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).

Commented [AR5]: Interesting and potentially inadvertent framing here: why is the reduction of SLCF emissions framed as opportunity, rather than the continuation of SLCF as a problem?

It seems predicated (see comments on section 1.1) that the current level of temperature is somehow baked in, and anything that puts us below that is an opportunity, rather than asking to what extent our future emissions are making the world warmer than it would be in the absence of those emissions (and hence, as for CO2, any emission makes the world warmer than it needs to be, and every reduction contributes to the same goal whether LLGHG or SLCF).

I suggested some edits and inserted a sentence above to illustrate how a more consistent framing might present the same information (that asks about the damages caused by *any* future emission of *any* gas).

Note: I'm not asking for removal of the information that reducing SLCF emissions reduces their contribution to temperature, whereas reducing CO2 emissions still increases temperature. This is important and could be brought out even more clearly. But the reduction in temperature from reduced SLCF emissions is only relative to the contribution they are causing right now, i.e. SLCF emissions do not have a cooling effect in themselves (in the way that emissions of sulfate aerosols have a cooling effect). The authors need to guard against implicit anchoring in a grand-fathering type thinking in the way they describe temperature outcomes.

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).

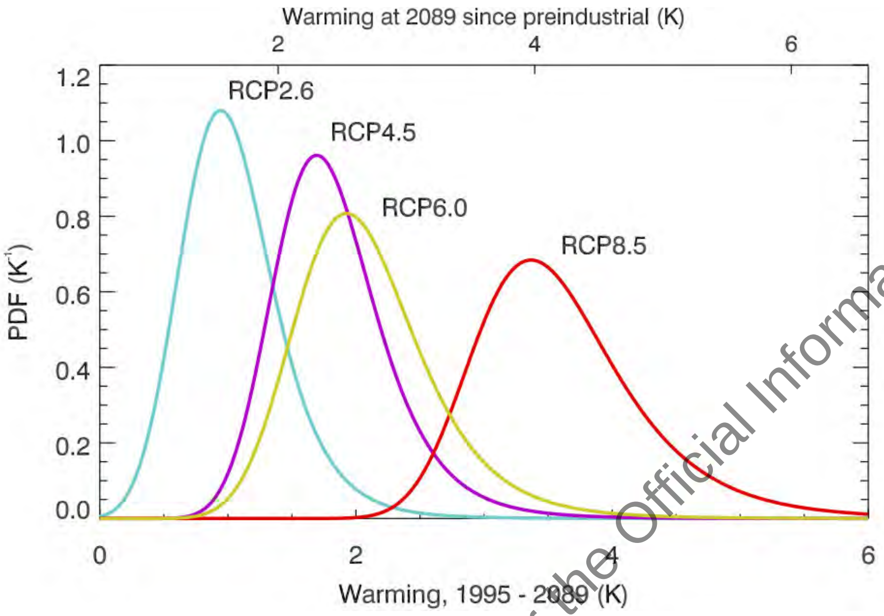


***Figure 2**: Constrained future warming estimates as probability distribution functions. based on revised climate sensitivity ranges from Sherwood et al. (2020). Results are shown for four representative concentration pathways. (Figure 23 from Sherwood et al. 2020).*

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).

Commented [AR6]: If it reduces total GWP100 by 25% this would mean that tropospheric O3 forcing from methane is close to zero – is this what is meant?

If yes, more info as this would be a major reversal of previous assessments (i.e. some explanation needed – do we no longer think that CH4 increases O3 when the range of NOx, CO and NMVOC concentrations are considered across the global atmosphere?)

Commented [AR7]: To what extent is this included in Smith et al 2018 above? Make clear whether this is additional or not. The overall impression I'm getting from this list is that the GWP100 would be revised downward, which is clearly not where the draft AR6 WGI report is landing. The authors obviously can't cite the report but the impression and expectation this text generates should not be inconsistent with the AR6 conclusions.

Commented [AR8]: What about Sterner & Johansson 2017, "The effect of climate–carbon cycle feedbacks on emission metrics"? Also proper citation missing for Gasser et al.

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

Commented [AR9]: I consider it a mistake to lead this section with emission metrics. Provide an understanding of the (physical and economic) trade-offs first, and bring a section on emission metrics last (they are a tool to simplify quantification of the trade-offs that exist in the more complex real world).

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.

Commented [AR10]: The text here should clarify that GWP* measures a different thing compared to GWP.

GWP measures the warming from a CH4 emissions relative to the absence of that emission, whereas GWP* measures the warming from a CH4 emission relative to the warming from a reference emissions level.

So the physical quantity that is being compared for SLCF emissions relative to the warming from CO2 is different for the two metrics – it's not that GWP* (as presented in the papers cited) does a better job than GWP, it does a different job.

This is important to bring out more clearly than the current text does.

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.

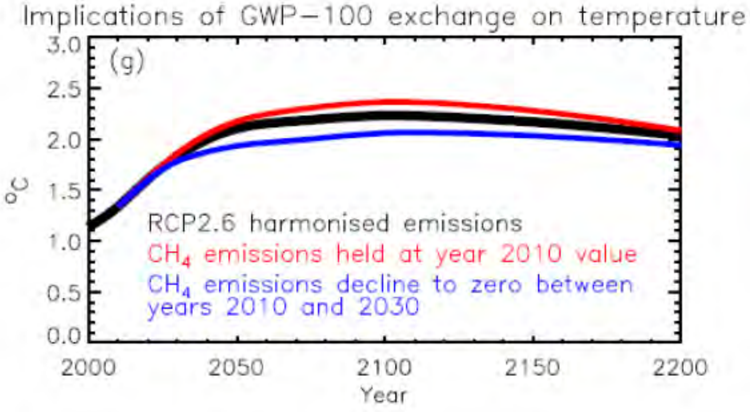
The GWP* concept and its potential applications has received criticism for only reflecting the additional warming effect of emissions relative to a chosen date and not the historical responsibility already caused due to past emissions (Rogelj and Schleussner, 2019).

Commented [AR11]: I don't think this is the key point from that critique – rather their point is that the GWP* use of a reference level *pretends* that past CH4 emissions create a historical liability in the same way that past CO2 emissions create a historical liability.

I.e. their criticism is that using GWP* in the way it's been presented in the literature and accompanying blogs shifts the ethical (and policy) framework to a grandfathering type approach – but without realising or acknowledging that this is what it does, precisely because it treats the current level of warming from CH4 as a 'historical responsibility' even though there isn't one.

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]

Commented [AR12]: There's some concern in IPCC about calling these pathways "cost-optimal" since this depends heavily on how the costs are specified and what's included (and what's not). Perhaps call them "Modelled economic least cost" pathways.

Commented [AR13]: I would start section 2 with either this section or the following one.

Starting with this section would make sense, not because cost-optimal is the "first best" starting point but because it is the only one we have.

The alternative would be to start with a set of climatically equivalent pathways (see Leahy et al 2020 for an illustration) – these could be (a) a pathway where both CH4 and CO2 go to zero (at different times) and (b) a pathway where CH4 remains constant and CO2 goes to zero (at an earlier time). One could even add a third pathway where CH4 is increasing and CO2 goes more negative more quickly.

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.

Commented [AR14]: IAMs ultimately are constrained to achieve a temperature goal, not an emissions goal. The emissions goal is then usually set within the IAM so that they deliver the temperature goal.

Tanaka and O'Neill 2018 (10.1038/s41558-018-0097-x) showed that e.g. a net-zero goal is neither necessary nor sufficient to achieve a specific temperature goal.

This is important because any emissions goal (also from a policy perspective), at least at the global level, has to be subservient to the temperature goal.

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[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)]

Commented [AR15]: Max and min potentially holds you hostage to extreme outliers. I suggest using either the interquartile range as in SR15, or the "likely" range (17th to 83rd percentile range)?

Commented [AR17]: Fundamental clarification needed early on: is "biogenic" assumed to be equal to "agricultural", or does this include waste?

Most methane from waste is also biogenic (and this is important because in New Zealand's legislation, methane from waste is part of the biogenic target).

Include a clear and prominent statement and explanation on this in the text.

Commented [AR16]: The short-hand labelling using square brackets is potentially confusing – I suggest separate columns for the additional information contained in square brackets.

Commented [AR18]: The short-hand labelling using square brackets is potentially confusing – I suggest separate columns for the additional information contained in square brackets.

Commented [AR19]: Add information about 2010 and/or 2018 emission levels to get a better sense of what amount of reduction this means. The LLGHG budget by definition entails zero emissions by the time of/around peak warming, so this information is less relevant for LLGHG, but where emissions don't drop to zero this information is critical to interpret the numbers.

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

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[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 - $GtCO_2e/yr$
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)

Commented [AR20]: This column replicates Table 1 – suggest merging both tables and creating a single table that contains key numerical information from the scenario database.

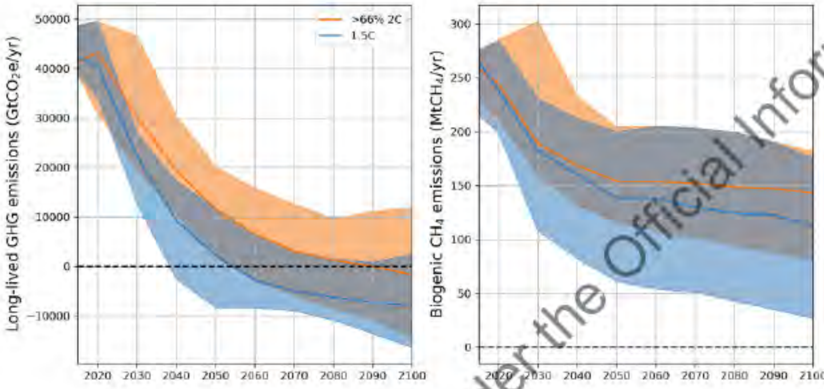


Figure 3: *The spread of GHG emission pathways in the IPCC SR1.5 scenarios database for Long-lived GHGs (CO_2 and N_2O) and biogenic CH_4. Solid lines denote the median of the scenario set.*

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

Commented [AR21]: This may be relevant; see

Harmsen et al, 2019: The role of methane in future climate strategies: mitigation potentials and climate impacts. Clim. Change, 10.1007/s10584-019-02437-2

And

Harmsen et al, 2019: Long-term marginal abatement cost curves of non-CO2 greenhouse gases. Environ. Sci. Policy, 99, 136–149, 10.1016/j.envsci 2019.05.013.

