He Pou a Rangi
Climate Change Commission

Official information request reference 2021-007

[redacted]

18 February 2021

Dear [redacted]

Thank you for your email of 9 February 2021, requesting information about the report on the science of pathways to 1.5 degrees. Our responses to your questions are given below.

1. ***The terms of reference for preparing the report – what questions were asked of the scientists***
   Please find attached the brief for the 1.5 degrees report.

2. ***Can you confirm that this advice was peer reviewed and by whom?***
   The piece was peer reviewed by:
   - Professor Myles Allen, the head of the Climate Dynamics group at the University of Oxford's Atmospheric, Oceanic and Planetary Physics Department
   - Dr Michelle Cain, Science and Policy Research Associate at the Oxford Martin School, University of Oxford – Dr Cain was recruited by Professor Allen to assist him
   - Dr Andy Reisinger, formerly the NZAGRC Deputy Director, in his private capacity as a New Zealand-based climate scientist.

3. ***The terms of reference for the peer reviews.***
   Please see the attached correspondence with Professor Allen and Dr Reisinger.

4. ***The findings of the peer reviews.***
   Please see the tracked changes/comments in the attached two draft versions of the Forster Fuglestvedt Millar report.

5. ***A copy of all correspondence between Commission staff and the reviewers over the course of completing the review.***
   Please see the attached email threads between the Commission's principal analyst, Matt Smith and Professor Allen (one chain) and Dr Reisinger (two chains).

I hope this answers your queries.

Please note that the Commission has a policy of proactive release of OIA responses to help others have access to more information so this letter will shortly be published on the website with your name and contact details redacted to protect your privacy.

Kind regards,

Jo Hendy
Chief Executive

Attachments:
1.5 degrees brief (Word)
Correspondence with Professor Allen and Dr Reisinger (PDFs)
Two copies of the Forster Fuglestvedt Millar report containing the peer reviewers' edits and comments

BRIEF PROVIDED TO REPORT AUTHORS

Context

Under the Zero Carbon Act, the New Zealand Climate Change Commission will be recommending emission budgets for the periods 2022-2026, 2026-2030 and 2031-2035. The Commission is required to consider a range of specific matters in its work and specifically consider the state of scientific advice. Section 5M states:

> *In performing its functions and duties and exercising its powers under this Act, the Commission must consider, where relevant,—*
> a. *current available scientific knowledge*

The Commission is also required to specifically consider scientific advice in advising on emissions budgets. Section 5ZC states:

> *The Commission and the Minister must—*
> *(b) have regard to the following matters:*
> *(ii) a broad range of domestic and international scientific advice.*

The report will assist the Commission in meeting these requirements, as it advises on the first three emission budgets.

In addition to the requirements to advise on emission budgets, the Minister for Climate Change, Hon. James Shaw, earlier in 2020 requested that the Commission provide him with advice on two matters:

1. The potential reductions in biogenic methane emissions which might eventually be required by New Zealand as part of a global effort under the Paris Agreement to limit the global average temperature increase to 1.5 degrees Celsius above pre-industrial levels;
2. Whether New Zealand's Nationally Determined Contribution (NDC) is compatible with a global effort to keep warming to 1.5 degrees above pre-industrial levels, and any recommended changes to ensure it is compatible with a global effort to keep warming to 1.5 degrees above pre-industrial levels.

The report we are seeking to have completed will assist the Commission in articulating what issues and questions are raised by "compatible with a global effort to keep warming to 1.5 degrees."

Description of Services

The Supplier is to produce a scientific report of approximately 10-20 pages. The purpose of the report is to concisely summarise the state of scientific understanding of what actions are needed to keep warming below 1.5 degrees, and to outline the policy and political choices that exist that are compatible with that goal. It will articulate the choices and assumptions that underly particular global pathways for different greenhouse gases. This will contribute to the Commission's analysis and recommendations on emissions budgets, the level of New Zealand's NDC, and on the long-term cuts to methane that may be required of New Zealand to contribute to the global efforts of limiting warming to 1.5 degrees.

The report needs to:

1. Summarise the state of scientific understanding of:
   - the different warming effect of different greenhouse gases;
   - different global pathways that are consistent with keeping warming to 1.5 degrees;
   - what levels the world needs to reduce emissions (annual and cumulative emissions) of different gases to, particularly methane, carbon dioxide and nitrous oxide, by 2030 and by 2050 in order to keep warming below 1.5 degrees.
2. Articulate the main choices and trade-offs that are available for the world while still being consistent with keeping warming below 1.5 degrees. This analysis will draw on a range of modelled pathways with variations that could include but are not limited to:
   - the speed of reaching net zero emissions of long-lived gases vs the level of ongoing methane emissions;

- the speed and extent to which carbon capture and storage is developed;
- the extent to which developed countries do more and reduce emissions faster than the global average, or developing countries take more time to reduce emissions to reflect their national circumstances.

3. Articulate the implications that are not optional for keeping warming below 1.5 degrees.

The report should *not* attempt to address what settings New Zealand should make within these choices, but only articulate what the choices are, and the report should not discuss policies needed to achieve particular types of reductions.

The report needs to be based on relevant and the most recent scientific studies, although it will be heavily informed by the IPCC special report on 1.5 degrees.

Matthew Smith

From: Andy Reisinger <[redacted]@mfe.govt.nz>
Sent: Friday, 16 October 2020 2:27 pm
To: Matthew Smith
Subject: RE: [UNCLASSIFIED] Science piece for peer review
Attachments: Forster Fuglestvedt Millar NetZero-NZ-report-DRAFT_V1-REVISION_AR.docx

Hi Matt – a substantial meeting today was cancelled, so I got some time to make comments after all.

It's a good first draft but it's not as clear and structured as it could (and in my view should) be, and it has a few holes in it that need filling.

My comments are inserted in the document, as comments or as track changes (but in quite a few cases, a track change is actually meant as a comment – simply looking for a way of getting my thoughts down quickly. All a bit rushed to get it down – but hopefully makes sense.)

I'll leave it to you how to use these comments (and of course get back to me if anything is unclear).

I'm not worried about anonymity; given that I work with Jan and Piers a lot and at least Jan would probably spot me as reviewer for many of my comments anyway – if it's easiest to transmit my comments to them directly as they are, fine with me. But I'm equally comfortable if you want to provide a filter and only transmit some comments to them and keep others to yourself – whatever works for you.

I hope this is useful (enough) – thanks for the chance to offer my input.

Cheers, Andy

From: Matthew Smith <[redacted]@climatecommission.govt.nz>
Sent: Monday, 12 October 2020 11:29 am
To: Andy Reisinger <[redacted]@mfe.govt.nz>
Subject: [UNCLASSIFIED] Science piece for peer review

[UNCLASSIFIED]

Hi Andy

Here is the draft science piece that Piers, Jan and Richard have produced. Would really appreciate your review comments. I've attached the brief they were given for context.

Are you able to provide comments on it by the end of this week?

Regards

Matt

CLIMATE CHANGE COMMISSION

Matthew Smith (he/him) | **Principal Analyst**
M [redacted]
E [redacted]@climatecommission.govt.nz
W climatecommission.govt.nz

Matthew Smith

From: Andy Reisinger <[redacted]@mfe.govt.nz>
Sent: Monday, 11 January 2021 9:58 pm
To: Matthew Smith
Subject: Re: [UNCLASSIFIED] Permission to use a figure of yours?

Hi Matt, thanks for getting in touch. Still trying to stick with a break for another couple of weeks, until your report lands on our doorstep! I hope you managed to get a bit of a break at least?

Absolutely no problem reproducing that figure. I'm looking forward to the final version of their report, and of course to the advice from the Commission!

Cheers Andy

Sent from phone, forgive typos and odd words

From: Matthew Smith <[redacted]@climatecommission.govt.nz>
Sent: Monday, January 11, 2021 2:10:56 PM
To: Andy Reisinger <[redacted]@mfe.govt.nz>
Subject: [UNCLASSIFIED] Permission to use a figure of yours?

[UNCLASSIFIED]

Hi Andy

I hope you had a good and restful break.

Jan and Piers and Richard have completed a final version of their piece on the science of 1.5 degrees and New Zealand's emissions. In their draft they have used a figure from your 2019 study and said they'd need to get permission to use it. As I've been corresponding with you a lot I said I'd ask on their behalf before we publish the final piece. Below is the figure they are planning to use and the preamble text before it. Are you ok with them using it?

3.1 National contribution to global warming.

New Zealand's historic contribution to global warming is estimated to be above 0.01°C, from large-scale deforestation prior to 1840 (Reisinger and Leahy, 2019). The warming is estimated to be around 0.003 °C from biogenic methane emissions, nitrous oxide and fossil fuel CO_2 (Figure 7). There are also small contributions from F-gases and fossil fuel methane, which are not included in the Figure.

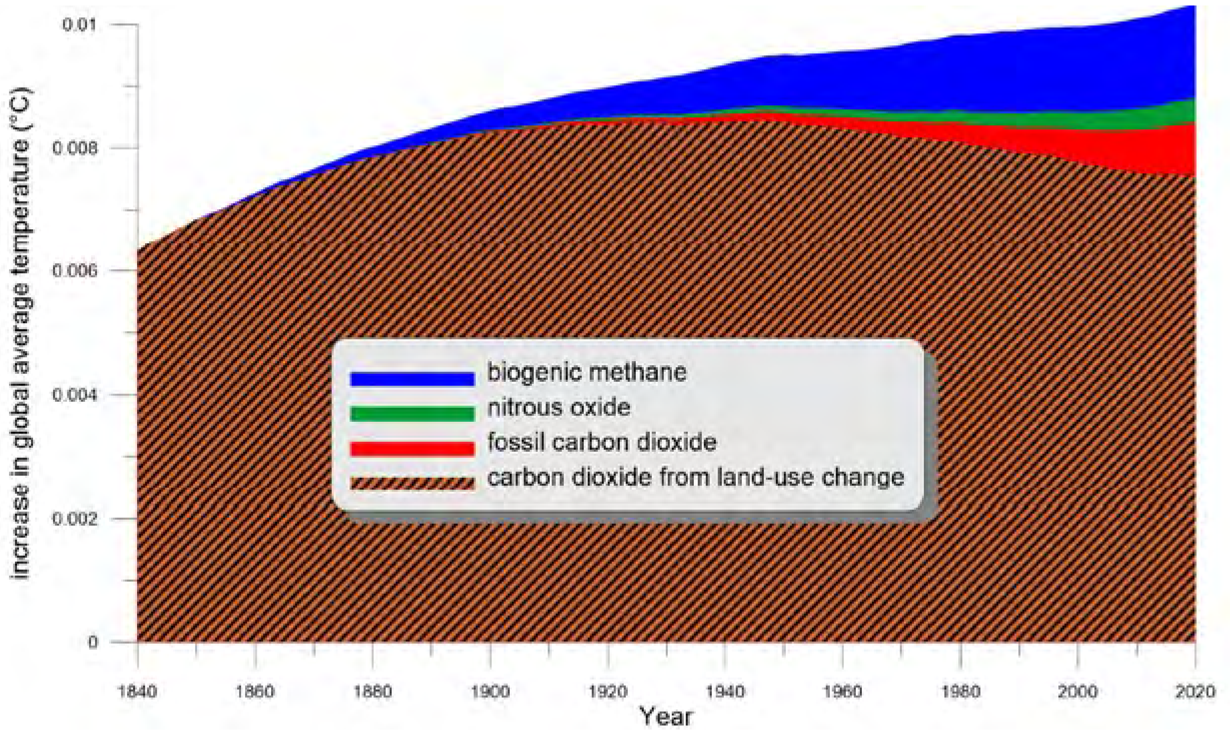

Figure 7: *Estimate of New Zealand's contribution to global warming from emissions until the end of 2019. Figure is taken from Reisinger and Leahy (2019).*

Cheers

Matt

He Pou a Rangi
Climate Change Commission

Matthew Smith (he/him) | **Principal Analyst**
M [redacted]
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W climatecommission.govt.nz

[UNCLASSIFIED]

Matthew Smith

From:	Myles Allen <[redacted]>
Sent:	Sunday, 15 November 2020 2:50 am
To:	Matthew Smith
Subject:	Re: [UNCLASSIFIED] RE: Electronic introduction between Myles Allen and the New Zealand Climate Change Commission
Attachments:	Forster Fuglestvedt Millar NetZero-NZ-report-DRAFT_V1-MRA_comments.docx

Dear Matthew,

I am so sorry this has taken me so long. In the interests of time, I have put suggested edits and comments directly into the Word document (and as you can see, I also recruited my colleague Michelle Cain to help, as it was clear I was falling badly behind). I am of course very happy for my identity to be disclosed.

Overall, the report is excellent and I have no major concerns about the science presented, apart from one major omission and one innovation that the authors suggest, which I don't think is correct and is anyway unnecessary.

The omission is any discussion of the role of Nature-based Climate Solutions in offsetting ongoing fossil fuel emissions. In a report on climate science considerations informing New Zealand's mitigation pathways, this seems a major gap, for reasons given in my comments. It doesn't need much discussion (indeed, my comments would probably do), but the issue needs to be flagged, together with the "fair-share" implications of New Zealand relying heavily on NbCS past 2050 particularly in the light of biogenic carbon released by earth system feedbacks.

The unnecessary innovation is figure 4. They use a simple linear regression to estimate the relationship between methane emission rates and cumulative CO2 emissions which seems to exaggerate the impact of falling methane emissions by about 40%. The reason is the way it is defined (average methane over the 20 years prior to peak warming, which is generally a period in which methane emissions are declining) and the way it is estimated (not controlling for the fact that peak warming across that subset of scenarios is still varying). The relationship is used to inform the discussion of what a 24 versus 47% reduction means for cumulative budgets, but in almost all cases, that reduction occurs by 2050, giving substantially higher methane emissions averaged over the 20 years prior to 2050. So the method really doesn't make sense, and in any case is completely unnecessary, when Cain et al (2019) or Collins et al (2020) both give perfectly good, tested and peer-reviewed formulae for translating changes in methane emission rates into cumulative CO2 warming-equivalent emissions. Using the Cain et al formula, I calculate the 200 GtCO2 quoted should be 145 GtCO2. The authors might argue "so what", but it seems a bit odd, when formulae exist in the literature to do precisely this comparison, to make up something new that gives a different answer.

But these are the only substantial quibbles I can come up with in an otherwise excellent report.

Myles

From: Matthew Smith <[redacted]@climatecommission.govt.nz>
Date: Friday, 13 November 2020 at 03:09
To: Myles Allen <[redacted]>
Subject: RE: [UNCLASSIFIED] RE: Electronic introduction between Myles Allen and the New Zealand Climate Change Commission

[UNCLASSIFIED]

Hi Myles

Is it worth us teeing up a phone call for Monday or Tuesday morning your time (evening our time) to talk about your feedback and we could talk through the key points even if you don't have time to write them up?

Cheers

Matt Smith

[UNCLASSIFIED]

From: Myles Allen <[redacted]>
Sent: Friday, 6 November 2020 10:29 pm
To: Matthew Smith <[redacted]@climatecommission.govt.nz>
Subject: Re: [UNCLASSIFIED] RE: Electronic introduction between Myles Allen and the New Zealand Climate Change Commission

I'm so sorry – also for making promises and failing to deliver. It's been a very full week, but I do have some time today. Failing today, I have the weekend. Myles

From: Matthew Smith <[redacted]@climatecommission.govt.nz>
Date: Friday, 6 November 2020 at 03:08
To: Myles Allen <[redacted]>
Subject: RE: [UNCLASSIFIED] RE: Electronic introduction between Myles Allen and the New Zealand Climate Change Commission

[UNCLASSIFIED]

Hi Myles

How are you going on the review of the 1.5 degree piece?

Kind regards

Matt

[UNCLASSIFIED]

From: Myles Allen <[redacted]>
Sent: Wednesday, 28 October 2020 10:19 pm
To: Matthew Smith [redacted]@climatecommission.govt.nz>
Subject: Re: [UNCLASSIFIED] RE: Electronic introduction between Myles Allen and the New Zealand Climate Change Commission

Dear Matthew,

I'm really sorry – for some reason this and the first follow-up email disappeared into my junk box – thank goodness your latest reminder made it through. I have no idea why this happened, but I will get a review to you by CoP tomorrow.

Myles

From: Matthew Smith <[redacted]@climatecommission.govt.nz>
Date: Sunday, 11 October 2020 at 23:34
To: Myles Allen <[redacted]>

Subject: RE: [UNCLASSIFIED] RE: Electronic introduction between Myles Allen and the New Zealand Climate Change Commission

[UNCLASSIFIED]

Hello Myles

Here is the draft paper on 1.5 degrees and different gases. I've also attached the brief the authors were given in pulling it together for context.

We'd really appreciate your peer review comments on the draft. What's your availability like in the next week or so? Is it possible to get your comments on it by early next week?

Kind regards

Matt Smith

CLIMATE CHANGE COMMISSION

Matthew Smith (he/him) | **Principal Analyst**
M [redacted]
E [redacted]@climatecommission.govt.nz
W climatecommission.govt.nz

[UNCLASSIFIED]

From: Matthew Smith
Sent: Wednesday, 30 September 2020 4:27 pm
To: 'Myles Allen' <[redacted]>
Subject: RE: [UNCLASSIFIED] RE: Electronic introduction between Myles Allen and the New Zealand Climate Change Commission

[UNCLASSIFIED]

Hi Myles

Just to let you know that the paper on 1.5 degree compatible pathways is a bit delayed. Piers, Jan and Richard were keen that we review it internally and they respond to that feedback before putting it to external review. We've just got them our feedback now so I think it's likely to be towards the end of next week when we'll be able to get it to you for your review.

Hope that's not too much of an inconvenience.

Kind regards

Matt Smith

[UNCLASSIFIED]

From: Myles Allen <[redacted]>
Sent: Tuesday, 22 September 2020 7:20 pm
To: Matthew Smith <[redacted]@climatecommission.govt.nz>; Phil Wiles

<[redacted]@climatecommission.govt.nz>
Subject: Re: [UNCLASSIFIED] RE: Electronic introduction between Myles Allen and the New Zealand Climate Change Commission

Dear Matt,

Apologies, yes, I thought I'd already agreed to do this. Looking forward to seeing their report.

Myles

From: Matthew Smith <[redacted]@climatecommission.govt.nz>
Date: Monday, 21 September 2020 at 22:34
To: Myles Allen <[redacted]>, Phil Wiles <[redacted]@climatecommission.govt.nz>
Subject: [UNCLASSIFIED] RE: Electronic introduction between Myles Allen and the New Zealand Climate Change Commission

[UNCLASSIFIED]

Hello Myles

Just to follow up on my message from last week – here's a little more detail on the brief of the work that Jan, Piers and Richard are doing.

Do let me know if you're interested in reviewing the work – I'm happy to schedule a call to discuss it, or to answer any other questions about it.

Kind regards

Matt Smith

CLIMATE CHANGE COMMISSION

Matthew Smith (he/him) | **Principal Analyst**
M [redacted]
E [redacted]@climatecommission.govt.nz
W climatecommission.govt.nz

[UNCLASSIFIED]

From: Matthew Smith
Sent: Monday, 14 September 2020 10:54 am
To: Myles Allen <[redacted]>; Phil Wiles <[redacted]@climatecommission.govt.nz>
Subject: RE: Electronic introduction between Myles Allen and the New Zealand Climate Change Commission

Hello Myles

As Rowena said, alongside our advice on emission budgets we have been asked to provide advice on New Zealand's NDC and long-term methane target with respect to what would be compatible with New Zealand contributing to a global effort to keep warming to 1.5 degrees. (You can see the exact wording of those requests in the terms of reference at https://ccc-production-media.s3.ap-southeast-2.amazonaws.com/public/Uploads/Section-5K-advice-04-2020/Terms-of-Reference-Section-5K-request.pdf).

