The Three Salient Global Mitigation Pathways Assessed in Light of the IPCC Carbon Budgets

Summary

This paper examines the levels of risk associated with three widely discussed global mitigation pathways: a 1.5°C marker pathway, a 2°C marker pathway, and a G8 marker pathway. A very large number of analyses and debates refer to these or similar pathways. This paper assesses the three pathways in the light of Working Group I's recently released contribution to the Intergovernmental Panel on Climate Change *Fifth Assessment Report* (IPCC 2013), which provides three specific global carbon dioxide (CO_2) budgets, and associates them with specific risks of a global surface temperature increase of more than 2°C by the end of this century, relative to the 1850–1900 average.

Figure 1 presents the three pathways. Their key features and the findings of our analysis can be summarized thus:

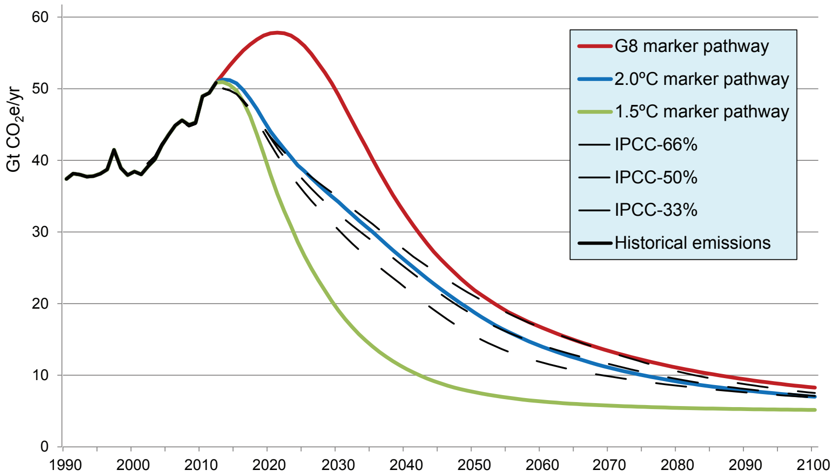

Figure 1. The three most politically salient mitigation pathways: G8 (red), 2°C (blue), and 1.5°C (green). Also shown (dotted lines) are three pathways consistent with the carbon budgets given by the IPCC, consistent with limiting warming to 2°C with 66%, 50%, and 33% probability, given non-CO_2 emissions as per RCP2.6.[3]

The **1.5°C marker pathway** is defined as the most challenging mitigation pathway that can still be defended as being techno-economically achievable (Höhne et. al. 2013). Emissions peak in 2014 and then decline (in all-gas terms) by as much as 7.1% per year. Cumulative greenhouse gas emissions for 2000–2100 are 1,720 gigatonnes CO_2 equivalent (1,720 Gt CO_2e). Our comparison of this pathway with the IPCC carbon budgets (which are all pegged to 2°C) does not allow us to estimate its likelihood of keeping warming below 1.5°C, but it does allow us to say that it has a significantly greater than 66% probability of staying below 2°C.

The **2°C marker pathway** is fashioned after well-known and often-cited emissions pathways that are typically presented as having a "likely" (greater than 67%, in the IPCC's terminology) chance of keeping warming below 2°C.[1] Emissions peak in 2014 and then decline (in all-gas terms) by as much as 3.4% per year. Cumulative emissions for 2000–2100 are 2,380 Gt CO_2e. Our comparison of this pathway with the IPCC budgets suggests that such pathways actually carry substantially higher risks than previously believed – they appear to have a less that 50% chance of holding warming below 2°C.

The **G8 pathway**, a marker of the high-level political consensus in developed countries, is based on specifications given in an official declaration of the Group of Eight industrialized countries at its 2009 Summit in L'Aquila, Italy (G8 2009). This pathway is not precisely specified in this declaration, but is sufficiently well-defined that we can compare it with the IPCC budgets. Emissions peak in 2021, decline (in all-gas terms) by a maximum of 4.5% per year, and have a cumulative budget of 2,860 Gt CO_2e.[2] We find that its chance of keeping below 2°C is far less than 33%.

Decision-makers face a choice among future pathways – a choice that will reflect political, economic and ethical considerations as much as science. This paper shows the consequences of choosing a less-ambitious pathway: a marked increase in climate risk. More specifically, it shows that, according to the IPCC's budget numbers, only the very ambitious 1.5°C has a high probability of holding warming below 2°C.

