to make and fulfil ambitious pledges must exceed the benefits of business as usual. The soft power of reputation is an important factor in this calculation. The power of reputation relies substantially on public engagement, and states and institutions display varying degrees of 'commitment sensitivity' — some are more likely to live up to their commitments and be more receptive to public pressure than others.

The twentieth century showed it was no longer acceptable for governments to use claims of sovereignty to defend human rights abuses[11], and the twenty-first century may show the same to be true for greenhouse gas emissions. Whether this will be the historical legacy of the Paris Agreement will depend not just on the legal architecture it establishes and the decisions that were made in December, 2015, but also on the vigour and sustained action of the people of the world expressing themselves in their economic and political behaviour as well as other areas of life. This is the only sure path to making the objectives of the Paris Agreement a reality. ❒

Jennifer Jacquet and Dale Jamieson are at the Department of Environmental Studies, New York University, 285 Mercer Street, New York, NY 10003, USA.
e-mail: jacquet@nyu.edu

References

1. Jamieson, D. *Reason in a Dark Time* (Oxford Univ. Press, 2014).
2. Schelling, T. *Am. Econ. Rev.* **82,** 1–14 (1992).
3. Galbraith, J. & Zaring D. T. *Cornell Law Rev.* **99,** 735–794 (2015).
4. Bénabou, R. & Tirole, J. *Laws and Norms* (The National Bureau of Economic Research, 2011).
5. Jacquet, J. *Is Shame Necessary? New Uses for an Old Tool* (Pantheon, 2015).
6. Jacquet, J., Hauert, C., Traulsen, A. & Milinski, M. *Biol. Lett.* **7,** 899–891 (2011).
7. Gerber, A. S., Green, D. P. & Larimer C. W. *Polit. Behav.* **32,** 409–422 (2010).
8. Alamar, B., Glantz, S. A. *Am. J. Pub. Health* **96,** 1359–1363 (2006).
9. Keohane, R. O. *After Hegemony* (Princeton Univ. Press, 1984).
10. Roth, K. *Hum. Rights Quart.* **26,** 63–73 (2004).
11. Simmons, B. A. *Mobilizing Human Rights: International Law in Domestic Politics* (Cambridge Univ. Press, 2009).
12. Mohamed, S. *Wash. Law Rev.* **90,** 1191–1254 (2013).
13. van Renssen, S. *Nature Clim. Change* **5,** 513–514 (2016).
14. Climate Action Tracker (accessed 13 February 2016); http://climateactiontracker.org/indcs.html
15. Jamieson, D. *Global Justice: Theory Practice Rhetoric* **8,** 23–42 (2015).

Acknowledgements

We are thankful for the valuable feedback from the participants in the University of Pennsylvania's Risk Regulation Seminar Series and for the reviewers' helpful suggestions.

COMMENTARY:

The 'best available science' to inform 1.5 °C policy choices

Glen P. Peters

An IPCC Special Report on 1.5 °C should focus on resolving fundamental scientific and political uncertainties, not fixate 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 United Nations Environment Programme (UNEP) Emissions Gap Report[4] and the United Nations Framework Convention on Climate Change (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 fundamental are ambiguities around which time period the target covers, 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 (ref. 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 insinuations 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.

Even more fundamental are questions around 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 Figs 1,2). The total cumulative carbon quota increases by 900 $GtCO_2$ if the temperature threshold increases from 1.5 °C to 2 °C with a 66% likelihood. The total quota for a 2 °C threshold increases by 800 $GtCO_2$ for a decrease in the likelihood from 66% to 50%. We already see some subtle shifts in the goalposts from 66% to 50% for more stringent scenarios[4,5], perhaps confirming concerns of keeping results politically palatable[9,10].

An uncertain quota

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 per 1,000 PgC, but gave no statistical distribution[11]. To determine the total carbon quota, the IPCC 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 ±250 $GtCO_2$ (Supplementary Tables 1,2).

Second, the quotas 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] (±300 $GtCO_2$ for 66% chance of 2 °C). Models generally estimate the non-CO_2-adjusted quotas[12], but these may vary nonlinearly 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 (±200 $GtCO_2$).