To assist us with this work, we have contracted a piece of work to summarise the science and describe the tradeoffs and tensions inherent in describing a contribution as 1.5 degrees compatible. The purpose of the report is to surface the value-judgements and choices that can be made within a 1.5 degree trajectory, without making any of those judgements. This will then assist us to be transparent about those value judgements in our advice.

We have contracted Jan Fuglestvedt with the support of Piers Forster and Richard Millar to complete the piece, and we were hoping you would be happy to peer review it. It will be 10-20 pages long, and should be available for peer review on 24 September – we'd be hopping to get review feedback back to the authors by 2 October. Is that something you'd be interested in and available to do?

Happy to schedule a call to discuss it if that would be easier.

Kind regards

Matt Smith

CLIMATE CHANGE COMMISSION

Matthew Smith (he/him) | **Principal Analyst**
M [redacted]
E [redacted]@climatecommission.govt.nz
W climatecommission.govt.nz

[UNCLASSIFIED]

From: Myles Allen <[redacted]@ouce.ox.ac.uk>
Sent: Friday, 11 September 2020 8:23 pm
To: Rowena Hume <[redacted]@beeflambnz.com>; Phil Wiles <[redacted]@climatecommission.govt.nz>; Matthew Smith <[redacted]@climatecommission.govt.nz>
Cc: Dylan Muggeridge <[redacted]@beeflambnz.com>
Subject: Re: Electronic introduction between Myles Allen and the New Zealand Climate Change Commission

Very happy to help.

Myles

From: Rowena Hume <[redacted]@beeflambnz.com>
Date: Friday, 11 September 2020 at 05:56
To: Myles Allen <[redacted]>, Phil Wiles <[redacted]@climatecommission.govt.nz>, "[redacted]@climatecommission.govt.nz" [redacted]
Cc: Dylan Muggeridge <[redacted]@beeflambnz.com>
Subject: Electronic introduction between Myles Allen and the New Zealand Climate Change Commission

Dear Myles,

It is my pleasure to electronically introduce you to Phil Wiles and Matt Smith at the New Zealand Climate Change Commission.

As you are aware the New Zealand Climate Change Commission, established earlier this year following enactment of the Zero Carbon Act in 2019, has been tasked with developing advice to provide to the Government by the end of May next year (2021) on what the first three 5-yearly emissions budgets for New Zealand under the Zero Carbon Act should be.

In addition to this, the Government has also asked the Commission to provide advice on 2 additional pieces of work:

1. A review of New Zealand's first Nationally Determined Contribution (NDC) under the Paris Agreement (30% (all gases) below 2005 levels by 2030), and any recommendations to change this NDC – in particular the Government wants to know if this NDC is compatible with the 1.5° Celsius goal.

2. Advice on the potential reductions in biogenic methane emissions which might eventually be required by New Zealand as part of a global effort under the Paris Agreement to limit the global average temperature increase to 1.5°Celsius above pre-industrial levels.

Matt Smith and Phil Wiles from the Commission secretariat (cc'd) are leading the development of this advice. In order to inform this work the Commission is undertaking a review of the science of methane. We at Beef + Lamb New Zealand have been working closely with the Commission, and offered a while back to put them in touch with you. The Commission has now reached out and would like you to peer review the piece they have commissioned on the science of methane.

Matt has therefore asked us if we could connect them with you, hence this email to introduce you electronically!

Matt, we will let you take it from here. We hope your collaboration will be fruitful, and have no doubt this will contribute to the Commission's advice being underpinned by robust science, something we are really looking forward to! We also remain available in any way we can over the next few months.

warm regards,

Rowena Hume

Rowena Hume | General Manager, Communications and Engagement
beef + lamb new zealand
level 4, wellington chambers, 154 featherston street, wellington 6011, new zealand
po box 121, wellington 6140, new zealand
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REVIEW BY PROFESSOR ALLEN

Climate Science Considerations of Net-Zero for New Zealand

Piers Forster (1), Richard Millar (2) and Jan Fuglestvedt (3)

1. **Priestley International Centre for Climate, University of Leeds, UK**
2. **UK Committee on Climate Change, UK**
3. **CICERO, Norway**

11 October 2020

Introduction

This report gives a brief overview of the current scientific understanding of emissions reductions needed to achieve the temperature ambitions of the Paris Agreement. It builds on the findings in the IPCC special Report on global warming of 1.5 °C and Special Report on Climate change and Land, as well as recent updates in the scientific literature. It focuses on the main characteristics of the emission pathways and what choices exist between mitigation of different greenhouse gases. We also discuss how different choices affect the prospects of meeting the Paris temperature goals.

1. Climate response to emissions of different GHGs

This first section examines how much warming greenhouse gas increases have committed us to and how well we understand the climate response to future emissions.

1.1 Committed warming

Future global warming largely depends on future global emissions of greenhouse gases (GHGs), but also from changes in other air pollutants. The concept 'committed warming' - or 'warming in pipeline' due to past emissions received increased attention in the context of the Paris Agreement aiming at 'holding 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'.

Based on the literature and knowledge available at the time, the SR1.5 concluded that past emissions alone are unlikely to commit the world to global warming in excess of 1.5°C. Does this conclusion still hold? There is new science emerging on the committed warming if CO_2 emissions fall to zero, the zero emission commitment (ZEC). There have also been additional warm years since 2018 and a revision of historic temperature records. The amount of warming for future GHG emissions before targets are passed also depends on emission changes in non-greenhouse gas pollutants. The sections below detail how understanding of each of these has progressed since the 2018 IPCC Special Report on global warming of 1.5 °C.

1.1.1 Historic warming estimates

Before we discuss future warming, in light of the Paris temperature target it is worth considering historic warming estimates. SR1.5 estimated that the human-induced warming had reached around 1°C (with a 0.8°C to 1.2°C range) by the end of 2017 above pre-industrial levels. This was based on averaging the first four datasets in Table 1.1 of that report. Since then these historic temperature datasets are in the process of being revised. We expect these revisions to lead to a slight increase in the warming to date overall (e.g. Kennedy et al. 2019, Kadow et al. 2020) and the years since 2017 have continued to be among the hottest in the instrumental record. The discussion of how we define globally average surface temperature was addressed in Chapter 2 of SR1.5 for the calculation of the remaining carbon budget. Chapter 2 employed two estimates of the warming to date. The traditional measure of global-mean surface temperature (GMST) is based on observations that use a combination of near surface air temperature over land and sea-ice regions and sea-surface temperature over open ocean regions. The second measure is one that combined the observations with model data to estimate the near surface air temperature trend everywhere. The latter choice was there estimated to lead to 10% higher levels of present day warming and therefore a reduced remaining carbon budget. This 10% uplift was a model calculation and more recent work suggests that it may not be borne out in real-world observations comparing night-time marine air temperature to sea-surface temperature data (e.g. Kennedy et al. 2019).

IPCC SR1.5 used the average of 1850-1900, the earliest period then available in the direct observational record with reliable estimates of the global average temperature, to approximate pre-industrial levels. There has been discussion of the choice of 1750 or 1850-1900 for the pre-industrial baseline. Using 1750 as a pre-industrial baseline could add around 0.05°C more warming to date but this is not estimated to be statistically significant (Hawkins et al., 2017).

In summary, we might expect further revisions and updates of the order one tenth of a degree to the historic surface temperature change since preindustrial times and these would have knock on effects for remaining carbon budget analyses. Note that by altering the historic temperature we are implicitly altering the applied relationship between global temperature and climate impacts. As an example, if we were to revise the present day historical warming upwards from 1.0°C to 1.1°C, the present day climate impacts do not alter, we instead would associate temperature levels (e.g. 1.1°C or 1.5°C) with lower levels of climate impact than previously, so avoiding 1.5°C of warming becomes a more stringent target (associated with a lower level of aggregate climate impacts than it was previously), rather than the revision pushing us closer to higher levels of future climate impact.

1.1.2 Non greenhouse gas emission changes

Changes in emissions that affect aerosol and those that affect ozone concentrations change future temperature and how close we are to temperature targets. Although generally 20-30 years of near-term warming is expected from reducing aerosol pollution from a combination of climate mitigation policies and air quality policies (Smith et al. 2018a; Samset et al. 2018), near term warming can be limited with well-designed policies targeting both short and long-lived pollutants (Shindell and Smith, 2019). Forster et al. (2020) examined the climate response to COVID-19 restrictions and showed that some of the short term warming from reduced SO2 emissions and less aerosol cooling was offset globally by a large near-term reduction in NOx and ozone from reduced transport emissions. This suggests reducing road transport emissions at the same time as SO2 emissions would lessen any near-term warming.

1.1.3 The zero emission commitment (ZEC)

MacDougall et al. (2020) conclude that the most likely value of the ZEC on multi-decadal timescales is close to zero, consistent with previous model experiments and theory, but at the same time pointing to the large uncertainty related to constraining this effect. The right panels on Figure 1 show that the ZEC can be either sign but is always less than +0.5°C across models, with a best estimate, based on current evidence of close to zero.

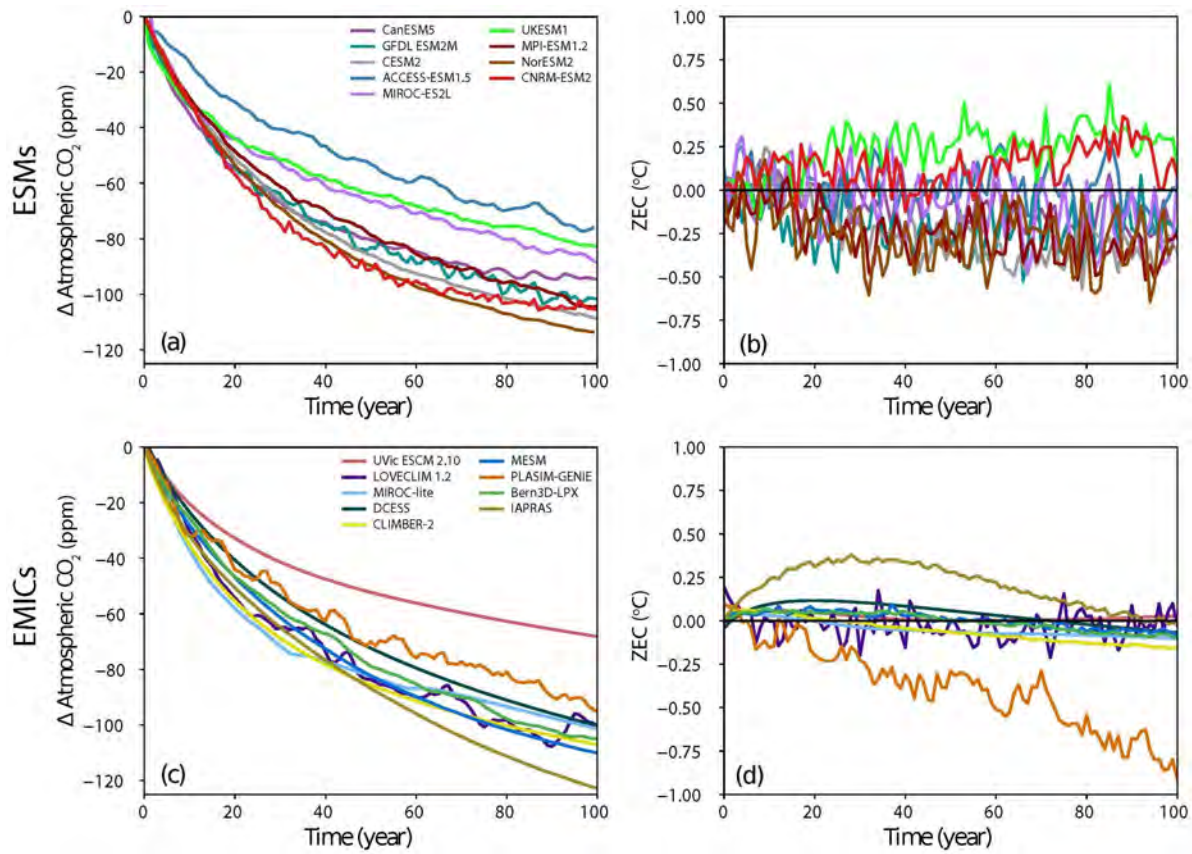


Figure 1. *Atmospheric* CO_2 *concentration anomaly and (b, d) Zero Emissions Commitment following the cessation of emissions during the experiment wherein 1000 PgC was emitted following the 1 % experiment (A1). ZEC is the temperature anomaly relative to the estimated temperature at the year of cessation. The top row shows the output for ESMs, and the bottom row shows the output for EMICs (MacDougall et al., 2020).*

The current common view is still that we are not expecting significant warming in the pipeline due to past GHG emissions. However, the uncertainties are large particularly on the role of future thawing of the permafrost and future wildfires. Nevertheless, some of the more dire warnings of tipping points (e.g. Steffen et al. 2018) are not born out in more careful assessments (e.g. Turetsky et al., 2020). Future GHG emissions from the global economy will be significantly more important for the amount of climate change experienced this century than feedbacks from Earth system processes. Nevertheless, such climate feedbacks cannot be ruled out and it might be prudent to factor these into remaining carbon budget estimates: Chapter 2 of SR1.5 allowed for the possibility of an extra 100 $GtCO_2$ on century timescales from such feedbacks (Table 2.2) and such an approach seems prudent, although it is difficult to estimate exactly how quickly or slowly these additional emissions might enter the atmosphere. It is unlikely that all of these Earth system emissions would have occurred by the time global CO_2 emissions must have reached net-zero and warming peaked to keep to the temperature level of the Paris Agreement long-term temperature goal (around 2050-2070) (see SR1.5 Chapter 2, Rogelj et al., 2019a and Rogelj et al., 2019b).

1.2 Greenhouse gas response

For future emissions of *long-lived GHGs* (LLGHG) (CO_2, N_2O, some F-gases) their global temperature impact is largely determined by their *cumulative* emissions. Nitrous oxide (N_2O) has a finite single perturbation lifetime unlike CO_2, and consequently behaves differently in the very long term, but can be treated as approximately equivalent to CO_2 (using GWP100; see section 2) when thinking about impacts for this century. As shown in SR1.5 and the scientific literature, these emissions need to come down to close to net zero (aggregate GWP100) to stop their warming contributions. As some level of N_2O emissions are expected to be unavoidable, this would require net negative emissions of CO_2.

On the other hand, for *Short Lived GHGs* (SLGHG) (CH_4, some F-gases) their global temperature impact depends (as a first order approximation) on the sustained *rate* of emissions. These emissions need to be stabilized (and then gradually reduced) to stop their further contributions to ever increasing global warming, but would not need to be reduced to zero. It is important to note that any level of sustained short-lived GHG emissions would still sustain raised global temperature above pre-industrial levels (as would net zero emissions of CO2: the only way to compensate for the impact of historical CO2 emissions is active removal of a comparable cumulative amount). The lower the emissions rate the lower the contribution of sustained SLGHG emissions to global temperature. Thus, these emissions represent an opportunity for reducing the current anthropogenically enhanced global temperature. Furthermore, SLGHGs also have longer-term climate impacts through their impact on carbon cycle (e.g. Gasser et al. 2017) and on other climate variables (e.g. sea level rise - Zickfeld et al., 2017).

Since AR5, scientific knowledge has developed further with improved understanding of several key processes in the climate system, and longer and improved observation series. The adoption of the Paris Agreement increased the focus on differences between 2°C and 1.5°C in terms of climate responses and impacts, as well as emission pathways compatible with the Paris Agreement ambitions. The IPCC Special Reports published since AR5 largely focus on low emissions pathways. Their assessments also confirm that the fundamental understanding of the climate system has remained largely the same since AR5. From consistency across these reports, there is a robust understanding of what needs to happen to global emissions to meet the temperature goal of the Paris Agreement.

In spite of the fundamental understanding remaining largely unchanged, uncertainties in radiative forcing and climate sensitivity affect the relationship between emissions and surface temperature change and there have been some relevant developments in these areas, discussed below.

1.2.1 Climate sensitivity

The latest generation of climate models from the sixth climate model intercomparison exercise (CMIP6) warm more than the previous generation and generally have greater equilibrium climate sensitivities (Forster et al. 2019; Tebaldi et al., 2020). However, a five year assessment of climate sensitivity comparing estimates using paleoclimate evidence, physical process evidence and the evidence from the 1850-2018 period (Sherwood et al. 2020) finds a much more constrained likely range for the equilibrium climate sensitivity that is robustly within 2.3 to 4.5°C. These estimates did not directly rely on the new generation of climate models so provides and independent assessment against which the new generation of complex climate models can be compared. This comparison suggests that the high warming estimates from some of the climate models are unlikely but cannot be ruled out entirely (Forster et al. 2019).

This updated evidence on the climate sensitivity indicates that the likely range of global warming projections due to uncertainty in the climate system response for projections of future climate changes under different global GHG emissions scenarios (see Section 1.2.3) would have a narrower range than similarly presented ranges in SR1.5 and AR5. As this revised uncertainty in the Earth's climate sensitivity largely affects that tails of the distribution, the central estimates of projected warming for the same emission scenario would likely still remain similar to those shown in SR1.5 and AR5 (see Figure 2).

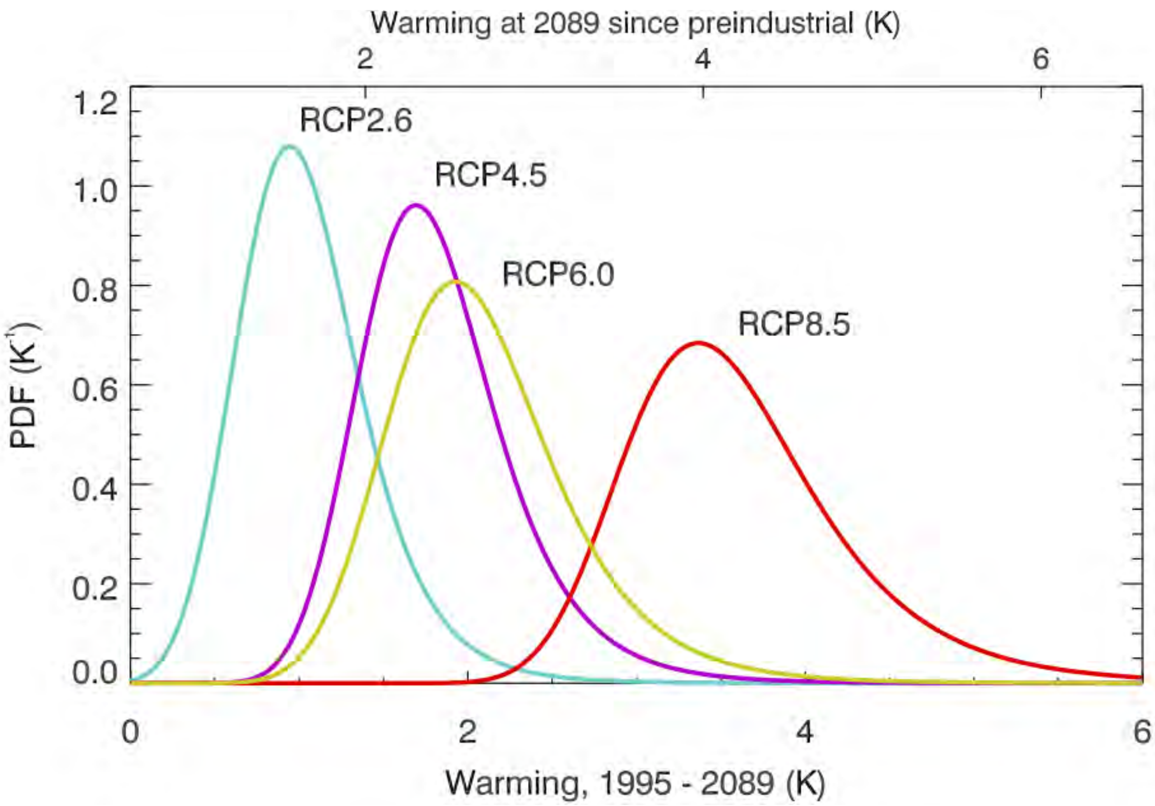


***Figure 2**: Constrained future warming estimates as probability distribution functions. based on revised climate sensitivity ranges from Sherwood et al. (2020). Results are shown for four representative concentration pathways. (Figure 23 from Sherwood et al. 2020).*

1.2.2 Radiative Forcing and Global Warming Potentials

The Effective Radiative Forcing (ERF) introduced in IPCC AR5 has now become the accepted way to compare the magnitude of different climate change mechanisms (Richardson et al., 2020). The ERF includes cloud related adjustments to the more traditional stratospherically adjusted radiative forcing, allowing a better comparison of the effect on global surface temperature across forcing agents.