	1.5°C marker pathway	2.0°C marker pathway	G8 marker pathway
Peak year	2014	2014	2021
2020 emissions (Gt CO_2e)	38	44	58
Peak rate of decline (fossil CO_2 / all gases)	-9.0% / -7.1%	-5.5% / -3.4%	-4.5% / -4.4%
Year of peak decline rate (fossil CO_2 / all gases)	2029 / 2020	2075 / 2019	2040 / 2035
% reduction by 2050 vs. 1990 (all gases)	-80%	-49%	-42%
Budget 2000–2050 (Gt CO_2/Gt CO_2e)	995 / 1,430	1,390 / 1,850	1,635 / 2,215
Budget 2012–2050 (Gt CO_2/Gt CO_2e)	605 / 910	1,000 / 1,330	1,245 / 1,695
Budget 2000–2100 (Gt CO_2/Gt CO_2e)	1,020 / 1,720	1,660 / 2,380	1,995 / 2,860
Budget 2012–2100 (Gt CO_2/Gt CO_2e)	630 / 1,200	1,275 / 1,860	1,610 / 2,335

Table 1. Key data for the three marker pathways.

1 In particular, the 2°C pathway is based on a Climate Action Tracker pathway developed by Climate Analytics, EcoFys and the Potsdam Institute for Climate Impact Research (http://climateactiontracker.org/assets/publications/ Global_pathway_data_public_2012-11-29.xls.) See also UNEP (2012).
2 This high maximum rate of decline could be reduced by requiring an earlier peak.
3 For a detailed discussion of the RCPs, see van Vuuren et al. (2011). For a "beginner's guide", see Wayne (2013).

Introduction

In climate policy debates, there is broad agreement on the need to reduce greenhouse gas emissions to avoid dangerous climate change impacts – but not on how fast or how soon. This paper examines the levels of risk associated with three global mitigation pathways: a 1.5°C marker pathway, a 2°C marker pathway, and the G8 pathway. These pathways or very similar ones them figure in a very large number of analyses and policy debates, as they correspond to three extremely important socio-political storylines.

This paper assesses the three pathways in the light of Working Group I's recently released contribution to the Intergovernmental Panel on Climate Change *Fifth Assessment Report* (IPCC 2013), which provided three specific global carbon dioxide (CO_2) budgets, and associated them with specific risks of a global surface temperature increase of more than 2°C by the end of this century, relative to the 1850–1900 average.

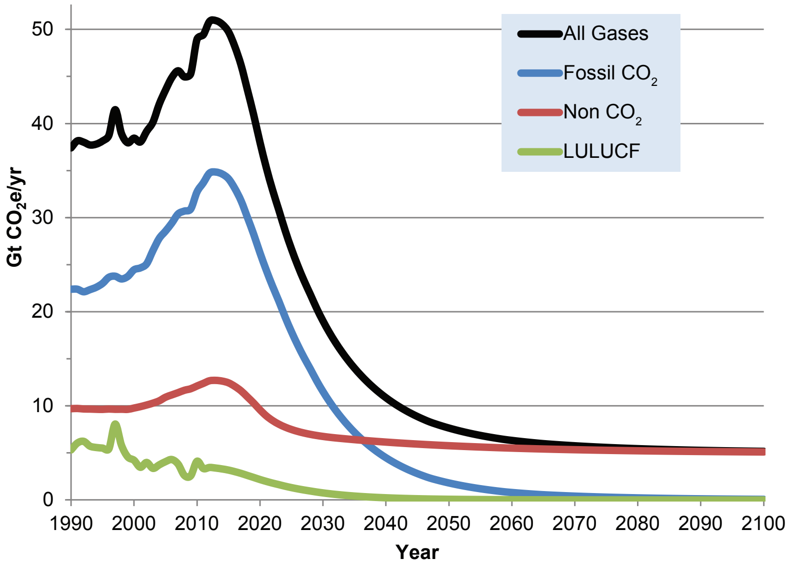

Figure 2: 1.5°C marker pathway, disaggregated into fossil CO_2, LULUCF CO_2, and non-CO_2 gases.

The 1.5°C marker pathway

The 1.5°C marker pathway is defined to be the most challenging mitigation pathway that can still be defended as techno-economically achievable (Höhne et al. 2013). Cumulative emissions of all greenhouse gases for 2000–2010 are 1,720 Gt CO_2. Non-CO_2 emissions have a "floor" of 5 Gt CO_2 annually, to account for the potentially irreducible requirements of agriculture.[4] Fossil-fuel emissions and emissions from land use, land-use change and forestry (LULUCF) both decline asymptotically to zero, with budgets of 930 and 89 Gt CO_2, respectively, for 2000–2100.

