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LETTER

Zero emission targets as long-term global goals for climate protection

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Abstract

Recently, assessments have robustly linked stabilization of global-mean temperature rise to the necessity of limiting the total amount of emitted carbon-dioxide (CO_2). Halting global warming thus requires virtually zero annual CO_2 emissions at some point. Policymakers have now incorporated this concept in the negotiating text for a new global climate agreement, but confusion remains about concepts like carbon neutrality, climate neutrality, full decarbonization, and net zero carbon or net zero greenhouse gas (GHG) emissions. Here we clarify these concepts, discuss their appropriateness to serve as a long-term global benchmark for achieving temperature targets, and provide a detailed quantification. We find that with current pledges and for a likely (>66%) chance of staying below 2 °C, the scenario literature suggests net zero CO_2 emissions between 2060 and 2070, with net negative CO_2 emissions thereafter. Because of residual non-CO_2 emissions, net zero is always reached later for total GHG emissions than for CO_2. Net zero emissions targets are a useful focal point for policy, linking a global temperature target and socio-economic pathways to a necessary long-term limit on cumulative CO_2 emissions.

1. Introduction

Global-mean temperature rise is to first order proportional to the cumulative amount of CO_2 emitted into the atmosphere. This emerging characteristic of the Earth System has now been widely studied (Allen *et al* 2009, Matthews *et al* 2009, Meinshausen *et al* 2009) and robustly assessed (Collins *et al* 2013, IPCC 2013). There are several direct implications of this proportionality (Knutti and Rogelj 2015), to which also the Intergovernmental Panel on Climate Change (IPCC) already alludes (Collins *et al* 2013, IPCC 2013, Stocker *et al* 2013, IPCC 2014a, Clarke *et al* 2014). For instance, any given level of temperature stabilization is associated with an upper bound on cumulative CO_2 emissions (IPCC 2013), sometimes termed a carbon budget or quota. Therefore, higher emissions in earlier decades imply lower emissions by the same amount later (Collins *et al* 2013, IPCC 2013). The proportionality between CO_2 and global-mean temperature also implies that limiting warming to any level requires annual net CO_2 emissions to be phased out to virtually zero (Matthews and Caldeira 2008), at the latest near the time when temperature stabilization is to be achieved (Matthews and Caldeira 2008, Ricke and Caldeira 2014, Zickfeld and Herrington 2015). Based on an assessment of scenarios that take into account possible evolutions of our global society (Clarke et al 2014), the IPCC Synthesis Report finds that to keep warming to below 2 °C with a likely (>66%) chance, such pathways would require cumulative emissions to be limited to around 1000 $GtCO_2$ after 2011 with near-zero long-lived greenhouse gases (GHG) by the end of the century (IPCC 2014a). Limiting warming to lower or higher levels would involve similar challenges but on different timescales (IPCC 2014a). With the publication—in 2013 and 2014—of the Fifth Assessment Report (AR5) of the IPCC, these insights have now become widely disseminated.

A further contribution to this dissemination was made by the UNEP Emissions Gap Report (UNEP 2014). In its 2014 edition, the UNEP Emissions Gap Report started from the IPCC AR5 findings on carbon budgets and explored how these emissions can be spread out over time, and when global carbon neutrality should be achieved (see further below).

Because of the authoritative character and the high visibility of these scientific assessments, these insights were quickly taken up by policymakers. For instance, they have found their way into the text which forms the basis for negotiation of a new global climate agreement under the United Nations Framework Convention on Climate Change (UNFCCC 2015). Many text proposals suggest setting a long-term global goal in terms of a timeline for achieving global net zero emissions. Such long-term global net zero goals can guide policymakers in their choice of near-term mitigation actions. Governments, businesses and investors invests in projects today that can last 50 years and more. An aspirational end point for CO_2 emissions can catalyse and facilitate choices that enable the required long-term transition to net zero carbon emissions.

However, the available UNFCCC text proposals also show that the precise meaning and applicability of concepts related to zero (carbon) emissions remain unclear. Indeed, a structured overview of these concepts is currently not available, and neither is a detailed quantification of their link to global temperature limits like 1.5 °C and 2 °C. We here fill this science-policy gap and discuss the strengths and limitations of various zero-emission concepts like carbon neutrality, full decarbonization, climate neutrality, (net) zero carbon emissions, and (net) zero GHG emissions. Additionally, we quantify their link to currently discussed global temperature objectives.

2. Different interpretations of zero

We first provide an overview and working definitions of different zero-emission concepts. Table 1 provides formulas for all definitions introduced below. Note that the terms carbon and CO_2 are used interchangeably.

Table 1. Overview of emission definitions and zero-emission concepts.

Emission definitions
$IC = E - CCS$
E: Annual CO_2 generation by energy and industrial processes
CCS: Annual capture and geological storage of CO_2
IC: Annual unabated CO_2 emissions from energy and industrial processes
$E = FFC + BFC + IA - BFU$
FFC: Annual CO_2 generation from combustion of fossil fuels (before application of CCS)
BFC: Annual CO_2 generation from combustion of biofuels (before application of CCS)
IA: Annual CO_2 generation from industrial activities (for example, cement production)
BFU: Annual CO_2 uptake during biofuel production
$NC = IC + LS - LR$
LS: Annual CO_2 emissions due to land use, land-use change and forestry (LULUCF)
LR: Annual CO_2 uptake/removals due to LULUCF (excluding biofuel production, BFU)
NC: Annual net CO_2 emissions
$NGHG = NC + EGHG$
EGHG: Annual emissions of non-CO_2 Kyoto-GHGs in CO_2-equivalence
NGHG: Annual net Kyoto-GHG emissions
Zero-emission concepts
Full decarbonization or reducing net CO_2 emissions from energy and industrial processes (after accounting for CCS) to zero:
$IC = 0$
Carbon neutrality or net zero CO_2 emissions:
$NC = 0$
Zero carbon emissions everywhere:
$E = 0$; $FFC = 0$; $BFC = 0$; $IA = 0$; $LS = 0$
Climate neutrality or net GHG emissions:
$NGHG = 0$

Historically, the term *decarbonization* has been used to denote the declining average carbon intensity of primary energy production over time (Fisher et al 2007), or, more generally, the reduction of carbon emissions from energy and industrial processes (Clarke et al 2014). Here, we keep this interpretation.