The establishment of ERF as the standard measure of forcing has helped improve the estimates of GHG metrics (such as the GWP), including for methane. A number of other factors studied in recent publications will also influence the GWP value for methane:

- Moving to ERF increases CO_2 radiative forcing but leads to a decrease in methane radiative forcing from cloud adjustments (Smith et al. 2018b). In of itself this would *decrease* the GWP100 by ~20%.
- Etminan et al. (2016) include the shortwave forcing from methane and updates to the water vapour continuum and account for the overlaps between carbon dioxide and nitrous oxide. In of itself this would *increase* the GWP100 by 25%.
- Thornill et al. (2020) quantify the indirect effect of methane on ozone radiative forcing and based on several models they find a significantly lower value than what was used in AR5 for GWP and GTP calculations. This could decrease the GWP100 by 25%.

- The results of Wang and Huang (2020) show that due to high cloud changes the stratospheric water contribution to methane GWP100 which was 15% in AR5 might be closer to zero in the ERF framework, in of itself *decreasing* the GWP by up to 15%.
- Gasser et al. gives a better description of how to account for climate carbon cycle feedbacks in emission metrics. AR5 included this feedback for non-CO_2 gases, which up to then was only included for the reference gas CO_2, and imply an underestimation of GWP values for non-CO_2 gases. Due to lack of sufficient literature at the time of writing AR5, the inclusion of this feedback effect was presented as tentative.

Studies have not yet tested these results or combined these analyses for an overall estimate of methane GWP. At this stage it is difficult to be more quantitative regarding the net result, but the IPCC Sixth Assessment Report will attempt to assess these and other studies, bringing different lines of evidence together to form a new comprehensive assessment next year.

Hodnebrog et al. (2020) gives an update of radiative efficiency and GWP and GTP values for halocarbons. New radiative efficiencies (RE) calculations are presented for more than 400 compounds in addition to the previously assessed compounds, and GWP calculations are given for around 250 compounds. Present-day radiative forcing due to halocarbons and other weak absorbers is 0.38 [0.33–0.43] W m^{-2}, compared to 0.36 [0.32–0.40] W m^{-2} in IPCC AR5 (Myhre et al., 2013), which is about 18% of the current CO_2 forcing.

1.2.3 Surface temperature projection estimates

Climate model emulators such as FaIR and MAGICC (employed in SR1.5) are often used to estimate global warming futures across multiple scenarios. Such reduced complexity climate models can either be set up to mimic the behaviour of global-mean surface temperature change from more complex models or can be set up in probabilistic form to match the assessed range of climate sensitivity and effective radiative forcing from other assessments or lines of evidence. Due to the prominent role of such models in projecting net zero scenarios in SR1.5, an intercomparison is currently underway (**https://www.rcmip.org/**) between a variety of these reduced complexity models. Preliminary results from this show that such models generally work well for projections of global surface temperature (Nicholls et al. 2020). Such models based on updated estimates of ERF and climate sensitivity can provide the basis for calculating national emissions contributions to global temperature changes and could also be used to understand the direct global temperature impacts of New Zealand's emissions (see Section 3.1).

2. Trade-offs in global emissions pathways to keep warming to 1.5°C

The previous section described how both long-lived and short-lived GHG emissions affect the climate system. Different combinations of future long-lived and shorter-lived GHG emissions trajectories can be consistent with achieving the long-term temperature goal of the Paris Agreement. This section looks at the evidence for trade-offs between these two dimensions at a global level, considering both pathways arising from cost-optimising economic models and from more idealised pathways.

2.1 Emission metrics

The Global Warming Potential (GWP) is defined as the time-integrated radiative forcing due to a pulse emission of a non-CO_2 gas, relative to a pulse emission of an equal mass of CO_2. It is used for expressing the effects of different emissions on a common scale; so-called 'CO_2 equivalent emissions'. The GWP was presented in the First IPCC Assessment (Houghton et al., 1990), where it was stated that "It must be stressed that there is no universally accepted methodology for combining all the relevant factors into a single global warming potential for greenhouse gas emissions. A simple approach has been adopted here to illustrate the difficulties inherent in the concept, …".

Since then, the GWP has become a widely used metric for aggregation of different gases to 'CO_2 equivalent emissions' in the context of reporting emissions as well as in designing and assessing climate policies. The GWP for a time horizon of 100 years was adopted as a metric to implement the multi-gas approach embedded in the United Nations Framework Convention on Climate Change (UNFCCC) and made operational in the 1997 Kyoto Protocol.

The numerical values for GWP have been updated in the successive IPCC reports, as a consequence of updated science but also due to the changes occurring in the atmosphere; in particular the CO_2 concentration to which the radiative forcing has a non-linear relation.

Since its introduction the concept has been evaluated and tested for use in design of mitigation policies. IPCC AR4 stated that "Although it has several known shortcomings, a multi-gas strategy using GWPs is very likely to have advantages over a CO_2-only strategy (O'Neill, 2003). Thus, GWPs remain the recommended metric to compare future climate impacts of emissions of long-lived climate gases." In IPCC AR5, the assessment concluded that "The choice of metric and time horizon depends on the particular application and which aspects of climate change are considered relevant in a given context. Metrics do not define policies or goals but facilitate evaluation and implementation of multi-component policies to meet particular goals. All choices of metric contain implicit value-related judgements such as type of effect considered and weighting of effects over time."

The Paris Agreement text does not explicitly specify any emission metric for aggregation of GHGs, but under the Paris rulebook adopted at COP 24 in Katowice [Decision 18/CMA.1, annex, paragraph 37], parties have agreed to use GWP100 values from the IPCC AR5 or GWP100 values from a subsequent IPCC assessment to report aggregate emissions and removals of GHGs and for accounting under NDCs. In addition, it is also stated that parties may use other metrics to report supplemental information on aggregate emissions and removals of greenhouse gases. Using CO2-e under GWP100 for reporting does not preclude the use of other metrics for policy, since CO2-equivalent values under different metrics are related by very simple formulae. CO2-e emissions of SLGHGs under GWP20 are typically about three times their value under GWP100, while CO2-warming-equivalent emissions under GWP* are four times the current value of CO2-e under GWP100 minus 3.75 time the value 20 years previously.

After IPCC AR5, new concepts have been published; some of them building on the similarity in behaviour of a sustained change in SLGHG and pulse of CO_2 (Allen et al., 2016), similar to the approach explored earlier by Lauder et al., (2013).

This new approach for comparing emissions, denoted GWP*, use the same GWP values, but apply rate of change in emissions of the short-lived gas, e.g. methane. Cain et al refined the concept to better represent the relationship between cumulative CO2-warming-equivalent emissions and modelled warming in diverse CH4 mitigation scenarios by taking into account the delayed warming impact of past methane emission increases. Lynch et al demonstrated this for idealized cases. Collins et al. (2019) take an analytical approach and derive the combined global temperature change potential (CGTP) metric for calculating an equivalence between a sustained step-change in SLCF emissions and a CO_2 emissions pulse. Collectively, these metrics that represent SLCF emissions with a rate of emissions of CO2 that would have the same impact on global temperatures are known as “warming-equivalent”.

These mixed step-pulse metrics can be used to aggregate SLGHG together with CO_2 and approximate the development of temperature relative to a reference year. In this way, the mixed step-pulse metrics allow for inclusion of SLGHG into the relation between cumulative CO_2-equivalents and temperature change.

The GWP* concept and its potential applications has received criticism for only reflecting the additional warming effect of emissions relative to a chosen date and not the historical responsibility already caused due to past emissions (Rogelj and Schleussner, 2019). Cain et al (2020) observe, however, that this is not an intrinsic property of the metric, but how it is applied, since a pre-industrial baseline could be used to reveal historical responsibility, as in Allen et al (2018).

Metrics can also be used for assessing the concept “GHG balance” as used in Article 4 in the Paris Agreement. Fuglestvedt et al. (2018) tested metrics for calculation of temperature response to various composition of GHGs and found that balance determined using GWP* imply constant temperatures once the balance has been achieved, whereas a balance based on GWP implies slowly declining temperatures if (and only if) the mix of GHGs contains a significant positive contribution from SLGHGs. Balance based on GWP could imply indefinite warming if SLGHG removal is used to balance ongoing CO2 emissions. This raises issues related to consistency between Article 4 and Article 2 in the Paris Agreement and what the ultimate temperature goal of the agreement is (Fuglestvedt et al. 2018; Schleussner et al., 2019). Tanaka and O’Neill (2018) find that net zero GHG emissions (in terms of GWP100) are not necessarily required to remain below 1.5°C or 2°C, assuming either target can be achieved without overshoot.

2.1 Global cost-optimal pathways

Global GHG emissions trajectories consistent with the Paris Agreement are often studied using Integrated Assessment Models (IAMs). These models of the energy and land-use systems allocate emissions reductions across sectors, countries, and gases to keep the overall ‘net present cost’ of the emissions reduction pathway as low as possible whilst achieving a specified global emissions goal.[1] These modelled pathways, regularly summarised and applied in the IPCC assessment reports and intergovernmental documents such as the ‘Emissions Gap’ reports from UN Environment, can be useful indicators of what an idealised ‘cost-effective’ global emissions pathways might look like across sectors, gases and regions, but do not explicitly incorporate additional considerations of fairness, political will or institutional capability which will all be important additional determiners of reductions in the real world.[2]

The balance of effort across the range of global cost-optimal pathways produced by international modelling groups of the 2018 IPCC Special Report on Global Warming of 1.5°C is summarised in Table 1 and Table 2, with trajectories for long-lived GHGs (CO_2 and N_2O) and biogenic CH_4 from these simulations shown in Figure 3.[3] As now relatively widely known, these pathways require significant deviations in the historical trends of global emissions. Whilst technological progress (including the falling costs of renewable power generation) has helped shift projected future emissions trajectories away from the highest emissions futures, expected emissions at the global level out to 2030 remain far from these trajectories.

Table 1: Summary statistics of global cost-optimal pathways (median is given, with max and min in parentheses - long-lived GHG emissions include only CO_2 and N_2O aggregated a using GWP100 value of 298)

Scenario grouping	Cumulative LLGHG emissions from 2020 to 2050 [to peak warming] - $GtCO_2e$	Rates of biogenic CH_4 emission at 2050 [over 20 years prior to peak warming] - $MtCH_4$/yr
1.5C (~50% probability)	545 (325 - 705) [To peak: 535 (360 - 810)]	140 (60 - 200) [Prior to peak: 175 (100 - 240)]
<2C (~66% probability)	790 (580 - 1060) [To peak: 930 (625 - 1430)]	155 (115 - 205) [Prior to peak: 155 (100 - 245)]

[1] In many IAMs this is achieved using a ‘shadow value of carbon’ for residual emissions. This is typically applied to non-CO_2 GHG emissions using the global warming potential (GWP) metric for a 100 year time horizon.

[2] ‘Cost-effectiveness’ is a principle for global action that was established in the UNFCCC, together with ‘common-but-differentiated responsibilities and respective capabilities’ suggesting that developed nations do more than developing nations to combat climate change.

[3] Methane emissions from the energy sector are not included within these plots but are an important source of emissions at the global level.

Table 2: Emissions rates of gases in global cost-optimal pathways (median is given, with max and min in parentheses - long-lived GHG emissions include only CO_2 and N_2O aggregated a using GWP100 value of 298)

Scenario grouping	2030		2050	
	Biogenic CH_4 - MtCH_4/yr	LLGHG - GtCO2e/yr	Biogenic CH_4 - MtCH_4/yr	LLGHG - GtCO_2e/yr
1.5C (~50% probability)	180 (110 - 230)	23 (14 - 28)	140 (60 - 200)	2.3 (-8.3 - 12)
<2C (~66% probability)	190 (160 - 300)	30 (20 - 46)	155 (115 - 205)	12 (1.9 - 20)

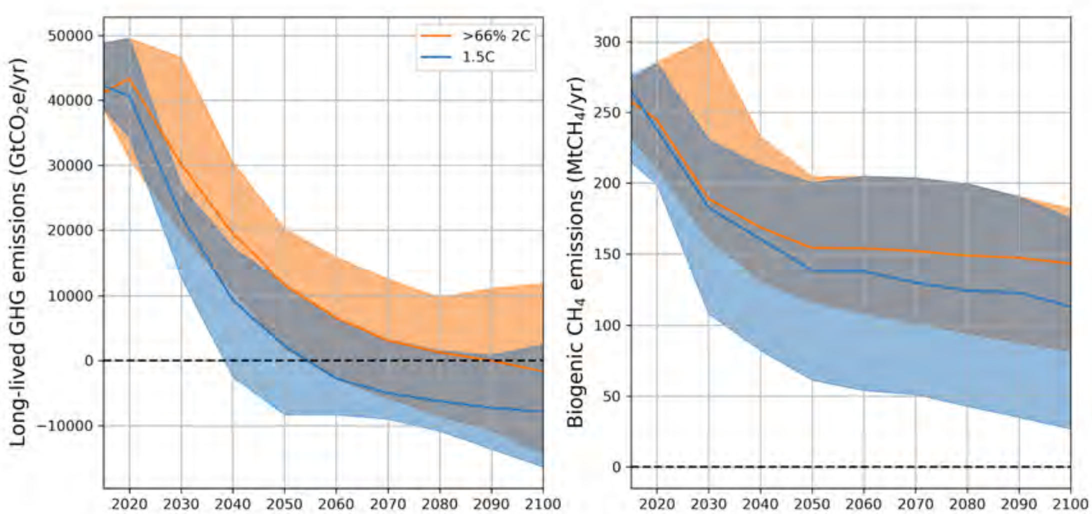


Figure 3: *The spread of GHG emission pathways in the IPCC SR1.5 scenarios database for Long-lived GHGs (CO_2 and N_2O) and biogenic CH_4. Solid lines denote the median of the scenario set.*

Figure 3 illustrates the different roles the two gases CO_2, CH_4 and N_2O can play in future model-based emissions pathways that are compatible with the temperature ambitions of the Paris

Agreement. The global emissions of CO_2 have to go to net zero around the middle or second half of the century, depending on level of temperature ambition. Large reductions in CH_4 and N_2O are also generally found to be needed but there is more variation. The model studies found that strong reductions in methane are needed in all pathways, but that net-zero CH_4 is not achieved in any pathway. For N_2O, the pathways show smaller reductions or even modest increases depending on the degree of future fertilizer use. N_2O emission pathways also do not reach net-zero. The large spread in possible pathways for emissions of CH_4 and N_2O are worth noting. However, in the vast majority of these cost-effective pathways emissions, CH_4 emissions are seen to decline by strongly mid-century. This reduces the level of global average CH_4-induced warming and allows for more warming from cumulative emissions of long-lived GHGs on the pathway to net zero emissions.

This scenario set is not a statistically well-defined set of simulations and should not be treated as such. It includes simulations where particular technologies are explicitly excluded as contributing to the emissions reductions (e.g. nuclear) and come from a wide set of models with varying levels of detail regarding the representation of energy system technologies, varying assumptions regarding their relative costs, and varying assumptions about global development (e.g. population, economic growth and development) in the absence of climate policies or impacts. Differences in the evolution of the global energy systems can be larger between different models as it can between different levels of climate ambition within the same model. Although the differing assumptions and outcomes in the land and agriculture sector have been studied (Popp et al., 2017), it is difficult to clearly identify the drivers of differences between the high-level global emissions outcomes without additional targeted experiments, and the fundamental drivers of different balances between reductions in biogenic methane and long-lived GHGs remain poorly understood.

After the completion of SR1.5, new scenarios have been developed by various scenario groups. These may give more insight to cost optimal emissions pathways for these gases and provide a stronger knowledge basis for options to reach the temperature goals.

2.2 Understanding trade-offs between shares of effort across gases in global mitigation pathways

The scenarios described in the previous section for global emissions share the effort between sectors and gases solely based on minimizing overall cost within the modelling framework. Other splits between reductions in different GHGs could be possible whilst achieving the same global temperature outcome, and may be more desirable when incorporating additional constraints regarding fairness, just transition, and societal preferences.

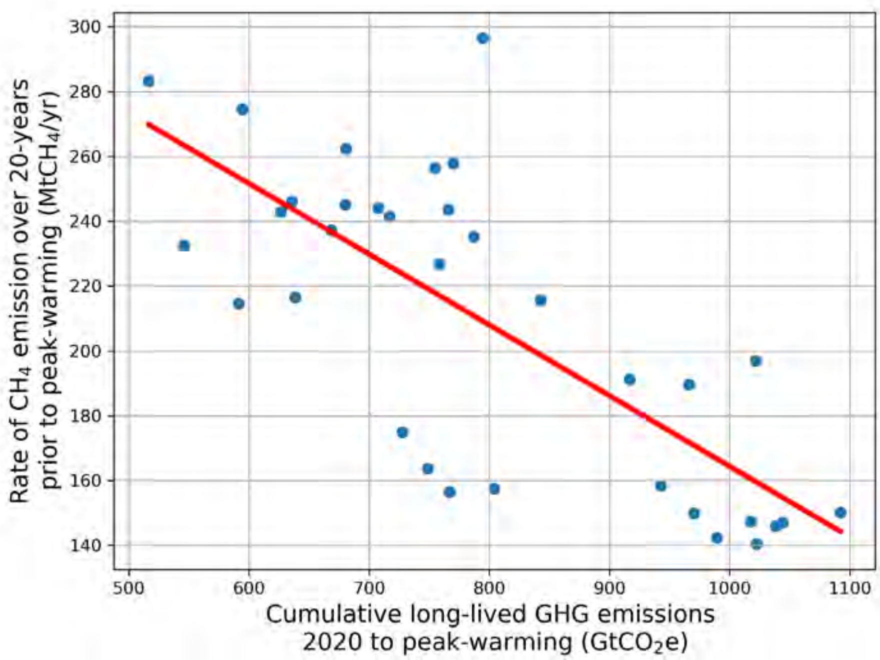


Figure 4: *Relation between CH_4 emissions 20 years prior to peak warming and the cumulative CO2-equivalent emissions (CO_2 + N_2O) based on GWP100 for scenarios that keep peak warming to 1.6-1.7C. This temperature range was chosen to give a large number of modelled scenarios that peak warming within this relatively narrow range.*

Emergent relationships between properties of this scenario ensemble can be used to explore alternative pathways not included in this scenario set. Figure 4 illustrates an alternative to the use of traditional metrics for comparing and trading across gases. It shows the relation between methane emissions prior to peak warming (y axis) and magnitude of allowed cumulative CO_2 and N_2O emissions aggregated at CO_2 equivalents based on GWP100 (x-axis) for scenarios with a very similar (within 0.1°C) peak warming outcome. This approximately linear derived relation reflects that the higher CH_4 emissions the more constrained the cumulative GHG/CO_2 budget we have. And the more the world reduces CH_4, the higher cumulative LLGHGs will be compatible with the peak temperatures (in this case 1.6-1.7°C). This relationship indicates that a 10 $MtCH_4$/yr reduction in the average rate of CH_4 emission over the two decades prior to the time of peak warming could allow for around an additional 45 $GtCO_2$-equivalents of long-lived GHG such as CO_2 and N_2O. Whilst this value will be somewhat sensitive to the specifics of the simple climate model emulator used to project the climate outcomes consistent with these emissions scenarios, and the effects of systematic variations in changes of aerosol forcing that may correlate with one of the axes, it offers a simple way to explore the trade-offs between these two dimensions.