Key features of the 1.5°C marker pathway include the aggressive front-loading of mitigation, the above-mentioned floor on non-CO_2 gases, and the absence of negative emissions of any kind.[5] This defines it as a highly precautionary pathway. Rather than allowing higher emissions in the early decades and assuming they'll be offset by negative CO_2 emissions in later decades (as in the IPCC's rapid-mitigation pathway, RCP 2.6) or by lower non-CO_2 emissions, this pathway emphasizes the need for immediate and dramatic mitigation. It can fairly be characterized as an "emergency mobilization" pathway.

On this pathway, global emissions peak in 2014; the fastest rate of fossil CO_2 reductions is 9% per year, and for all gases combined, it is 7.1%. Cumulative non-CO_2 emissions are lower than those in the RCP2.6 pathway by about 20%, but annual non-CO_2 emissions still remain above a fairly high minimum level ("floor") of around 5 Gt CO_2e. This plausible but optimistic estimate of the irreducible emissions of methane and N_2O associated with agriculture limits the extent to which the overall target depends on a miracle in agricultural technology – or, in a less sanguine view, the sacrifice of adequate nutrition for the preservation of the climate.

1.5°C marker pathway				
Peak year: 2014	Maximum rate of annual fossil CO_2 reduction: 9.0%			
Annual emissions (Gt CO_2e)	**2010**	**2020**	**2050**	**2100**
	49	38	8	5
Cumulative Emissions	**2000-2011**	**2012-2050**	**2000-2050**	**2000-2100**
Fossil CO_2 Budget (Gt CO_2)	345	527	907	930
LULUCF CO_2 Budget (Gt CO_2)	44	31	88	89
All CO_2 Budget (Gt CO_2)	388	558	995	1,018
Non-CO_2 Budget (Gt CO_2e)	132	291	436	702
All Gas Budget (Gt CO_2e)	520	849	1,431	1,720

Table 2: Detailed budget by gas and source for 1.5°C marker pathway. CO_2e is calculated using 100-year global warming potentials per Forster et al. (2007).

4 The appropriate "floor" for emissions from agriculture remains an open question. Even basic categories are vague, since a CO_2 component of agriculture that isn't from land clearing is typically grouped with industrial CO_2 emissions. Nonetheless, current agricultural emissions of CH_4 and N_20 are estimated at 5 to 6 Gt CO_2e annually, and we use that range as our floor. It seems plausible that both population growth and more equitable access to food can be offset by improvements in agricultural practices and technology. Bowerman et al. (2011) test the significance of alternative floors and find that they matter a lot, and CO_2 budgets would be reduced if higher floors were assumed.

5 Because the emissions budgets that define these pathways are net budgets, negative emissions (whether from afforestation, biochar, BECCS, or even free air capture) can still legitimately be part of a mitigation scenario consistent with this 1.5ºC pathway. If negative emissions become practical, this would simply allow larger positive emissions while holding to the same net budget and same risk of exceeding 1.5ºC. Alternatively, these technologies could make possible a more rapid reduction of net radiative forcing and a corresponding reduction in the risk of adverse impacts and the costs of adaptation.

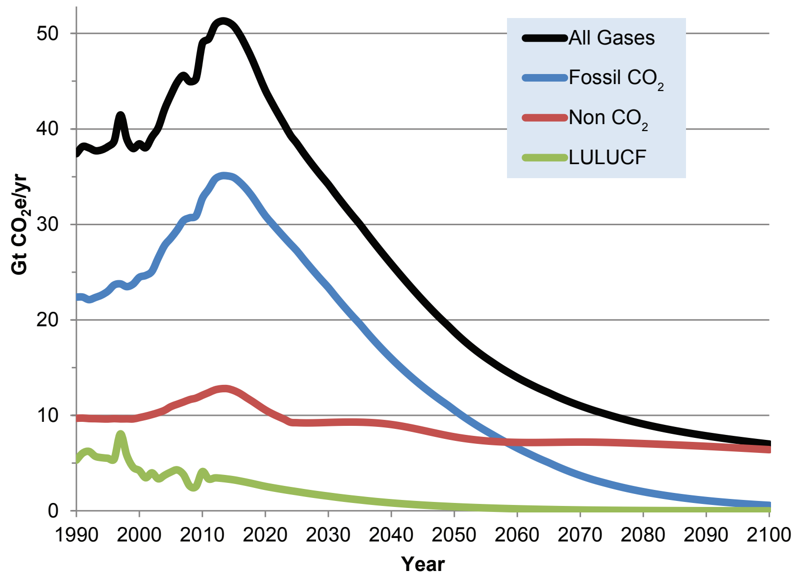

Figure 3: 2°C marker pathway, disaggregated into fossil CO_2, LULUCF CO_2, and non-CO_2 gases.

