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. ❐

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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).

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Additional information

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

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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

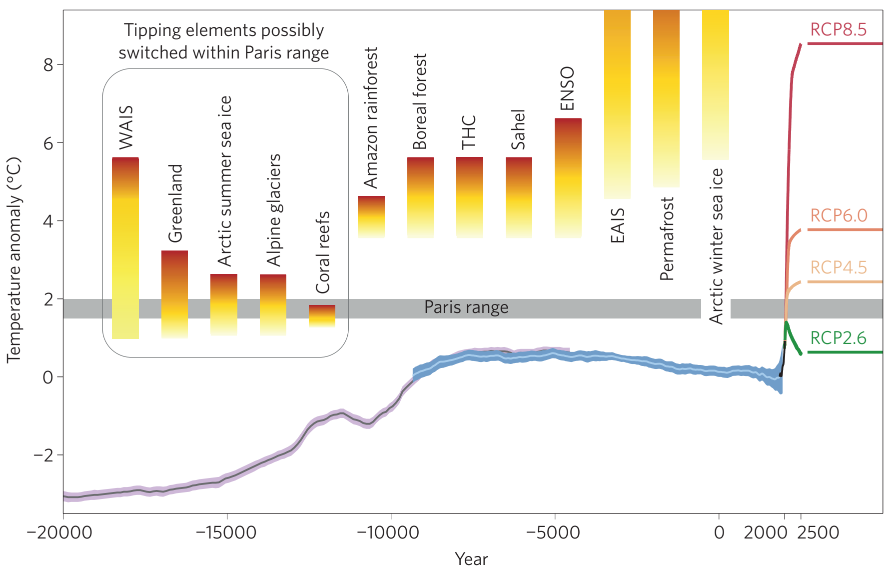

Figure 1 | Tipping elements in context of the global mean temperature evolution. Shown is the global-mean surface temperature evolution from the Last Glacial Maximum through the Holocene, based on palaeoclimatic proxy data[35,36] (grey and light blue lines, with the purple and blue shading showing one standard deviation), instrumental measurements since 1750 AD (HadCRUT data, black line) and different global warming scenarios for the future (see ref. 37 for the latter). Threshold ranges for crossing various tipping points where major subsystems of the climate system are destabilized have been added from ref. 8, 14 and 37–40. (Note that we follow the tipping point definition of Lenton *et al.*[8] which does not require irreversibility, so that sea ice cover is included here.) The range for the West Antarctic Ice Sheet (WAIS) has been adapted to account for the observation that part of it has probably tipped already[10,11]. THC, thermohaline circulation; ENSO, El Niño–Southern Oscillation; EAIS, East Antarctic Ice Sheet.

benchmark for the human enterprise. In view of the monumental implications of that benchmark, it is imperative to review the adequacy of the Paris target.

Our assessment begins with decomposing the term adequacy into three crucial components, namely (1) necessity, (2) feasibility and (3) simplicity. The latter dimension is often ignored, but is tremendously important for political recognition and implementation, as we shall explain. The feasibility question has been studied thoroughly not least by the IPCC in its Fifth Assessment Report[2] (AR5). The preliminary conclusion is that the 2 °C line may be held with remarkably low economic cost, if only the political will can be mustered. However, the feasibility issue is well worth revisiting in light of the Paris aspiration to limit warming to 1.5 °C. We begin, however, by reviewing the necessity of a global warming limit, guided by the latest insights from climate science.

Necessity

The UNFCCC, established in 1992 at the Earth Summit in Rio de Janeiro, defines its ultimate goal (in the famous Art. 2) that demands to stabilize greenhouse gas (GHG) concentrations at levels that prevent "dangerous anthropogenic interference with the climate system". This phrase has been a bonanza for lawyers and political scientists ever since, who came up with many different and partly contradictory interpretations. Being climate scientists, we concentrate on the terms that allow for a concrete operationalization of that goal, namely 'dangerous' and 'climate system'. A straightforward interpretation then emerges: "GHG emissions that would modify the character of the climate system in a way that creates intolerable risks for humankind must be avoided." As a sensible conclusion, the Holocene mode of operation of the planetary environmental machinery needs to be preserved.