This relationship illustrated in Figure 4 can provide a simple, but relatively accurate, way of estimating the implications of a the difference between a 47% and 24% cut in global biogenic methane emissions relative to 2017 levels by 2050 (the range of reductions in biogenic CH_4

emissions reductions within the New Zealand Zero Carbon Act) in terms of the equivalent effort in cumulative long-lived GHG emissions savings. Approximately 56% of global methane emissions are from biogenic origin (Hoesley et al., 2018). This means that the difference in the 2050 CH_4 emissions rate between a global reduction of 24% and a reduction of 47% (relative to 2017 levels) is approximately 47 $MtCH_4$/yr in absolute terms. Based on the relationship approximated from Figure 4 this would mean that around 200 $GtCO_2$-equivalents of additional cumulative long-lived GHG (CO_2 + N_2O) mitigation would be required if the world as a whole reduced its biogenic CH_4 emissions by only 24% by 2050 compared to one in which they are reduced by 47% whilst achieving the same peak temperature outcome. This is approximately 35% of the cumulative long-lived GHG emissions over 2020-2050 in the median IPCC SR1.5 keeping warming to below 1.5°C with no or low overshoot (Table 1).

As an alternative to the TCRE approach for calculation of remaining carbon budgets, Collins et al. (2018), applied a process based approach to assess the importance of methane reductions for the 1.5°C target. Their modelling approach included indirect effects of methane on tropospheric ozone, stratospheric water vapour and the carbon cycle. They find a robust relationship between decreased CH_4 concentration at the end of the century and increased amount of cumulative CO_2 emissions up to 2100. This relationship is independent of climate sensitivity and temperature pathway. In terms of relation between end of the century emission changes in CH_4 and CO_2, their results achieve similar results as those obtained by Allen et al., 2016 in a GWP* context. Collins et al., 2018, also point out that the non-climate benefits of mitigating CH_4 can be significantly larger than indicated by IAM studies.

2.3 Implications of post-2050 net-negative emissions

Section 1 summarised how emissions of long-lived GHG need to fall to net-zero to stop contributing to rising global temperature. Peak warming generally occurs around 2050 in scenarios that keep warming to 1.5C with ~50% probability - approximately corresponding with the date of global net-zero CO_2 emissions (Figure 2.6 in UK CCC, 2019). Although net long-lived GHG emissions remain positive at the time of net-zero CO_2 emissions (due to some residual N_2O emissions in all scenarios), the effect of falling methane emissions over the decades prior to 2050 (which reduces CH_4-induced warming) offsets this.

Many of these scenarios continue to reduce CO_2 emissions further so that global CO_2 (and long-lived GHG) emissions go net-negative. This has the effect of reducing temperatures after peak warming has been reached, but doesn't significantly contribute to the level of peak warming achieved. In many scenarios that peak warming at around 1.5°C (or less than 0.1°C of overshoot) by 2050 the net-negative CO_2 emissions largely contribute to temperatures declining from their peak to around 1.3°C by 2100. Alternative pathways exist that would avoid these net-negative emissions - for example Rogelj et al (2019b) shows that pathways which reach net-zero CO_2 emissions around 2040 and then maintain this level still achieve a peak temperature around 1.5°C with warming remaining around this level out to 2100. For scenarios that do significantly overshoot a 1.5°C target level in the middle of the century, significant amounts of global net negative CO_2 emissions would be necessary to return warming to 1.5°C by 2100. For example, temperatures peaking around 1.7 °C, would require around 200 $GtCO_2$ of negative emissions over the 21st century to return temperatures to 1.5C, but if temperatures peaked at 1.85 °C around 400 $GtCO_2$ of negative emissions would be required (Rogelj et al. 2019b). In the long-term (centennial timescales) it may be necessary to have a certain amount of net negative global CO_2 emissions even to sustain global temperature at a constant level. This is to counter any slow Earth System feedbacks such as permafrost thawing which would add to atmospheric concentrations (and therefore warming) over long-timescales (see Section 1.1).

The relationship across the scenarios between cumulative long-lived GHG emissions and the rate of CH_4 emissions identified in Section 2.2 also helps elucidate the tradeoffs between further reductions in trajectories of biogenic methane emissions post-2050 and net-negative CO_2 emissions after reaching net-zero.

These results again make the case for early action to reduce emissions of LLGHGs. As such actions can both reduce peak temperatures and the level of negative emissions technology needed to achieve a 2100 temperature goal. This is relevant for several reasons. *Firstly*, there are implications of allowing overshoot on the global energy system. In a world that is trying to reduce global temperatures after 2050 there might be a greater need for energy generation associated with the removal of CO_2 from the atmosphere (such as through bioenergy with carbon capture and storage - BECCS) than in a world that is not trying to decline temperatures after 2050. This might therefore change the make-up of a desirable electricity generation mix in the decades prior to 2050. In such pathways you also need to worry about competing interests for land-use (see IPCC Special Report on Climate Change and Land). *Secondly*, any sustained post 2050 methane abatement could also help reduce temperatures and reduce the dependence on long-term net negative CO_2 emissions, indicating an interdependence of the post-2050 trajectories between the gases in a world of declining temperature (see also Figure 6). *Thirdly*, even if temperature targets are reached, some long-term net negative GHG emissions might need to be sustained.

3. Considerations for national pathways consistent with keeping warming to 1.5°C

Section 2 considered the tradeoffs between mitigation of different greenhouse gases. This section discusses other considerations that could be taken into account in national pathways.

3.1 National contribution to global warming

The research outlined in Sections 1 and 2 and much previous research shows that methane emission changes have a different time evolving climate impact than a CO_2 emission change. This means that a national emission pathway that specifies the change in aggregated greenhouse gas emissions will not necessarily follow the same global warming, as different combinations of long-lived GHGs and shorter-lived GHGs can give the same overall CO_2 equivalent emission trajectory (when aggregated using GWP100 values) (e.g., Fuglestvedt et a., 2000, Fuglestvedt et al., 2003; Myhre et al., 2013; Allen et al., 2016; Allen et al., 2018). Globally the ambiguity generated for realistic strong mitigation pathways has been found to be important at the 10% level (or 0.17°C) (Denison et al., 2020). However, larger ambiguities could exist at sector and country level; e.g., in countries such as New Zealand where methane emissions represent a larger fraction of total greenhouse gas emissions. To illustrate this, the blue and green lines (or the purple and red) in Figure 5 illustrate global warming contributions from two pathways with the same GWP100 based total CO_2 equivalent emission trajectory but different CO_2 and biogenic CH_4 trends. The green pathway has 47% biogenic CH_4 reductions by 2050 but at the expense of extra CO_2 emissions (to match the CO_2-equivalent emissions of the blue line) and does not reach net zero CO_2 emissions by 2050, which happens in the blue pathway. Initially the extra biogenic CH_4 reduction under the GWP100 CO_2 equivalent assumption (green line) gives more cooling. However, after 2100, the long-term warming effect of the extra CO_2 emissions would be expected to dominate and give more warming eventually. If New Zealand were to specify a single CO_2-equivalent emission reduction target based on GWP100, the up to 20% difference in resulting global warming trajectory illustrated by the pairs or curves in Figure 5, gives the scale of the ambiguity introduced.

The blue and red curves in Figure 5 approximate the range of New Zealand's possible future contributions to global warming since 1990 under current policies, assuming that emissions do not change after 2050. Under both 24% and 47% biogenic CH_4 reduction policies, New Zealand is beginning to reduce its contribution to global warming by 2050. Under 24% reduction policies, the 2050 contribution to global warming from New Zealand's matches today's level of New Zealand's contribution to global warming. Under 47% biogenic CH_4 reduction policies, the 2050 contribution to warming level approximately matches that from 2015.

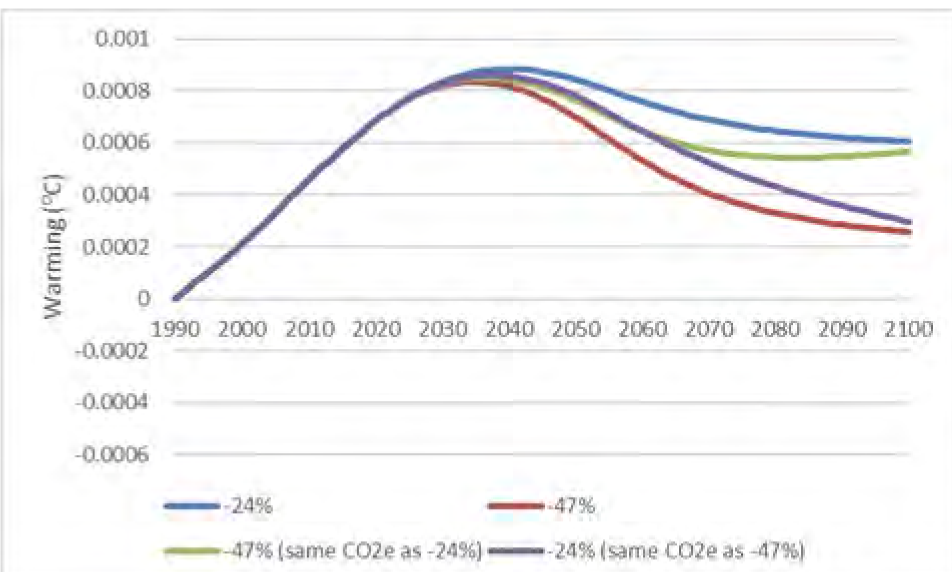
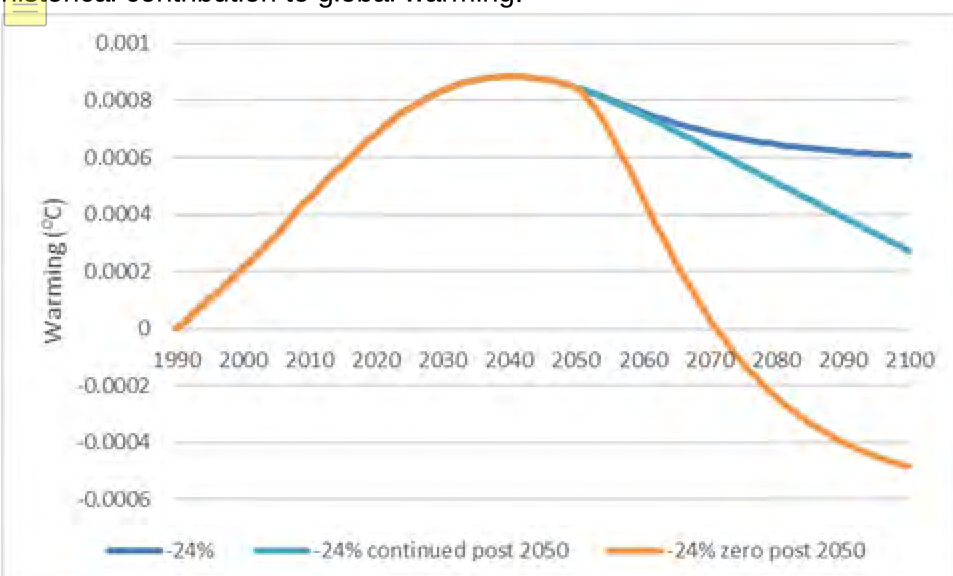


Figure 5: *An illustration of New Zealand's contribution to global warming since 1990. The blue and red pathways reach net zero emissions in 2050 for LLGHGs and fossil fuel CH_4, and have either 24% (blue) or 47% (red) reductions in biogenic CH_4 from 2017 levels to 2050. The green line has 47% biogenic CH_4 reduction but additional emissions of CO_2 to match the CO_2e emissions of the blue line based on IPCC AR4 GWP100 values. Emissions from 2050 do not alter. New*

Zealand emissions from 1990-2018 are taken from https://www.mfe.govt.nz/climate-change/state-of-our-atmosphere-and-climate/new-zealands-greenhouse-gas-inventory. The estimate using the impulse response functions provided in the IPCC 5th Assessment Report for calculating GHG metrics as a simple climate model to assess the temperature implications of a national emissions pathway. Non-GHG contributions to warming (e.g. aerosol emissions) are not part these scenarios.

Contributions to global temperature rise are sensitive to the shape of the emissions reduction profile as well as the end point reached in 2050 or any other year when mitigation and emission changes might stop. This is particularly so for LLGHG pollutants, but less so for short-lived pollutants. Early reductions in LLGHGs have lower cumulative LLGHG emissions and overall less climate impact in the longer term (also see Section 2.3). In the near-term front loaded trajectories might lead to a rise in temperature from reductions in co-emitted pollutants resulting in less aerosol cooling (see Section 1.1.2), the near-term rise and peak temperatures can also be reduced by early action on SLGHGs.

What happens to emissions after 2050 is important for the longer term response (see Sections 2.3 and 4.2). This is theoretically explored in Figure 6, which keeps net-zero CO_2 emissions at zero after 2050 but varies methane emission reductions across a range of options from the highest temperature response (no change in emissions) to the largest cooling (biogenic emissions drop to zero after 2050). These results illustrate that although the choices of biogenic emission pathway up until 2050 do influence New Zealand's contribution to global warming, either choice should begin to reverse the country level contribution to further warming after 2040. However, the figure also shows that it is the choices after 2050 that really matter in the longer term, where continued decline of biogenic CH_4 would be needed after this date to begin to reverse New Zealand's historical contribution to global warming.



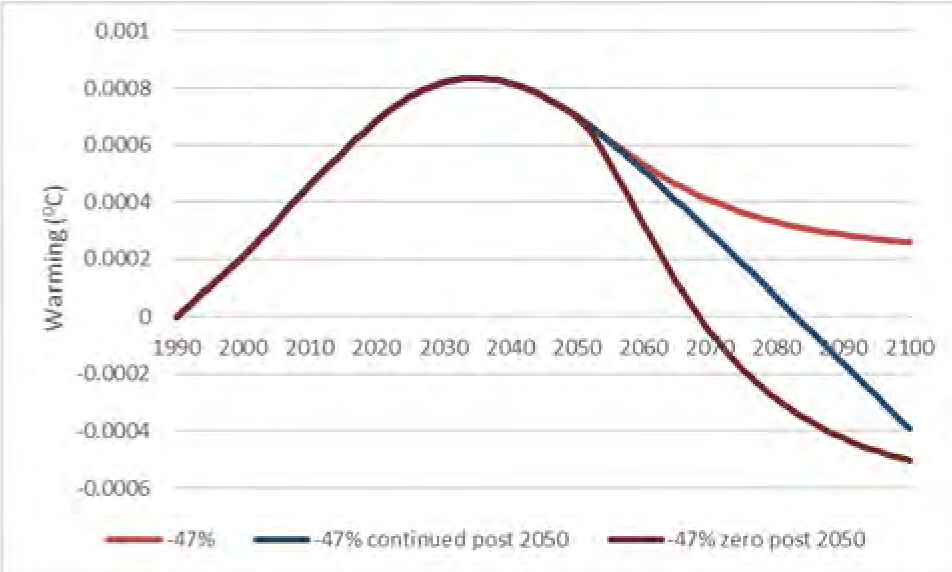


Figure 6: *As Figure 5, except emissions reductions continue beyond 2050. 24% biogenic CH_4 reduction by 2050, shown in the top panel and 47% reduction in the bottom panel. The panels have three scenarios: emissions unchanged after 2050, matching Figure 5; the biogenic methane reduction rate continuing after 2050; or biogenic methane emissions suddenly decline to zero after 2050.*

3.2 Fairness and equity

When determining either net zero targets dates or proportioning the remaining carbon budget into national quotas, choices have to be made regarding fairness, equity and burden sharing. These are obviously not straightforward and can have a large effect on levels of ambition for mitigation reduction (see Figure 7 and Figure 3.9 from the UK CCC, 2019).

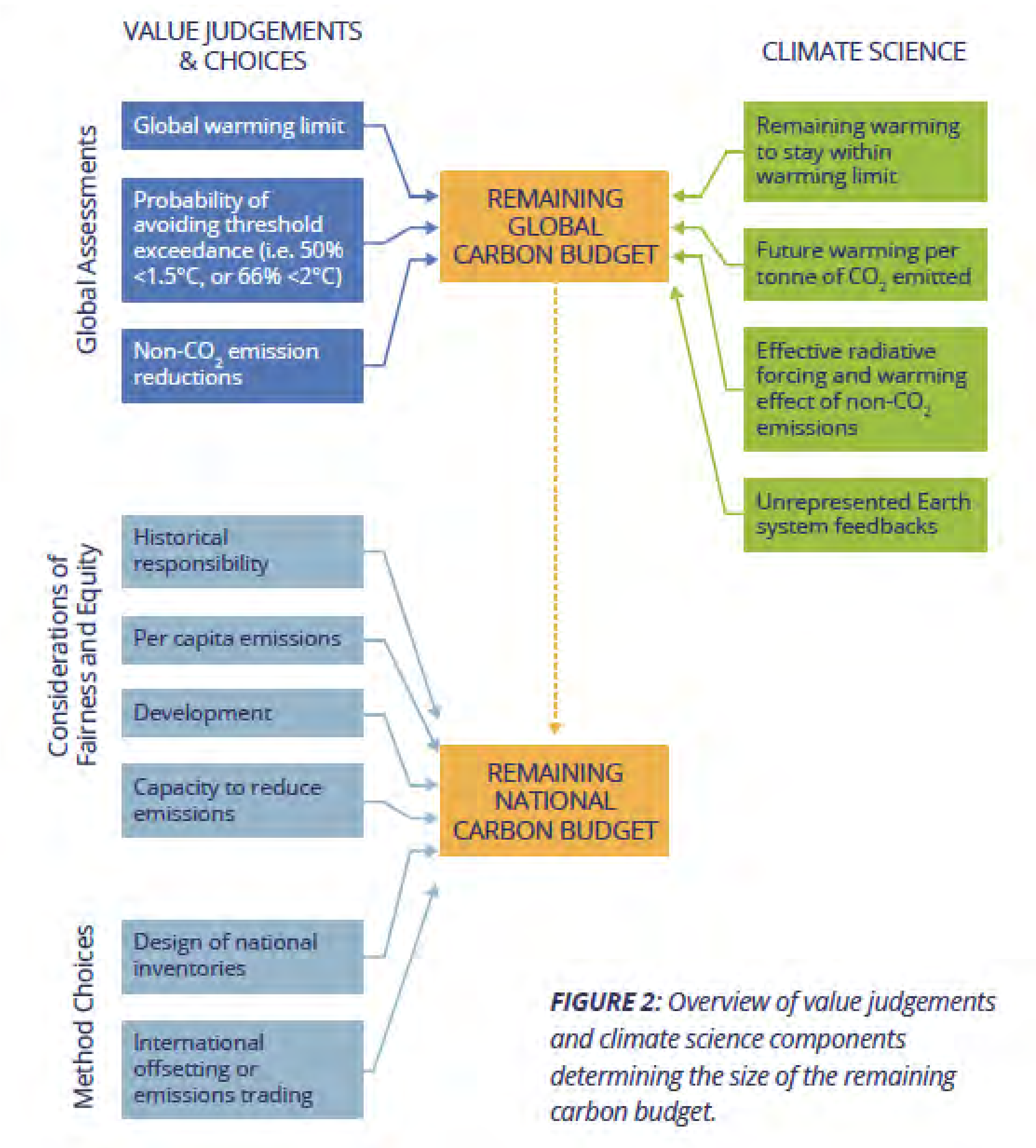


Figure 7: *Methodological, fairness and equity choices when creating national carbon budgets from the global remaining carbon budget. Figure 2 from the 2019 CONSTRAIN report https://constrain-eu.org/. See also Rogelj et al. (2019a).*

When comparing national emission pathways, it is important to consider different national starting points. The same '1.5C consistent' mitigation actions measured by cost or other measure of effort could result in different rates of emissions reductions in different regions depending on national circumstances and their respective capabilities to cut emissions. This includes the share of hard-to-abate emissions within a country profile today. For example, if the energy sector is already mostly decarbonised, the national emissions might not fall as quickly as the global average, whose rapid decline over the 2020s in 1.5°C scenarios is associated primarily with the rapid removal of coal from the electricity generation mix. Assessing whether a nation is taking the ‘1.5C consistent’ actions with its planned emissions reduction pathway needs to be more nuanced than a simple comparison with the global average reductions. It also needs to consider additional effort, outside of the domestic emissions account that a country might be undertaking to support the global transition (e.g. climate finance provision, purchase of credits through international markets, technology transfer etc.) to form a holistic picture of whether planned action to 2030 is 1.5°C-aligned.