Full decarbonization of the global economy thus means that annual unabated CO_2 emissions from energy and industrial processes are zero on the global scale. Unabated CO_2 emissions here refer to CO_2 emissions from energy and industrial activities that are not balanced by CO_2 sequestration by means of carbon capture and geological storage (CCS; see table 1). The G7 recently included this terminology in its summit declaration (G7 2015). The G7 statement of decarbonization 'over the course of the century' can be regarded as the process of decarbonization with *full decarbonization* as its end point, towards the end of the century.

Similarly, *carbon neutrality* of the global economy denotes that *total* annual CO_2 emissions are zero on the global scale. This concept thus covers all anthropogenic sources of CO_2, including energy, industrial, and land-use emissions. Carbon neutrality can be used as a synonym for the scientific term *net zero carbon emissions*: for every remaining ton of CO_2 emitted due to human activities, exactly one ton of CO_2 is actively removed from the atmosphere due to (other) human activities.

Zero carbon emissions (without the *net* qualifier) is a more hypothetical concept. This goal—when applied to each possible emission sector (ActionAid *et al* 2015) (table 1)—cannot be derived from the IPCC assessment or the current scenario literature (Clarke *et al* 2014). Not a single scenario in the IPCC scenario database (methods) achieves zero carbon emissions everywhere, as even in the most extreme mitigation scenarios residual CO_2 emissions from, e.g., the transport sector can be found. More fundamentally, it seems unlikely that human systems, including the land-use system, can be reduced to zero emissions everywhere. For instance, the cutting and burning of a single tree produces anthropogenic carbon emissions.

Neither carbon neutrality (i.e., net zero carbon emissions), nor full decarbonization imply zero emissions everywhere or in all sectors. Moreover, carbon neutrality also does not imply full decarbonization, as remaining energy and industry-related emissions could be compensated by CO_2 removals achieved by afforestation and reforestation. Finally, also full decarbonization can still imply a remainder of *gross* emissions from energy and industry, as long as negative emissions (e.g. biomass use combined with CCS—BECCS) compensate for this.

Climate neutrality can be interpreted in many ways. It was introduced more than a decade ago (see description in Worth 2005) and further disseminated by UNEP (UNEP 2008, 2011). At a global scale it has been defined as 'living in a way which produces no net GHG emissions' (UNEP 2008). In scientific terms this hence corresponds to achieving *net zero GHG emissions*. In the scientific literature (UNEP 2014), net zero global GHG emissions are taken as the point in which total global Kyoto-GHG emissions (methods) become net zero—which means that any residual CO_2 and non-CO_2 emissions (for example, methane or nitrous oxide; expressed in units of CO_2 equivalence) are compensated by negative emissions of CO_2.

As for carbon emissions, *zero GHG emissions* (in absence of the qualifier *net*) would imply that no anthropogenic GHG emissions would occur anywhere —an implausible scenario given that for some parts of the agricultural, grazing, and life-stock sectors only low technical mitigation potentials have yet been identified (Smith *et al* 2014).

3. Conceptual clarity

Unfortunately, the scientific definitions provided in the previous section do not eliminate all possible sources of confusion. Misinterpretation is still possible because (i) some of the concepts require further specifications in addition to the definitions provided above, (ii) other definitions can be imagined for the same concept, or (iii) a particular concept has already a common (non-scientific) use in policy circles which is different from its purely scientific meaning. We here clarify these possible sources of confusion.

Compared to concepts that focus solely on CO_2, including all GHGs comes with some complications. First, the compelling logic of a finite budget strictly applies only to CO_2, not to non-CO_2 gases. For any temperature stabilization level, CO_2 emissions have to become net zero once the budget is exhausted. However, non-CO_2 emissions (like biogenic methane or nitrous oxide) could theoretically be continued forever at stable, low levels. This is because those non-CO_2 gases have limited lifetimes, while carbon that is released into the interconnected Earth system (comprising atmosphere, biosphere and oceans) will increase atmospheric CO_2 concentrations on timescales of at least millennia (Joos *et al* 2012). Second, CO_2-equivalence of non-CO_2 emissions can be based on a variety of metrics, the choice of which incorporates normative judgements about the trade-offs between policy targets (Deuber *et al* 2013, Myhre *et al* 2013). Most commonly, global-warming-potential-weighted emissions over a 100 year period (GWP-100) are used—for example, within the UNFCCC (2002)—but many other options are available (Fuglestvedt *et al* 2003, Myhre *et al* 2013).

Net zero emission targets have a more direct scientific meaning than *neutrality* concepts. For example, climate neutrality could also be defined in a broader sense, instead of only referring to Kyoto-GHG emissions. Such a definition could account for all anthropogenic influences, such as air pollutants and the modification of the Earth's surface albedo due to anthropogenic land-use changes (Brovkin *et al* 2013). The spatial heterogeneity of short-lived forcers and land-use patterns forfeits the possibility of a full spatial climate neutrality—although it would be theoretically possible at an annual and global average scale.

