Informing policy in accordance with best available science

Glen Peters, Center for International Climate and Environmental Research – Oslo (CICERO), Norway

An Intergovernmental Panel on Climate Change (IPCC) Special Report on 1.5°C should focus on resolving fundamental scientific and political uncertainties, not a fixation on developing unachievable mitigation pathways.

The Paris Agreement exceeded the expectations of many, with an ambitious temperature target and a long-term goal to guide future mitigation. Achieving a global temperature increase of "well below 2°C", while allowing for the possibility of 1.5°C, requires a "global peaking of greenhouse gas emissions as soon as possible … and to undertake rapid reductions thereafter to achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century"[1]. The long-term mitigation goal is broadly consistent with a range of mitigation scenarios assessed in the IPCC Fifth Assessment Report (AR5)[2], and more recent studies[3], but there are sufficient uncertainties to ensure years of scientific and political debate.

There does not seem to be a broad understanding of the challenges to achieve the long-term mitigation goal, particularly when technical and political feasibility are considered. Misunderstanding the challenges may mean that policy efforts are misdirected making 1.5°C/2°C quickly unachievable. Here I build on key findings in the IPCC AR5[2], the UNEP Emissions Gap Report[4] and the UNFCCC Intended Nationally Determined Contributions (INDC) Synthesis Report[5], to identify key scientific knowledge gaps on mitigation pathways that need to be addressed in the potential IPCC Special Report specifically requested by policy makers in Paris[1]. The IPCC was invited to assess both impacts and mitigation[1], but I only focus on mitigation.

Well below 2°C

A key ambiguity in the Paris Agreement is what "well below 2°C" means. Interpretations on 'well below' are likely to persist, but more fundamentally, are ambiguities about the time-period the target is binding and the likelihood of staying below the target given a variety of different emission pathways.

The IPCC finds the increase in the global temperature between the average of the 1850–1900 period and the 2003–2012 period is 0.78°C[6], but recent data suggests that 2015 was 1°C greater than the base period[7] and preliminary analysis suggests that February 2016 exceeded 1.5°C above pre-industrial temperatures[8]. The time period and method of temporal averaging, in combination with interannual variability, will lead to constant innuendo that 1.5°C/2°C has been exceeded. Together with a potential peak and decline in temperatures after carbon dioxide removal[2] (CDR), it may not be known for many decades if 1.5°C/2°C has been exceeded or successfully avoided.

More fundamentally, is the required mitigation to avoid 1.5°C/2°C given uncertainties in the climate system. The IPCC AR5 gave prominence to the near-linear relationship between temperature increase and cumulative carbon emissions as a policy relevant tool[6]. Primarily due to uncertainties in the climate system, cumulative carbon quotas are stated probabilistically with the IPCC reporting values for a 33%, 50%, and 66% likelihood of exceeding different temperature thresholds[6]. Changing the temperature threshold or probability has significant implications (Supplementary Figures 1 & 2). The total cumulative carbon quota increases by 900GtCO_2 if the temperatures threshold increases from 1.5°C to 2°C with a 66% likelihood. The total quota for a 2°C threshold decreases by 800GtCO_2 for a decrease in the likelihood from 66% to 50%. We already see some subtle shifts in the goal posts from 66% to 50% for more stringent scenarios[4,5], perhaps confirming concerns of keeping results politically palatable[9,10].

An uncertain budget

The high profile cumulative carbon quota concept carries several and significant uncertainties, many of which are not fully appreciated, and these limit the political usefulness of the quota concept. First, a key uncertainty with the cumulative emission concept are the carbon-only quotas. The IPCC reported a likely range (one standard deviation) based on expert judgement of 0.8-2.5°C/1000PgC, but gave no statistical distribution[11]. To determine the total carbon quota, the IPCC later assumed a normal distribution[11]. If a lognormal distribution is used instead, or if the range has small changes, the 66% quota for a 2°C threshold may vary by ±250GtCO_2 (Supplementary Table 1 & 2). Second, the budgets need to be adjusted for the temperature contribution from non-CO_2 emissions leading to a large spread depending on the scenario and methodology applied[12] (±300GtCO_2 for 66% chance of 2°C). Models generally estimate the non-CO_2 adjusted quotas[12], but these may vary non-linearly with temperature due to the different behaviour of CO_2 and non-CO_2 emissions. Third, the non-CO_2 adjusted quota is reduced by past CO_2 emissions introducing an additional uncertainty from historical cumulative emissions (±200GtCO_2). Combining these uncertainties using simple uncorrelated error propagation, the remaining budget from 2016 for 2°C with 66% likelihood could be 850±450GtCO_2 to one standard deviation (see Supplementary Information). Despite efforts to reduce these uncertainties, it is likely that many of the uncertainties on the remaining quota will remain persistently large, questioning the direct applicability of carbon quota concept in policy.