Summary and conclusions

Section 1,presented a brief update of the science on past and future warming from greenhouse gases. Section 2 illustrated global tradeoff considerations in strong mitigation emission pathways and Section 3 considered implications for deriving national strategies.

In the further development of policy towards New Zealand’s contribution to the global effort of achieving the Paris Temperature Goals, our report has highlighted several issues and choices that would benefit from consideration. These are outlined below:

4.1 Evolving science

As knowledge is being developed and assessment reports are being published, it is important to be clear and transparent about what is used as the basis for the policy design; i.e. which values and which definitions are adopted and used and how they might be revised as science understanding evolves.

4.2 Defining net zero

There are different choices to how net-zero is defined both in terms of allowable sinks, in terms of which gases are included in the target and any emission metric choice. Also important is the boundary of the system and if consumption or territorial emissions are addressed and emission trading is allowed.

The SR1.5 used two main indicators of net zero emissions: 1) a CO_2 only and 2) an aggregate of GHGs expressed as CO_2-equivalent emissions based on GWP100. See e.g Table 2.4 in SR1.5. As shown in the table, net zero emissions are typically achieved several years later for the aggregated net zero GHG as compared to the CO_2-only net zero.

Choices of approach not only need to consider the physical science uncertainty but also need to consider the overall objectives of the climate policy and the practicalities of usage and communication. As illustrated in Section 3.1, the selection of greenhouse gases and as well as the emission metric used will have a significant effect on timing and efforts to achieve net zero and on the resulting global warming. The UK legislated for a net zero target in terms of GWP100 emissions. One of the reasons given was that such a target would actively decrease its future warming commitment over time (see Section 2.1 and 3.1). For New Zealand to continue to decrease its future warming commitment after 2050, additional CH_4 reductions and/or negative emissions of CO_2 would be needed (Section 3.1).

Emission metrics are used for comparing and trading of emissions of gases with different physical characteristics on a common scale. GWP100 has been widely adopted for aggregating emission of gases to so-called 'CO_2-equivalent emissions'. But different mixes of long and short lived gases included in the same amount of CO_2-equivalent emissions will give different temperature outcomes over time, and the use of the concept therefore introduces ambiguity in temperature outcome. New metric concepts have been presented in the literature after AR5; e.g., the GWP* concept which approximates the temperature response over time from emission paths. Which metric is chosen and the rationale for the choice needs consideration and clear communication of which purpose and goal it is meant to serve. As shown in Section 2.2, an alternative approach based on the emergent relation between CH_4 emissions prior to temperature peak and cumulative CO_2 and N_2O could be considered as an alternative or supplement, depending on the policy objectives.

The Paris Agreement aims for a net-zero type target on a global basis. In the development of mitigation strategies for a single country it is important to consider how the plans for net zero might be achieved internationally and how a nation's plan fits into the international effort (i.e., which countries might achieve net negative, net zero or net positive emissions, and how international trading is used).

4.3 Life after net-zero

As shown in the pathways in SR1.5, achieving net zero GHG is just one part of the challenge in limiting future warming. Plans for the further path of emissions of the individual gases after net zero target is achieved also need to be addressed and communicated, particularly how greenhouse gas removal can be sustained given finite and competing interest for land resources (see Section 3.1).

4.3 Defining national high-ambition pathways

Which fairness and equity principles that are applied as rationale for New Zealand's efforts are important to communicate as a part of a mitigation strategy. As New Zealand's starting position in terms of sectoral emissions is different from other nations, a high ambition emission reduction trajectory might look quite different to a high ambition pathway from another country. In particular, many countries are expected to rapidly decarbonise their power sector out to 2030, leading to large national emission reductions in the 2020s. Countries such as New Zealand (and the UK) where the power sector is already mostly decarbonised, urgent actions are needed on other sectors such as buildings and transport for mitigation compatible with Paris Agreement ambitions, that might take longer to manifest themselves in emissions trends. Therefore relatively modest emissions reductions might suffice in the 2020s to keep warming to 1.5°C, compared to what is required by the world as a whole. These could still be seen as ambitious provided the groundwork is laid for large reductions in the 2030s (see Section 3.2).

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Climate Science Considerations of Net-Zero for New Zealand

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11 October 2020

Introduction

This report gives a brief overview of the current scientific understanding of emissions reductions needed to achieve the temperature ambitions of the Paris Agreement. It builds on the findings in the IPCC special Report on global warming of 1.5 °C and Special Report on Climate change and Land, as well as recent updates in the scientific literature. It focuses on the main characteristics of the emission pathways and what choices exist between mitigation of different greenhouse gases. We also discuss how different choices affect meeting the Paris temperature goals.

1. Climate response to emissions of different GHGs

This first section examines how much warming greenhouse gas increases have committed us to and how well we understand the climate response to future emissions.

1.1 Committed warming

Future global warming largely depends on future global emissions of greenhouse gases (GHGs), but also from changes in other air pollutants. The concept 'committed warming' - or 'warming in pipeline' due to past emissions received increased attention in the context of the Paris Agreement aiming at 'holding 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'.

Based on the literature and knowledge available at the time the SR1.5 concluded that past emissions alone are unlikely to commit the world to global warming in excess of 1.5°C. Does this conclusion still hold? There is new science emerging on the committed warming if CO_2 emissions fall to zero, the zero emission commitment (ZEC). There have also been additional warm years since 2018 and a revision of historic temperature records. The amount of warming for future GHG emissions before targets are passed also depends on emission changes in non-greenhouse gas pollutants. The sections below detail how understanding of each of these has progressed since the 2018 IPCC Special Report on global warming of 1.5 °C.

1.1.1 Historic warming estimates

Before we discuss future warming, in light of the Paris temperature target it is worth considering historic warming estimates. SR1.5 estimated that the human-induced warming had reached around 1°C (with a 0.8°C to 1.2°C range) by the end of 2017 above pre-industrial levels. This was based on averaging the first four datasets in Table 1.1 of that report. Since then these historic temperature datasets are in the process of being revised. We expect these revisions to lead to a slight increase in the warming to date overall (e.g. Kennedy et al. 2019, Kadow et al. 2020) and the years since 2017 have continued to be among the hottest in the instrumental record. The discussion of how we define globally average surface temperature was addressed in Chapter 2 of SR1.5 for the calculation of the remaining carbon budget. Chapter 2 employed two estimates of the warming to date. The traditional measure of global-mean surface temperature (GMST) is based on observations that use a combination of near surface air temperature over land and sea-ice regions and sea-surface temperature over open ocean regions. The second measure is one that combined the observations with model data to estimate the near surface air temperature trend everywhere. The latter choice was there estimated to lead to 10% higher levels of present day warming and therefore a reduced remaining carbon budget. This 10% uplift was a model calculation and more recent work suggests that it may not be borne out in real-world observations comparing night-time marine air temperature to sea-surface temperature data (e.g. Kennedy et al. 2019).

IPCC SR1.5 used the average of 1850-1900, the earliest period then available in the direct observational record with reliable estimates of the global average temperature, to approximate pre-industrial levels. There has been discussion of the choice of 1750 or 1850-1900 for the pre-industrial baseline. Using 1750 as a pre-industrial baseline could add around 0.05°C more warming to date but this is not estimated to be statistically significant (Hawkins et al., 2017).

In summary, we might expect further revisions and updates of the order one tenth of a degree to the historic surface temperature change since preindustrial times and these would have knock on effects for remaining carbon budget analyses. Note that by altering the historic temperature we are implicitly altering the applied relationship between global temperature and climate impacts. As an example, if we were to revise the present day historical warming upwards from 1.0°C to 1.1°C, the present day climate impacts do not alter, we instead would associate temperature levels (e.g. 1.1°C or 1.5°C) with lower levels of climate impact than previously, so avoiding 1.5°C of warming becomes a more stringent target (associated with a lower level of aggregate climate impacts than it was previously), rather than the revision pushing us closer to higher levels of future climate impact.

1.1.2 Non greenhouse gas emission changes

Changes in emissions that affect aerosol and those that affect ozone concentrations change future temperature and how close we are to temperature targets. Although generally 20-30 years of near term warming is expected from reducing aerosol pollution from a combination of climate mitigation policies and air quality policies (Smith et al. 2018a; Samset et al. 2018), near term warming can be limited with well designed policies targeting both short and long-lived pollutants (Shindell and Smith, 2019). Forster et al. (2020) examined the climate response to COVID-19 restrictions and showed that some of the short term warming from reduced SO2 emissions and less aerosol cooling was offset globally by a large near-term reduction in NOx and ozone from reduced transport emissions. This suggests reducing road transport emissions at the same time as SO2 emissions would lessen any near-term warming.

1.1.3 The zero emission commitment (ZEC)

MacDougall et al. (2020) conclude that the most likely value of the ZEC on multi-decadal timescales is close to zero, consistent with previous model experiments and theory, but at the same time pointing to the large uncertainty related to constraining this effect. The right panels on Figure 1 show that the ZEC can be either sign but is always less than 0.5°C across models, with a best estimate, based on current evidence of close to zero.

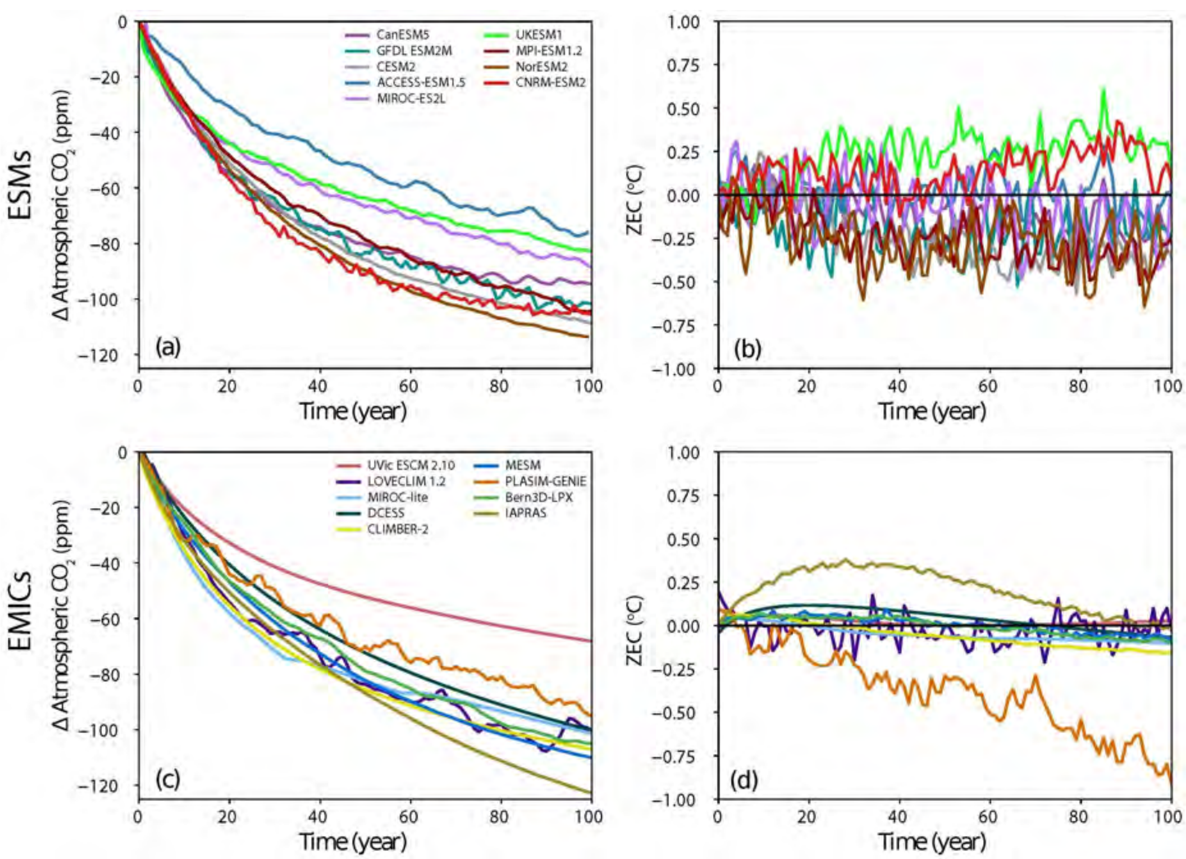
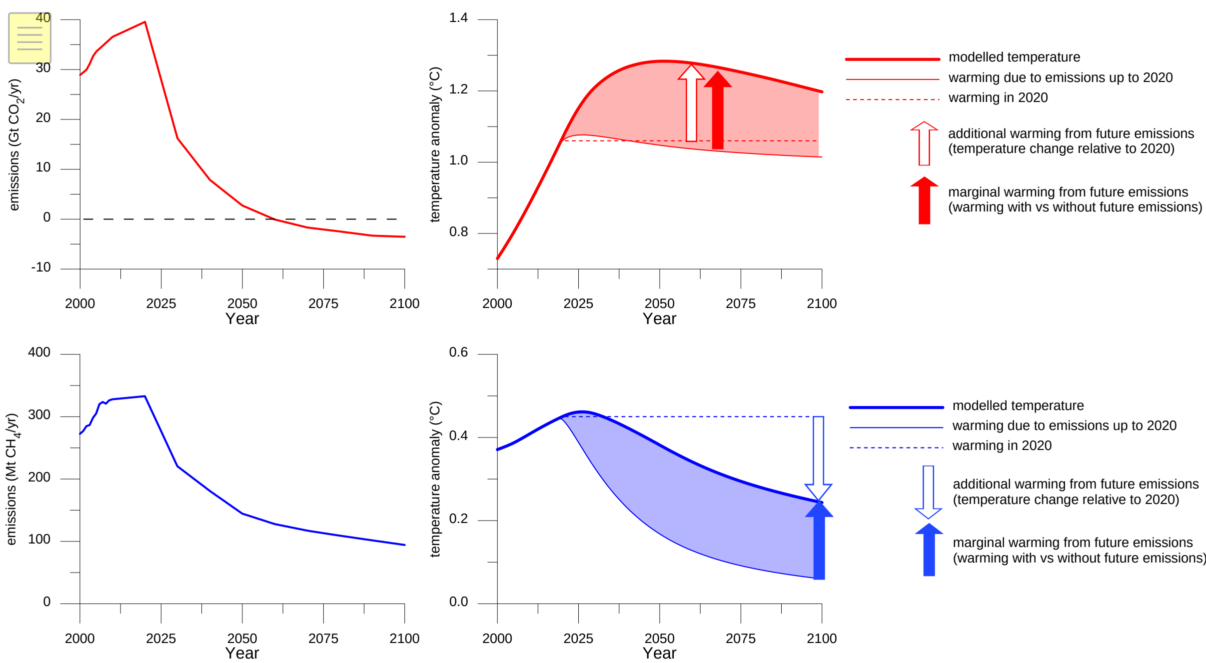


Figure 1. *Atmospheric* CO_2 *concentration anomaly and (b, d) Zero Emissions Commitment following the cessation of emissions during the experiment wherein 1000 PgC was emitted following the 1 % experiment (A1). ZEC is the temperature anomaly relative to the estimated temperature at the year of cessation. The top row shows the output for ESMs, and the bottom row shows the output for EMICs (MacDougall et al., 2020).*

The current common view is still that we are not expecting significant warming in the pipeline due to past GHG emissions. However, the uncertainties are large particularly on the role of future thawing of the permafrost and future wildfires. Nevertheless, some of the more dire warnings of tipping points (e.g. Steffen et al. 2018) are not born out in more careful assessments (e.g. Turetsky et al., 2020). Future GHG emissions from the global economy will be significantly more important for the amount of climate change experienced this century than feedbacks from Earth system processes. Nevertheless, such climate feedbacks cannot be ruled out and it might be prudent to factor these into remaining carbon budget estimates: Chapter 2 of SR1.5 allowed for the possibility of an extra 100 $GtCO_2$ on century timescales from such feedbacks (Table 2.2) and such an approach seems prudent, although it is difficult to estimate exactly how quickly or slowly these additional emissions might enter the atmosphere. It is unlikely that all of these Earth system emissions would have occurred by the time global CO_2 emissions must have reached net-zero and warming peaked to keep to the temperature level of the Paris Agreement long-term temperature goal (around 2050-2070) (see SR1.5 Chapter 2, Rogelj et al., 2019a and Rogelj et al., 2019b).



1.2 Greenhouse gas response

For future emissions of *long-lived GHGs* (LLGHG) (CO_2, N_2O, some F-gases) their global temperature impact is largely determined by their *cumulative* emissions. Nitrous oxide (N_2O) has a finite single perturbation lifetime unlike CO_2, and consequently behaves differently in the very long term, but can be treated as approximately equivalent to CO_2 (using GWP100; see section 2) when thinking about impacts for this century. As shown in SR1.5 and the scientific literature, these emissions need to come down to close to net zero to stop their warming contributions. As some level of N_2O emissions are expected to be unavoidable, this would require net negative emissions of CO_2.

On the other hand, for *Short Lived GHGs* (SLGHG) (CH_4, some F-gases) their global temperature impact depends (as a first order approximation) on the sustained *rate* of emissions. These emissions need to be stabilized (and then steadily declined) to stop their further contributions to ever increasing global warming, but would not need to be reduced to zero. It is important to note that any level of sustained short-lived GHG emissions would still sustain raised global temperature above pre-industrial levels. Any amount of continued CH_4 emissions thus creates additional warming over and above the warming caused by CO_2 emissions. The lower the emissions rate the lower the contribution of sustained SLGHG emissions to global temperature. Reducing these emissions is therefore an important part of limiting the overall rise in global temperature. Furthermore, SLGHGs also have longer-term climate impacts through their impact on carbon cycle (e.g. Gasser et al. 2017) and on other climate variables (e.g. sea level rise - Zickfeld et al., 2017).

Since AR5, scientific knowledge has developed further with improved understanding of several key processes in the climate system, and longer and improved observation series. The adoption of the Paris Agreement increased the focus on differences between 2°C and 1.5°C in terms of climate responses and impacts, as well as emission pathways compatible with the Paris Agreement ambitions. The IPCC Special Reports published since AR5 largely focus on low emissions pathways. Their assessments also confirm that the fundamental understanding of the climate system has remained largely the same since AR5. From consistency across these reports, there is a robust understanding of what needs to happen to global emissions to meet the temperature goal of the Paris Agreement.

In spite of the fundamental understanding remaining largely unchanged, uncertainties in radiative forcing and climate sensitivity affect the relationship between emissions and surface temperature change and there have been some relevant developments in these areas, discussed below.

1.2.1 Climate sensitivity

The latest generation of climate models from the sixth climate model intercomparison exercise (CMIP6) warm more than the previous generation and generally have greater equilibrium climate sensitivities (Forster et al. 2019; Tebaldi et al., 2020). However, a five year assessment of climate sensitivity comparing estimates using paleoclimate evidence, physical process evidence and the evidence from the 1850-2018 period (Sherwood et al. 2020) finds a much more constrained likely range for the equilibrium climate sensitivity that is robustly within 2.3 to 4.5°C. These estimates did not directly rely on the new generation of climate models so provides and independent assessment against which the new generation of complex climate models can be compared. This comparison suggests that the high warming estimates from some of the climate models are unlikely but cannot be ruled out entirely (Forster et al. 2019).