The 2°C marker pathway

The 2°C marker pathway is closely based on the Climate Action Tracker (CAT) 2°C pathway and essentially matches the reference pathway in the United Nations Environment Programme (UNEP) "emissions gap" reports (see footnote 1 and UNEP 2012). It has been corrected for recent history, but otherwise has the same profile and cumulative CO_2e emissions. Like the 1.5°C marker pathway, it peaks immediately (2014). Its rate of fossil CO_2 decline then increases gradually, reaching 3% in 2019, 4% in 2036, and 6% (the maximum) in 2066; for all gases combined, the maximum rate of decline reaches 3.4% Also like the CAT 2°C pathway, its emissions in 2020 are 44 Gt CO_2e. Cumulative emissions (2000–2100) are about 1,420 Gt CO_2 for fossil fuels, 110 Gt CO_2 for LULUCF, and 850 Gt CO_2e from non-CO_2 gases, totaling about 2,380 Gt CO_2e. We have adopted the RCP2.6 emissions pathway for the non-CO_2 component of the 2°C marker pathway.

Like the 1.5°C marker pathway, this pathway front-loads mitigation, assumes no negative emissions, and has a substantial non-CO_2 floor out to 2100. However, and despite the fact that it would represent a dramatic change from business as usual, it is not an "emergency pathway" in the same sense as the 1.5°C marker pathway. The 2°C pathway, as challenging as it might be, is more "realistic". For example, a variety of parties, including UNEP (2012 and previous publications), have searched for ways to close the gap between today's pledges and UNEP's widely cited 44 Gt CO_2 2020 global emissions target. They have found such ways, and while the required policies would represent substantial transformations in energy policy, investment patterns and governance systems, they are all well within reach.

How big is the difference in climate risk between the 1.5°C and 2°C marker pathways? Climate Action Tracker has estimated (based on the MAGICC climate model) that its 2°C pathway, upon which the 2°C marker is modeled, has a roughly 67% chance of keeping global warming below 2°C in 2100 ("likely" in the IPCC's terminology). Our calibration with IPCC's *AR5*, however, suggests that it actually has less than a 50% chance of holding the 2°C line – compared with a much greater than 66% chance for the 1.5°C marker pathway.

2.0°C marker pathway				
Peak year: 2014	Maximum rate of annual fossil CO_2 reduction: 5.5%			
Annual emissions (Gt CO_2e)	**2010**	**2020**	**2050**	**2100**
	49	44	19	7
Cumulative Emissions	**2000-2011**	**2012-2050**	**2000-2050**	**2000-2100**
Fossil CO_2 Budget (Gt CO_2)	345	890	1,235	1,420
LULUCF CO_2 Budget (Gt CO_2)	45	65	110	110
All CO_2 Budget (Gt CO_2)	390	955	1,345	1,530
Non-CO_2 Budget (Gt CO_2e)	130	380	510	850
All Gas Budget (Gt CO_2e)	520	1,235	1,855	2,380

Table 3: Detailed budget by gas and source for 2°C marker pathway. CO_2e is calculated using 100-year global warming potentials per Forster et al. (2007).

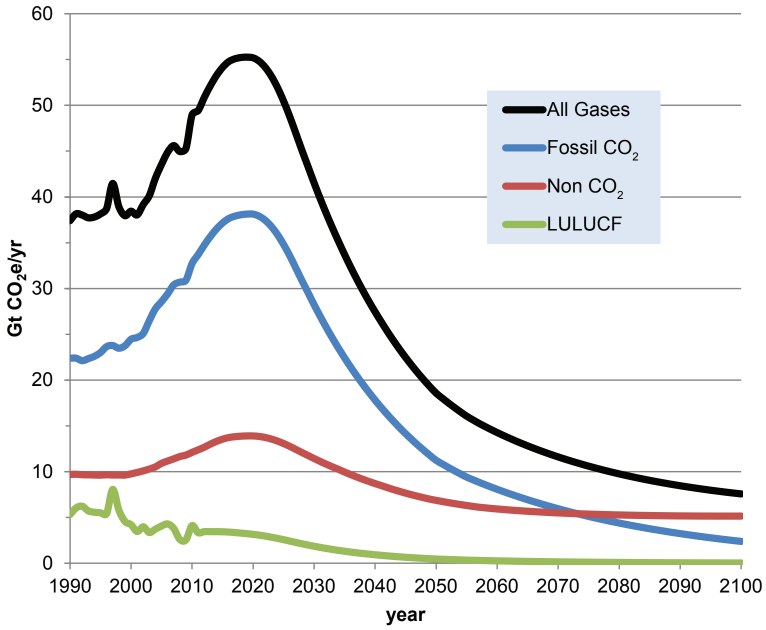

Figure 4: The G8 pathway, disaggregated into fossil CO_2, LULUCF CO_2, and non-CO_2 gases.