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.

Commented [AR22]: Framing bias: this presents methane reductions as something you do to increase allowed CO2 emissions, whereas one could equally present the (early) date of net-zero CO2 emissions as something you do to allow CH4 not to go to zero.

This more symmetrical framing should be brought out in this section, rather than imply a plausible starting point and then a deviation to benefit CO2.

This would build on the climatically equivalent physical emission pathways suggested above and an example (Leahy et al) pasted below.

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.

Commented [AR23]: Need to be clearer whether you mean land-use dynamics and resulting CH4 and CO2 emissions are not well understood, or whether you mean the climatic consequences and trade-offs of different CH4 and CO2 emissions are not well understood.

I'd strongly disagree with the latter – the climatic trade-offs between CH4 and CO2 emissions are clear.

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.

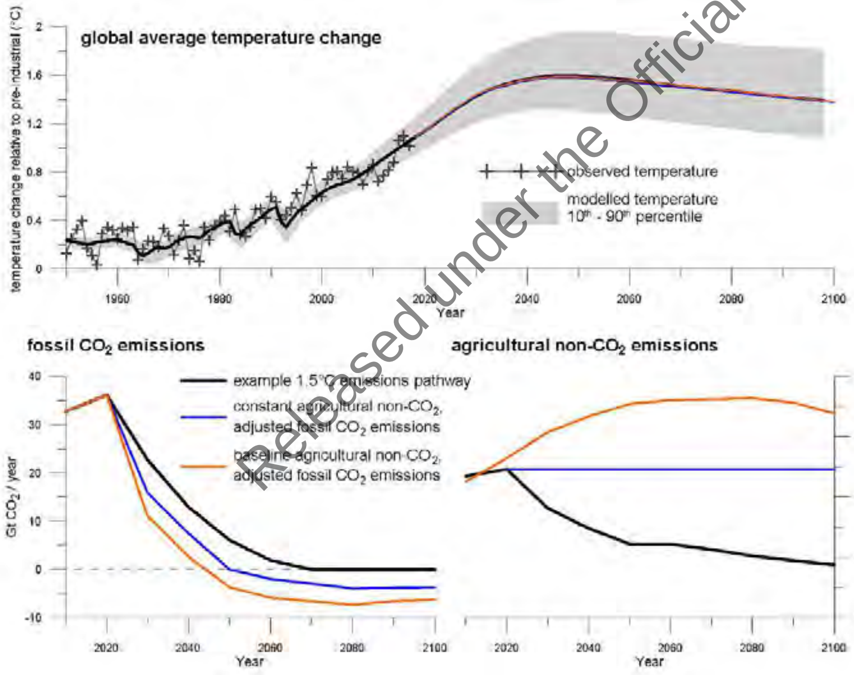
I suggest this section could go first in section 2 – setting out the different ways in which CH4 and CO2 emissions can be combined from a physical perspective, demonstrating the physical trade-offs in simple terms (higher sustained CH4 emissions means getting to net-zero LLGHG earlier, and vice versa. 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.

Commented [AR25]: The above physical scenarios would be a useful way of showing (some extreme forms of) alternative choices, while keeping a clear eye on the trade-offs that this involves (e.g. we may have a societal preference for maintaining ruminant animal husbandry, but if we want to stick to 1.5 degrees, this means going net-negative CO2 by 2040, etc).

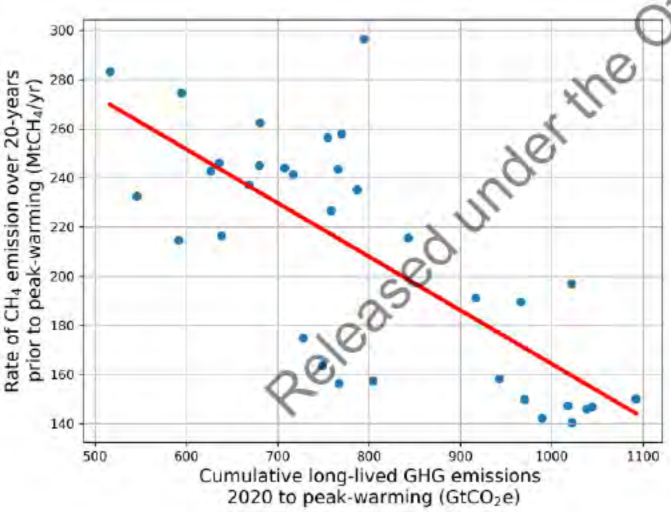


Figure 4: *Relation between CH_4 emissions 20 years prior to peak warming and the cumulative CO2-equivalent emissions (CO_2 + N_2O) based on GWP100 for scenarios that keep peak warming to 1.6-1.7C. This temperature range was chosen to give a large number of modelled scenarios that peak warming within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

Commented [AR26]: These numbers suggest that the authors are confusing agricultural and biological CH4 emissions

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).

Commented [AR27]: By definition since peak warming only occurs around the point of net-zero CO2 emissions

Commented [AR28]: Give more explanation here: if there is no further temperature rise, you either have zero other LLGHG emissions or declining SLCF emission. In practice you can only have the latter.

So avoiding further temperature rise after net-zero CO2 entails either net-negative CO2 or continuously falling SLCF emissions.

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.

Commented [AR29]: This could be spelled out more clearly, using CGTP estimates from Collins et al to show the relative magnitude.

I.e. if a scenario assumes the removal of X Gt CO2 between 2050 and 2100 (e.g. because you want to reduce temperature below its 2050 peak by a given amount), you could achieve the same outcome by keeping CO2 emissions at net-zero but permanently reducing CH4 emissions rate by another X Mt.

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.

Commented [AR30]: This para is less clear than it could be.

My main issue is that the first sentence talks about the benefit of early action to reduce LLGHGs, but the points that follow are all about the interaction between LLGHG and SLCF mitigation.

Reconsider what the point(s) are you want to make, and perhaps make other points in a separate para.

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.

Commented [AR31]: I'm missing a more fundamental statement upfront here that says that there is no good (physical) reason why a national pathway should follow either the global temperature or the global emissions trajectory, given different national circumstances and different mix of sectors with different LLGHG and SLCF mixes.

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.

Commented [AR32]: Add a comment that this is a counterfactual assumption, and that one would expect emissions to reduce further post-2050 (even if global emissions were to remain constant post-2050 – which is implausible already – it seems even less plausible that national emissions would remain constant, given global equity dimensions).

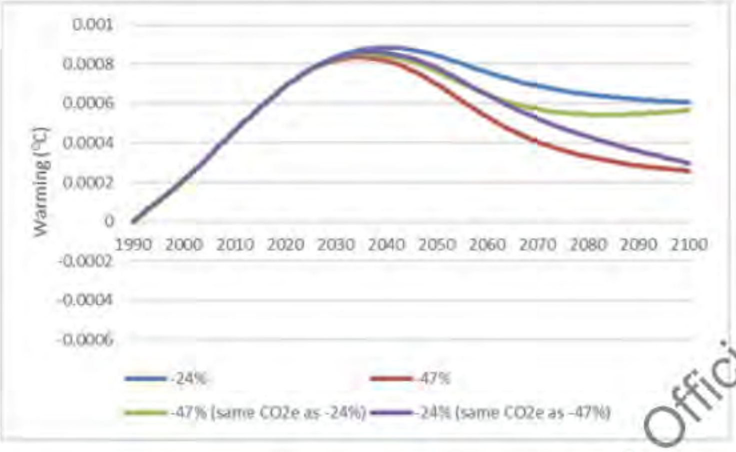


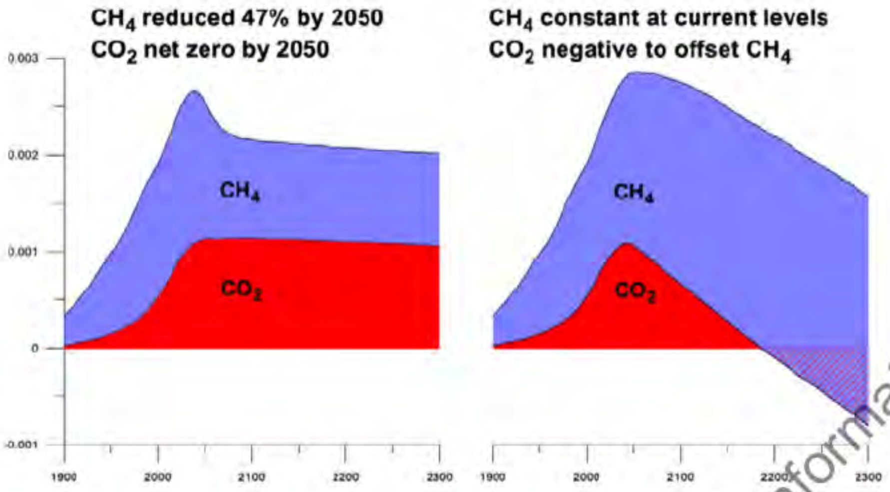
Figure 5: *An illustration of New Zealand's contribution to global warming since 1990. The blue and red pathways reach net zero emissions in 2050 for LLGHGs and fossil fuel CH_4, and have either 24% (blue) or 47% (red) reductions in biogenic CH_4 from 2017 levels to 2050. The green line has 47% biogenic 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.*

Commented [AR33]: Spell out that this shows the warming from <u>emissions</u> starting in 1990 (not the warming in addition to warming in 1990).

Commented [AR34]: This is a confusing assumption – I can't see a plausible policy framework that would lead to such an emission trajectory.

What you could model (see pasted graph below) is what happens if NZ sets a -24% or -47% target for CH4 but then, rather than actually reducing CH4 by that amount, CH4 emissions remain constant and additional CO2 reductions/removals occur to meet the CH4 target via CO2-equivalent reductions.

This is a scenario actively proposed/considered by some people in the agriculture sector who consider the CH4 target too stringent while at the same time feeling that there is CO2 sequestration potential that they should be allowed to count against their emissions.



Commented [AR35]: (Andy Reisinger, own model calculations using MAGICC 6.3. Pathways have the same CO2-eq emissions but right hand side uses additional CO2 removals rather than CH4 reductions. The figure shows that NOT abating CH4 and abating CO2 even more instead results in a greater contribution to warming until the 2nd half of he 22nd century, but a lower contribution after that – assuming hat emissions remain unchanged after 2050, which is clearly counterfactual of course.)