This updated evidence on the climate sensitivity indicates that the likely range of global warming projections due to uncertainty in the climate system response for projections of future climate changes under different global GHG emissions scenarios (see Section 1.2.3) would have a narrower range than similarly presented ranges in SR1.5 and AR5. As this revised uncertainty in the Earth's climate sensitivity largely affects that tails of the distribution, the central estimates of projected warming for the same emission scenario would likely still remain similar to those shown in SR1.5 and AR5 (see Figure 2).

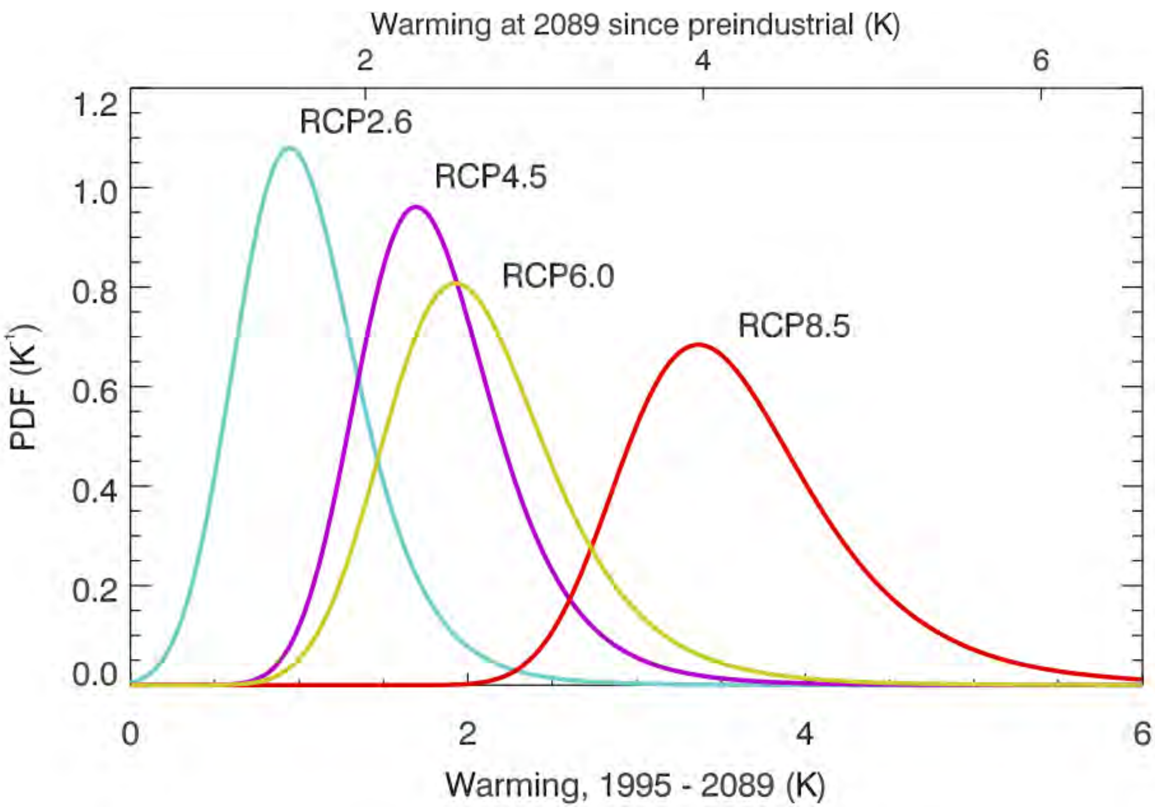


***Figure 2**: Constrained future warming estimates as probability distribution functions. based on revised climate sensitivity ranges from Sherwood et al. (2020). Results are shown for four representative concentration pathways. (Figure 23 from Sherwood et al. 2020).*

1.2.2 Radiative Forcing and Global Warming Potentials

The Effective Radiative Forcing (ERF) introduced in IPCC AR5 has now become the accepted way to compare the magnitude of different climate change mechanisms (Richardson et al., 2020). The ERF includes cloud related adjustments to the more traditional stratospherically adjusted radiative forcing, allowing a better comparison of the effect on global surface temperature across forcing agents.

The establishment of ERF as the standard measure of forcing has helped improve the estimates of GHG metrics (such as the GWP), including for methane. A number of other factors studied in recent publications will also influence the GWP value for methane:

- Moving to ERF increases CO_2 radiative forcing but leads to a decrease in methane radiative forcing from cloud adjustments (Smith et al. 2018b). In of itself this would *decrease* the GWP100 by ~20%.

- Etminan et al. (2016) include the shortwave forcing from methane and updates to the water vapour continuum and account for the overlaps between carbon dioxide and nitrous oxide. In of itself this would *increase* the GWP100 by 25%.
- Thornill et al. (2020) quantify the indirect effect of methane on ozone radiative forcing and based on several models they find a significantly lower value than what was used in AR5 for GWP and GTP calculations. This could decrease the GWP100 by 25%.
- The results of Wang and Huang (2020) show that due to high cloud changes the stratospheric water contribution to methane GWP100 which was 15% in AR5 might be closer to zero in the ERF framework, in of itself *decreasing* the GWP by up to 15%.
- Gasser et al. gives a better description of how to account for climate carbon cycle feedbacks in emission metrics. AR5 included this feedback for non-CO_2 gases, which up to then was only included for the reference gas CO_2, and imply an underestimation of GWP values for non-CO_2 gases. Due to lack of sufficient literature at the time of writing AR5, the inclusion of this feedback effect was presented as tentative.

Studies have not yet tested these results or combined these analyses for an overall estimate of methane GWP. At this stage it is difficult to be more quantitative regarding the net result, but the IPCC Sixth Assessment Report will attempt to assess these and other studies, bringing different lines of evidence together to form a new comprehensive assessment next year.

Hodnebrog et al. (2020) gives an update of radiative efficiency and GWP and GTP values for halocarbons. New radiative efficiencies (RE) calculations are presented for more than 400 compounds in addition to the previously assessed compounds, and GWP calculations are given for around 250 compounds. Present-day radiative forcing due to halocarbons and other weak absorbers is 0.38 [0.33–0.43] W m^{-2}, compared to 0.36 [0.32–0.40] W m^{-2} in IPCC AR5 (Myhre et al., 2013), which is about 18% of the current CO_2 forcing.

1.2.3 Surface temperature projection estimates

Climate model emulators such as FaIR and MAGICC (employed in SR1.5) are often used to estimate global warming futures across multiple scenarios. Such reduced complexity climate models can either be set up to mimic the behaviour of global-mean surface temperature change from more complex models or can be set up in probabilistic form to match the assessed range of climate sensitivity and effective radiative forcing from other assessments or lines of evidence. Due to the prominent role of such models in projecting net zero scenarios in SR1.5, an intercomparison is currently underway (**https://www.rcmip.org/)** between a variety of these reduced complexity models. Preliminary results from this show that such models generally work well for projections of global surface temperature (Nicholls et al. 2020). Such models based on updated estimates of ERF and climate sensitivity can provide the basis for calculating national emissions contributions to global temperature changes and could also be used to understand the direct global temperature impacts of New Zealand’s emissions (see Section 3.1).

2. Trade-offs in global emissions pathways to keep warming to 1.5°C

The previous section described how both long-lived and short-lived GHG emissions affect the climate system. Different combinations of future long-lived and shorter-lived GHG emissions trajectories can be consistent with achieving the long-term temperature goal of the Paris Agreement. This section looks at the evidence for trade-offs between these two dimensions at a global level, considering both pathways arising from cost-optimising economic models and from more idealised pathways.

2.1 Emission metrics

The Global Warming Potential (GWP) is defined as the time-integrat-ed RF due to a pulse emission of a non-CO_2 gas, relative to a pulse emission of an equal mass of CO_2. It is used for transforming the effects of different emissions to a common scale; so-called 'CO_2 equivalent emissions'. The GWP was presented in the First IPCC Assessment (Houghton et al., 1990), where it was stated that "It must be stressed that there is no universally accepted methodology for combining all the relevant factors into a single global warming potential for greenhouse gas emissions. A simple approach has been adopted here to illustrate the difficulties inherent in the concept, …".

Since then, the GWP has become a widely used metric for aggregation of different gases to 'CO_2 equivalent emis-sions' in the context of reporting emissions as well as in designing and assessing climate policies. The GWP for a time horizon of 100 years was adopted as a metric to implement the multi-gas approach embedded in the United Nations Framework Convention on Climate Change (UNFCCC) and made operational in the 1997 Kyoto Protocol.

The numerical values for GWP have been updated in the successive IPCC reports, as a consequence of updated science but also due to the changes occurring in the atmosphere; in particular the CO_2 concentration to which the radiative forcing has a non-linear relation.

Since its introduction the concept has been evaluated and tested for use in design of mitigation policies. IPCC AR4 stated that "Although it has several known shortcomings, a multi-gas strategy using GWPs is very likely to have advantages over a CO_2-only strategy (O'Neill, 2003). Thus, GWPs remain the recommended metric to compare future climate impacts of emissions of long-lived climate gases." In IPCC AR5, the assessment concluded that "The choice of metric and time horizon depends on the particular application and which aspects of climate change are considered relevant in a given context. Metrics do not define policies or goals but facilitate evaluation and implementation of multi-component policies to meet particular goals. All choices of metric contain implicit value-related judgements such as type of effect considered and weighting of effects over time."

The Paris Agreement text does not explicitly specify any emission metric for aggregation of GHGs, but under the Paris rulebook adopted at COP 24 in Katowice [Decision 18/CMA.1, annex, paragraph 37], parties have agreed to use GWP100 values from the IPCC AR5 or GWP100 values from a subsequent IPCC assessment to report aggregate emissions and removals of

GHGs and for accounting under NDCs. In addition, it is also stated that parties may use other metrics to report supplemental information on aggregate emissions and removals of greenhouse gases.

After IPCC AR5, new concepts have been published; some of them building on the similarity in behaviour of a sustained change in SLCF and pulse of CO_2 (Allen et al., 2016), similar to the approach explored earlier by Lauder et al., (2013).

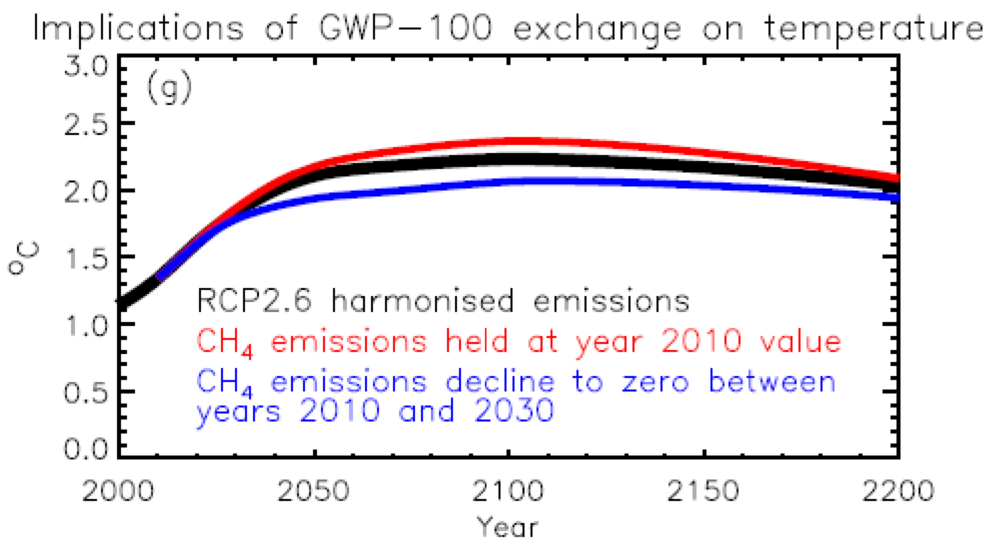
This new approach for comparing emissions, denoted GWP*, use the same GWP values, but apply rate of change in emissions of the short-lived gas, e.g. methane. Cain et al. (2019) refined the concept by an improved representation of temperature change for diverse CH_4 emissions trajectories that approximates warming calculated using cumulative CO_2-equivalent emissions based on GWP* rather than GWP100 (Lynch et al., 2020). Collins et al. (2019) take an analytical approach and derive the combined global temperature change potential (CGTP) metric for calculating an equivalence between a sustained step-change in SLCF emissions and a CO_2 emissions pulse.

These mixed step-pulse metrics can be used to aggregate SLGHG together with CO_2 and approximate the development of temperature relative to a reference year. In this way, the mixed step-pulse metrics allow for inclusion of SLGHG into the relation between cumulative CO_2-equivalents and temperature change.

The GWP* concept and its potential applications has received criticism for only reflecting the additional warming effect of emissions relative to a chosen date and not the historical responsibility already caused due to past emissions (Rogelj and Schleussner, 2019).

Metrics can also be used for assessing the concept “GHG balance” as used in Article 4 in the Paris Agreement. Fuglestvedt et al. (2018) tested metrics for calculation of temperature response to various composition of GHGs and found that balance determined using GWP* imply constant temperatures once the balance has been achieved, whereas a balance based on GWP implies slowly declining temperatures. This raises issues related to consistency between Article 4 and Article 2 in the Paris Agreement and what the ultimate temperature goal of the agreement is (Fuglestvedt et al. 2018; Schleussner et al., 2019). Tanaka and O’Neill (2018) find that net zero GHG emissions (in terms of GWP100) are not necessarily required to remain below 1.5°C or 2°C, assuming either target can be achieved without overshoot.

The section could very usefully include an illustration of what happens with GWP_{100}-based trade-offs between CH4 and CO2 – similar to what was done in Huntingford et al 2015 (pasted below).



This would help demonstrate how big the 'danger' is or isn't when using GWP100 to make trade-offs between gases within a prescribed CO2-eq emissions pathway. It would also show that reducing CH4 by more and reducing CO2 by less using GWP_{100} results in a cooler, not warmer, climate during the 21st century and lower peak temperatures than a reference emissions pathway (shown by the figure I have pasted above). I consider this important because I've heard even some scientists claim that substituting CO2 abatement with CH4 abatement inevitably leads to a warmer world. The figure shows that it would be true in the very long run (and if we maintain this trade-off in perpetuity into the 22nd century) but the opposite is true for the entire 21st century. This report has a chance to bring some nuance to blunt and in their bluntness incorrect claims.

2.1 Global cost-optimal pathways

Global GHG emissions trajectories consistent with the Paris Agreement are often studied using Integrated Assessment Models (IAMs). These models of the energy and land-use systems allocate emissions reductions across sectors, countries, and gases to keep the overall 'net present cost' of the emissions reduction pathway as low as possible whilst achieving a specified global temperature goal.[1] These modelled pathways, regularly summarised and applied in the IPCC assessment reports and intergovernmental documents such as the 'Emissions Gap' reports from UN Environment, can be useful indicators of what an idealised 'cost-effective' global emissions pathways might look like across sectors, gases and regions, but do not explicitly incorporate additional considerations of fairness, political will or institutional capability which will all be important additional determinants of reductions in the real world.[2]

[1] In many IAMs this is achieved using a 'shadow value of carbon' for all emissions. This is typically applied to non-CO_2 GHG emissions using the global warming potential (GWP) metric for a 100 year time horizon.

[2] 'Cost-effectiveness' is a principle for global action that was established in the UNFCCC, together with 'common-but-differentiated responsibilities and respective capabilities' suggesting that developed nations do more than developing nations to combat climate change.

The balance of effort across the range of global cost-optimal pathways produced by international modelling groups of the 2018 IPCC Special Report on Global Warming of 1.5°C is summarised in Table 1 and Table 2, with trajectories for long-lived GHGs (CO_2 and N_2O) and biogenic CH_4 from these simulations shown in Figure 3.[3] As now relatively widely known, these pathways require significant deviations in the historical trends of global emissions. Whilst technological progress (including the falling costs of renewable power generation) has helped shift projected future emissions trajectories away from the highest emissions futures, expected emissions at the global level out to 2030 remain far from these trajectories.

Table 1: Summary statistics of global cost-optimal pathways (median is given, with max and min in parentheses - long-lived GHG emissions include only CO_2 and N_2O aggregated a using GWP100 value of 298)

Scenario grouping	Cumulative LLGHG emissions from 2020 to 2050 [to peak warming] - $GtCO_2e$	Rates of biogenic CH_4 emission at 2050 [over 20 years prior to peak warming] - $MtCH_4$/yr
1.5C (~50% probability)	545 (325 - 705) [To peak: 535 (360 - 810)]	140 (60 - 200) [Prior to peak: 175 (100 - 240)]
<2C (~66% probability)	790 (580 - 1060) [To peak: 930 (625 - 1430)]	155 (115 - 205) [Prior to peak: 155 (100 - 245)]

Table 2: Emissions rates of gases in global cost-optimal pathways (median is given, with max and min in parentheses - long-lived GHG emissions include only CO_2 and N_2O aggregated a using GWP100 value of 298)

Scenario grouping	2030	2050

[3] Methane emissions from the energy sector are not included within these plots but are an important source of emissions at the global level.

	Biogenic CH_4 - $MtCH_4$/yr	LLGHG - GtCO2e/yr	Biogenic CH_4 - $MtCH_4$/yr	LLGHG - $GtCO_2$e/yr
1.5C (~50% probability)	180 (110 - 230)	23 (14 - 28)	140 (60 - 200)	2.3 (-8.3 - 12)
<2C (~66% probability)	190 (160 - 300)	30 (20 - 46)	155 (115 - 205)	12 (1.9 - 20)

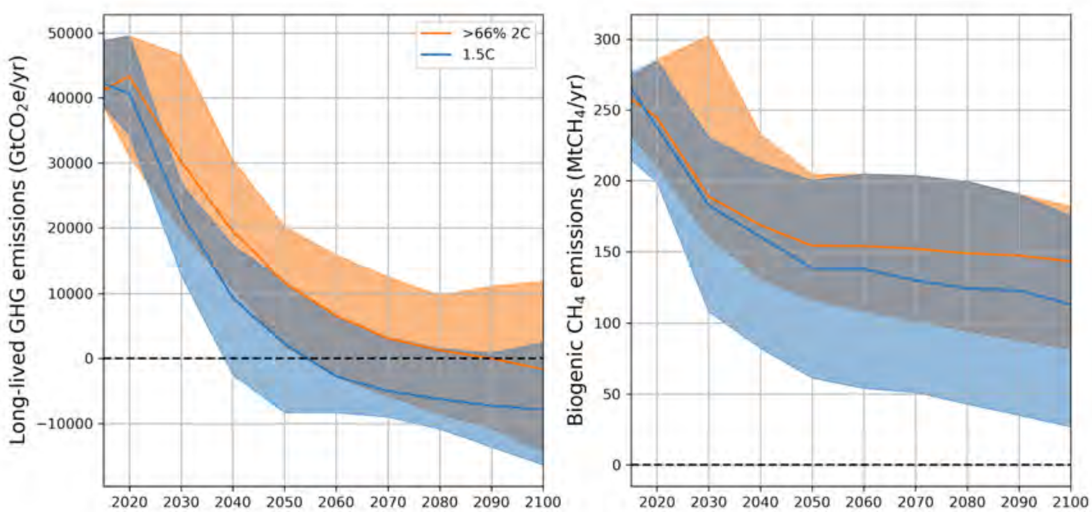


Figure 3: *The spread of GHG emission pathways in the IPCC SR1.5 scenarios database for Long-lived GHGs (CO_2 and N_2O) and biogenic CH_4. Solid lines denote the median of the scenario set.*

Figure 3 illustrates the different roles the two gases CO_2, CH_4 and N_2O can play in future model-based emissions pathways that are compatible with the temperature ambitions of the Paris Agreement. The global emissions of CO_2 have to go to net zero around the middle or second half of the century, depending on level of temperature ambition. Large reductions in CH_4 and N_2O are also generally found to be needed but there is more variation. The model studies found that strong reductions in methane are needed in all pathways, but zero CH_4 is not achieved in any pathway. Note that this is not necessarily or not only because CH_4 is a short-lived gas but because models assume that abatement costs become very high for some emission sources. For N_2O, the pathways show smaller reductions or even modest increases depending on the degree of future fertilizer use. N_2O emission pathways also do not reach net-zero. The large spread in possible pathways for emissions of CH_4 and N_2O are worth noting, reflecting different assumptions about abatement costs including potential for demand-side changes. However, in the vast majority of these cost-effective pathways emissions, CH_4 emissions are seen to decline by strongly mid-century. This reduces the level of global average CH_4-induced warming relative to the warming these emissions are causing at present and allows for more warming from cumulative emissions of long-lived GHGs on the pathway to net zero emissions.