In fact, the sustenance of Holocene climate conditions under which Homo sapiens thrived while the Neolithic Revolution established human civilization was an early key argument in favour of the 2 °C guardrail (ref. 3; see also ref. 4). One of the authors (H.J.S.) in the 1990s helped to start the related political process that eventually led, via the German government and the EU, to the current global climate benchmarking. Limiting global warming to at most 2 °C, with an option to amend this to 1.5 °C after a scientific review, was first agreed upon at the UNFCCC Conference of the Parties in Cancun, 2010[5].

Today, Earth system science has come of age and can provide robust evidence for the intuitive assumption that it is not a good idea to leave the "safe operating space" of humanity[6,7], and that this space is well within the Paris confines. The keywords in this context are non-linearity and irreversibility. Impacts research indicates that unbridled anthropogenic climate change would be most likely to play out in a disruptive and irreparable way. This becomes clear when one moves from the conventional, yet valuable, realms of analysis ("How will wheat yields vary with changes in local temperature, precipitation, insolation etc?") to the macro-components, mega-patterns and super-ecosystems that determine how the climate system functions as a whole ("When will the Greenland Ice Sheet collapse under progressive global warming?"). These critical entities have been called tipping elements[8], since their character is closely related to certain pockets of planetary state space. This means that those elements may be destroyed, damaged or transmuted if critical threshold values (tipping points) of key environmental parameters are transgressed.

The impressive advances made by climate system research over the past two decades allow us to draw the first 'big pictures' of planetary criticality, identifying both tipping elements and their respective niches. There is compelling evidence that almost all of them are affected by anthropogenic warming in some way or another. Put briefly, the worldwide environmental risks scale with global warming, or more precisely, with the mean surface temperature deviation from pre-industrial levels, ΔT. This insight is summarized and visualized in Fig. 1.

This diagram provides an indispensable map for global stewardship[9]. It roughly decomposes the temperature space into four qualitatively distinct domains: the first one (D_0) embraces the range between the Last Glacial Maximum and the Holocene Climate Optimum in which the pre-industrial human enterprise was born. The second one (D_2) is the ΔT range between 1 °C and 3 °C and thus includes the Paris range. From Fig. 1 it is immediately apparent that even if global warming is limited to below 2 °C, some important tipping elements may already be harmed or transformed. In fact, the tipping point for marine ice sheet instability in the Amundsen Basin of West Antarctica may well have been crossed already, and the risk of crossing further tipping points will increase with future warming[10,11]. Significant impacts of climate change are projected already for a warming of 1.5 °C above pre-industrial levels, and have been shown to rise substantially between 1.5 °C and 2 °C (ref. 12). The difference between 1.5 °C and 2 °C of global warming is apparent when considering long-term sea-level rise: Even holding global warming to 2 °C may lead to 2–3 metres of rise by the year 2300, still rising then at twice the rate as today, whereas a 1.5 °C scenario could see the peak sea level at a median estimate of 1.5 m above 2000[13].

Beyond 2 °C the course would be set for a complete deglaciation of the Northern Hemisphere, threatening the survival of many coastal cities and island nations. Global food supply would be jeopardized by novel extreme-event regimes, and major ecosystems such as coral reefs forced into extinction[14]. Yet, staying within the Paris target range, the overall Earth system dynamics would remain largely intact. Progressing into the third domain (D_4) on the other hand, with global warming reaching 3–5 °C, would seriously harm most tipping elements. For warming levels beyond this range (spanning the fourth domain D_8), the world as we know it would be bound to disappear.

Note that the individual elements in Fig. 1 do not come with a sharp tipping point, but with a 'tipping bar' that basically grows in length with increasing ΔT for obvious reasons. These uncertainty bars will either shrink with advancing scientific understanding or collapse through factual evidence.

Thus Fig. 1 does not provide perfect guidance for climate policymakers, yet this is as good as it can get today. The risk clustering as reflected by the map is actually a most valuable orientation: clearly, it would be highly risky to transgress the D_2 range, and madness to let the planet slip into the D_8 domain where practically all tipping elements would be pushed out of their current mode of operation. However, a 2 °C strategy is not a safe bet, and the world's governments therefore were wise to set the limit at "well below 2 °C" and aspire to 1.5 °C. This target was also supported by the UNFCCC's own scientific review and consultation process in preparation of the Paris summit, involving over 70 climate experts[15]. In summary, there is a convincing rationale for the Paris target as derived from Earth system analysis.