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.

Commented [AR36]: This is not very relevant for NZ given very low sulfate emissions. Suggest this is revised to make it relevant to NZ

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.

Commented [AR37]: I've read this several times and s ill am not sure what it is actually saying

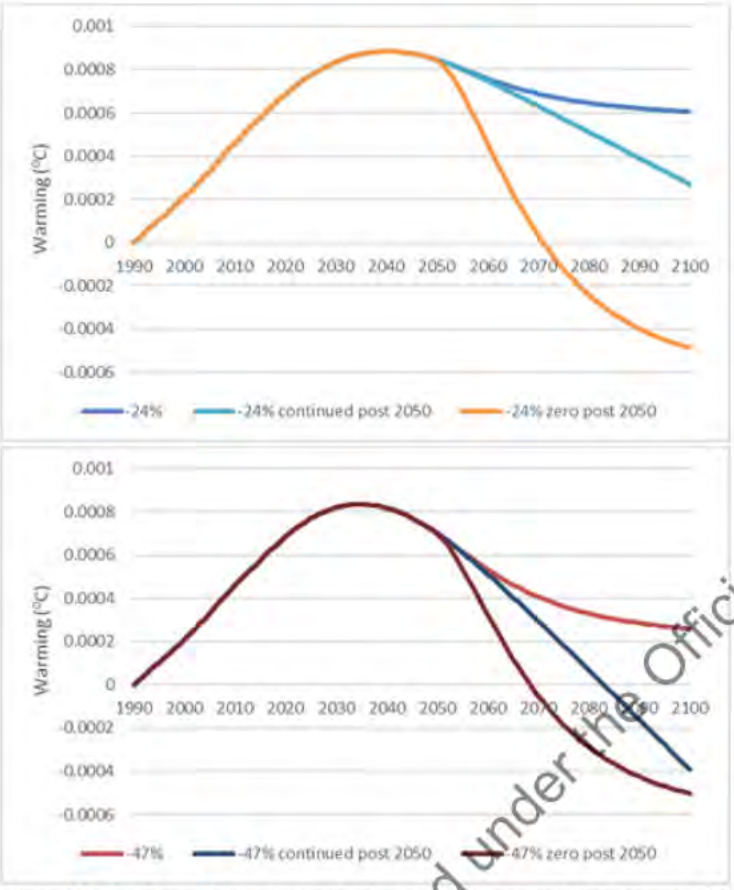


Figure 6: *As Figure 5, except emissions reductions continue beyond 2050. 24% biogenic CH_4 reduction by 2050, shown in the top panel and 47% reduction in the bottom panel. The panels have three scenarios: emissions unchanged after 2050, matching Figure 5; the biogenic methane reduction rate continuing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

Commented [AR38]: I find it unhelpful to have a completely counterfactual thought experiments (CH4 dropping to zero instantaneously) in his context of national policy choices.

Such a thought experiment would be better in section 1.1 as flagged above, in the context of zero emissions commitment.

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).

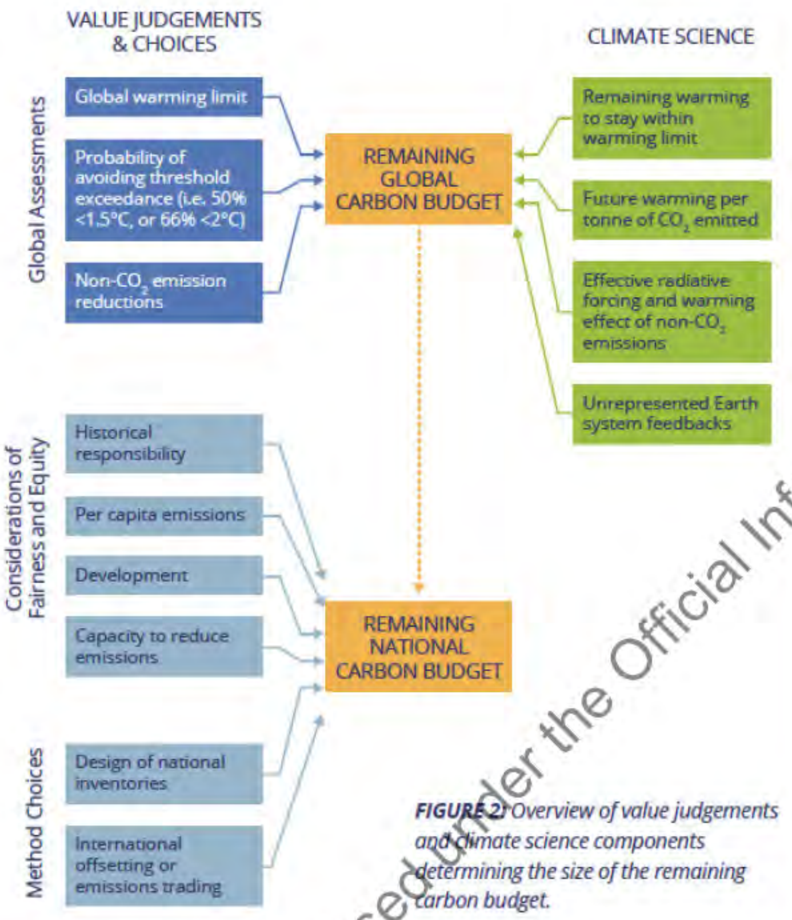


***FIGURE 2:** Overview of value judgements and climate science components determining the size of the remaining carbon budget.*

***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

Commented [AR39]: I have a major problem with the framing in this figure. It works for an economy dominated by CO2 emissions but not for NZ.

Specifically, the issue I have is that the non-CO2 emission reductions are bundled only into the global assessment and make no appearance in the remaining national carbon budget.

Whereas for NZ, the choice about national non-CO2 abatement has a major influence on the remaining national carbon budget.

What this report needs for NZ is a parallel consideration of a global CH4 emission rate (mirroring the remaining global carbon budget), and a national CH4 emission rate (using all the same equity principles).

And then an interaction between the national CH4 emission rate and the national remaining carbon budget for an overall equity picture.

Otherwise I feel this figure is badly misleading in focusing the equity conversation only on CO2 and somehow bracketing out choices about non-CO2, even though they are of fundamental importance in an economy with a high share of non-CO2 emissions.

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.

Commented [AR40]: Overall I'm missing a clear statement that CH4 emissions cannot be dealt with as part of a remaining carbon budget using GWP100, but that the same equity dimensions apply in principle to the CH4 emission rate as for the remaining carbon budget. And that there are trade-offs between the two.

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.

Commented [AR41]: I feel this goes off on a tangent – the brief didn't ask the authors to define net-zero and I don't think the domestic conversation would become easier if this report did.

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.

Commented [AR42]: It's not just a question of overall policy objectives but policy implementation as well

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).

Commented [AR43]: I strongly disagree with this statement and find no basis for it in the literature cited here.

No individual country action or emission keeps warming below 1.5°C in itself.

The SR15 is unambiguous about transformative change being needed in all sectors and regions to achieve a 1.5°C limit. If some countries already have lower emissions from some sectors than others, then this can only mean that they need to turn their attention to other sectors or to harder-to-abate sources more quickly than others, not that they can go slow for a while.

What's more, given that gross per capita emissions even of CO2 only in both the UK and NZ are above the global average right now, and that NZ CH4 and N2O emissions are much higher than global average, I don't see any way to support the statement as written.

This may just be an inadvertent interpretation and the authors mean something else – but I suggest considerable care is needed in the conclusions unless the authors want this report being summarised as "international experts say moderate emission reductions by New Zealand are sufficient over the next decade to limit warming to 1.5°C".

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DRAFT VERSION 1

Climate Science Considerations of Net-Zero for New Zealand

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Executive Summary

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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 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

The physical climate understanding of greenhouse gas response remains broadly similar to the assessments of IPCC SR1.5 and IPCC AR5. Based on new science, a narrowing of likely projected ranges of temperature may be expected. Updated quantifications of contributions to the total climate impact of methane will likely lead to changes of the net climate response per tonne of methane emissions relative to carbon dioxide.

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 do not (likely) 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 CO2 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 details how understanding of each of these has progressed since the 2018 IPCC Special Report.

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 1C (with a 0.8C to 1.2C 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 budgets. 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. In the years either side of SR1.5, there has also 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 0.05C more warming to date but this is not estimated to be statistically significant (Hawkins et al., 2017).

In summary, we can expect further revisions of the order 0.1C 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 1C to 1.1C, the present day climate impacts do not alter, we instead would associate 1.1 C (or 1.5 C) with lower levels of climate impact than previously, so avoiding 1.5C 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 most 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 0.5C across models, with a best estimate, based on current evidence of close to zero.