Linking back to my main comment on section 1.1, I feel it would be helpful to show what amount of warming in an RCP2.6 pathway is caused by future emissions of CO2 and CH4, and what amount is caused by past emissions. This would help illustrate how much future emissions (which are under our control) contribute to future total warming, rather than being inadvertently anchored in the warming that we happen to be causing right now but that does not present a historical commitment for SLCFs.

This scenario set is not a statistically well-defined set of simulations and should not be treated as such. It includes simulations where particular technologies are explicitly excluded as contributing to the emissions reductions (e.g. nuclear) and come from a wide set of models with varying levels of detail regarding the representation of energy system technologies, varying assumptions regarding their relative costs, and varying assumptions about global development (e.g. population, economic growth and development) in the absence of climate policies or impacts. Differences in the evolution of the global energy systems can be larger between different models as it can between different levels of climate ambition within the same model. Although the differing assumptions and outcomes in the land and agriculture sector have been studied (Popp et al., 2017), it is difficult to clearly identify the drivers of differences between the high-level global emissions outcomes without additional targeted experiments, and the fundamental drivers of different balances between reductions in biogenic methane and long-lived GHGs remain poorly understood.

After the completion of SR1.5, new scenarios have been developed by various scenario groups. These may give more insight to cost optimal emissions pathways for these gases and provide a stronger knowledge basis for options to reach the temperature goals.

2.2 Understanding trade-offs between shares of effort across gases in global mitigation pathways

I feel this section is fundamental but least well developed – it lacks a clear structure.

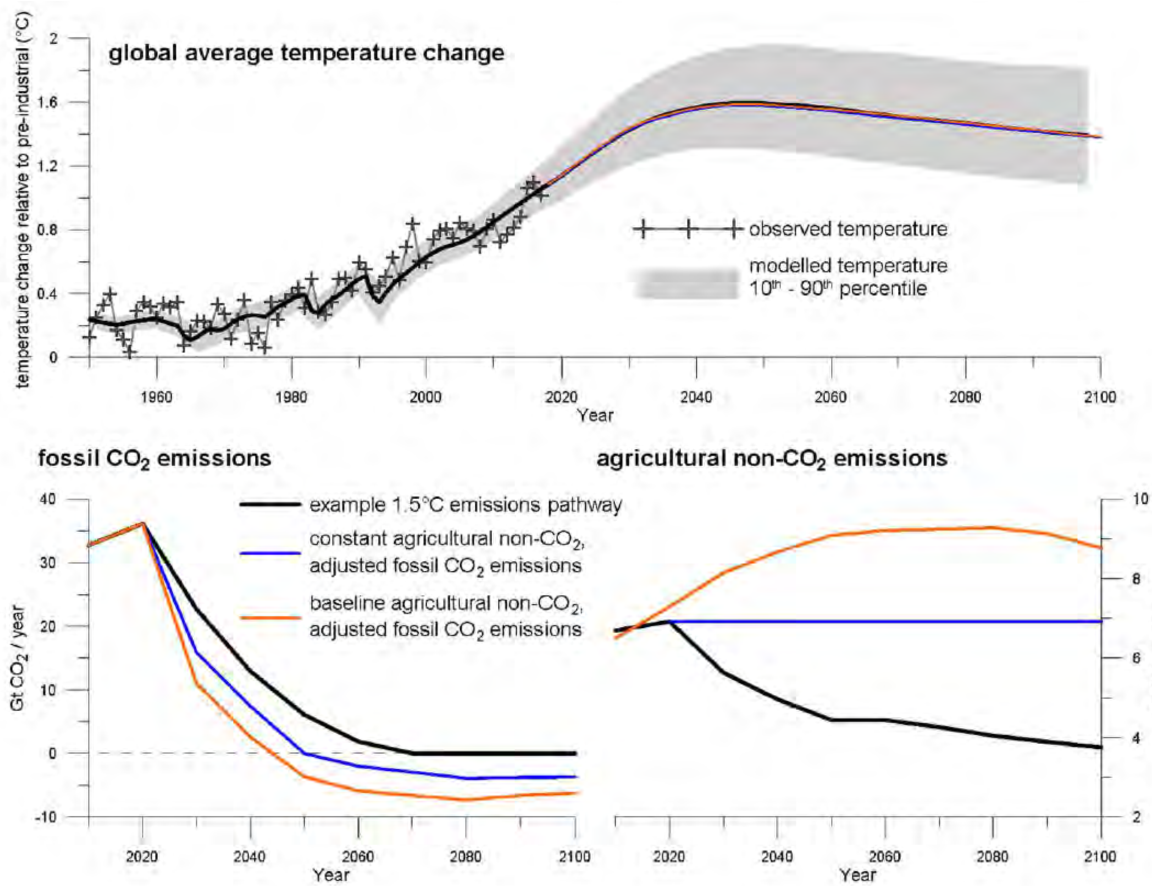
I suggest this section could go first in section 2 – setting out the different ways in which CH4 and CO2 emissions can be combined from a physical perspective, demonstrating the physical trade-offs in simple terms (higher sustained CH4 emissions means getting to net-zero LLGHG earlier, and vice versa. Illustrate this by figures – but avoid anchoring this in a 'first-best' approach since there is no physically first-best pathway – multiple options are all equivalent in their climate outcomes).

The climatically equivalent pathways (see Leahy et al 2020 below for an example of what I mean) could be (a) a pathway where both CH4 and CO2+N2O go to net zero (at different times) and (b) a pathway where CH4 remains constant and CO2+N2O go to net zero (at an earlier time). Adjust emissions and timing of zero such that modelled temperature is the same in both. Could add a third pathway where CH4 is increasing and CO2+N2O goes negative. Make clear as an aside that all pathways that reach net-zero CO2+N2O imply sustained negative CO2 emissions.

This would show the physical option space without prejudicing one or the other – and then one can locate the 'cost-optimal' pathway within this physical option space and bring in a discussion of other non-physical constraints and trade-offs.

You can then bring in economic/feasibility constraints and trade-offs (e.g. we can't get to zero CH4 so some level of sustained CH4 emissions is inevitable – which is ok as long as LLGHG go to net-zero early enough – but if sustained CH4 emissions are too high, this requires LLGHG emissions to reach net-zero at an infeasibly early point in time and or increases global costs substantially because it would force premature retirement of long-lived infrastructure).

An example of climatically equivalent well-below 2°C pathways (although here focusing on trade-offs between agricultural non-CO2 and fossil CO2 emissions, not on CH4 vs LLGHG) is shown below. Something equivalent could be constructed easily focusing on global CH4 vs fossil CO2 and would be very useful for this report to show the physical option space.



Leahy, S. C., H. Clark, and A. Reisinger, 2020: Challenges and prospects for agricultural greenhouse gas mitigation pathways consistent with the Paris Agreement. Front. Sustain. Food Syst., advance on-line, 1–15, https://doi.org/10.3389/fsufs.2020.00069.

The section should also more clearly separate out choices up to peak warming, and choices post-peak warming (consistent with Rogelj et al 2019: A new scenario logic for the Paris Agreement long-term temperature goal. Nature, 573, 357–363, https://doi.org/10.1038/s41586-019-1541-4). Section 2.3 below sort of does that but it needs to be motivated here I think – i.e. make clear that one goal is to limit peak temperature to a certain level, and another one is what we want temperature to do after the peak (decline or be relatively constant). For peak temperature, SLCF matter mainly in their rate of emissions for a few decades prior (which, incidentally for a 1.5 target, means starting now!) whereas for post-peak temperature, the question is do we want temperature decline (how quickly, how much?) and we can achieve this by CO2 removal or by further reductions in SLCF emissions (or a combination of both).

The scenarios described in the previous section for global emissions share the effort between sectors and gases solely based on minimizing overall cost within the modelling framework. Other splits between reductions in different GHGs could be possible whilst achieving the same global temperature outcome, incorporating additional constraints regarding perceptions of fairness, just transition, and societal preferences.

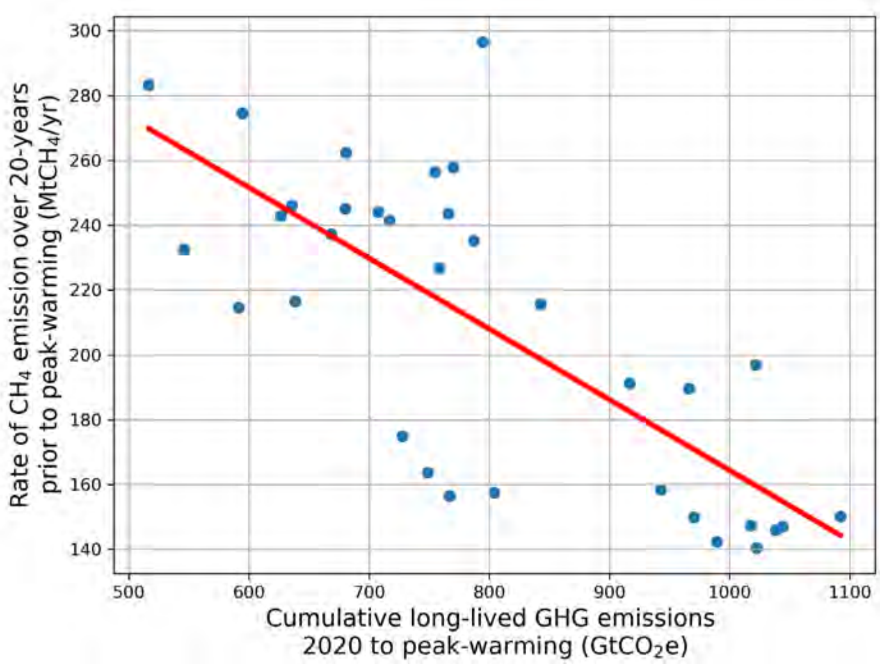


Figure 4: *Relation between CH_4 emissions 20 years prior to peak warming and the cumulative CO2-equivalent emissions ($CO_2 + N_2O$) based on GWP100 for scenarios that keep peak warming to 1.6-1.7C. This temperature range was chosen to give a large number of modelled scenarios that peak warming within this relatively narrow range.*

Emergent relationships between properties of this scenario ensemble can be used to explore alternative pathways not included in this scenario set. Figure 4 illustrates an alternative to the use of traditional metrics for comparing and trading across gases. It shows the relation between methane emissions prior to peak warming (y axis) and magnitude of allowed cumulative CO_2 and N_2O emissions aggregated at CO_2 equivalents based on GWP100 (x-axis) for scenarios with a very similar (within 0.1°C) peak warming outcome. This approximately linear derived relation reflects that the higher CH_4 emissions the more constrained the cumulative GHG/CO_2 budget we have. And the more the world reduces CH_4, the higher cumulative LLGHGs will be compatible with the peak temperatures (in this case 1.6-1.7°C). This relationship indicates that a 10 MtCH_4/yr reduction in the average rate of CH_4 emission over the two decades prior to the time of peak warming could allow for around an additional 45 GtCO_2-equivalents of long-lived GHG such as CO_2 and N_2O. Whilst this value will be somewhat sensitive to the specifics of the simple climate model emulator used to project the climate outcomes consistent with these emissions scenarios, and the effects of systematic variations in changes of aerosol forcing that may correlate with one of the axes, it offers a simple way to explore the trade-offs between these two dimensions.

This relationship illustrated in Figure 4 can provide a simple, but relatively accurate, way of estimating the implications of a the difference between a 47% and 24% cut in global biogenic methane emissions relative to 2017 levels by 2050 (the range of reductions in biogenic CH_4 emissions reductions within the New Zealand Zero Carbon Act) in terms of the equivalent effort in cumulative long-lived GHG emissions savings. Approximately 56% of global methane emissions are from biogenic origin (Hoesley et al., 2018). This means that the difference in the 2050 CH_4 emissions rate between a global reduction of 24% and a reduction of 47% (relative to 2017 levels) is approximately 47 MtCH_4/yr in absolute terms. Based on the relationship approximated from Figure 4 this would mean that around 200 GtCO_2-equivalents of additional cumulative long-lived GHG (CO_2 + N_2O) mitigation would be required if the world as a whole reduced its biogenic CH_4 emissions by only 24% by 2050 compared to one in which they are reduced by 47% whilst achieving the same peak temperature outcome. This is approximately 35% of the cumulative long-lived GHG emissions over 2020-2050 in the median IPCC SR1.5 keeping warming to below 1.5°C with no or low overshoot (Table 1).

As an alternative to the TCRE approach for calculation of remaining carbon budgets, Collins et al. (2018), applied a process based approach to assess the importance of methane reductions for the 1.5°C target. Their modelling approach included indirect effects of methane on tropospheric ozone, stratospheric water vapour and the carbon cycle. They find a robust relationship between decreased CH_4 concentration at the end of the century and increased amount of cumulative CO_2 emissions up to 2100. This relationship is independent of climate sensitivity and temperature pathway. In terms of relation between end of the century emission changes in CH_4 and CO_2, their results achieve similar results as those obtained by Allen et al., 2016 in a GWP* context. Collins et al., 2018, also point out that the non-climate benefits of mitigating CH_4 can be significantly larger than indicated by IAM studies.

It would be useful if this report could clarify how much (or how little) difference there is between warming from biogenic and fossil CH4. I'm exposed to a lot of conversations where people assume that the warming from fossil CH4 would be fundamentally, much greater than the warming from biogenic CH4. Simply stating the difference in GWP values would not be enough since those same people often assume that GWP is fundamentally flawed anyway. Show it in a graph (i.e. what's the temperature change if biogenic CH4 emissions were fossil CO2 emissions)?

2.3 Implications of post-2050 net-negative emissions

Section 1 summarised how emissions of long-lived GHG need to fall to net-zero to stop contributing to rising global temperature. Peak warming generally occurs around 2050 in scenarios that keep warming to 1.5C with ~50% probability - approximately corresponding with the date of global net-zero CO_2 emissions (Figure 2.6 in UK CCC, 2019). Although net long-lived GHG emissions remain positive at the time of net-zero CO_2 emissions (due to some residual N_2O emissions in all scenarios), the effect of falling methane emissions over the decades prior to 2050 (which reduces CH_4-induced warming) offsets this.

Many of these scenarios continue to reduce CO_2 emissions further so that global CO_2 (and long-lived GHG) emissions go net-negative. This has the effect of reducing temperatures after peak warming has been reached, but doesn't significantly contribute to the level of peak warming achieved. In many scenarios that peak warming at around 1.5°C (or less than 0.1°C of overshoot) by 2050 the net-negative CO_2 emissions largely contribute to temperatures declining from their peak to around 1.3°C by 2100. Alternative pathways exist that would avoid these net-negative emissions - for example Rogelj et al (2019b) shows that pathways which reach net-zero CO_2 emissions around 2040 and then maintain this level still achieve a peak temperature around 1.5°C with warming remaining around this level out to 2100. For scenarios that do significantly overshoot a 1.5°C target level in the middle of the century, significant amounts of global net negative CO_2 emissions would be necessary to return warming to 1.5°C by 2100. For example, temperatures peaking around 1.7 °C, would require around 200 $GtCO_2$ of negative emissions over the 21st century to return temperatures to 1.5C, but if temperatures peaked at 1.85 °C around 400 $GtCO_2$ of negative emissions would be required (Rogelj et al. 2019b). In the long-term (centennial timescales) it may be necessary to have a certain amount of net negative global CO_2 emissions even to sustain global temperature at a constant level. This is to counter any slow Earth System feedbacks such as permafrost thawing which would add to atmospheric concentrations (and therefore warming) over long-timescales (see Section 1.1).

The relationship across the scenarios between cumulative long-lived GHG emissions and the rate of CH_4 emissions identified in Section 2.2 also helps elucidate the tradeoffs between further reductions in trajectories of biogenic methane emissions post-2050 and net-negative CO_2 emissions after reaching net-zero.

These results again make the case for early action to reduce emissions of LLGHGs. As such actions can both reduce peak temperatures and the level of negative emissions technology needed to achieve a 2100 temperature goal. This is relevant for several reasons. *Firstly*, there are implications of allowing overshoot on the global energy system. In a world that is trying to reduce global temperatures after 2050 there might be a greater need for energy generation associated with the removal of CO_2 from the atmosphere (such as through bioenergy with carbon capture and storage - BECCS) than in a world that is not trying to decline temperatures after 2050. This might therefore change the make-up of a desirable electricity generation mix in the decades prior to 2050. In such pathways you also need to worry about competing interests for land-use (see IPCC Special Report on Climate Change and Land). *Secondly*, any sustained post 2050 methane abatement could also help reduce temperatures and reduce the dependence on long-term net negative CO_2 emissions, indicating an interdependence of the post-2050 trajectories between the gases in a world of declining temperature (see also Figure 6). *Thirdly*, even if temperature targets are reached, some long-term net negative GHG emissions might need to be sustained.

3. Considerations for national pathways consistent with keeping warming to 1.5°C

Section 2 considered the tradeoffs between mitigation of different greenhouse gases. This section discusses other considerations that could be taken into account in national pathways.

3.1 National contribution to global warming

The research outlined in Sections 1 and 2 and much previous research shows that methane emission changes have a different time evolving climate impact than a CO_2 emission change. This means that a national emission pathway that specifies the change in aggregated greenhouse gas emissions will not necessarily follow the same global warming, as different combinations of long-lived GHGs and shorter-lived GHGs can give the same overall CO_2 equivalent emission trajectory (when aggregated using GWP100 values) (e.g., Fuglestvedt et a., 2000, Fuglestvedt et al., 2003; Myhre et al., 2013; Allen et al., 2016; Allen et al., 2018). Globally the ambiguity generated for realistic strong mitigation pathways has been found to be important at the 10% level (or 0.17°C) (Denison et al., 2020). However, larger ambiguities could exist at sector and country level; e.g., in countries such as New Zealand where methane emissions represent a larger fraction of total greenhouse gas emissions. To illustrate this, the blue and green lines (or the purple and red) in Figure 5 illustrate global warming contributions from two pathways with the same GWP100 based total CO_2 equivalent emission trajectory but different CO_2 and biogenic CH_4 trends. The green pathway has 47% biogenic CH_4 reductions by 2050 but at the expense of extra CO_2 emissions (to match the CO_2-equivalent emissions of the blue line) and does not reach net zero CO_2 emissions by 2050, which happens in the blue pathway. Initially the extra biogenic CH_4 reduction under the GWP100 CO_2 equivalent assumption (green line) gives more cooling. However, after 2100, the long-term warming effect of the extra CO_2 emissions would be expected to dominate and give more warming eventually. If New Zealand were to specify a single CO_2-equivalent emission reduction target based on GWP100, the up to 20% difference in resulting global warming trajectory illustrated by the pairs or curves in Figure 5, gives the scale of the ambiguity introduced.

The blue and red curves in Figure 5 approximate the range of New Zealand's possible future contributions to global warming since 1990 under current policies, assuming that emissions do not change after 2050. Under both 24% and 47% biogenic CH_4 reduction policies, New Zealand is beginning to reduce its contribution to global warming by 2050. Under 24% reduction policies, the 2050 contribution to global warming from New Zealand's matches today's level of New Zealand's contribution to global warming. Under 47% biogenic CH_4 reduction policies, the 2050 contribution to warming level approximately matches that from 2015.