Feasibility

The Paris climate target is highly ambitious, if not aspirational. The long lifetime of CO_2 in the atmosphere implies a strictly limited total carbon budget and thus forces us to reach zero emissions — if warming is to be stopped at all. The climate target determines the speed of the decarbonization process: for a 66% probability of staying below 2 °C of warming, cumulative CO_2 emissions after 2011 need to be constrained to another 1,000 $GtCO_2$ (ref. 37, Table 2.2). In order to not exceed 1.5 °C of warming, they would need to be restricted to an additional 400 $GtCO_2$ compared to 2011 levels (see Fig. 2).

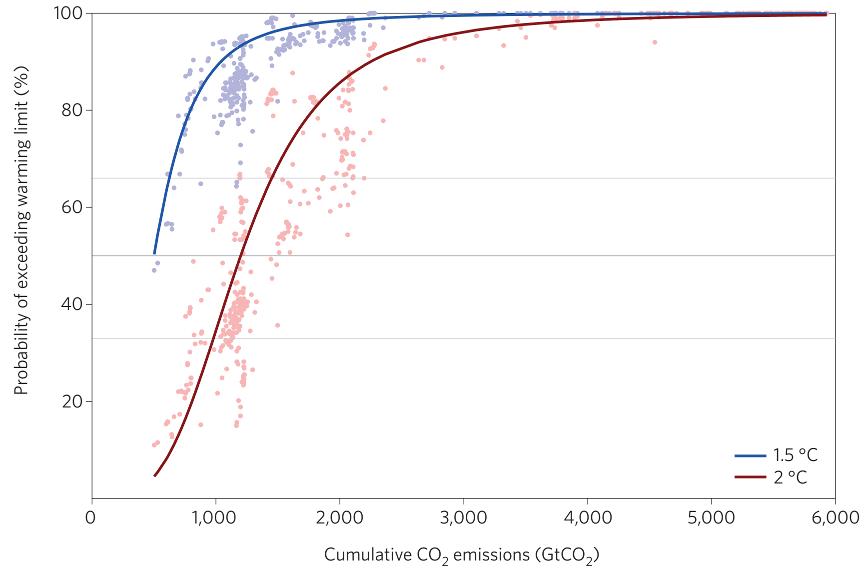

Figure 2 | Likelihood of exceeding the 1.5 °C and 2 °C global warming limits. Given are the probabilities of exceeding 1.5 °C (blue) and 2 °C (red) of global warming as a function of cumulative CO_2 emissions from 2011 to 2100, derived with MAGICC6[41,42] based on the IPCC AR5 scenarios. Detailed information on each scenario and model is provided in the IPCC AR5 Scenario Database[43] (hosted at IIASA and accessed via the AR5 scenario explorer[44]). Solid lines are sigmoidal fits[45] to the MAGICC6 results.

Several analysts have recently claimed that the 2 °C line is already untenable[16,17], but they failed to underpin their 'impossibility hypothesis' with concrete calculations, so the prime reference point remains the monumental 2014 assessment provided by Working Group III of the IPCC[2]. This assessment concludes that the 2 °C guardrail can be respected at moderate cost under certain (not entirely unreasonable) assumptions, including the realization of 'negative-emissions' schemes. However, the enormous challenges associated with massive atmospheric CO_2 removal or negative emissions have been highlighted by several experts[18]. A recent study[19] nevertheless maintains that anthropogenic global warming could be confined to 1.5 °C, an environmental excursion that would probably allow for the survival of most of the low-lying island states. The Paris Agreement[1] formally invites the IPCC to explore — by 2018, in a Special Report — global emissions pathways consistent with the lower end of the temperature target range.

The 2014 IPCC analysis has to be applauded for shattering the sweeping infeasibility myth. However, the authors of this Commentary are not convinced that decarbonization will necessarily come in the form of such a planned, smooth, centennial-scale transition.