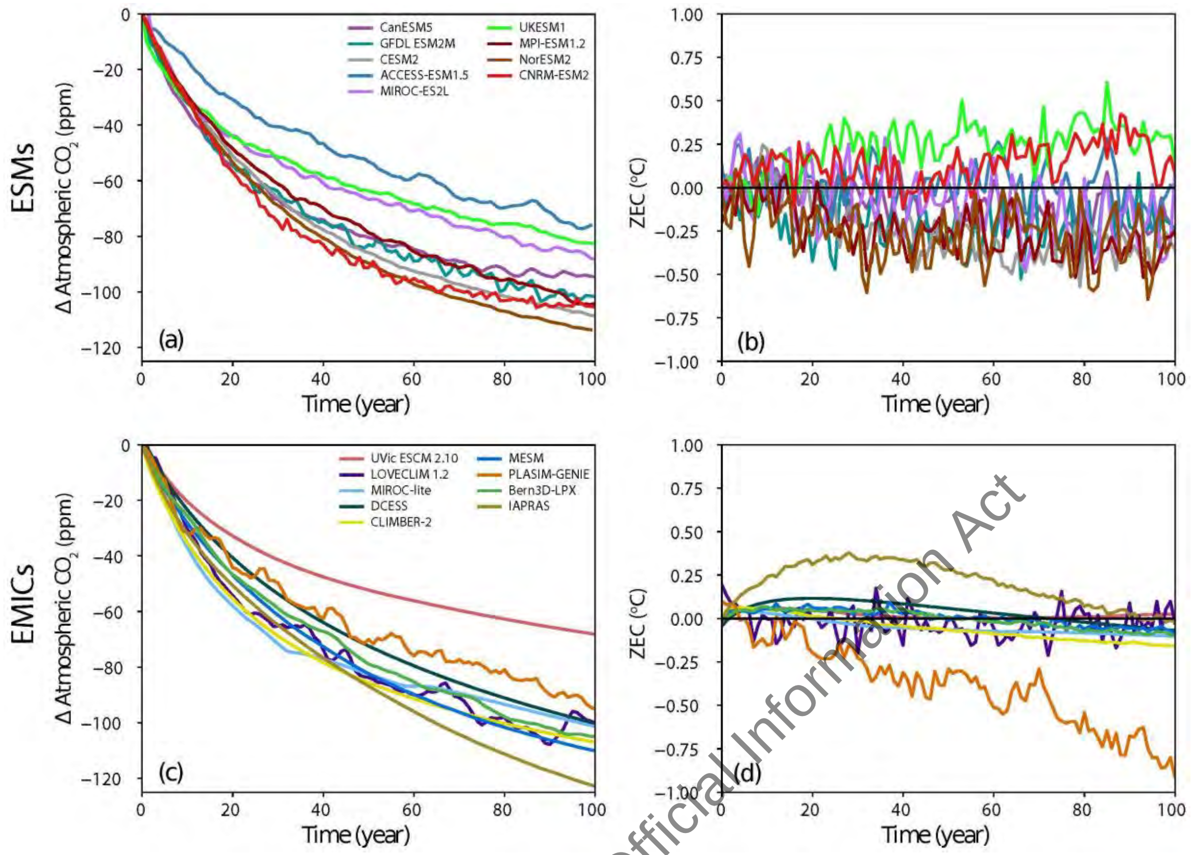

Figure 1: Atmospheric CO2 concentration anomaly and (b, d) Zero Emissions Commitment following the cessation of emissions during the experiment wherein 1000 PgC was emitted following the 1 % experiment (A1). ZEC is the temperature anomaly relative to the estimated temperature at the year of cessation. 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 GtCO2 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 and it is unlikely that all of these Earth system emissions would have occurred by the time global CO2 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) (CO2, N2O, some F-gases) their global temperature impact is largely determined by their *cumulative* emissions. Nitrous oxide (N2O) has a finite single perturbation lifetime unlike CO2, and consequently behaves differently in the very long term, but can be treated as approximately equivalent to CO2 (using GWP100) when thinking about impacts for this century. As shown in SR1.5 and the scientific literature, these emissions need to come down to approximately (near to) net zero to stop their warming contributions. As some level of N2O emissions are expected to be unavoidable, this would require net negative emissions of CO2.

On the other hand, for *Short Lived GHGs* (SLGHG) (CH4, some F-gases) their global temperature impact depends (as a first order approximation) on the sustained rate of emissions. These emissions need to be stabilised (and then steadily declined) to stop their 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. 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.) and on other climate variables (e.g. SLR - Zickfeld et al., 2017).

Since IPCC published its fifth assessment report (AR5) in 2014, the scientific knowledge has developed further with enhanced 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 2C and 1.5C in terms of climate responses and impacts, as well as emission pathways compatible with the Paris Agreement ambitions. However, the fundamental understanding of the climate system has remained largely the same since IPCC AR5 - with a robust understanding of what needs to happen to global emissions to meet the temperature goal of the Paris Agreement

Regarding the emissions caused by anthropogenic activities, there have been some updates to the numerical values of key climate metrics and also some changes to relevant concepts. Topics that are particularly relevant to the discussions in this section are outlined 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).

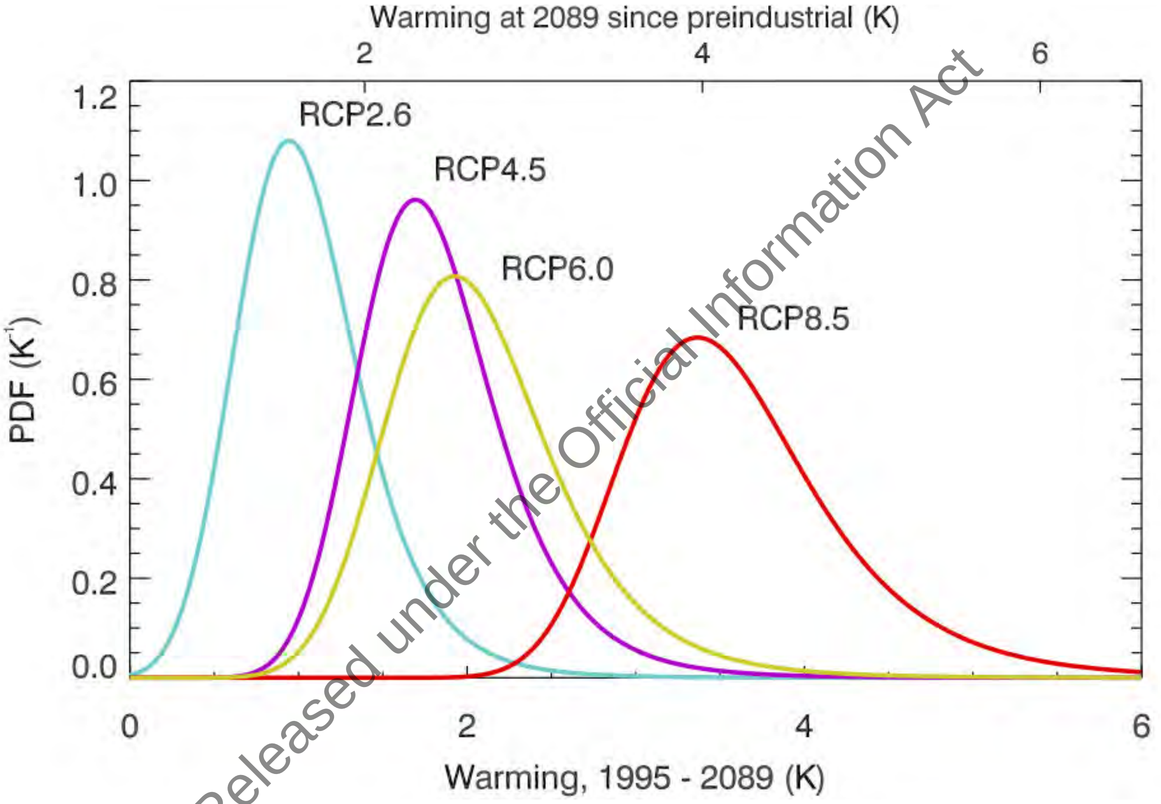

Figure 2. Constrained future warming estimates as probability distribution functions. based on revised climate sensitivity ranges from Sherwood et al. (2020). Results are shown for four representative concentration pathways. (Figure 23 from Sherwood et al. 2020).

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, including for methane. A number of other factors studied in recent publications will also influence the GWP value for methane:

- Moving to ERF increases CO2 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 GWP-100 by ~20%.
- Etminan et al. 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 GWP-100 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 GWP-100 by 25%.
- The results of Wang and Huang (2020) show that due to high cloud changes the stratospheric water contribution to methane GWP-100 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-CO2 gases, which up to then was only included for the reference gas CO2, and imply an underestimation of GWP values for non-CO2 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 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 bring all these 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 CO2 forcing.

1.2.3 Surface temperature projection estimates and novel emission metrics

New concepts for combined step-pulse metrics have been introduced and applied in studies by Allen et al., 2016; Allen et al., 2018, Cain et al., 2019; Collins et al., 2016, Collins et al., 2018, Lynch et al., 2019. These give an alternative approach for comparison of SLGHGs and LLGHG that factors in the specific time dependence of the response to different forcing agents, see Figure 3.

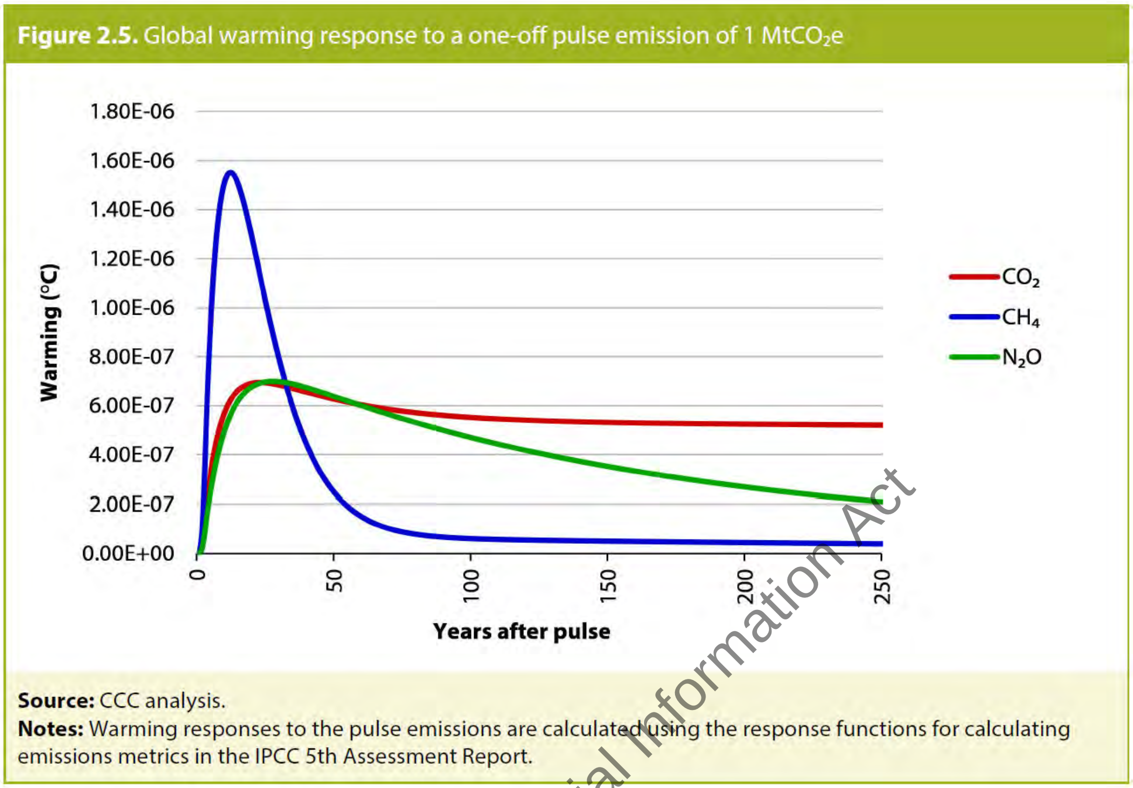

Figure 2.5. Global warming response to a one-off pulse emission of 1 $MtCO_2e$

Source: CCC analysis.
Notes: Warming responses to the pulse emissions are calculated using the response functions for calculating emissions metrics in the IPCC 5th Assessment Report.