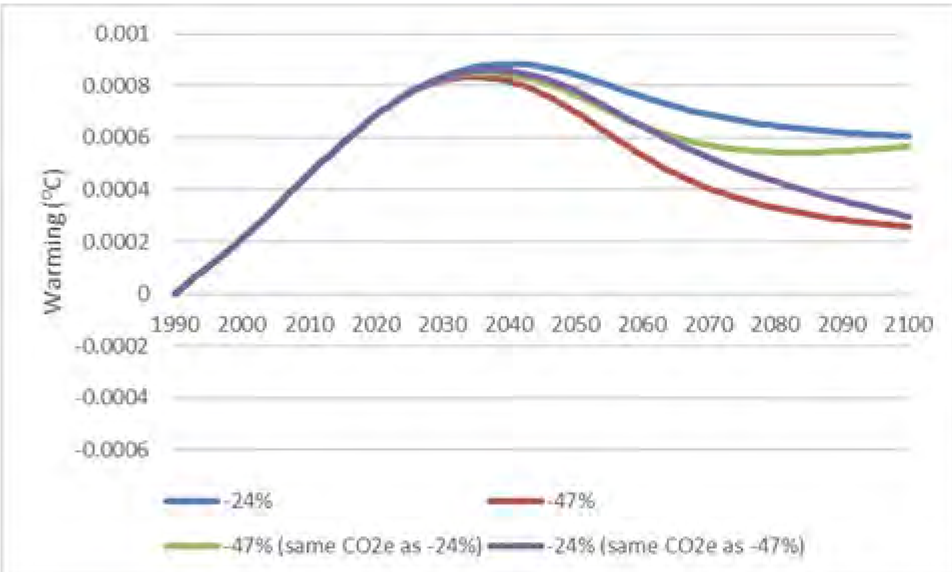
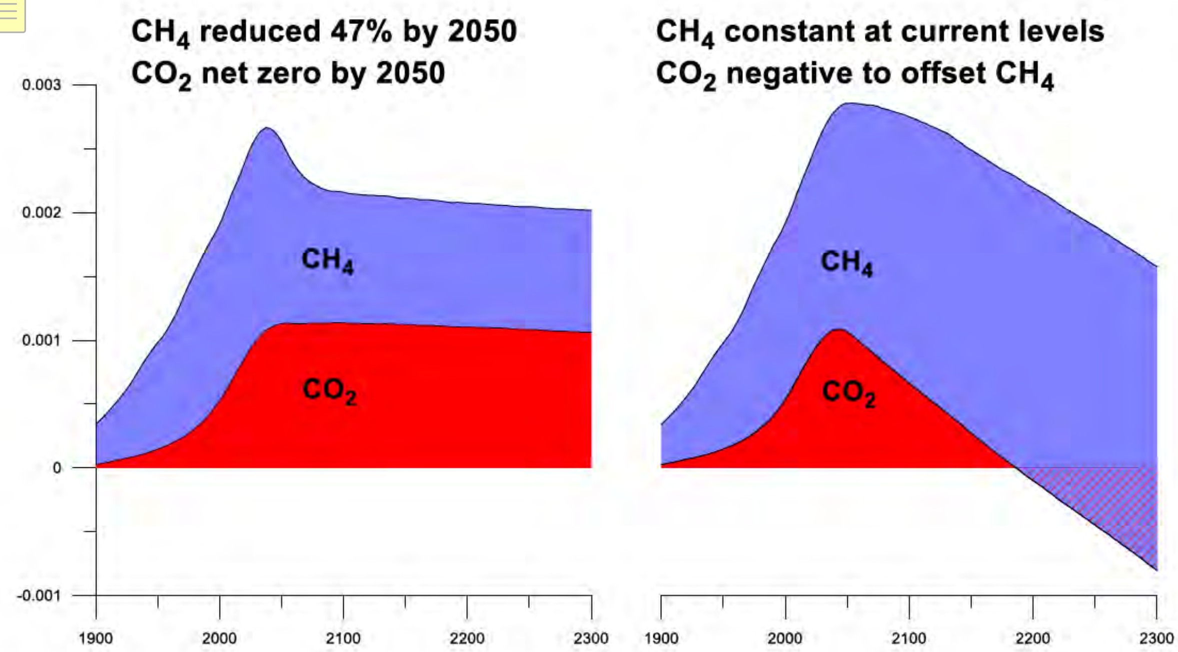


Figure 5: *An illustration of New Zealand's contribution to global warming since 1990. The blue and red pathways reach net zero emissions in 2050 for LLGHGs and fossil fuel CH_4, and have either 24% (blue) or 47% (red) reductions in biogenic CH_4 from 2017 levels to 2050. The green line has 47% biogenic CH_4 reduction but additional emissions of CO_2 to match the CO_2e emissions of the blue line based on IPCC AR4 GWP100 values. Emissions from 2050 do not alter. New Zealand emissions from 1990-2018 are taken from https://www.mfe.govt.nz/climate-change/state-of-our-atmosphere-and-climate/new-zealands-greenhouse-gas-inventory. The estimate using the impulse response functions provided in the IPCC 5th Assessment Report for calculating GHG metrics as a simple climate model to assess the temperature implications of a national emissions pathway. Non-GHG contributions to warming (e.g. aerosol emissions) are not part these scenarios.*



Contributions to global temperature rise are sensitive to the shape of the emissions reduction profile as well as the end point reached in 2050 or any other year when mitigation and emission changes might stop. This is particularly so for LLGHG pollutants, but less so for short-lived pollutants. Early reductions in LLGHGs have lower cumulative LLGHG emissions and overall less climate impact in the longer term (also see Section 2.3). In the near-term front loaded trajectories might lead to a rise in temperature from reductions in co-emitted pollutants resulting in less aerosol cooling (see Section 1.1.2), the near-term rise and peak temperatures can also be reduced by early action on SLGHGs.

What happens to emissions after 2050 is important for the longer term response (see Sections 2.3 and 4.2). This is theoretically explored in Figure 6, which keeps net-zero CO_2 emissions at zero after 2050 but varies methane emission reductions across a range of options from the highest temperature response (no change in emissions) to the largest cooling (biogenic emissions drop to zero after 2050). These results illustrate that although the choices of biogenic emission pathway up until 2050 do influence New Zealand's contribution to global warming, either choice should begin to reverse the country level contribution to further warming after 2040. However, the figure also shows that it is the choices after 2050 that really matter in the longer term, where continued decline of biogenic CH_4 would be needed after this date to begin to reverse New Zealand's historical contribution to global warming.

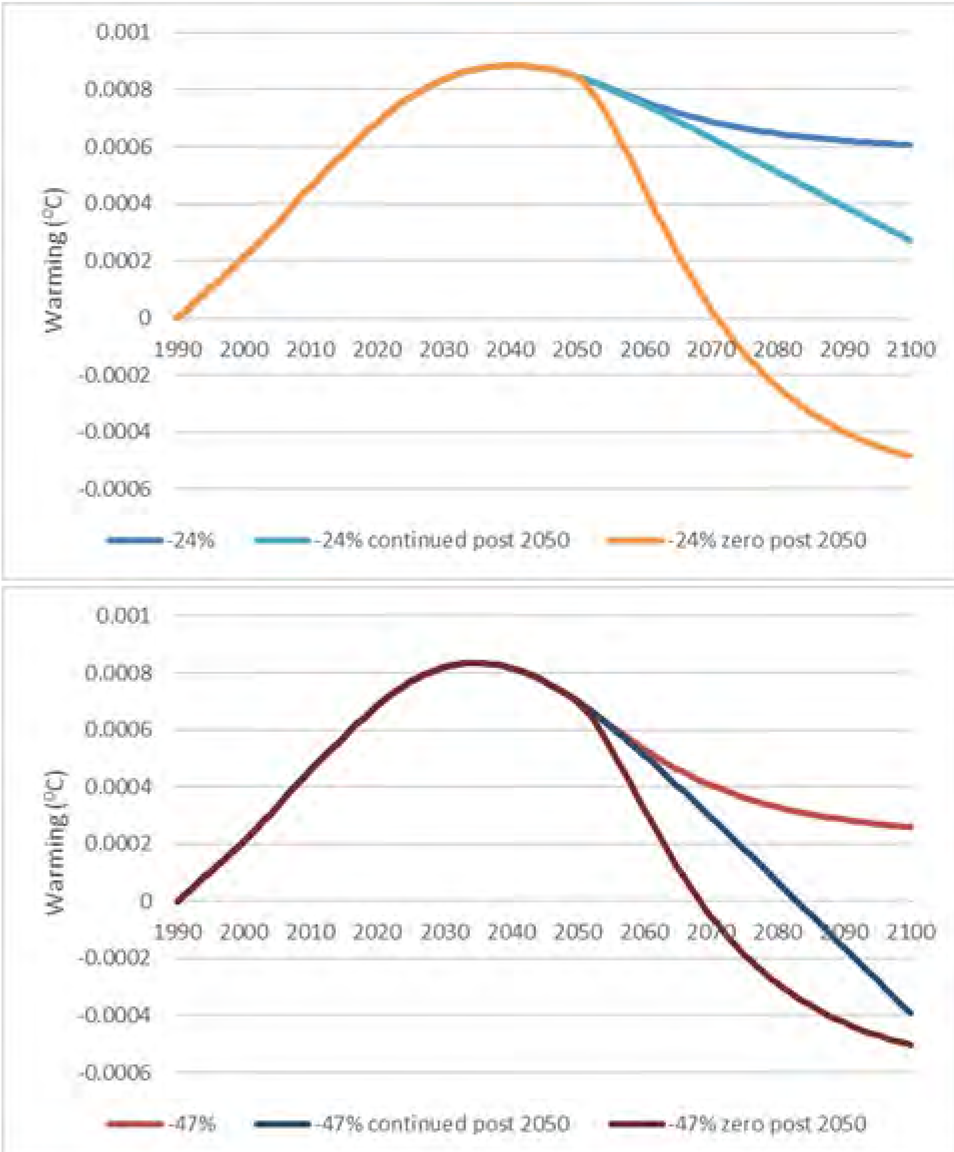


Figure 6: *As Figure 5, except emissions reductions continue beyond 2050. 24% biogenic CH_4 reduction by 2050, shown in the top panel and 47% reduction in the bottom panel. The panels have three scenarios: emissions unchanged after 2050, matching Figure 5; the biogenic methane reduction rate continuing after 2050; or biogenic methane emissions suddenly decline to zero after 2050.*

3.2 Fairness and equity

When determining either net zero targets dates or proportioning the remaining carbon budget into national quotas, choices have to be made regarding fairness, equity and burden sharing. These are obviously not straightforward and can have a large effect on levels of ambition for mitigation reduction (see Figure 7 and Figure 3.9 from the UK CCC, 2019).

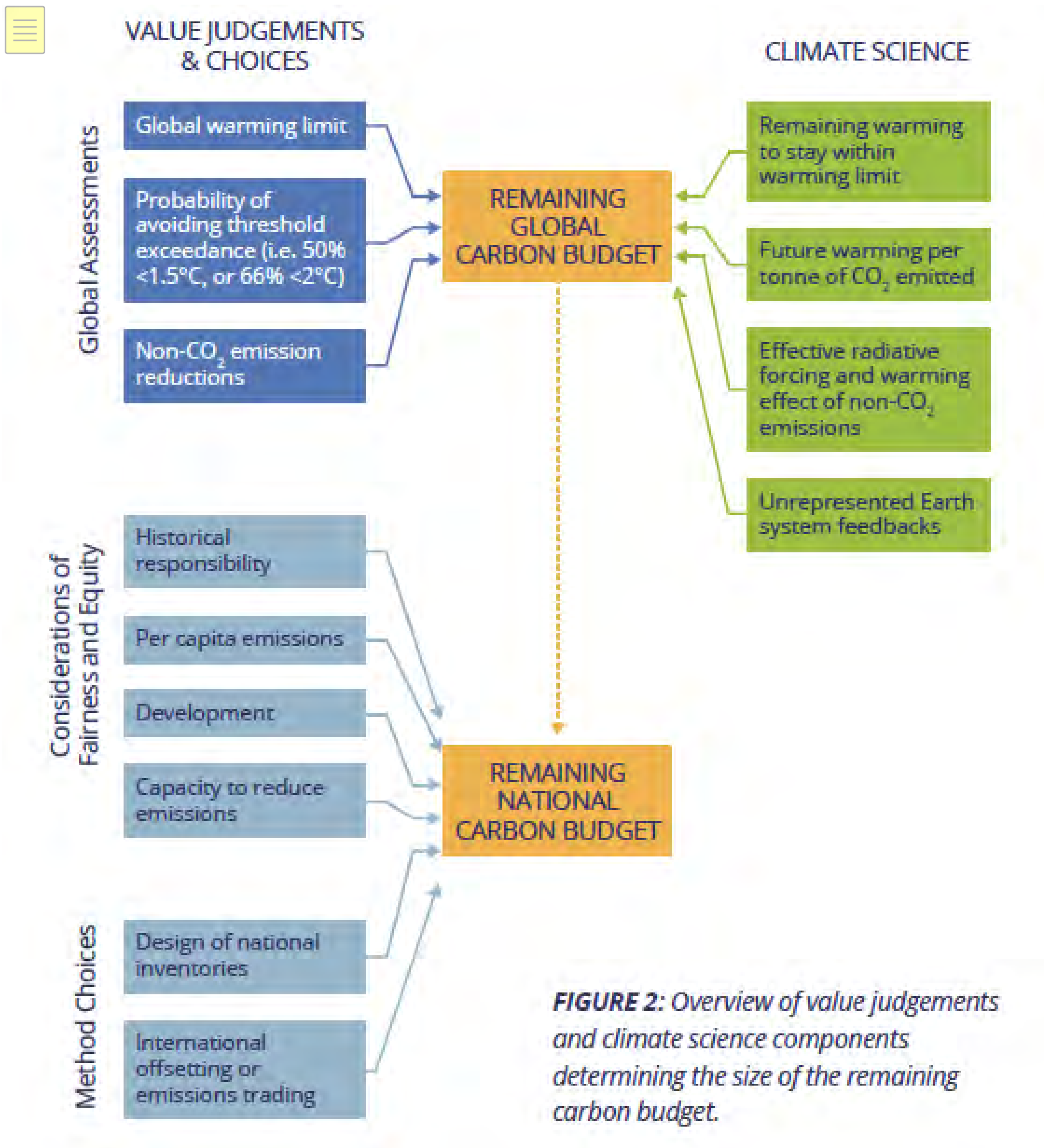


Figure 7: *Methodological, fairness and equity choices when creating national carbon budgets from the global remaining carbon budget. Figure 2 from the 2019 CONSTRAIN report https://constrain-eu.org/. See also Rogelj et al. (2019a).*

When comparing national emission pathways, it is important to consider different national starting points. The same '1.5C consistent' mitigation actions measured by cost or other measure of effort could result in different rates of emissions reductions in different regions depending on national circumstances and their respective capabilities to cut emissions. This includes the share of hard-to-abate emissions within a country profile today. For example, if the energy sector is already mostly decarbonised, the national emissions might not fall as quickly as the global average, whose rapid decline over the 2020s in 1.5°C scenarios is associated primarily with the rapid removal of coal from the electricity generation mix. Assessing whether a nation is taking the '1.5C consistent' actions with its planned emissions reduction pathway needs to be more nuanced than a simple comparison with the global average reductions. It also needs to consider additional effort, outside of the domestic emissions account that a country might be undertaking to support the global transition (e.g. climate finance provision, purchase of credits through international markets, technology transfer etc.) to form a holistic picture of whether planned action to 2030 is 1.5°C-aligned.

Summary and conclusions

Section 1,presented a brief update of the science on past and future warming from greenhouse gases. Section 2 illustrated global tradeoff considerations in strong mitigation emission pathways and Section 3 considered implications for deriving national strategies.

In the further development of policy towards New Zealand's contribution to the global effort of achieving the Paris Temperature Goals, our report has highlighted several issues and choices that would benefit from consideration. These are outlined below:

4.1 Evolving science

As knowledge is being developed and assessment reports are being published, it is important to be clear and transparent about what is used as the basis for the policy design; i.e. which values and which definitions are adopted and used and how they might be revised as science understanding evolves.

4.2 Defining net zero

There are different choices to how net-zero is defined both in terms of allowable sinks, in terms of which gases are included in the target and any emission metric choice. Also important is the boundary of the system and if consumption or territorial emissions are addressed and emission trading is allowed.

The SR1.5 used two main indicators of net zero emissions: 1) a CO_2 only and 2) an aggregate of GHGs expressed as CO_2-equivalent emissions based on GWP100. See e.g Table 2.4 in SR1.5. As shown in the table, net zero emissions are typically achieved several years later for the aggregated net zero GHG as compared to the CO_2-only net zero.

Choices of approach not only need to consider the physical science uncertainty but also need to consider the overall objectives of the climate policy and the practicalities of usage and communication. As illustrated in Section 3.1, the selection of greenhouse gases and as well as the emission metric used will have a significant effect on timing and efforts to achieve net zero and on the resulting global warming. The UK legislated for a net zero target in terms of GWP100 emissions. One of the reasons given was that such a target would actively decrease its future warming commitment over time (see Section 2.1 and 3.1). For New Zealand to continue to decrease its future warming commitment after 2050, additional CH_4 reductions and/or negative emissions of CO_2 would be needed (Section 3.1).

Emission metrics are used for comparing and trading of emissions of gases with different physical characteristics on a common scale. GWP100 has been widely adopted for aggregating emission of gases to so-called 'CO_2-equivalent emissions'. But different mixes of long and short lived gases included in the same amount of CO_2-equivalent emissions will give different temperature outcomes over time, and the use of the concept therefore introduces ambiguity in temperature outcome. New metric concepts have been presented in the literature after AR5; e.g., the GWP* concept which approximates the temperature response over time from emission paths relative to a reference level. Which metric is chosen and the rationale for the choice needs consideration and clear communication of which purpose and goal it is meant to serve. As shown in Section 2.2, an alternative approach based on the emergent relation between CH_4 emissions prior to temperature peak and cumulative CO_2 and N_2O could be considered as an alternative or supplement, depending on the policy objectives and the way this information would be used to provide abatement incentives for individual sectors.

The Paris Agreement aims for a net-zero type target on a global basis. In the development of mitigation strategies for a single country it is important to consider how the plans for net zero might be achieved internationally and how a nation's plan fits into the international effort (i.e., which countries might achieve net negative, net zero or net positive emissions, and how international trading is used).

4.3 Life after net-zero

As shown in the pathways in SR1.5, achieving net zero GHG is just one part of the challenge in limiting future warming. Plans for the further path of emissions of the individual gases after net zero target is achieved also need to be addressed and communicated, particularly how greenhouse gas removal can be sustained given finite and competing interest for land resources (see Section 3.1).

4.3 Defining national high-ambition pathways

Which fairness and equity principles that are applied as rationale for New Zealand's efforts are important to communicate as a part of a mitigation strategy. As New Zealand's starting position in terms of sectoral emissions is different from other nations, a high ambition emission reduction trajectory might look quite different to a high ambition pathway from another country. In particular, many countries are expected to rapidly decarbonise their power sector out to 2030, leading to large national emission reductions in the 2020s. Countries such as New Zealand (and the UK) where the power sector is already mostly decarbonised, urgent actions are needed on other sectors such as buildings and transport for mitigation compatible with Paris Agreement ambitions, that might take longer to manifest themselves in emissions trends. Therefore relatively modest emissions reductions might suffice in the 2020s to keep warming to 1.5°C, compared to what is required by the world as a whole. These could still be seen as ambitious provided the groundwork is laid for large reductions in the 2030s (see Section 3.2).

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