Finally, we indicated above that net zero carbon emissions can be achieved by balancing any remaining CO_2 emissions by CO_2 removals of exactly the same amount. Scientifically, the terms CO_2 removals and so-called *negative emissions* (Obersteiner *et al* 2001, Ciais *et al* 2013, Tavoni and Socolow 2013, Clarke *et al* 2014) are synonymous with respect to what the atmosphere sees. They are both anthropogenic in origin and therewith distinct from the natural carbon uptake via the carbon cycle. However, they are conceptually connected to fundamentally different activities when used in international climate negotiating settings, because the term *removals* has already been used earlier in the climate policy discourse to denote something more specific: in the UNFCCC, CO_2 removals refer to the uptake of CO_2 due to human activities in the land use, land-use change, and forestry sector (LULUCF, for example, see UNFCCC 2014). *Negative emissions*, on the other hand, would refer to technological solutions like bioenergy in combination with CO_2 capture and permanent geological storage (BECCS; see section 6.5 in Ciais *et al* 2013 and section 6.9 in Clarke *et al* 2014 for a longer discussion of negative emissions). Up to now, emission accounting within the UNFCCC was focussed on historical and near-term GHG emissions and LULUCF removals. In this context, geological CCS and *negative emissions* achieved by BECCS did not play a role. The provenance and permanence of CO_2 removals and *negative emissions* can thus be interpreted very differently in the context of international negotiations.

Furthermore, the term *net emissions* is also commonly used in submissions by countries to the UNFCCC, although it remains legally undefined. In this setting, the term *net* is used to refer to the sum of energy and industry-related emissions (referred to as *gross* emissions) and emissions and removals from the LULUCF sector. Finally, it is also used in the context of national emission inventories when accounting for the transfer and/or acquisition of international emission trading units of one kind or another.

Therefore, care needs to be taken when using the terms *net* or *removals,* because quite different implications for policy could be inferred by non-scientists. While 'net' emission concepts mostly look at the balance of emissions across the complete range of sectors, this does not exclusively need to be the case. For example, *full decarbonization* considers the *net* outcome of positive and negative emissions across the energy and industry sectors only. In this case, remaining emissions from some energy-related sources, e.g. the transport sector, can be offset by BECCS power plants in the electricity sector.

4. Methods

We re-analyse the scenarios of the IPCC AR5 Scenario Database (hosted at the International Institute for Applied Systems Analysis and available at https://secure.iiasa.ac.at/web-apps/ene/AR5DB/), complemented with scenarios from three studies (Luderer *et al* 2013, Rogelj *et al* 2013a, 2013b) that additionally explored scenarios that return warming to below 1.5 °C in 2100, as assessed in Rogelj *et al* (2015). These scenarios are generated with process-detailed integrated assessment models, which represent the complex interaction between the energy, economy, and land-use systems to derive cost-effective emission pathways for prescribed climate change mitigation targets. They do not account for the damages from climate change. In most cases, the scenarios assume globally coordinated mitigation action from a certain year onward, for example, starting in 2010 or in 2030, or after a transitional phase of fragmented climate action. Besides the stringency of mitigation action, scenarios also vary the availability of mitigation technologies (for example, future availability of nuclear energy or the maximum bio-energy potential) or the assumed future energy demand.

Temperature outcomes were computed with the reduced complexity carbon-cycle and climate model MAGICC (Meinshausen *et al* 2011) in a probabilistic setup (Meinshausen *et al* 2009, Rogelj *et al* 2012) consistent with the IPCC AR5 climate sensitivity assessment (Rogelj *et al* 2014).

The IPCC AR5 Scenario Database does not sample cumulative carbon budgets evenly (figure 1(a)). This is because the database was to a large extent populated by the scenarios resulting from large model-intercomparison projects that all explored very similar forcing or cumulative emissions targets. These targets were very often in line with limiting warming to below 2 °C. Therefore, the IPCC Scenario Database is particularly useful for exploring question regarding the 2 °C limit, but potentially less useful for other—both higher and lower—limits.

Smoothing spline quantile regressions are computed by first applying a moving window over the dataset and calculating the quantile values per window. Subsequently, a smoothing spline fit was applied to all calculated quantile points. Scenarios that do not reach net zero CO_2 emissions during the 21st century are included in the percentiles, and are reported as 'post-2100'. A jack-knife resampling was applied to test the variance of our median estimates (Efron and Stein 1981).

The Kyoto-basket (UNFCCC 1998) of GHGs which we analyse from the scenarios contains CO_2, as well as methane (CH_4), nitrous-oxide (N_2O), hydrofluorocarbons, perfluorinated compounds, and sulphur-hexafluoride (SF_6). In this study, we use 100 year GWPs as provided in the IPCC Second Assessment report to aggregate CO_2 equivalent emissions of these gases (although the climate model calculations are independent from that metric, as concentrations and forcings are calculated separately for each gas).