Expanding the budget

A problematic feature of the carbon quota concept is that the quota is not fixed, and can be temporarily increased by removing carbon from the atmosphere, often leading to temperature overshoot[2]. Taken to its extreme, the continued use of CDR beyond 2100, allows almost any temperature limit to be achieved depending on the scale and duration of CDR. Nearly all the 2°C scenarios assessed by the IPCC use CDR leading to net negative emissions (below zero) by 2100[2,13]. The IPCC AR5 assessed[2] 116 scenarios consistent with a likely chance of keeping global average temperature below 2°C. Of the 112 2°C scenarios reporting sufficient data, 108 use large-scale Carbon Capture and Storage (CCS), 107 remove carbon from the atmosphere by combining bioenergy with CCS, and 101 have net negative emissions (below zero) by 2100. The few scenarios that do not use CCS require rapid emission reductions with close to zero emissions before 2050 (Supplementary Figure 4). According to the scenarios[2], the current enthusiasm of ramping up renewable technologies, even at high rates, is unlikely to be sufficient for a 1.5°C/2°C goal.

The UNEP Emissions Gap Report[4] and the UNFCCC INDC Synthesis Report[5] used a smaller subset of scenarios that followed a baseline to 2020 before implementing a globally uniform carbon price (Figure 1). This subset of scenarios is arguably more applicable and relevant for the Paris Agreement[4,5] then the full set of scenarios assessed in the IPCC AR5. However, methods of presenting these scenarios often hide policy relevant details by only showing scenario ranges and not individual scenarios (Figure 1a shaded region). These 'Delay 2020' scenarios all lead to net negative emissions from fossil fuel and industry from about 2060 (Figure 1b). They deploy significant amounts of CCS on fossil fuels and bioenergy with levels (Figure 1c) comparable to current emissions of around 40GtCO_2/yr. CDR can also occur via afforestation, with one model removing about 20GtCO_2/yr in 2030 and 2040 (Figure 1d), a level far greater than all other models[2], but potentially consistent with bottom up estimates[14]. Supplementary Figure 5 outlines other key characteristics of these scenarios.

Most large-scale CDR is realised in models by combining bioenergy with CCS[2] (BECCS), both technologies of which have deep uncertainties. There is a broad-debate on bioenergy potentials, with high agreement up to 100EJ/yr in 2050, medium agreement up to 300EJ/yr, and low agreement beyond 300EJ/yr[15]. The 'Delay 2020' scenarios use around 150EJ/yr by 2050 and 300EJ/yr by 2100 (Supplementary Figure 5), overlapping the highly debated bioenergy potential levels. CCS allows the continued use of fossil fuels, but technical and political difficulties mean that CCS is well behind the progress envisaged 10 years ago[16] with only about 28MtCO_2/yr capture capacity in 2015[17], with the actual levels of permanent storage unknown. The combination of these technologies to give large-scale BECCS deployment is highly uncertain[9], but models indicate that BECCS is relatively inexpensive in the long term based on potential technology development and assumed discounting rates[18].

Generally, models have only used BECCS and afforestation to remove carbon from the atmosphere[2], but other approaches include enhanced weathering, direct air capture, ocean fertilisation and biochar. Studies indicate that all CDR technologies have a variety of economic, biophysical, and ecological constraints that may limit their use[13,19,20]. To maximise CDR, the optimal strategy is likely to use several CDR technologies in parallel to avoid the constraints of large-scale deployment of any one technology.

Back to fossil fuels

A common call after the adoption of the Paris Agreement was that it spelt the end of fossil fuels. CDR allows more (positive) emissions now and into the future[13], and this facilitates the long-term survival of fossil fuels. The reality is that 1.5°C/2°C only spells the end for fossil fuels if there is no CCS or BECCS (Supplementary Figure 4). High levels of CCS and BECCS allow fossil fuels to be used well into the future, including several models that use high levels of coal well into the second half of the century but with more rapid reductions in oil consumption as it is difficult to have CCS for oil consumption (see Supplementary Figure 5). These results further emphasise the need to reduce key uncertainties associated with CCS[16] and CDR[19], particularly in the context of future investments in fossil-fuel based assets.