If these uncertainties are combined using simple uncorrelated error propagation, the remaining quota from 2016 for 2 °C with 66% likelihood could be 850 ±450 $GtCO_2$ to one standard deviation (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 the carbon quota concept in policy.

Expanding the quota

A problematic feature of the quota concept is that the quotas are not fixed, and can be temporarily exceeded 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 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 Fig. 4). According to the scenarios[2], the current ramping up of 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 (Fig. 1). This subset of scenarios is arguably more applicable and relevant for the Paris Agreement[4,5] than the full set of scenarios assessed in the IPCC AR5[2]. However, methods of presenting these scenarios often hide policy-relevant details by only showing scenario ranges and not individual scenarios (Fig. 1a shaded region). These 'Delay 2020' scenarios all lead to net negative emissions from fossil fuel and industry from about 2060 (Fig. 1b). They deploy significant amounts of CCS on fossil fuels and bioenergy (Fig. 1c) with levels comparable to current emissions of around 40 $GtCO_2\ yr^{-1}$. CDR can also occur via afforestation, with one model removing about 20 $GtCO_2\ yr^{-1}$ in 2030 and 2040 (Fig. 1d), a level far greater than all other models[2], but potentially consistent with bottom up estimates[14]. Supplementary Fig. 5 outlines other key characteristics of these scenarios.

Most large-scale CDR is realized in models by combining bioenergy with CCS[2] (BECCS), but both technologies currently have deep uncertainties. There is a broad debate on bioenergy potentials, with high agreement up to 100 EJ yr^{-1} in 2050, medium agreement up to 300 EJ $yr^{-1}$and low agreement beyond 300 EJ yr^{-1} (ref. 15; EJ, exajoules). The 'Delay 2020' scenarios use around 150 EJ yr^{-1} by 2050 and 300 EJ yr^{-1} by 2100 (Supplementary Fig. 5), overlapping the highly debated bioenergy potential levels. CCS could allow 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 28 $MtCO_2\ yr^{-1}$ 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 fertilization 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 maximize 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.

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 Fig. 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 due to a lack of CCS (see Supplementary Fig. 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.

Despite considerable uncertainties, CDR plays 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 offsets emissions of other greenhouse gases[13], such as methane, which is hard to mitigate in the agriculture sector (for example, paddy rice, wetlands