The G8 marker pathway

The G8 marker pathway is based on the emissions goals expressed by the ministers of the G8 at their 2009 conference at L'Aquila, Italy (G8 2009). The L'Aquila text is ambiguous in several key ways, as it specifies only that the peak must be "as soon as possible" and omits the reference year against which goal the 50% reduction in "global emissions" by 2050 is to be calculated. We have interpreted this as a pathway that peaks immediately after 2020 and uses a 2005 base year for the 2050 reduction of 50%. The G8's failure to explicitly state 1990 as the base year, and the fact that this comes from the G8 countries (some of which have used 2005 as a base year for their pledges) suggests that our use of 2005 as the base year is justifiable in the G8 marker pathway. A more stringent interpretation of the *de facto* official pathway would arise if it were based on the 1990 base year proposed by the EU, but this proposal has not been accepted by the G8.[6]

Overall the G8 pathway has CO_2 emissions over the century of about 2,000 Gt CO_2, and total emissions of about 2,900 Gt CO_2e. This pathway, with a maximum annual rate of fossil CO_2 emissions reduction of 4.5%, is not unambitious by conventional measures, but given that it has a much less than a 33% chance of keeping warming below 2°C, it cannot plausibly be called a 2°C pathway.

How we estimate climate risk for the three pathways

Calculating a temperature change from a given emissions pathway – even in probabilistic terms – is not a simple task. It was only with the widely cited publication of a landmark

G8 marker pathway				
Peak year: 2021	Maximum rate of annual fossil CO_2 reduction: 4.5%			
Annual emissions (Gt CO_2e)	**2010**	**2020**	**2050**	**2100**
	49	58	22	8
Cumulative Emissions	**2000-2011**	**2012-2050**	**2000-2050**	**2000-2100**
Fossil CO_2 Budget (Gt CO_2)	345	1,165	1,510	1,860
LULUCF CO_2 Budget (Gt CO_2)	45	80	125	135
All CO_2 Budget (Gt CO_2)	390	1,245	1,635	1,995
Non-CO_2 Budget (Gt CO_2e)	130	380	510	850
All Gas Budget (Gt CO_2e)	520	1,625	2,145	2,845

Table 3: Detailed budget by gas and source for the "G8 pathway." CO_2e is calculated using 100-year global warming potentials per Forster et al. (2007).

6 The EU's goal requires a peak in 2020 and a 50% reduction in 2050 below 1990 levels, rather than 2005 levels. This would lead to a somewhat smaller CO_2 budget (roughly 1,390 Gt CO_2 for 2012–2100 instead of 1,605 Gt CO_2e) and all-gas budget (2,095 Gt CO_2e instead of 2,335 Gt CO_2e). This would give it a far better chance than the G8 pathway of keeping warming below 2°C, but still considerably less than a 33% chance.

	>66% chance	>50% chance	>33% chance
Cumulative (1880 forward) CO_2 budget (Gt CO_2) (assuming no non-CO_2 forcing)	3,667	4,437	5,720
Historical (1880-2011) CO_2 emissions (Gt CO_2)	1947	1,947	1,947
Adjusted CO_2 budget (1880 forward) (Gt CO_2) (assuming non-CO_2 forcings from RCP2.6)	2,933	3,080	3,227
Remaining (2012 forward) CO_2 budget (Gt CO_2)	986	1133	1280

Table 4: The IPCC's three carbon budgets, translated into more easily digestible form.

paper, Meinshausen et al. (2009), that 2°C risk probabilities were systematized in a widely accepted manner. The Meinshausen paper was supplemented by a calculator (giving results derived from the MAGICC climate model) that provided 2°C risk probabilities (including an often-cited "illustrative default") based on 2000–2050 cumulative CO_2 emissions. These estimates were very widely adopted – for example, to provide the figures in the influential Carbon Tracker Initiative (2011) study on "unburnable carbon," and in 350.org's "Do the Math" campaign. As noted above, many of the 2°C pathways now in use in climate policy, such as the Climate Action Tracker 2°C pathway and the principal reference pathway in UNEP's "emissions gap" reports, are similarly based on the Meinshausen analysis.