A balancing act

Despite considerable uncertainties, CDR play a critical role in 2°C scenarios and this is explicitly acknowledged in the Paris Agreement where it is required to have a "balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century"[1]. CDR offset emissions of other greenhouse gases[13], such as methane that is hard to mitigate in the agriculture sector (e.g., paddy rice, wetlands, and ruminants). This places particular importance on common emission metrics to compare different greenhouse gases. Currently, countries report greenhouse gas emissions using a Global Warming Potential with a 100 year time-horizon (GWP100). The GWP100 has been critiqued from many angles[21], but a pertinent critique for the Paris Agreement is that the GWP100 is not a metric for the temperature response and it has a fixed time horizon which is not relevant as time converges towards 2100. The Global Temperature Potential (GTP) overcomes both of these weaknesses[22], but changing to a new metric may have high political costs. Since the GWP has higher values for key greenhouse gases, the use of a GWP in the "balance" may require greater CO_2 reductions by placing more weight on non-CO_2 emissions.

The elephant in the room

Given the range of scientific uncertainties, perhaps the biggest uncertainty are political choices[23]. Very few 2°C scenarios assume plausible political narratives, questioning the applicability of the scenarios in a political context. Of the 116 2°C scenarios assessed by the IPCC[2], 76 scenarios have the implementation of globally uniform carbon prices in 2010, with others following a baseline before implementing a globally uniform carbon price in 2020 (24 scenarios) or 2030 (15 scenarios). The UNEP Emission Gap Report[4] and the UNFCCC INDC Synthesis Report[5], both used scenarios that have a globally uniform carbon price starting in 2020 (Figure 1), though, one could justifiably debate the realism of this. A near-term globally uniform carbon price is practically infeasible on many levels (governance, politics), but it is nevertheless a useful modelling baseline for assessing the cost-penalties of alternative modelling assumptions[2]. Nearly all the literature informing global climate policy uses these strong policy assumptions[2-5]. There is an urgent need for scenarios based on more realistic policy assumptions, in additional to a broader range of technological pathways that capture political realities (e.g., broad political and social support for renewables, but limited support for CCS).

The role for policy-relevant science

The Paris Agreement placed the words “in accordance with best available science” in the long-term temperature goal. It is unclear why, but it does emphasise that there are many key scientific knowledge gaps to be resolved before one can say, with confidence, whether 1.5°C or 2°C are realistic temperature goals. There is certainly the need, and demand[1], for an IPCC Special Report. Prioritising research to fill the existing knowledge gaps will lead to a more balanced and valued Special Report[24]. This commentary has outlined several gaps:

- Methodologies to track progress towards the aims of the Paris Agreement, clearly specifying methods for temporal and spatial averaging of temperatures and the desired likelihood to stay below given temperature levels;
- Systematic analysis of uncertainties, applicability, and policy usefulness of the cumulative emission (quota) concept;
- A focus on communicating the characteristics and uncertainties of emission pathways, and not hiding details in aggregated model ensembles (Figure 1 and Supplementary Figure 5);
- Long-term and stable interdisciplinary research framework for all types of carbon dioxide removal;
- Reduction in uncertainties on the potential for large-scale deployment of key technologies – energy efficiency, bioenergy, fossil fuels, carbon capture and storage, renewable technologies – focussing on political, social, economic and technical challenges and opportunities;
- The implementation of more realistic policy assumptions in modelling frameworks, grounded in research on political feasibility and social acceptability.

A fertile ground for future research is greater collaboration with the social and political sciences and humanities, going far beyond the technical analysis that dominated AR5 Working Group 3. Within a short time frame (2018), one could debate if the literature will be mature enough to provide a robust assessment[24] that goes sufficiently beyond the IPCC AR5. Greater integration of the natural and social sciences is needed to fill the knowledge gaps, and a new generation of economic models may be necessary[25]. If a Special Report is too soon, it will be biased by existing material or material from groups already working on these questions. For the slow process of science to work, a broad range of research across interdisciplinary groups with appropriate funding needs to be mobilised.

