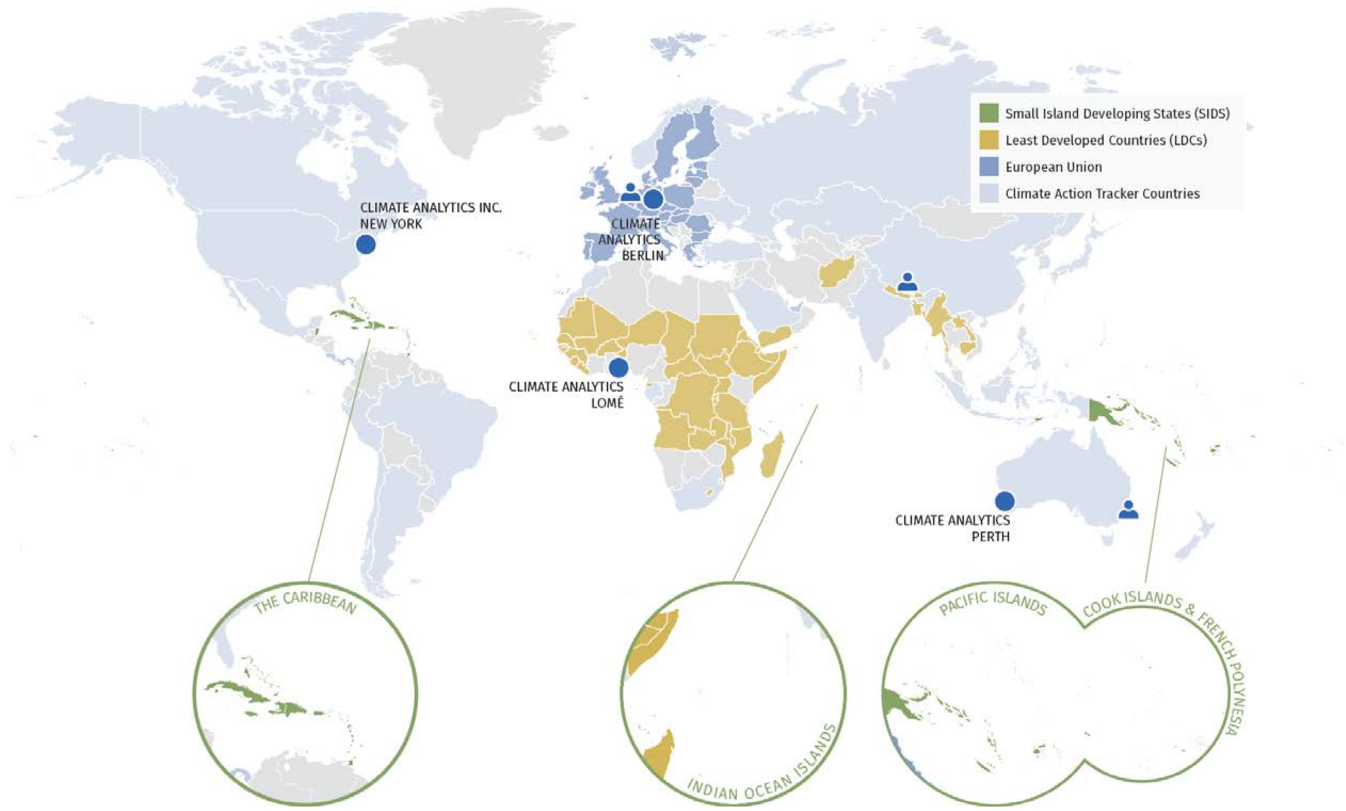

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