However, and critically, the *Fifth Assessment Report* (IPCC 2013) presents more conservative estimates of the budgets associated with various 2°C risk probabilities. In particular, it gives the 2°C-compliant carbon budgets as follows:

> *Limiting the warming caused by anthropogenic CO_2 emissions alone with a probability of >33%, >50%, and >66% to less than 2°C since the period 1861–1880, will require cumulative CO_2 emissions from all anthropogenic sources to stay between 0 and about 1560 GtC, 0 and about 1210 GtC, and 0 and about 1000 GtC since that period respectively. These upper amounts are reduced to about 880 GtC, 840 GtC, and 800 GtC respectively, when accounting for non-CO_2 forcings as in RCP2.6. An amount of 531 [446 to 616] GtC, was already emitted by 2011.*

Converting these figures from gigatonnes of carbon (GtC) to gigatonnes of carbon-dioxide equivalent (Gt CO_2e) and then partitioning those CO_2e gigatonnes between CO_2 and non-CO_2 (per the discussion below) and distributing them across time, as shown in Figure 1, yields the figures in Table 4.

For ease of comparison, Figure 5 shows the cumulative budgets from 2012 forward for the three marker pathways in Gt CO_2 terms.

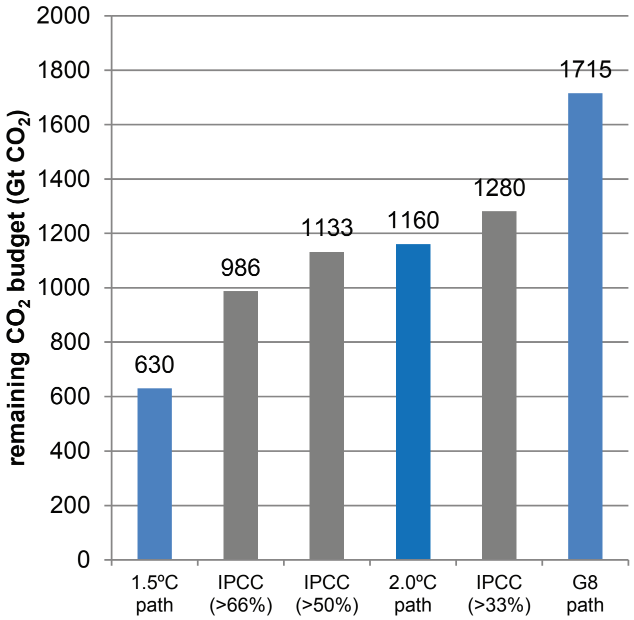

Figure 5: The remaining (post 2012, forward to exhaustion) CO_2 budgets associated with the three mitigation pathways, as well as the IPCC's three carbon budgets, shown in exactly the same terms.

	1.5°C marker	2°C marker	G8 marker
2012-2100 Total GHG emissions (Gt CO_2e)	1,200	1,860	2,325
2012-2100 non-CO_2 greenhouse gases (Gt CO_2e)	570	720	720
2012-2100 CO_2 emissions (Gt CO_2)	630	1,140	1,605
Remaining (2012 forward) CO_2 budget (Gt CO_2)	630	1,160	1,715

Table 5: The 2012-2100 emissions budgets associated with the marker pathways (along with the RCP2.6 Representative Concentration Pathway), expressed in Gt CO_2 terms for comparison with the IPCC budgets (figures rounded to nearest 5 Gt CO_2).

From this, we can draw conclusions about risk probabilities that are consistent with the analysis in the IPCC's AR5:

- The 1.5°C marker pathway, with 630 Gt CO_2 of emissions from 2012 forward, would have a significantly greater than 66% chance of keeping warming below 2°C, as both its CO_2 and non-CO_2 budgets are significantly lower than those behind the IPCC's 66% pathway.

- The 2°C marker pathway would have a 33% to 50% probability of keeping warming below 2°C, as its carbon budget lies between the IPCC 33% and 50% budgets, (while its non-CO_2 emissions are equivalent to the RCP2.6 emissions assumed by the IPCC).

- The G8 marker pathway has a CO_2 budget well above the IPCC's 33% budget. Given this, it cannot be plausibly considered to be a 2°C pathway, notwithstanding the fact that the G8's formally stated its emissions goals in the context of the 2°C objective.

Pathways, assumptions and risks

As the "2°C threshold" came to define the global climate effort, it became common to characterize any given emissions pathway or greenhouse gas budget by its probability of forcing a temperature increase of 2°C or more. More recently, as the risks of 2°C have become clearer and stricter targets such as 350 ppm[7] and 1.5°C have come to the fore, this standard practice has been applied to these targets as well. However, it is important to note that there is no unique pathway associated with any given temperature or risk threshold. Many different pathways can yield the same likelihood of exceeding 2°C, or any other target.