5. Global long-term emission goals

A limit on cumulative CO_2 emissions is required to halt global-mean temperature rise to any level and hence implies that annual global CO_2 emissions have to become net zero at some point in time. We explore the implications of this geophysical requirement by means of a re-analysis of emission scenarios. First, we explore the typical timing of annual CO_2 emissions reaching net zero levels as a function of cumulative CO_2 emissions in the 21st century (figure 1). Then, we provide the characteristics of long-term zero emission goals for global temperature objectives (figure 2) and look at the effectiveness of carbon neutrality targets (figure 3). Finally, we quantify the influence of higher

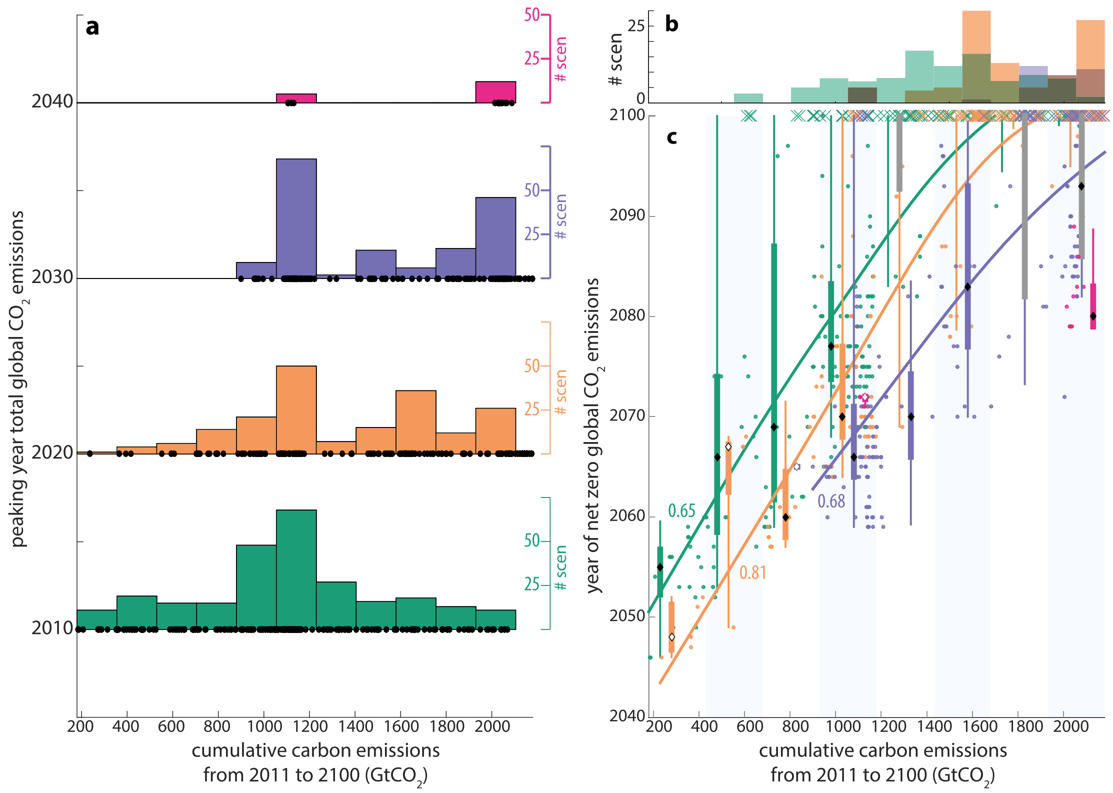

Figure 1. Influence of peak year of global CO_2 emissions on timing of net zero global CO_2 emissions. (a) Distribution of cumulative carbon emissions from 2011 to 2100 and peak year for total global CO_2 emissions. (b) Distribution of scenarios not achieving net zero global CO_2 emissions before in the 21st century. (c) Relationship between cumulative carbon emissions from 2011 to 2100 and timing of global CO_2 emissions reaching net zero levels. Green, orange, purple, and pink colours in panel (b) and (c) refer to the peaking years shown in panel (a). Dots indicate single scenarios. Diamonds show medians, and box plots and whiskers indicate the central 50 and 90% range, respectively, over each shaded bin. Empty diamonds indicate that less than 10 scenarios are available in a given bin and for a given peaking year; filled diamonds indicate the opposite. Coloured boxes indicate that more than 80% of the scenarios actually achieve net zero CO_2 emissions before 2100; grey boxes the opposite. Diagonal lines in panel (c) are smoothing splines over all data points for each peaking year, respectively. Numbers in panel (c) are R^2 values for the respective fits.