Figure 3 pulse response functions in global surface air temperature for CO2, N2O and CH4 based on IPCC-AR5 functions. Figure is taken from Figure 2.5 of the UK CCC report on *Land use: Policies for a Net Zero UK* published in January 2020.

These step-pulse metrics perform a similar role to climate model emulators such as FaIR and MAGICC which are typically used to estimate global warming histories 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.

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

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 Agreemetnl. 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 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 1.5C is summarised in Table 1 and Table 2, with trajectories for each of CO2, CH4 and N2O from these simulations shown in Figure 4. 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 CO2 and N2O aggregated a using GWP100 value of 298)

Scenario grouping	Cumulative CO2 emissions from 2020 to 2050 [to peak	Cumulative LLGHG emissions from 2020 to 2050 [to peak	Rates of CH4 emission at 2050 [over 20 years prior to

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[1] In many IAMs this is achieved using a 'shadow value of carbon' for residual emissions. This is typically applied to non-CO2 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.

	warming] - GtCO2	warming] - GtCO2e	peak warming] - MtCH4/yr
1.5C (~50% probability)	475 (250 - 640) [To peak: 465 (310 - 730)]	545 (325 - 705) [To peak: 535 (360 - 810)]	170 (70 - 240) [Prior to peak: 220 (125 - 300)]
<2C (~66% probability)	725 (520 - 985) [To peak: 815 (555 - 1255)]	790 (580 - 1060) [To peak: 930 (625 - 1430)]	195 (125 - 340) [Prior to peak: 190 (120 - 340)]

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 CO2 and N2O aggregated a using GWP100 value of 298)

Scenario grouping	2030				2050			
	CO2 - GtCO2/yr	CH4 - MtCH4/yr	N2O - MtN2O/yr	LLGHG - GtCO2e/yr	CO2 - GtCO2/yr	CH4 - MtCH4/yr	N2O - MtN2O/yr	LLGHG - GtCO2e/yr
1.5C (~50% probability)	20 (11 - 25)	245 (130 - 290)	8.4 (5.7 - 12)	23 (14 - 28)	0.45 (-11 - 10)	170 (70 - 240)	7.4 (4.6 - 15)	2.3 (-8.3 - 12)
<2C (~66% probability)	27 (17 - 42)	270 (190 - 410)	9.6 (5.7 - 14)	30 (20 - 46)	9.2 (-0.65 - 18)	195 (125 - 340)	8.1 (5.8 - 15)	12 (1.9 - 20)

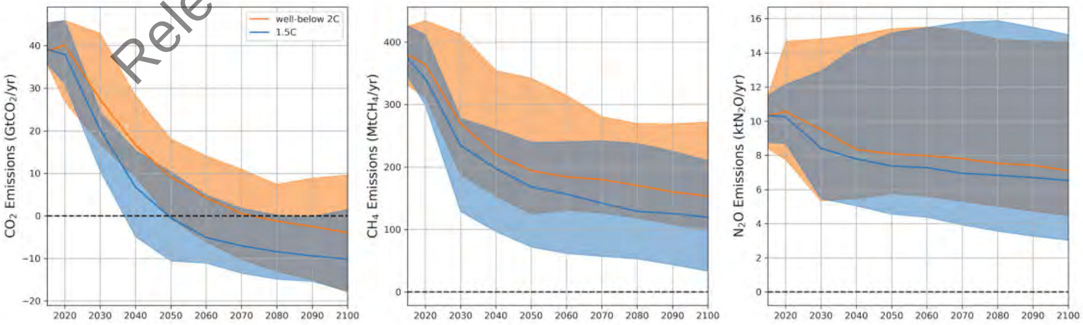

Figure 4 The spread of GHG emission pathways in the IPCC SR1.5 scenarios database for CO2, CH4 and N2O. Solid lines denote the median of the scenario set.

Figure 4 illustrates the different roles the three gases CO2, CH4 and N2O can play in future model based emissions pathways that are compatible with the temperature ambitions of the

Paris Agreement. The global emissions of CO2 have to go to net zero around the middle or second half of the century, depending on level of temperature ambition. Large reductions in CH4 and N2O 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 CH4 is not achieved in any pathway. For N2O, the pathways show smaller reductions or even modest increases depending on the degree of future fertilizer use. N2O emission pathways also do not reach net-zero. The large spread in possible pathways for emissions of CH4 and N2O are worth noting. However, in the vast majority of these cost-effective pathways emissions, CH4 emissions are seen to decline by strongly mid-century. This reduces the level of global average CH4-induced warming and allows for more warming from cumulative emissions of long-lived GHGs on the pathway to Net Zero emissions.

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.

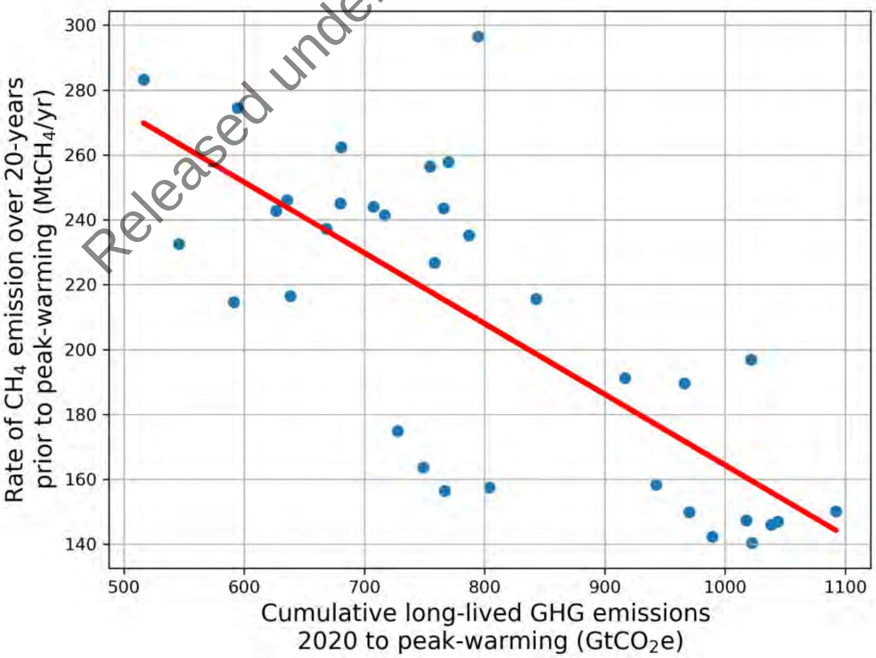

Figure 5: Relation between CH4 emissions 20 years prior to peak warming and the cumulative CO2-equivalent emissions (CO2 + N2O) based on GWP-100 for scenarios that keep peak warming to 1.6-1.7C. This temperature range was chosen to give a large number of modelled scenarios that peak warming within this 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 5 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 CO2 and N2O emissions aggregated at CO2 equivalents based on GWP-100 (x-axis) for scenarios with a very similar (within 0.1C) peak warming outcome. This approximately linear derived relation reflects that the higher CH4 emissions the more constrained the cumulative GHG/CO2 budget we have. And the more the world reduces CH4, the higher cumulative LLGHGs will be compatible with the peak temperatures (in this case 1.6-1.7C). This relationship indicates that a 10 MtCH4/yr reduction in the average rate of CH4 emission over the two decades prior to the time of peak warming could allow for around an additional 45GtCO2e of long-lived GHG such as CO2 and N2O. 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. [To add in next draft more on the physical basis for this relationship and how it compares to other assessments e.g. Collins et al., 2016 ERL]

This relationship 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 CH4 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, van Marle et al). This means that the difference in the 2050 CH4 emissions rate between a global reduction of 24% and a reduction of 47% (relative to 2017 levels) is approximately 47 MtCH4/yr in absolute terms. Based on the relationship approximated from Figure 5 this would mean that around 200 GtCO2e of additional cumulative long-lived GHG (CO2 + N2O) mitigation would be required if the world as a whole reduced its biogenic CH4 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 1.5C with no or low overshoot (Table 1).

2.3 Implications of post-2050 net-negative emissions

Many global emission pathways analysed in SR1.5 overshoot 1.5C or 2C targets but return to below these temperature thresholds by 2100 after temperatures have peaked. Chapter 2 of SR1.5 found that pathways with less near term action resulted in higher peak warming levels and subsequently relied on more net negative global emissions of CO2 after temperatures peaked to reduce the global warming level by 2100. The level of peak warming is not that affected by achieving net-negative emissions (it instead occurs around the time that global CO2 emissions reach net-zero), but the degree of cooling after temperatures have peaked is strongly affected (Rogelj et al. 2019b). For example, temperatures peaking around 1.7 C, would require around 200 GtCO2 of negative emissions over the 21st century to return temperatures to 1.5C, but if temperatures peaked at 1.85C around 400 GtCO2 of negative emissions would be required (Rogelj et al. 2019b).