Conversely, and notwithstanding the IPCC's decision to specify 2°C emission budgets, an emission budget alone does not fully determine the probability of limiting warming to 2°C (or to any other given threshold). Other factors must also be specified. In general, once you have an emissions budget, there are three additional choices to make: how to distribute emissions reductions over time, how to allocate the budget between CO_2 and non-CO_2 greenhouse gases, and whether "negative emissions" are considered, and to what degree.[8]

Front-loading vs. back-loading of emissions reductions

Any given emissions budget can be distributed in a way that favors near-term or far-term reductions ("front-loading" into the first decades, or "back-loading" to later decades). There are several common arguments for deferring mitigation, such as that it reduces immediate costs, making it easier to generate political support, and that it reduces total costs through discounting and technological change. The latter argument is particularly problematic, for as the International Energy Agency has noted, deferring mitigation is probably a "false economy" and can significantly increase total costs over time.[9] Back-loading also increases projected impacts and risks in a variety of ways, the most important being that it may cut off future options. For example, if impacts are greater than expected or if the effectiveness of mitigation measures is lower, more mitigation may be required than initially anticipated. And while it may be possible to compensate with additional investment or mitigation effort, it may not be – some goals may simply have slipped out of reach, or might require undesirable measures (e.g. geoengineering) that would not otherwise have been necessary.

This is not to trivialize the extreme difficulties posed by a dramatic transition from today's world of steadily growing global emissions to a new world of rapid and sustained global reductions. But it does suggest that a precautionary pathway should front-load mitigation to the greatest extent possible.

CO_2 vs. non-CO_2 emissions

Another crucial element in the risk estimation of different emissions pathways is the set of assumptions made about non-CO_2 greenhouse gases. In the IPCC's pathways, non-CO_2 forcings are taken to be consistent with RCP2.6, and we have done likewise for the 2°C marker pathway and G8 pathway. Non-CO_2 emissions in the 1.5°C pathway, on the other hand, are taken to be about 20% lower cumulatively than in RCP2.6, and to level off toward the second half of the century at a minimum level roughly equal to the RCP2.6 level; this to account for the emissions associated with agriculture. (See the detailed discussion of the 1.5°C marker pathway.)

As noted previously, assumptions about non-CO_2 emissions are extremely important, and yet the role and dynamics of non-CO_2 gases and other forcings (e.g., black carbon and sulfate aerosols) are complex and often confusing. For example, the influential papers by Rogelj et. al (2011; 2012), which use the same model calibration as Meinshausen et. (2009) but the non-CO_2 emissions specified in RCP2.6, produce significantly higher CO_2 emissions budgets than Meinshausen et. al. (2009). Similarly, the IPCC's budgets, which also use the RCP2.6 non-CO_2 forcings, give a 33% budget (33% chance of not exceeding 2°C) that is 2,053 Gt CO_2 larger than its 66% budget when excluding

7 This figure refers to parts per million of CO_2 in the atmosphere; for the week beginning on 20 October 2013, the average recorded by the U.S. National Oceanic & Atmospheric Administration's Earth System Research Laboratory at Mauna Loa was 393.95 ppm; see http://www.esrl.noaa.gov/gmd/ccgg/trends/weekly.html.

8 It is differences in assumptions about emissions that lead to the very different emissions budgets associated with particular risk levels in recent papers – most prominently by Rogelj et al. (2011; 2012) – relative to the estimates made by Meinshausen et. al. (2009). The critical point here is that the Rogelj et al. papers use the same parameterizations of the MAGICC model. For example, Meinshausen (2009) estimates the CO_2 budget for a 67% chance of staying below 2ºC to be ~1160 Gt CO_2 between 2000 and 2050 and ~1680 Gt CO_2e, while Rogelj et al. (2011) estimates emissions of the "median" pathway with a >66% chance of staying below 2ºC to be ~1880 Gt CO_2e between 2000 and 2050. The changed assumptions come from the incorporation of assumptions about non-CO_2 gases from the RCP2.6 emissions pathway, as opposed to the "Equal Quantile Walk" method used in Meinshausen et al. (2009).

9 For example, the 2011 World Energy Outlook (IEA 2011) states: "Delaying action is a false economy: for every $1 of investment avoided in the power sector before 2020 and additional $4.3 would need to be spent after 2020 to compensate for the increased emissions."

non-CO_2 forcings. This difference, which is ultimately related to the fact that different greenhouse gases have different radiative implications over time, drops to a mere 294 Gt CO_2 when non-CO_2 forcings are included in the comparison (see Table 4).

For all these reasons, the relationship between CO_2 emissions, non-CO_2 emissions and climate risk is quite uncertain – which further justifies precaution when making non-CO_2-related target-mitigation-pathway tradeoffs.