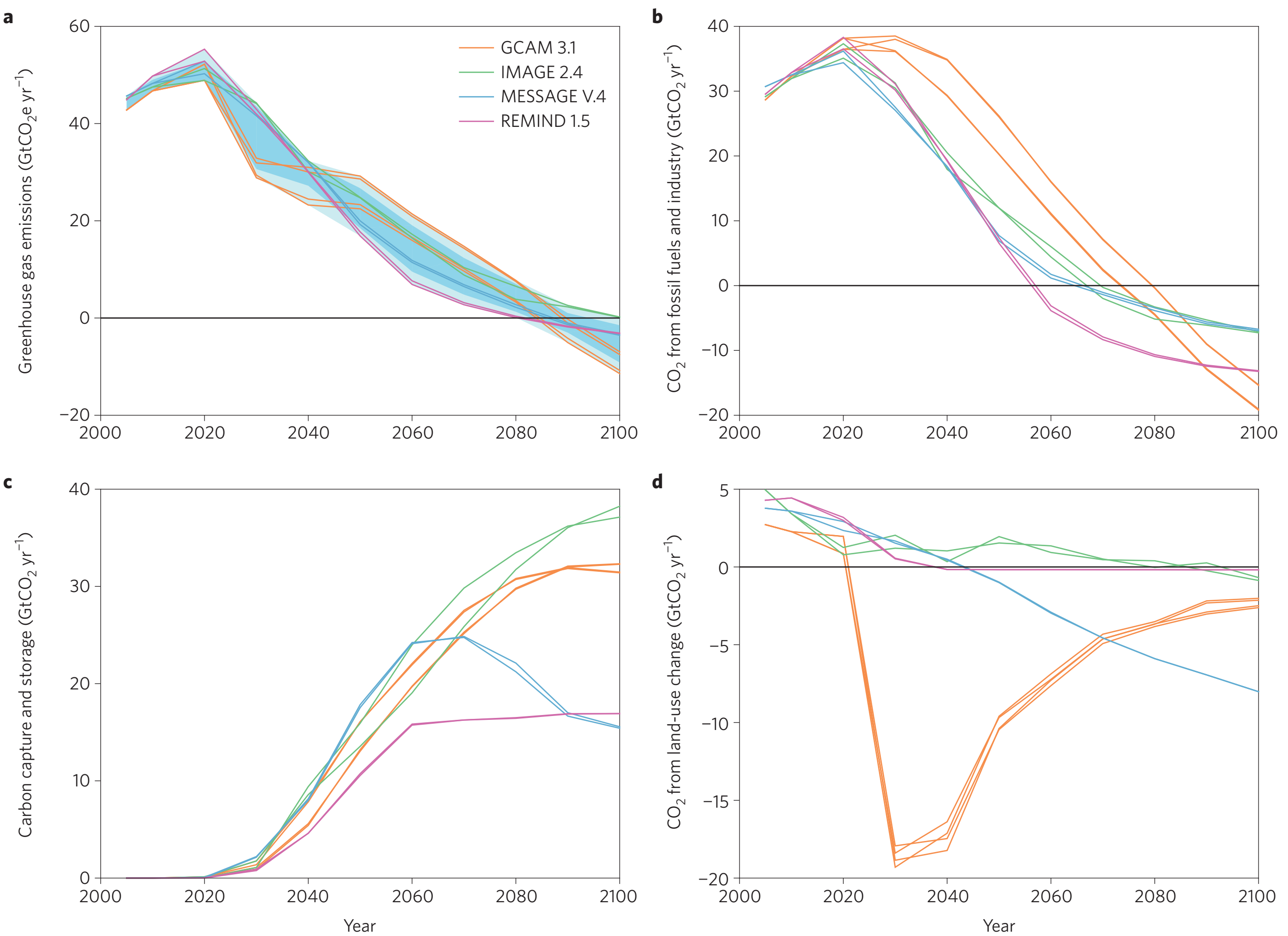

Figure 1 | The ten scenarios from the IPCC AR5[2] and used in the UNEP Emissions Gap Report[4], coloured by the model name and version. The scenarios assume the implementation of the Durban Platform pledges (Kyoto II; ref. 26) and then the implementation of a uniform global carbon price from 2020 (Supplementary Table 3). **a**, Greenhouse gas emissions (in CO_2 equivalents, CO_2e) 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 ten scenarios. The shading hides the number of scenarios, the number of models, and other characteristics of the scenarios (**b**–**d**, and Supplementary Fig. 5). The legend also relates to **b**-**d**. **b**, CO_2 emissions from fossil fuels and industry showing the large removal of carbon from the atmosphere from 2060 onwards. **c**, Carbon capture and storage, fossil fuels and bioenergy, with values in 2100 similar in scale to current emissions (**b**). **d**, CO_2 emissions from land-use change, showing the large afforestation in GCAM.

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 approaches 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 role for policy-relevant science

Given the range of scientific uncertainties, perhaps the biggest uncertainty is the political choice[23]. Very few 2 °C scenarios assume plausible political narratives, questioning the applicability of the scenarios in a political context.

Of the 116 scenarios for 2 °C assessed by the IPCC[2], 76 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 (Fig. 1), although 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 addition to a broader range of technological pathways that capture political realities (for example, broad political and social support for renewables, but limited support for CCS).

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. Prioritizing research to fill the existing knowledge gaps will lead to a more balanced and valued Special Report[24]. In this Commentary I have outlined several gaps:

- Defining 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.
- A 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, without details becoming obscured in aggregated model ensembles (Fig. 1 and Supplementary Fig. 5).
- Developing a 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 — focusing 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 III. Within a short time-frame (with the report due by 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 mobilized. ❐

Glen P. Peters is at the Center for International Climate and Environmental Research – Oslo (CICERO), Norway.
e-mail: glen.peters@cicero.oslo.no