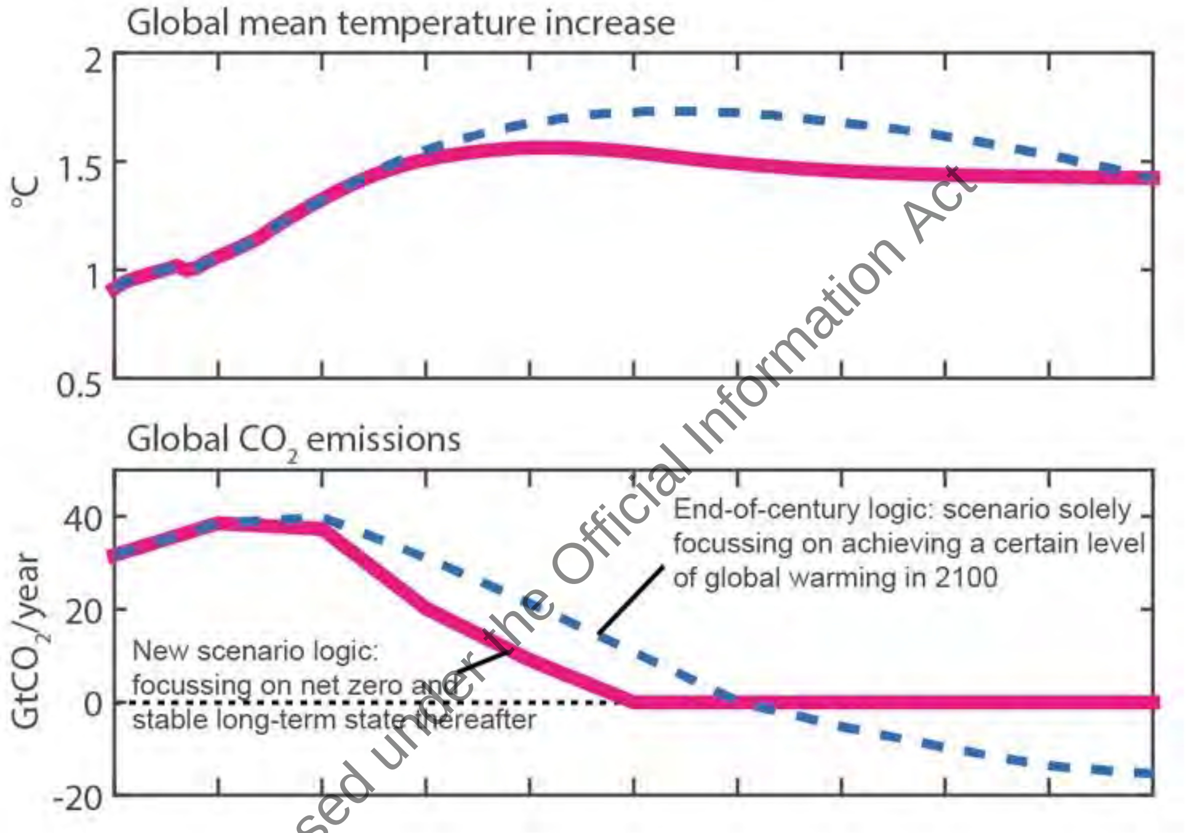

Figure 6: From Rogelj et al (2019b). The purple and dashed blue lines reach the same temperature in 2100, but the higher cumulative emissions from 2020 to 2050 in the dashed blue case means that temperatures overshoot 1.5C and requires compensating net negative emissions to cool the climate in the second half of the century. The purple line shows that it is possible to keep warming to 1.5C without net negative emissions if cumulative emissions are kept sufficiently low over the period between now and reaching net-zero as temperatures approximately stabilise at this point. [Get copyright permission before publication?]

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 CO2 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. Secondly, any sustained post 2050 methane abatement could also help reduce temperatures and reduce the dependence on long-term net negative CO2 emissions, indicating an interdependence of the post-2050 trajectories between the gases in a world of declining temperature . Thirdly, even if temperature targets are reached, some long-term net negative GHG emissions might need to be sustained to counter any slow Earth System feedbacks such as permafrost thawing as highlighted by the SPM in IPCC SR1.5 (see Section 1.1).

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

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 CO2 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 CO2 equivalent emission trajectory (when aggregated using GWP100 values). 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 grey lines in Figure 7 illustrate global warming contribution from two pathways with the same GWP-100 based CO2 equivalent emission trajectory but different CO2 and CH4 trends. The grey pathway has 47% CH4 reductions by 2050 but at the expense of extra CO2 emissions (to match the CO2-equivalent emissions of the blue line) and does not reach net zero CO2 emissions by 2050, which happens in the blue pathway. Initially the extra CH4 reduction under the GWP-100 CO2 equivalent assumption (grey line) gives more cooling but after 2100, the long-term warming effect of the extra CO2 emissions would be expected to dominate and give more warming eventually. If New Zealand were to specify a single CO2e emission reduction target based on GWP-100, the up to 20% difference in global warming trajectory gives the scale of the ambiguity introduced.

The blue and orange curves in Figure 7 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 CH4 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 matches that seen today. Under 47% CH4 reduction policies, the 2050 contribution to warming level approximately matches that in 2015. Note that what happens to emissions after 2050 is important for the longer term response (see Sections 2.3 and 4.2).

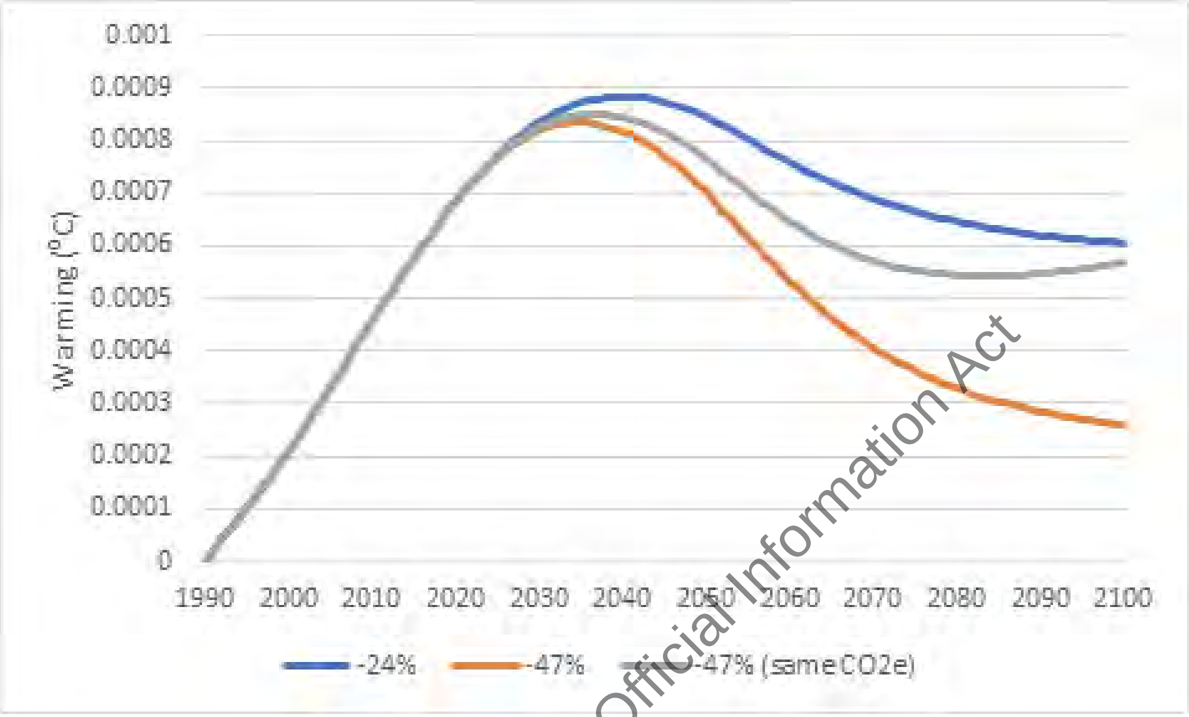

Figure 7. An illustration of New Zealand's contribution to global warming since 1990. The blue and orange pathways reach net zero emissions in 2050 for LLGHGs and fossil fuel CH4, and have either 24% (blue) or 47% (orange) reductions in biogenic CH4 from 2017 levels to 2050. The grey line has 47% biogenic CH4 reduction but additional emissions of CO2 to match the CO2e emissions of the blue line based on IPCC AR4 GWP 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 asses the temperature implications of a national emissions pathway, non-GHG contributions to warming (e.g. aerosol emissions) are not included in this calculation.

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. This is particularly so for long-lived GHG 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 team (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.

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 8 and Figure 3.9 from the UK CCC Net Zero Report, 2019).

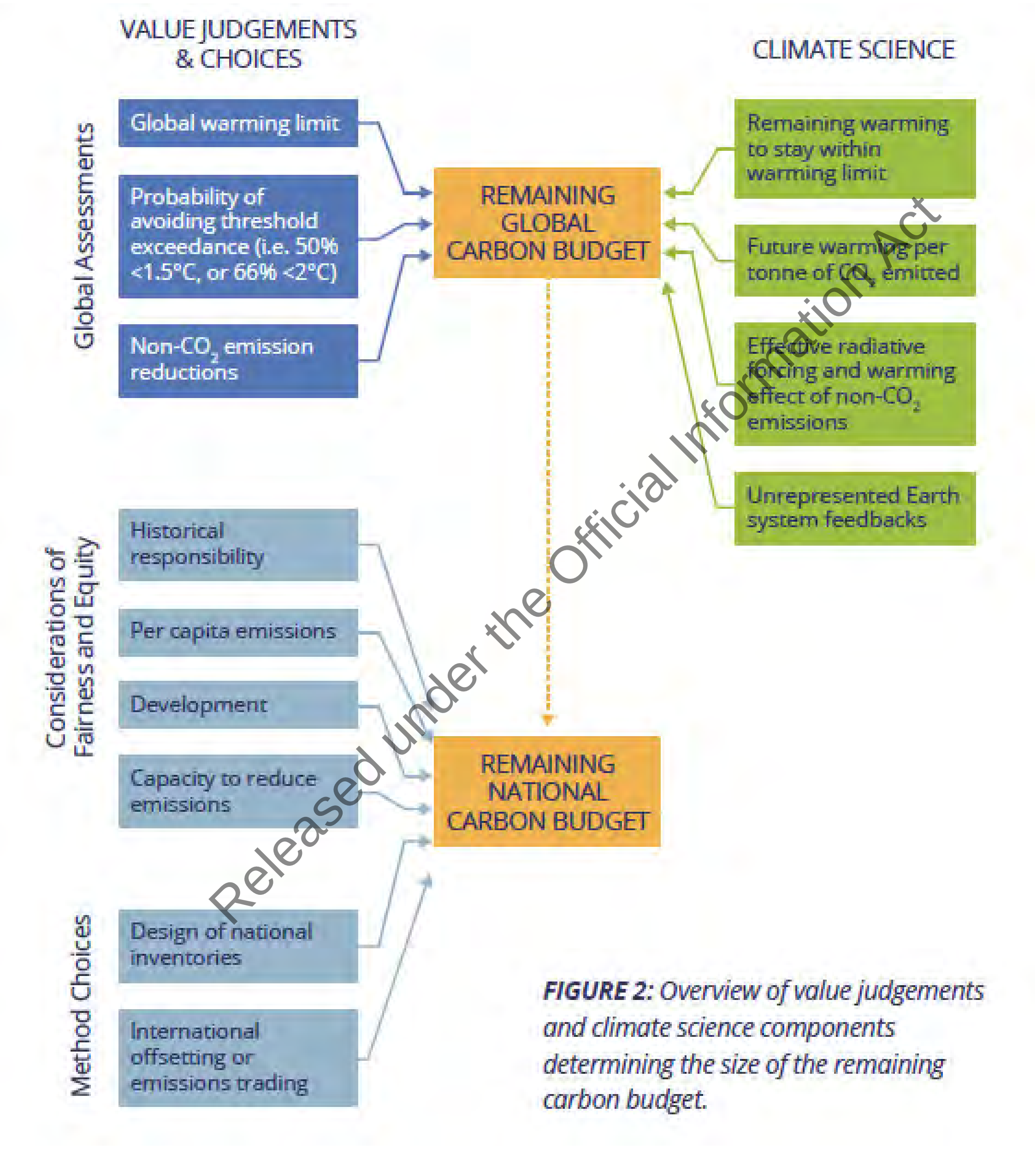

FIGURE 2: *Overview of value judgements and climate science components determining the size of the remaining carbon budget.*

Figure 8. 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 1.5C 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 1.5C-aligned.