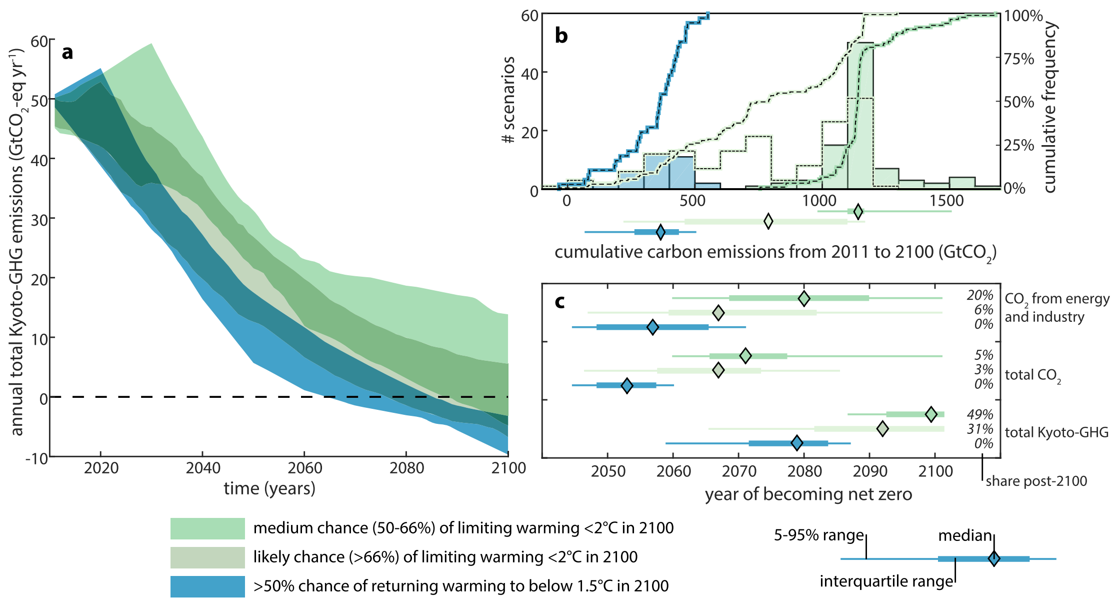

Figure 2. Cumulative CO_2 and net zero characteristics of 1.5 °C and 2 °C scenarios. (a) Annual Kyoto-GHG emissions over time for 1.5 °C and 2 °C scenarios (10th–90th percentile ranges). (b) Statistics of cumulative CO_2 emissions from 2011 to 2100 per scenario group; (c) Statistics of timing of emissions becoming net zero. Data is provided for unabated CO_2 emissions from energy and industrial sources, net total CO_2 emissions, and net total Kyoto-GHG emissions. Percentages next to the bars in panel (c) indicate the share of scenarios that do not achieve net zero levels before 2100 in the respective category and for the respective gas.

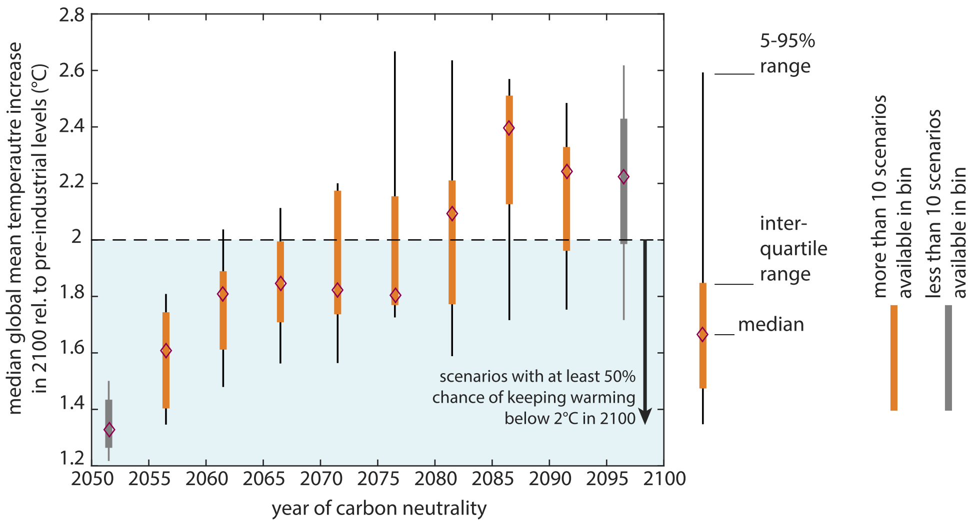

Figure 3. Effectiveness of global carbon neutrality targets. Relationship between year of carbon neutrality and global mean temperature increase in 2100, relative to pre-industrial levels. Unless global carbon neutrality is achieved around mid-century, it seems that achieving global carbon neutrality is a necessary, yet not a sufficient, condition for limiting warming to below 2 °C by 2100 with at least 50% chance. Similar relationships for the timing of net global Kyoto-GHG emissions and of unabated CO_2 from energy and industrial sources becoming zero is shown in supplementary figure S5.