Negative emissions

The term "negative emissions" designates CO_2 that is removed from the atmosphere, and can refer to either techno-industrial processes (e.g., Biomass Energy with Carbon Capture and Sequestration, or BECCS) or changes in land-use practices that yield substantial enhancement of carbon sinks (e.g. afforestation and low-carbon agro-ecological techniques).[11] While the economic practicality of large-scale negative-emissions programs remain undemonstrated, some of the possibilities are easily imaginable – for example, we could plant great numbers of trees[12] – and a wide range of published scenarios do consider the large-scale removal of CO_2 from the atmosphere in the second half of the century. Indeed, this is argued by many to be a necessity.[13]

However, although practical negative emission options would prove a great boon, it is risky to assume their future availability at large scale. Doing so tempts decision-makers to defer ambitious near-term mitigation while claiming to be adhering to a 2°C target, even though, in fact, that target is slowly drifting out of reach. As noted above, back-loading emission reductions increases risk in dangerous ways.

In sum, the assumptions that are made in these three areas – front-loading vs. back-loading, CO_2 vs. non-CO_2 mitigation, and negative emissions – have the direct result of specifying mitigation pathways that allow for larger or smaller fossil-fuel CO_2 budgets. Critically, they also allow larger or smaller emissions in the near future.

Conclusions

The three marker pathways presented in this paper have significantly different risks associated with them. Making certain plausible assumptions with respect to front-loading, non-CO_2 mitigation, and negative emissions, we can compare the emissions budgets associated with these pathways to those presented in the IPCC's *AR5*. By so doing, we can conclude the following:

- The 1.5°C market pathway has a considerably greater than 66% chance of keeping the warming below 2°C. We are unable to draw meaningful conclusions about its odds with respect to the 1.5°C target, but we are able to say that it is alone among these pathways in having a high probability of holding the 2°C line.

- The 2°C marker pathway has a slightly less than 50% chance of keeping warming below 2°C. The very influential family of pathways that is represents carry substantially higher risks of exceeding 2°C than was previously estimated.

- The G8 marker pathway has much less than a 33% chance of keeping warming below 2°C. In fact, it cannot plausibly be taken as a 2°C pathway, and this notwithstanding the fact that the 2009 G8 declaration stated its emissions goals in the context of the 2°C objective.

Decision-makers now face a choice among future pathways. The temptation to choose a pathway that allows us to defer action will be great, but deferral has consequences. It increases the reliance on future technological breakthroughs (e.g. negative emission technologies) that may not prove available. As *AR5* explains, for example, there are risks of carbon-cycle feedbacks that would accelerate non-anthropogenic emissions (e.g. the release of methane hydrates, or increased wildfires, or the accelerated deterioration of the Greenland ice sheet). And it increases the risk of truly catastrophic impacts, such as several meters of sea-level rise. It is helpful, in this context, to remember that 2°C – once considered the plausible margin of "dangerous" climate change – is now widely understood among climate scientists to mark the approximate point of transition from "dangerous" to "extremely dangerous" climate change, and possibly to altogether unmanageable levels of warming (see, e.g., Anderson and Bows 2011).

Ultimately, the choice of a global mitigation pathway reflects political, economic and ethical considerations as much as scientific ones. These decisions are inseparable from the assignment of newly-scarce emissions rights across countries and classes and generations, and choices about who will bear the associated costs and risks. And this, of course, is why the subject of ambitious mitigation pathways is so fraught, and so crucial. An "emergency transition" like the one implied by the 1.5°C pathway (and arguably the 2°C pathway as well) will be neither cheap nor easy, and this despite the vast flowering of low-emissions energy technology that's now on the near horizon. The budget approach makes it obvious that, despite the difficulties, such a transition is necessary.

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10 In particular, methane has a short atmospheric lifetime, whereas N_2O and many F-gases have lifetimes comparable to CO_2 or longer.

11 The particular confusion here is that a broad category of non-land-use CO_2 emissions is frequently called "fossil fuel emissions", even though it usually includes modern biofuels used for energy, and often non-energy industrial CO_2 emissions (e.g. from cement manufacturing) as well.

12 For example, Hansen et. al. (2011) estimate the total 21st century biosequestration potential at 100 GtC, which is equivalent to about 370 Gt CO_2, based entirely on afforestation and reforestation.

13 Often, mitigation deferral is wearily accepted as necessary. For example, *Adequacy and feasibility of the 1.5C long-term global limit* (Schaeffer et al. 2013) notes: "Constrained by real emissions until 2010 and energy-economic reduction potential until the 2020s, the 1.5°C scenarios necessarily require net-negative CO_2 emissions in the second half of the 21st Century. The later the emissions peak, the more CO_2 needs to be removed starting around the 2050s."

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