Summary and conclusions

NOTE THESE ARE VERY ROUGH AND WE WOULD LIKE GUIDENCE ON IMPORTANT ASPECTS TO INCLUDE

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 (Fuglestvedt et al., 2018). Also important is the boundary of the system and if consumption or territorial are addressed and emission trading is allowed.

The SR1.5 used two main indicators of net zero emissions: 1) a CO2 only and 2) an aggregate of GHGs expressed as CO2-equivalent emissions based on GWP-100. 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 CO2-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 GWP-100 emissions. One of the reasons given was that such a target would actively decrease its future warming commitment over time. For New Zealand to continue to decrease its future warming commitment after 2050, additional CH4 reductions and/or negative emissions of CO2 would be needed (Section 3.1).

The temperature effect of trading CO2 and CH4 emissions will give different temperature effects over time depending on chosen emission metric (e.g., Fuglestvedt et al., 2003; 2018; Allen et al., 2018). Which metric is chosen and the rationale for the choice needs consideration and clear communication. As shown in Section 2.2, an alternative approach based on the emergent relation between CH4 emissions prior to temperature peak and cumulative CO2 and N2O could be considered as an alternative, 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 needs to be addressed and communicated, particularly how greenhouse gas removal can be sustained given finite and competing interest for land resources.

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 than required of the world as a whole in the 2020s to keep warming to 1.5C 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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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.

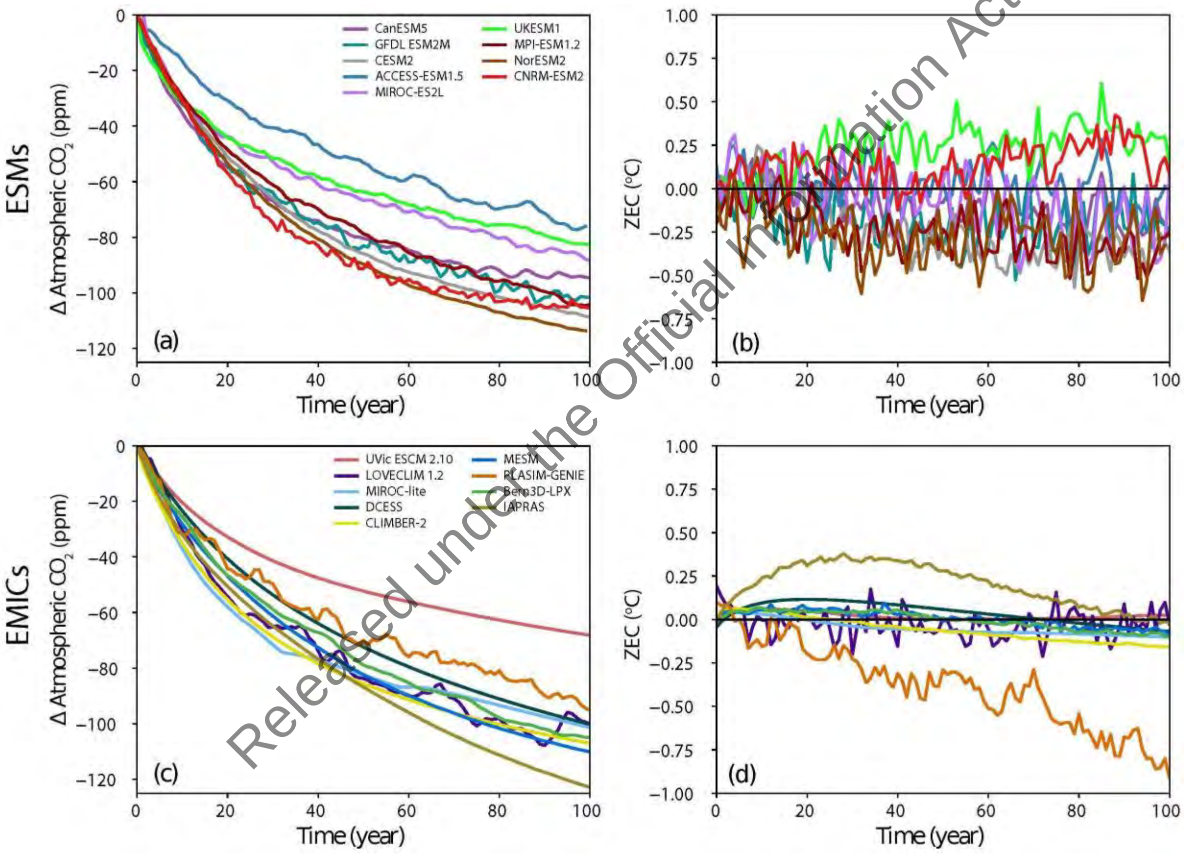

Figure 1. *Atmospheric* CO₂ *concentration anomaly and (b, d) Zero Emissions Commitment following the cessation of emissions during the experiment wherein 1000 PgC was emitted following the 1 % experiment (A1). ZEC is the temperature anomaly relative to the estimated temperature at the year of cessation. 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. 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).

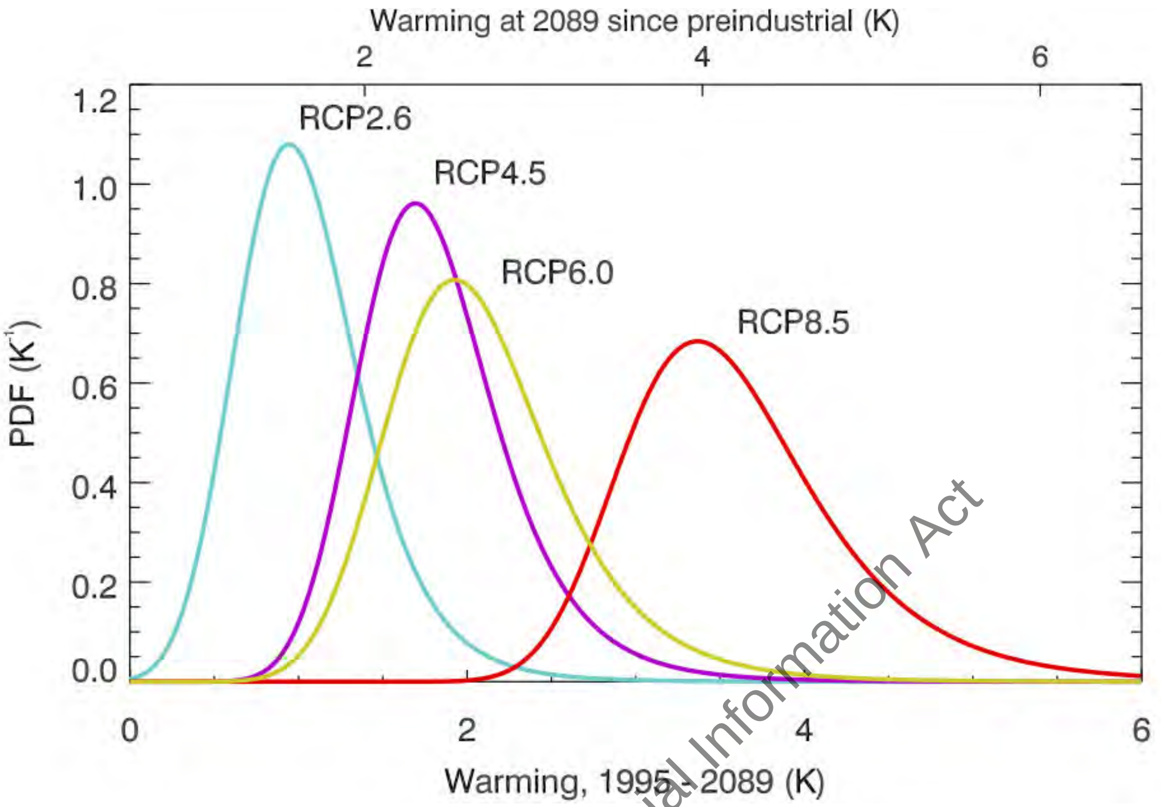

Figure 2*: Constrained future warming estimates as probability distribution functions. based on revised climate sensitivity ranges from Sherwood et al. (2020). Results are shown for four representative concentration pathways. (Figure 23 from Sherwood et al. 2020).*

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-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.

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

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[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.

