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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 (CO₂). Halting global warming thus requires virtually zero annual CO₂ 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 CO₂ emissions between 2060 and 2070, with net negative CO₂ emissions thereafter. Because of residual non-CO₂ emissions, net zero is always reached later for total GHG emissions than for CO₂. 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 CO₂ emissions.

1. Introduction

Global-mean temperature rise is to first order proportional to the cumulative amount of CO₂ 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 CO₂ 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 CO₂ and global-mean temperature also implies that limiting warming to any level requires annual net CO₂ 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 GtCO₂ 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 invest in projects today that can last 50 years and more. An aspirational end point for CO₂ 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 CO₂ are used interchangeably.

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

Emission definitions
$IC = E - CCS$ <i>E</i> : Annual CO ₂ generation by energy and industrial processes <i>CCS</i> : Annual capture and geological storage of CO ₂ <i>IC</i> : Annual unabated CO ₂ emissions from energy and industrial processes $E = FFC + BFC + IA - BFU$ <i>FFC</i> : Annual CO ₂ generation from combustion of fossil fuels (before application of CCS) <i>BFC</i> : Annual CO ₂ generation from combustion of biofuels (before application of CCS) <i>IA</i> : Annual CO ₂ generation from industrial activities (for example, cement production) <i>BFU</i> : Annual CO ₂ uptake during biofuel production $NC = IC + LS - LR$ <i>LS</i> : Annual CO ₂ emissions due to land use, land-use change and forestry (LULUCF) <i>LR</i> : Annual CO ₂ uptake/removals due to LULUCF (excluding biofuel production, BFU) <i>NC</i> : Annual net CO ₂ emissions $NGHG = NC + EGHG$ <i>EGHG</i> : Annual emissions of non-CO ₂ Kyoto-GHGs in CO ₂ -equivalence <i>NGHG</i> : Annual net Kyoto-GHG emissions
Zero-emission concepts
<i>Full decarbonization or reducing net CO₂ emissions from energy and industrial processes (after accounting for CCS) to zero:</i> $IC = 0$ <i>Carbon neutrality or net zero CO₂ emissions:</i> $NC = 0$ <i>Zero carbon emissions everywhere:</i> $E = 0; FFC = 0; BFC = 0; IA = 0; LS = 0$ <i>Climate neutrality or net GHG emissions:</i> $NGHG = 0$

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 CO₂ emissions from energy and industrial processes are zero on the global scale. Unabated CO₂ emissions here refer to CO₂ emissions from energy and industrial activities that are not balanced by CO₂ 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 CO₂ emissions are zero on the global scale. This concept thus covers all anthropogenic sources of CO₂, 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 CO₂ emitted due to human activities, exactly one ton of CO₂ 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 CO₂ 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 CO₂ 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 CO₂ and non-CO₂ emissions (for example, methane or nitrous oxide; expressed in units of CO₂ equivalence) are compensated by negative emissions of CO₂.

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 CO₂, including all GHGs comes with some complications. First, the compelling logic of a finite budget strictly applies only to CO₂, not to non-CO₂ gases. For any temperature stabilization level, CO₂ emissions have to become net zero once the budget is exhausted. However, non-CO₂ emissions (like biogenic methane or nitrous oxide) could theoretically be continued forever at stable, low levels. This is because those non-CO₂ gases have limited lifetimes, while carbon that is released into the interconnected Earth system (comprising atmosphere, biosphere and oceans) will increase atmospheric CO₂ concentrations on time-scales of at least millennia (Joos *et al* 2012). Second, CO₂-equivalence of non-CO₂ 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 (Fuglestad *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 CO₂ emissions by CO₂ removals of exactly the same amount. Scientifically, the terms CO₂ 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, CO₂ removals refer to the uptake of CO₂ 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 CO₂ 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 CO₂ 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).