We think that a better chance to deliver on the Paris promises can be generated by an alternative and more plausible route: in order to avoid the need to recourse to negative emissions as a late-regrets magic bullet (with questionable outcome), renewable energies and efficiency technologies could be scaled up exponentially, more rapidly than envisaged in the integrated assessment models behind the IPCC scenarios. We expect that such a 'technical explosion' will be matched by an 'induced implosion' of the incumbent industrial metabolism nourished by coal, oil and gas. Among the driving processes, investment dynamics is crucial, and this dynamic might in fact transgress its own tipping point in response to the narrative transpiring from Paris. This has often been described as the bursting of the 'carbon bubble'[20]. Yet what could be concrete triggers of such a disruptive change in asset fluxes?

We can think of at least three causative pathways, which all have to do with expectation and fear. First, there is the classical hypothesis that a strong climate agreement paves the way towards carbon-pricing instruments that will be adopted by more and more nation states in the medium term. As a consequence, investors anticipating the so-induced rise in fossil business costs should make the rational

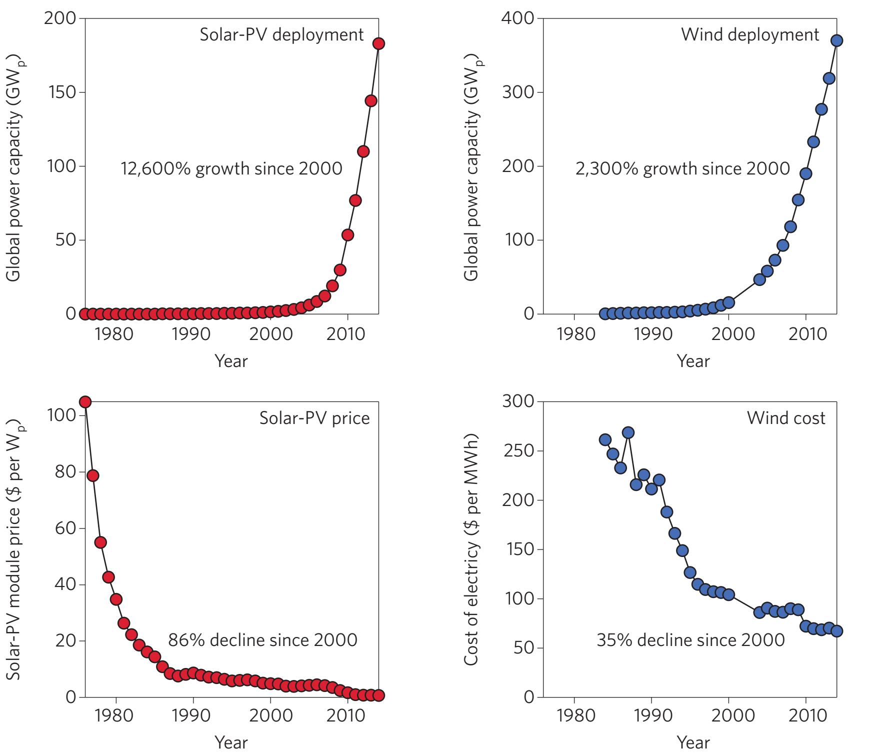

Figure 3 | Beginning of induced implosion? The installed capacity of solar and wind power generation has grown at rates far exceeding expectations. At the same time, the costs for solar and wind power have dropped rapidly, by 35% since the year 2000 for wind electricity, and by 86% for solar modules. Figure adapted with permission from ref. 30; © 2015 MIT.

choice to opt out of that business. Second, there is a growing risk/chance that morals are going to interfere significantly with economics. The so-called divestment campaign has become a global social movement that demands leaving most of the fossil fuel resources in the ground[21,22]. In public, many business leaders and government officials still try to ridicule or dismiss this sentiment surge within civil society. Yet in private conversations they admit their worries that particularly institutional investors (such as pension funds or big foundations) might be 'infected' by the divestment virus. Third, there is Schumpeter's 'creative destruction' that might instigate a systemic innovation of the existing economic structures. Let us briefly elaborate on this: when studying industrial history for a better understanding of transformational processes, one encounters certain evidence for a semi-quantitative rule, known as Pareto Principle[23], which states that in heterogeneous community production systems, roughly 80% of the total output is typically generated by roughly 20% of the individual units involved. The Italian economist Vilfredo Pareto originally formulated this empirical rule in his studies about the distribution of population and wealth and provided a number of supporting observations. The '80–20 law' was later found to work in numerous other contexts, including prominent examples from manufacturing, quality control, computing science and hazard protection[24,25].