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	
	Biogenic CH_4 - $MtCH_4$/yr	LLGHG - GtCO2e/yr	Biogenic CH_4 - $MtCH_4$/yr	LLGHG - $GtCO_2e$/yr
1.5C	180 (110 -	23 (14 - 28)	140 (60 - 200)	2.3 (-8.3 -

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

(~50% probability)	230)			12)
<2C (~66% probability)	190 (160 - 300)	30 (20 - 46)	155 (115 - 205)	12 (1.9 - 20)

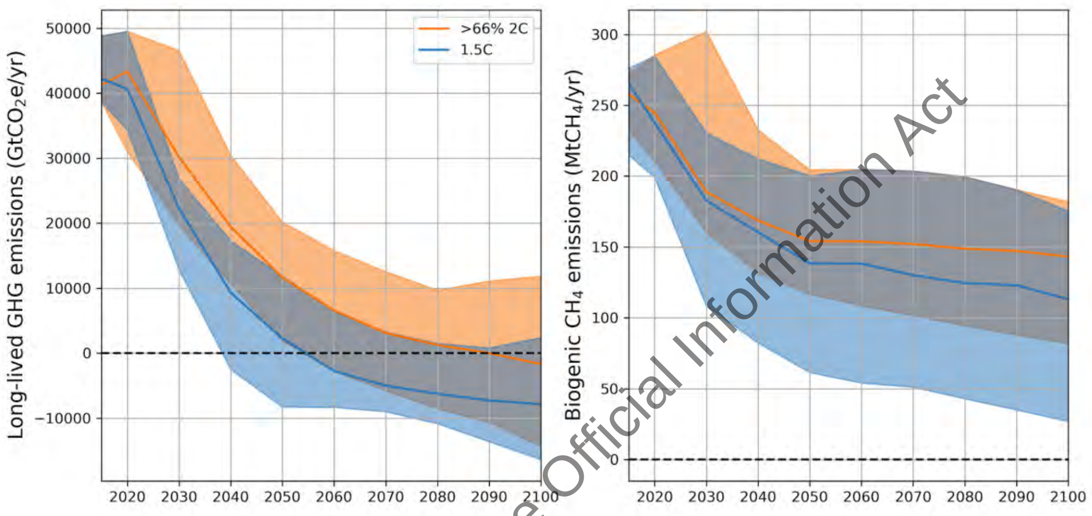

Figure 3: *The spread of GHG emission pathways in the IPCC SR1.5 scenarios database for Long-lived GHGs (CO_2 and N_2O) and biogenic CH_4. Solid lines denote the median of the scenario set.*

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.

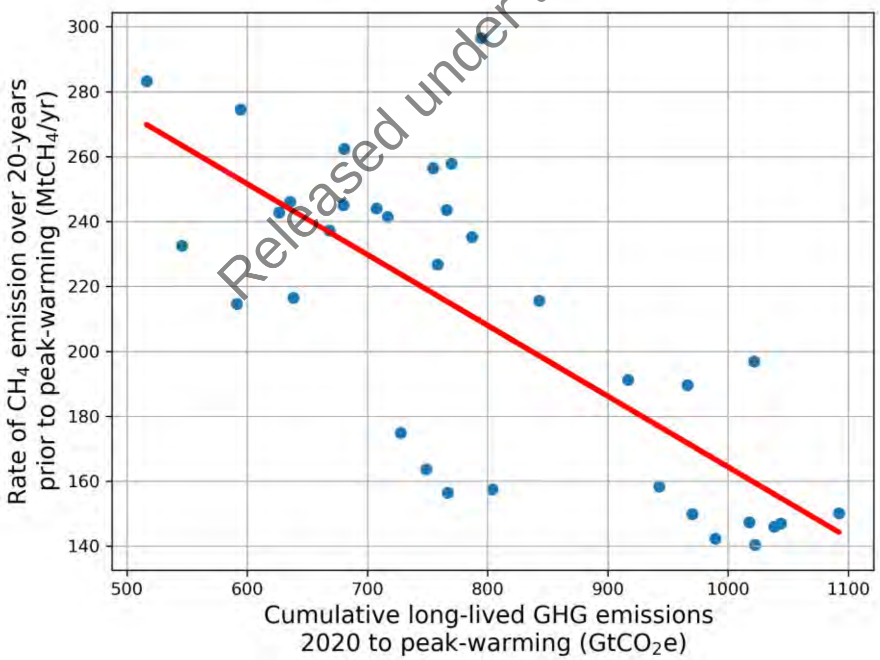

Figure 4: *Relation between CH_4 emissions 20 years prior to peak warming and the cumulative CO2-equivalent emissions (CO_2 + N_2O) based on GWP100 for scenarios that keep peak warming to 1.6-1.7C. This temperature range was chosen to give a large number of modelled scenarios that peak warming within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

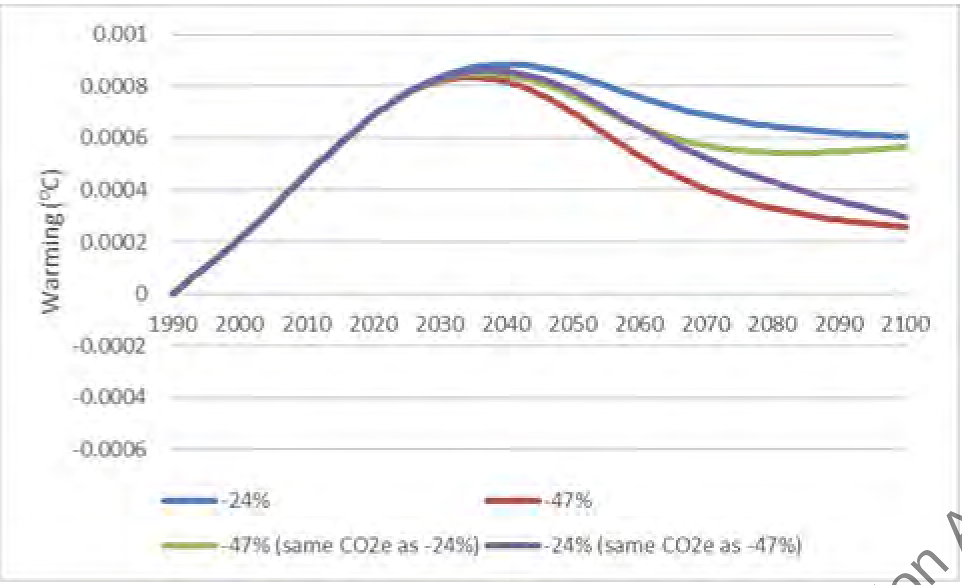

Figure 5: *An illustration of New Zealand's contribution to global warming since 1990. The blue and red pathways reach net zero emissions in 2050 for LLGHGs and fossil fuel* CH_4*, and have either 24% (blue) or 47% (red) reductions in biogenic* CH_4 *from 2017 levels to 2050. The green line has 47% biogenic* CH_4 *reduction but additional emissions of* CO_2 *to match the* CO_2*e 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.

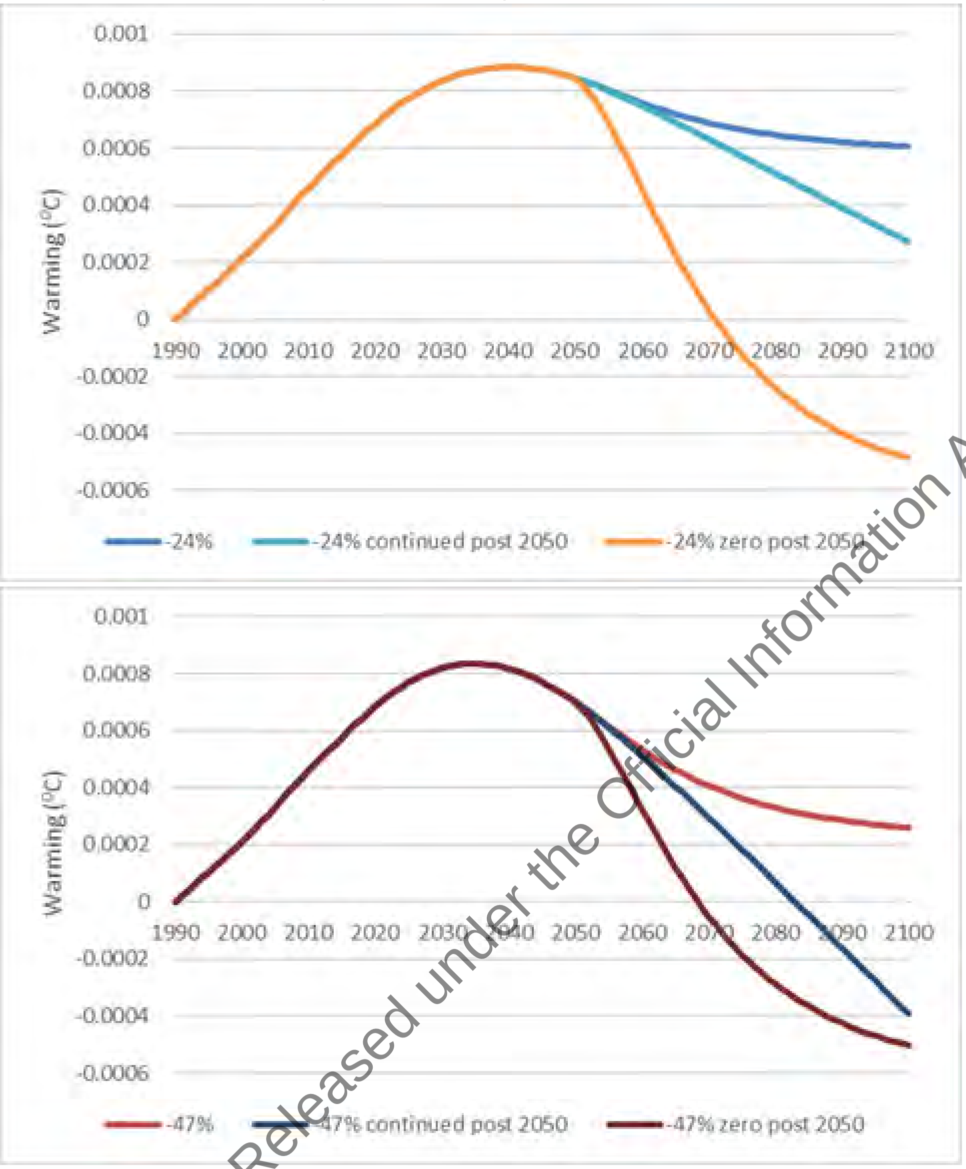

Figure 6: *As Figure 5, except emissions reductions continue beyond 2050. 24% biogenic CH_4 reduction by 2050, shown in the top panel and 47% reduction in the bottom panel. The panels have three scenarios: emissions unchanged after 2050, matching Figure 5; the biogenic methane reduction rate continuing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