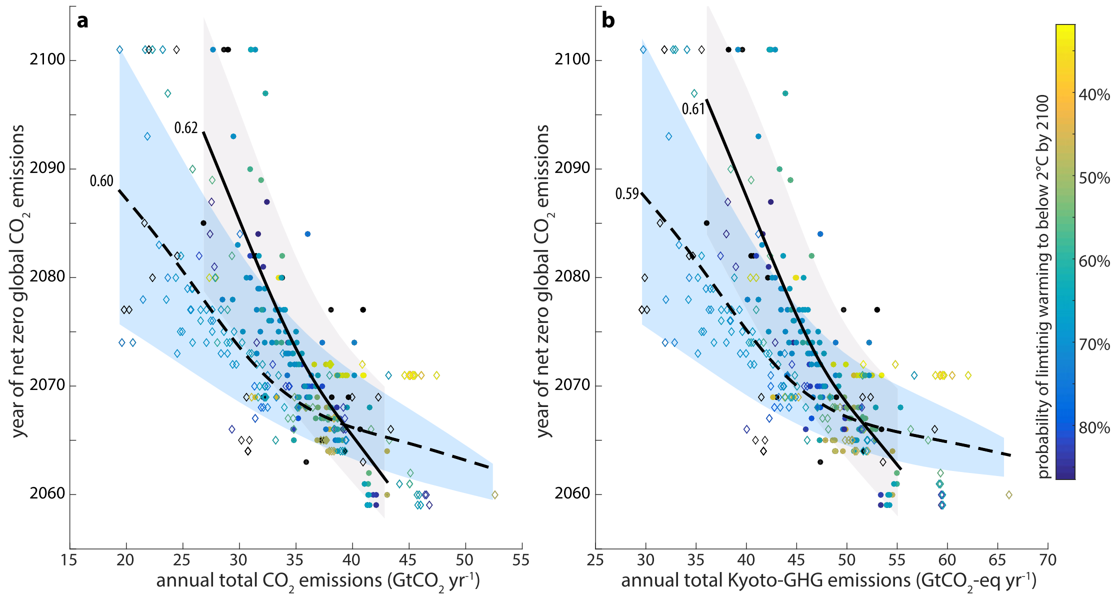

Figure 4. Influence of near-term emission levels in 2020 and 2030 on timing of net zero global CO_2 emissions during the 21st century. Timing of net zero global CO_2 emissions as a function of annual total CO_2 (panel a) and Kyoto-GHGs (panel b) emissions in 2020 (dots) and 2030 (diamonds), respectively. Black solid and dashed lines represent smoothing spline fits for the years 2020 and 2030, respectively. The encompassing grey and blue shaded ranges are smoothing spline quantile regressions onto the 10th and the 90th percentile for the years 2020 and 2030, respectively. Dots and diamonds are colour-coded based on their probability of limiting warming to below 2 °C by 2100. All shown scenarios have cumulative CO_2 emissions from 2011 to 2100 between 930 and 1180 $GtCO_2$. Numbers in the panels are R^2 values for the respective median fits.

or lower near-term emission levels (in 2020 and 2030) on these zero emission goals (figures 4 and 5).

The IPCC (2014b) reported that scenarios having a likely (>66%) chance to stay below 2 °C, limit cumulative CO_2 emissions to 630–1180 $GtCO_2$ over the 2011–2100 period. Our scenario analysis suggests that the vast majority of such scenarios would reach net zero CO_2 before about 2080 (figure 1, all years rounded to the nearest 5). CO_2 budgets are here defined over the 2011–2100 period, and about 155 $GtCO_2$ was emitted from 2011 to 2014 (Friedlingstein *et al* 2014, Le Quéré *et al* 2014). Also for higher CO_2 budgets of up to about 1600 $GtCO_2$ net zero CO_2 emissions are often achieved before 2100, depending on the near-term evolution of emissions (figure 1(c) and below).

To directly link these insights to temperature objectives, we now use probabilistic temperature projections computed for each of the scenarios. This

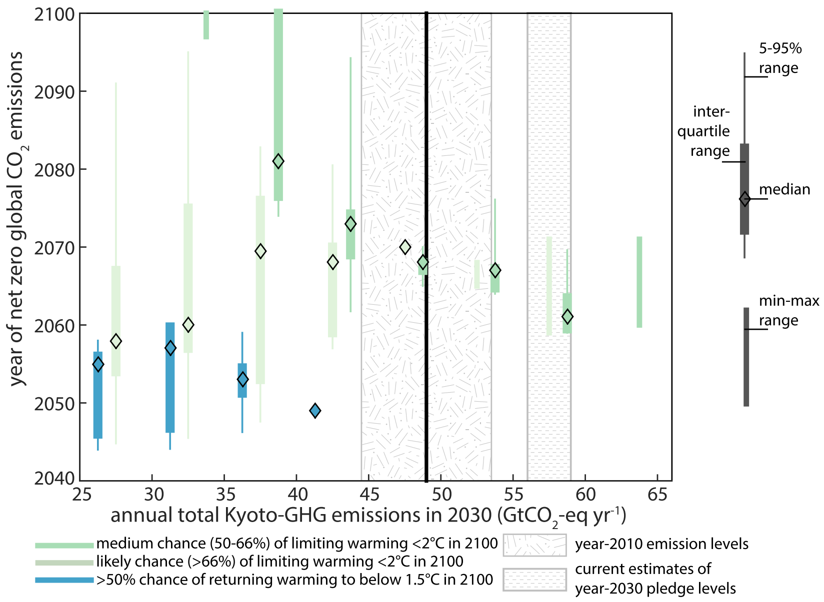

Figure 5. Influence of near-term (2030) Kyoto-GHG emission levels on timing of global CO_2 emissions becoming net zero for 1.5 °C and 2 °C scenarios. Year-2010 estimates and 90% uncertainty range are from Blanco *et al* (2014). The year-2030 emission levels estimated to result from the current pledges are from UNEP (2014). Vertical ranges show the statistics per window of 5 $GtCO_2$-eq, starting at 25 $GtCO_2$-eq. If less than 10 scenarios are available in for a give window and a give temperature goal, only the minimum-maximum range is provided. If only one value is available, this value is indicated by a single diamond. The influence of near-term Kyoto-GHG emissions on the timing of net global Kyoto-GHG emissions and unabated CO_2 from energy and industrial sources becoming zero is shown in supplementary figures S1 and S2, respectively.

approach links temperature objectives to geophysical constraints on cumulative CO_2 emissions and technologically feasible emission trajectories. Two temperature limits are currently the focus of the international climate negotiations, a 1.5 °C and a 2 °C limit relative to pre-industrial levels (see table 2 for precise definitions). Figure 2(a) shows that to stay below any of these limits, important reductions in the annual emissions of the aggregated Kyoto-GHGs are projected. With CO_2 making up about three quarters of current Kyoto-GHG emissions (Edenhofer *et al* 2014), this implies that cumulative CO_2 emissions over the 21st century are capped at low levels.

We find that to limit warming to below 2 °C with at least 66% chance, median cumulative CO_2 emissions from 2011 to 2100 are 790 $GtCO_2$, with an interquartile range of 470–1085 $GtCO_2$ (figure 2(b), table 2; values rounded to the nearest 5 $GtCO_2$). This range compares well to the abovementioned IPCC range of 630–1180 $GtCO_2$. Our median estimate is lower than the IPCC range because our analysis includes studies that explore more stringent mitigation targets (Luderer *et al* 2013, Rogelj *et al* 2013a, 2013b, 2015) than those included in the IPCC Scenario Database. Finally, our results are also consistent with the 1000 $GtCO_2$ value provided in the IPCC Synthesis Report (IPCC 2014a). Supplementary text 1 provides a detailed comparison. To return warming to below 1.5 °C by 2100, we find a median CO_2 budget of 365 $GtCO_2$, and an interquartile range of 275–425 $GtCO_2$.