With respect to the Paris Agreement, the Pareto Principle could come into play in two different ways[26]: following the 'law of the vital few', it can be argued that the decarbonization of the world will be led by a critical minority of key agents that advance transformative action. In fact, the intended nationally determined contributions submitted by crucial countries in the run-up to COP21 are not sufficient in terms of medium-term emissions reductions, yet may initialize an accelerating diversion of development pathways away from fossil trajectories. China has recently announced the closure of a thousand coal mines as its coal use is falling and expected to continue its decline, and India appears very serious about implementing its colossal renewables target announced before Paris. These are self-amplifying developments that have the potential to tip the global market scales.

Based on certain observations from industrial history and investment behavior (see, for example, ref. 27) we submit here also a different Pareto-type hypothesis: if a traditional and a novel business paradigm compete with each other, the old one tends to implode once the new one reaches a market penetration of about 15–20 percent (according to appropriate metrics). On the one hand, it can be argued that investors will perceive an alternative systems option as too marginal as long as its business share is clearly below 10%. For instance, in the 1990s solar electricity was expected to never rise to significance. On the other hand, asset managers are looking for emerging opportunities, where they are ahead of the pack and can expect above-average returns. Once the alternative systems option exceeds around a quarter of the overall pertinent business volume, it cannot be considered a smart minority choice any more. These two arguments combine to delineate a "basin of venture capital attraction" centred in the 15–20% domain.

The share of new renewables is rapidly increasing[28], especially in the electricity sector, and might quickly pass through this critical domain, as several examples on the national level teach us. A prime country example is provided by Denmark, which increased its wind share in total power demand to a new record in 2015, moving from 17% to 42% within just one decade[29]. By contrast, the renewables contribution to the overall global energy consumption only rose from 17% in 2004 to 19% in 2013[28]. This does not indicate, however, that the dynamics got stuck in the 15–20% range; those numbers only mask several dramatic developments: first, the pertinent lion's share still refers to the 'old' renewables such as traditional biomass and conventional hydroelectricity, which are either resource-restricted or highly capital/planning-intensive. Those problems are much less serious for the 'new' renewables such as solar photovoltaics (solar PV), which has virtually no supply limits and is perfectly scalable. Second, entire energy market sectors such as transportation are poised for transformational change towards electrification, not least by imminent advances in storage technologies and operations. Therefore, we expect the new renewables to take the lead and to push the total renewables share quickly beyond the 20% line.

A recent study[30] confirms that the deployment of solar and wind power capacities worldwide has increased exponentially while the costs of solar and wind power generation have fallen in a similarly non-linear fashion (Fig. 3). In retrospective, these developments may be considered as transgression of regional and global tipping points.

Although the induced implosion remains an educated speculation for now, we have already witnessed the bankruptcy of at least 27 US coal companies in recent years, including this January Arch Coal, one of the US's largest coal producers, and Oregon has just become the first US state to pass law that eliminates coal-fired power by 2035 at the latest.

Simplicity

Beyond necessity and feasibility, the 2 °C guardrail has a comparative advantage over competing targets, something that cannot be overrated in the world of 'realpolitik': the guardrail is easy to grasp and to memorize. Planetary surface temperature naturally reflects the quintessence of the global-warming challenge, and many impacts increase in proportion with it. That the 2 °C confinement proposal has become a focal point for climate discourse worldwide is the result of an extended process going back as far as the 1980s[31].

In 1994, the top German government advisory body for environmental issues, WBGU, introduced the 'tolerable windows approach' (ref. 3; see also refs 32 and 33), which tried to sketch a 'safe operating domain'[6] in climate phase space. The original window was actually two-dimensional, spanned by the global temperature anomaly ΔT and its time derivative $\mathrm{d}\Delta T/\mathrm{d}T$, and had a curvilinear contour. Intensive discussions within the scientific community and with pertinent stakeholders led to a perpetual simplification process reducing the contour complexity to the straight 2 °C line.