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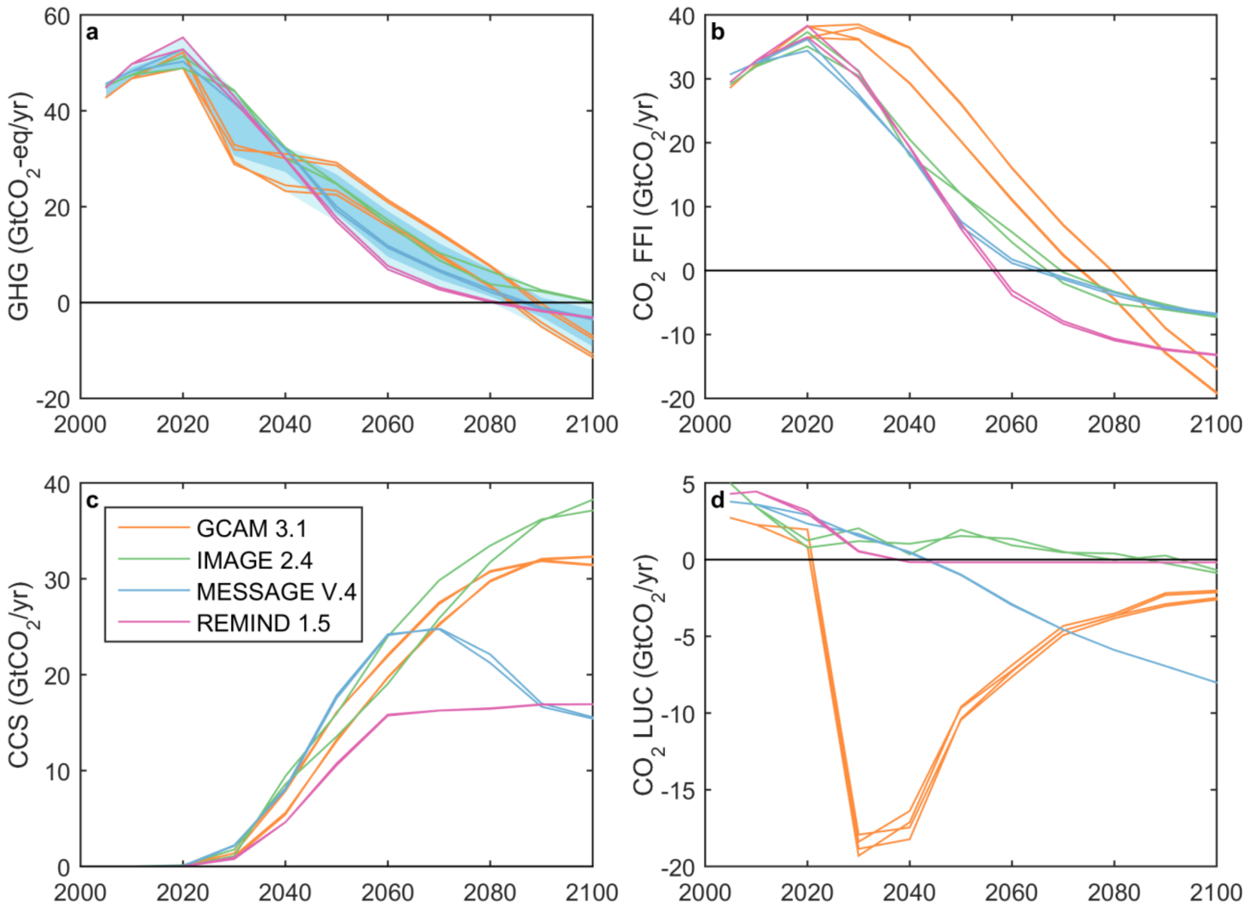

*Figure 1: The 10 scenarios from the IPCC AR5 and used in the UNEP Emissions Gap Report, coloured by the model name and version. The scenarios assume the implementation of the Durban Platform pledges (Kyoto II) and then the implementation of a uniform global carbon price from 2020. **a**: Greenhouse Gas (GHG) emissions from all sources and sinks, with only the shaded region shown in the UNEP Emissions Gap Report where shading shows the full range (light shading) and 20-80% range (dark shading) of the 10 scenarios. The shading hides the number of scenarios, the number of models, and other characteristics of the scenarios (**b**, **c**, **d**, and Supplementary Figure 5). **b**: CO_2 emissions from fossil fuels and industry (FFI) showing the large removal of carbon from the atmosphere from 2060 onwards. **c**: Carbon capture and storage (CCS), fossil fuels and bioenergy, with values in 2100 similar in scale to current emissions (**b**). **d**: CO_2 emissions from land-use change (LUC), showing the large afforestation in GCAM.*

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