These budgets then translate into a corresponding timing of achieving global net zero emissions (figure 2(c); table 2). The median year of achieving net zero CO_2 emissions in scenarios which limit warming to below 2 °C with >66% chance is around 2065, with an interquartile range of approximately 2060–2075. In more than 95% of the cases net zero CO_2 emissions are achieved before 2100. For Kyoto-GHG emissions, median net zero levels are achieved around 2090 and about two-thirds of the scenarios reach net zero Kyoto-GHG levels before 2100. As negative emissions technologies are only available for CO_2, the timing of net zero Kyoto-GHG emissions will always be later than the timing of net zero CO_2 emissions. Only when CO_2 emissions are already net negative on a global scale, net zero Kyoto-GHG emissions will be achieved. For 1.5 °C consistent scenarios both the timing of net zero CO_2 and Kyoto-GHGs is about a decade earlier. These estimates are consistent with the UNEP Gap Report (UNEP 2014) estimates, taking into account differing assumptions about the near term (supplementary text 1).

Because of the unstructured character of the IPCC AR5 Scenario Database, the above-mentioned estimates can be subject to sampling bias. Explicitly testing for any model-sampling bias shows that the median estimates reported in table 2 are surrounded by an uncertainty that is of the order of the interquartile or 5–95th percentile range for 2 °C and 1.5 °C, respectively (see supplementary table 1). This reflects the higher uncertainty surrounding the 1.5 °C related estimates, because only two models provided scenarios that fall within that category.

Table 2. Internally consistent sets of global long-term targets related to warming limits of 1.5 °C and 2 °C. Overview of cumulative total CO_2 emissions from 2011 to 2100, as well as the time of CO_2 emissions from energy and industrial sources, the time of total global CO_2 emissions, the time of total global Kyoto-GHG emissions becoming net zero. Additionally, an indication of the influence of currently projected near-term (2030) emission levels in line with the country pledges (UNEP 2014) (56–59 $GtCO_2$-eq/yr) is provided based on figure 5. Values are derived from our full scenario ensemble.

	Timing of reaching net zero levels (year[a])			
Cumulative CO_2 emissions[a] from 2011–2100 ($GtCO_2$)	CO_2 from energy and industrial sources[b]	Global total CO_2	Kyoto-GHGs	Influence of currently projected near-term (2030) emission levels in line with country pledges
Global temperature goal				
Limiting warming to below 2 °C relative to pre-industrial levels with a medium (50%–66%) chance in 2100				
1140 [1110–1150] (985–1500)	2080 [2070–2090] (2060–2100)	2070 [2065–2075] (2060–2100)	2100 [2095–2100] (2085–2100)	Current pledges imply net zero global CO_2 emissions earlier than the inter-quartile range (i.e., between 2060 and 2065)
Limiting warming to below 2 °C relative to pre-industrial levels with a likely (>66%) chance in 2100				
790 [470–1085] (225–1165)	2065 [2060–2080] (2045–2100)	2065 [2060–2075] (2045–2085)	2090 [2080–2100] (2065–2100)	Current pledges imply net zero global CO_2 emissions at lower end of the interquartile range (between 2060 and 2070), but only very few feasible scenarios are available in this case.
Returning warming to below 1.5 °C relative to pre-industrial levels with a >50% chance in 2100				
365 [275–425] (70–500)	2055 [2050–2065] (2045–2070)	2055 [2050–2055] (2045–2060)	2080 [2070–2085] (2060–2085)	No scenarios available from 2030 levels implied by current pledges. Pledges should be strengthened to achieve at least a 20% reduction from 2010 levels (i.e., 2030 GHG levels of about 40 $GtCO_2$-eq/yr)

[a] Rounded to nearest 5 $GtCO_2$ or nearest 5 year—format: median [interquartile range] (5th to 95th percentile range).

[b] Referring to unabated CO_2 emissions from energy and industrial sources—see table 1.

Finally, we look at this question from the opposite perspective: what is the range of temperature outcomes consistent with a global net zero CO_2 emissions target year? Figure 3 shows that while the large majority of scenarios that achieve global carbon neutrality in the 2060–2075 period keep median warming in 2100 below 2 °C, this is not a sufficient condition. The total amount of emissions emitted until the moment of reaching carbon neutrality and the amount of non-CO_2 warming at that point (Rogelj *et al* 2015), also play an additional role.

6. Near-term delay implies earlier net zero carbon

Relatively higher emissions in the near term require more rapid reductions and lower emissions afterwards (Collins *et al* 2013, Knutti and Rogelj 2015). This trade-off implies that, for a given CO_2 budget, net zero levels are reached earlier in time if mitigation is delayed. Figure 1(c) illustrates the relationship between the timing of when global CO_2 emissions peak and the resulting years in which net zero CO_2 emissions would need to be achieved. Our analysis shows for example that for CO_2 budgets in the 930–1180 $GtCO_2$ range, a delay of two decades in the peak in global CO_2 emissions would imply the need to reach net zero CO_2 emissions about 15 years earlier.