Several alternatives to the 2 °C target have been proposed since then, which were categorized and systematically analysed in ref. 34. The authors conclude that the risks and uncertainties associated with the alternative options were so substantial that decision makers might be inclined to fully commit to the 2 °C target "as the least unattractive course of action". For all practical purposes, it turned out to be impossible to add more technicalities to an objective that needs to appeal to non-scientists.

Such lessons are taught to every researcher who engages with the world of politics. This may be deplored by some, but it is a truth that complicated operationalizations of Article 2 that have occasionally been suggested (such as ocean heat content or CO_2-equivalent greenhouse gas concentrations in ppm) have no chance of being appreciated — neither by the multilateral system nor the ordinary citizens, since already the units of measure are meaningless to them. In particular, stakeholders have been unable to recognize, let alone embrace, the more sophisticated criterion of temperature change rate (relevant to ecosystems migration, for instance). This is not a fatal deficiency, however, as limiting global warming to less than 2 °C implicitly also constrains the time derivative. In that vein it can be argued that one has to propose something that is "as simple as possible, but not simpler" (A. Einstein). The 2 °C guardrail seems to satisfy that criterion as well.

As a matter of fact, the dramatic days (and nights) of Paris have proven this in a quite unexpected way. The most important accomplishment of COP21 was the reconciliation of the 'North' and the 'South' for the sake of a common climate strategy. This could only be achieved through the adoption of the 1.5 °C aspiration — along with the legally binding 2 °C limit — as the self-determined goal of the developing world. Sentiments such as self-esteem actually play a big role in the multi-lateral theatre, and quite rightly so. But such sentiments can only play out if you have tangible issues to argue about. It is hard to imagine, for instance, that 195 nations would negotiate the tolerable upper-ocean heat content in terms of an exajoule limit. By way of contrast, the global temperature limit proposals allowed every party to take a stance.

Almost miraculously, the countries of the world — from Saudi Arabia to the US, from the Solomon Islands to China — have agreed on a sensible, science-based climate target in Paris, albeit very late in the game. This is a historical achievement and a genuine triumph of reason. Now the pressure is on to implement that consensus in time, in order to avoid the looming humanitarian tragedy for good. ❒