References

1. *Adoption of the Paris Agreement* FCCC/CP/2015/L.9/Rev1 (United Nations Framework Convention on Climate Change, 2015).
2. Clarke, L. *et al.* in *Climate Change 2014: Mitigation of Climate Change* (eds Edenhofer, O. *et al.*) Ch. 6 (IPCC, Cambridge Univ. Press, 2014).
3. Rogelj, J. *et al. Nature Clim. Change* **5,** 519–527 (2015).
4. *The Emissions Gap Report 2015* (United Nations Environment Programme, 2015).
5. *Synthesis Report on the Aggregate Effect of the Intended Nationally Determined Contributions* (United Nations Framework Convention on Climate Change, 2015).
6. IPCC *Climate Change 2014: Synthesis Report* (eds Pachauri, R. K. & Meyer, L. A.) (Cambridge Univ. Press, 2014).
7. Met Office. *2015: The Warmest Year on Record, say Scientists*; www.metoffice.gov.uk/news/releases/archive/2016/2015-global-temperature (accessed 24 January 2016).
8. Holthaus, E. *Our Planet's Temperature Just Reached a Terrifying Milestone* http://go.nature.com/kBYAgX (2016).
9. Anderson, K. *Nature Geosci.* **8,** 898–900 (2015).
10. Geden, O. *Nature* **521,** 27–28 (2015).
11. Collins, M. *et al.* in *Climate Change 2013: The Physical Science Basis* (eds Stocker, T. F. *et al.*) 1029–1136 (IPCC, Cambridge Univ. Press, 2013).
12. Rogelj, J. *et al. Nature Clim. Change* **6,** 245–252 (2016).
13. Fuss, S. *et al. Nature Clim. Change* **4,** 850–853 (2014).
14. Houghton, R. A., Byers, B. & Nassikas, A. A. *Nature Clim. Change* **5,** 1022–1023 (2015).
15. Creutzig, F. *et al. GCB Bioenergy* **7,** 916–944 (2014).
16. de Coninck, H. & Benson, S. M. *Annu. Rev. Environ. Resour.* **39,** 243–270 (2014).
17. *The Global Status of CCS: 2015* (Global CCS Institute, 2015); http://go.nature.com/aXPQAU
18. van Vuuren, D. P., van Sluisveld, M. & Hof, A. F. *Implications of Long-Term Scenarios for Medium-Term Targets (2050)* (PBL Netherlands Environmental Assessment Agency, 2015); http://go.nature.com/16LZaH
19. Smith, P. *et al. Nature Clim. Change* **6,** 42–50 (2015).
20. Williamson, P. *Nature* **530,** 153–155 (2016).
21. Myhre, G. *et al.* in *Climate Change 2013: The Physical Science Basis* (eds Stocker, T. F. *et al.*) 659–740 (IPCC, Cambridge Univ. Press, 2013).
22. Shine, K. P., Berntsen, T., Fuglestvedt, J. S., Stuber, N. & Skeie, R. B. *Phil. Trans. R. Soc. A* **365,** 1903–1914 (2007).
23. Rogelj, J., McCollum, D. L., Reisinger, A., Meinshausen, M. & Riahi, K. *Nature* **493,** 79–83 (2013).
24. Hulme, M. *Nature Clim. Change* **6,** 222–224 (2016).
25. Stern, N. *Nature* **530,** 407–409 (2016).
26. Kriegler, E. *et al. Clim. Change Econ.* **4,** 1340008 (2013).

Acknowledgements
G.P.P. was supported by the Research Council of Norway project 209701.

Additional information
Supplementary information is available in the online version of the paper.

Published online: 11 April 2016

COMMENTARY:

Why the right climate target was agreed in Paris

Hans Joachim Schellnhuber, Stefan Rahmstorf and Ricarda Winkelmann

The Paris Agreement duly reflects the latest scientific understanding of systemic global warming risks. Limiting the anthropogenic temperature anomaly to 1.5–2 °C is possible, yet requires transformational change across the board of modernity.

Last December, after some 20 years of negotiations under the auspices of the United Nations Framework Convention on Climate Change (UNFCCC), a historic, binding climate agreement was reached in Paris. At the twenty-first Conference of the Parties (COP21), 195 nations committed[1] to "holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5 °C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change". This establishes nothing less than a centennial