Not only the timing of the global peak in emissions influences when net zero CO_2 emissions are achieved, also the level at which emissions peak plays a role. Figure 4 illustrates this for CO_2 emissions budgets of 930–1180 $GtCO_2$, roughly consistent with a global warming limit of 2 °C (table 2). Both for near-term CO_2 and Kyoto-GHG emission levels (in the years 2020 and 2030), a clear relationship with the timing of global CO_2 emissions becoming net zero is found.

For instance, to stay within the specified CO_2 emission budget, year-2030 CO_2 emission levels of about 45 $GtCO_2$ correspond to global CO_2 emissions reaching net zero levels around 2065 (median estimate, 10th–90th percentile range of 2060–2070). Lower 2030 CO_2 levels of about 25 $GtCO_2$ would correspond to reaching net zero CO_2 later, around 2080 (10th–90th percentile range of 2070–2090). As emission levels of CO_2 and non-CO_2 gases are coupled—if not because they are emitted by the same technologies then through policy mechanisms under the UNFCCC—a similar trade-off between near and long term can be found for Kyoto-GHGs. Both later and higher peaking thus implies higher emission reduction rates (Rogelj *et al* 2013a, IPCC 2014b).

Finally, we apply these insights to our temperature-based scenario subsets (table 2) in order to better understand the uncertainties in the timing of CO_2 emissions becoming net zero. Later peaking consistently advances the timing of reaching net zero total CO_2 emissions given a specified CO_2 budget. This relationship also exists in the subsets of 1.5 °C and 2 °C consistent scenarios. For instance in scenarios that limit warming to below 2 °C with 50%–66% chance, for each 10 $GtCO_2$-eq/yr that emissions are lower in 2030, the time of achieving net zero total CO_2 emissions is delayed by about a decade (figure 5). Without a further strengthening over the coming years, current pledges would imply that global net zero total CO_2 emissions need to be reached between 2060 and 2070 for achieving a 50%–66% chance of staying below 2 °C (figure 4 and S2). Kyoto-GHG emissions would decline to net zero at around 2090 (figure S1). In contrast, having already embarked onto a long-term mitigation pathway by 2030 (with emission in the 35–40 $GtCO_2$-eq/yr range), would postpone the timing of net zero CO_2 emissions by between 15 to more than 30 year.

However, figure 5 also shows that for 1.5 °C consistent scenarios and scenarios limiting warming to below 2 °C with >66% chance this relationship is less clear. The underlying reasons for this are limitations of the scenario sampling in the IPCC scenario database and hence also of our scenario ensemble (methods). Only a limited number of scenario studies is available for those ambitious mitigation scenarios and the available scenarios and models do not sample near-term developments evenly (figure 5). Furthermore, cumulative carbon budgets tend to decrease together with the near-term evolution of emissions (figure S3).

Although the timing of net zero CO_2 emissions is generally moved forward with higher near-term emissions given a fixed CO_2 budget, this trade-off is thus less visible in the two most stringent scenario subsets because also the CO_2 budget is generally reduced in our scenarios. Incidentally scenarios with higher 2030 emissions and a 66% chance of limiting warming to below 2 °C are also generated by a different subset of models than those at the lower end, but this only influences the timing to a small degree (figure S4). These insights highlight the critical importance of verifying possible biases in scenario re-analysis arising from uneven sampling in *ensembles of opportunity*.

Furthermore, with increasing near-term emissions, models will also find it increasingly difficult to keep emissions within given cumulative emissions budgets up to the point that no feasible solutions can be produced (Rogelj *et al* 2013a, IPCC 2014b). Infeasible scenarios are often not reported (Tavoni and Toll 2010). This results in very few available scenarios for the lowest temperature levels (1.5 °C) and the highest probabilities (>66%) in case year-2030 Kyoto-GHG emission levels exceed 45 $GtCO_2$-eq/yr. At 2030 emission levels below 45 $GtCO_2$-eq/yr, also returning warming to below 1.5 °C by 2100 would remain an option—entailing, however, net zero total CO_2 emissions at around 2045–2060.

Finally, besides the level of near-term emissions, the uncertainty in the timing of global CO_2 becoming zero can be influenced by the CO_2 pathway, the potential for negative emissions, and the non-CO_2 mitigation potential. However, the unstructured nature of our scenario set, does not allow for a robust analysis of these issues.

7. Conclusions

Global *net zero emission* targets are scientifically clearer defined than *neutrality* concepts, which require additional definitions. CO_2-related targets (like net zero carbon emissions or full decarbonization) have a compelling direct link to the finding of climate science on CO_2 budgets—the most important anthropogenic radiative forcing agent. These CO_2-related targets can complement targets on the broader Kyoto-GHG emissions basket, so that contributions of non-CO_2 gases to climate change are also brought under control.

Net zero emission targets (including full decarbonization) are useful focal points (Jaeger and Jaeger 2010) for policy, providing a link between technologically feasible socio-economic pathways and a long-term limit on cumulative CO_2 emissions. From a climate point of view, capped cumulative CO_2 emissions remain the highest priority for temperature stabilization. Emissions in every year contribute to this CO_2 budget, and delaying mitigation over the coming decades increases the pressure to achieve net zero CO_2 emissions earlier in this century. Once global net zero CO_2 emissions are achieved, also the cumulative CO_2 budget will be effectively capped.

Finally, internally consistent sets of global long-term goals emerge from our re-analysis: for each global temperature target, a set of CO_2 budgets, near-term (2030) global emission levels and a year range for achieving net zero total CO_2 emissions can be specified (table 2). This information can help policymakers to verify the internal consistency and scientific integrity of the on-going UNFCCC climate negotiations.

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