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References

1. *Adoption of the Paris Agreement* FCCC/CP/2015/L.9/Rev.1 (UNFCCC, 2015).
2. IPCC *Climate Change 2014: Mitigation of Climate Change* (eds Edenhofer, O. *et al.*) (Cambridge Univ. Press, 2014).
3. German Advisory Council on Global Change *Scenario for the Derivation of Global CO_2-Reduction Targets and Implementation Strategies* (WBGU, 1995).
4. Jaeger, C. C. & Jaeger, J. *Reg. Environ. Change* **11,** S15–S26 (2011).
5. *Report of the Conference of the Parties on its Sixteenth Session, held in Cancun from 29 November to 10 December 2010. Addendum: Part Two: Action taken by the Conference of the Parties at its Sixteenth Session* (UNFCCC, 2010).
6. Rockström, J. *et al. Nature* **461,** 472–475 (2009).
7. Steffen, W. *et al. Science* **347,** 736 (2015).
8. Lenton, T. M. *et al. Proc. Natl Acad. Sci. USA* **105,** 1786–1793 (2015).
9. Steffen, W. *et al. AMBIO* **40,** 739–761 (2011).
10. Joughin, I., Smith, B. E. & Medley, B. *Science* **344,** 735–738 (2014).
11. Rignot, E., Mouginot, J., Morlighem, M., Seroussi, H. & Scheuchl, B. *Geophys. Res. Lett.* **41,** 3502–3509 (2014).
12. Schleussner, C. F. *et al. Earth Syst. Dynam.* **7,** 327–351 (2016).
13. Schaeffer, M., Hare, W., Rahmstorf, S. & Vermeer, M. *Nature Clim. Change* **2,** 867–870 (2012).
14. Frieler, K. *et al. Nature Clim. Change* **3,** 165–170 (2013).
15. *Report on the Structured Expert Dialogue on the 2013–2015 Review* FCCC/SB/2015/INF.1 (UNFCCC, 2015).
16. Victor, D. G. & Kennel, C. F. *Nature* **514,** 30–31 (2014).
17. Geden, O. *Nature* **521,** 27–28 (2015).
18. Smith, P. *et al. Nature Clim. Change* **6,** 42–50 (2016).
19. Rogelj. J. *et al. Nature Clim. Change* **5,** 519–527 (2015).
20. *Unburnable Carbon 2013: Wasted Capital and Stranded Assets* (Carbon Tracker and the Grantham Research Institute on Climate Change and the Environment, 2013).
21. Vaughan, A. Fossil fuel divestment: a brief history. *The Guardian* (9 October 2014).
22. McGlade, C. & Ekins, P. *Nature* **517,** 187–190 (2015).
23. Pareto, V. *Manual of Political Economy* (Oxford Univ. Press, 1969).
24. Gen, M. & Cheng, R. *Genetic Algorithms and Engineering Optimization* (Wiley, 2002).
25. *Introduction to Risk-Based Decision-Making* (United States Coast Guard, 2016).
26. Rockström, J. & Schellnhuber, H. J. *Paris, Potlatch and Pareto.* (The Earth League, 2015).
27. German Advisory Council on Global Change *A Social Contract for Sustainability* (WBGU, 2011).
28. *Renewables 2015 Global Status Report.* (REN21 Secretariat, 2015).
29. New record-breaking year for Danish wind power. *Energinet* (15 January 2016); http://energinet.dk/EN/El/Nyheder/Sider/Dansk-vindstroem-slaar-igen-rekord-42-procent.aspx
30. Trancik, J. *et al. Technology Improvement and Emissions Reductions as Mutually Reinforcing Efforts: Observations from the Global Development of Solar and Wind Energy, Technical Report.* (MIT, 2015); http://trancik.scripts.mit.edu/home/wp-content/uploads/2015/11/PolicyBrief.pdf
31. Krause, F., Bach, W. & Koomey, J. *From Warming Fate to Warming Limit: Benchmarks to a Global Climate Convention* (International Project for Sustainable Energy Paths, 1989).
32. Petschel-Held, G. & Schellnhuber, H. J. *Cost-Benefit Analyses of Climate Change* (ed. Toth, F. L.) 121–139 (Birkhäuser Basel, 1998)
33. Schellnhuber, H. J. *Climatic Change* **100,** 229–238 (2010).
34. Jordan, A. *et al. Climate Policy* **13,** 751–769 (2013).
35. Marcott, S. A., Shakun, J. D., Clark, P. U. & Mix, A. C. *Science* **339,** 1198–1201 (2013).
36. Shakun, J. D. *et al. Nature* **484,** 49–54 (2012).
37. IPCC *Climate Change 2014: Synthesis Report* (eds Pachauri, R. K. & Meyer, L. A.) (Cambridge Univ. Press, 2014).
38. Robinson, A., Calov, R. & Ganopolski, A. *Nature Clim. Change* **2,** 429–432 (2012).
39. Lenton, T. M. *AMBIO* **41,** 10–22 (2012).
40. Levermann, A. *et al. Climatic Change* **110,** 845–878 (2012).
41. Meinshausen, M., Raper, S. C. B. & Wigley, T. M. L. *Atmos. Chem. Phys.* **11,** 1417–1456 (2011).
42. Rogelj, J., Meinshausen, M. & Knutti, R. *Nature Clim. Change* **2,** 248–253 (2011).
43. IPCC *AR5 Scenario Database* (IIASA, accessed 16 January 2016); https://tntcat.iiasa.ac.at/AR5DB/
44. *AR5 scenario explorer* (PIK, accessed 16 January 2016); http://www.pik-potsdam.de/primap-live/ar5-scenario-explorer/
45. Ricke, K. L., Moreno-Cruz, J. B., Schewe, J., Levermann, A. & Caldeira, K. *Nature Geosci.* **6,** 5–6 (2016).

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Correction

In the Commentary "Why the right climate target was agreed in Paris" (*Nature Clim. Change* **6,** 649–653; 2016), in the first paragraph of the 'Feasibility' section, 'ref. 38, Table 2.2' should have read 'ref. 37, Table 2.2'. Corrected in the online versions after print: 13 July 2016.