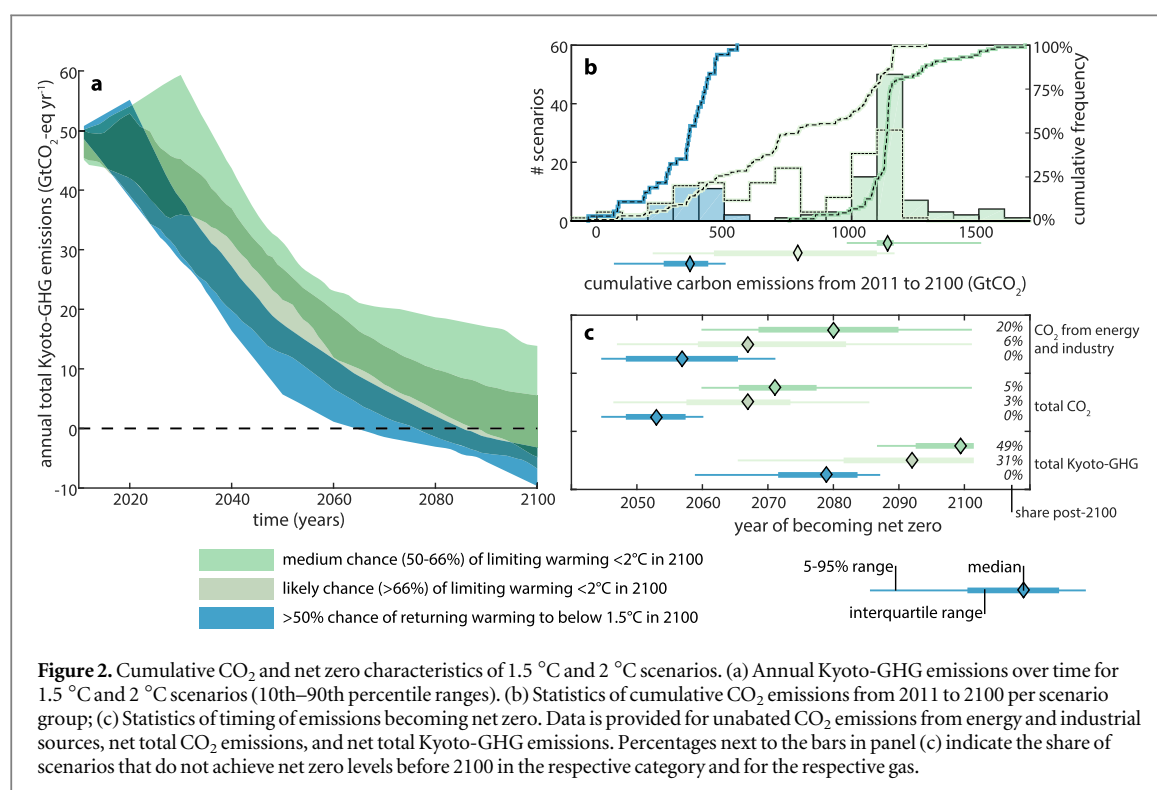
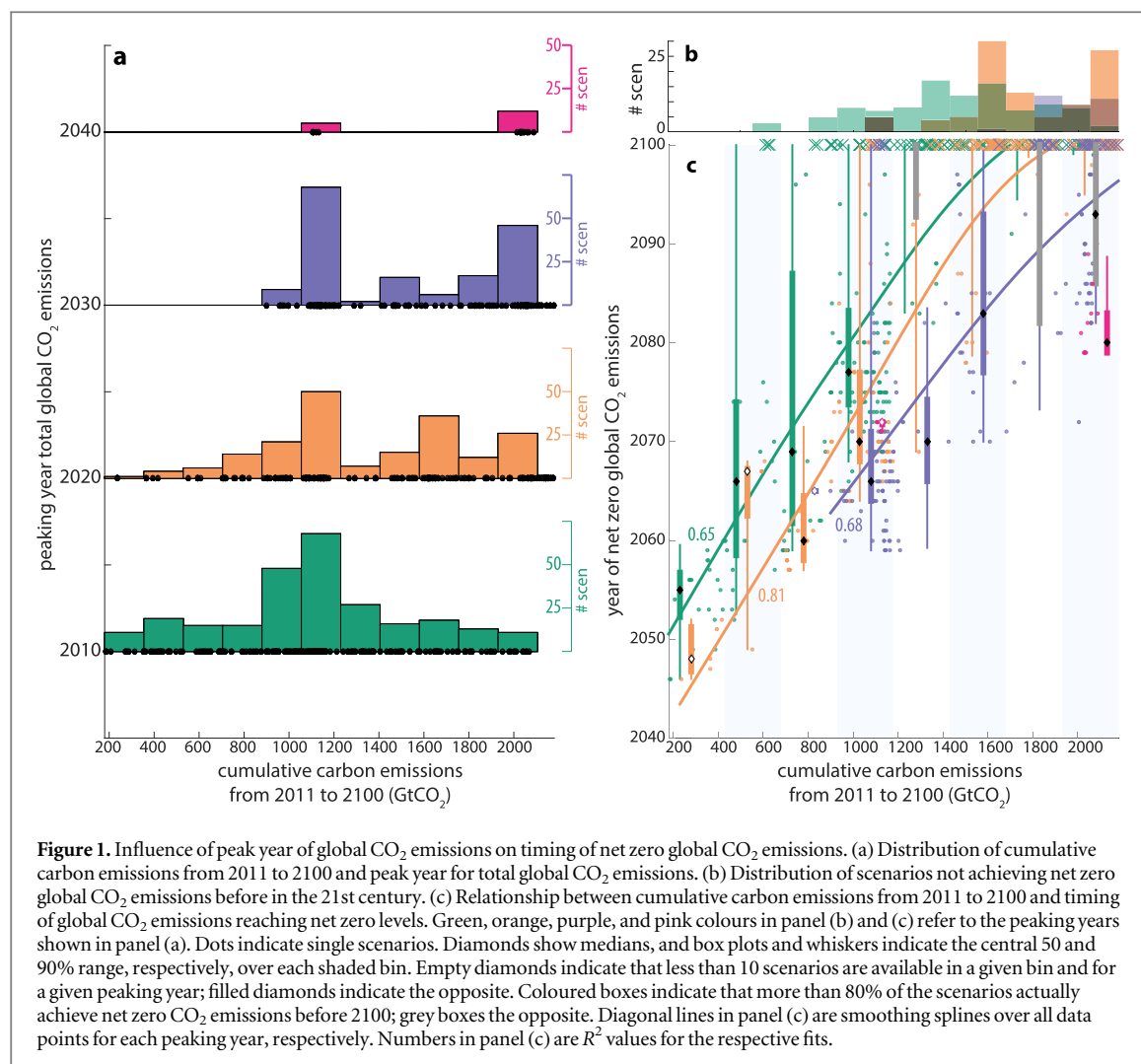
The IPCC AR5 Scenario Database does not sample cumulative carbon budgets evenly (figure 1(a)). This is because the database was to a large extent populated by the scenarios resulting from large model-inter-comparison projects that all explored very similar forcing or cumulative emissions targets. These 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.

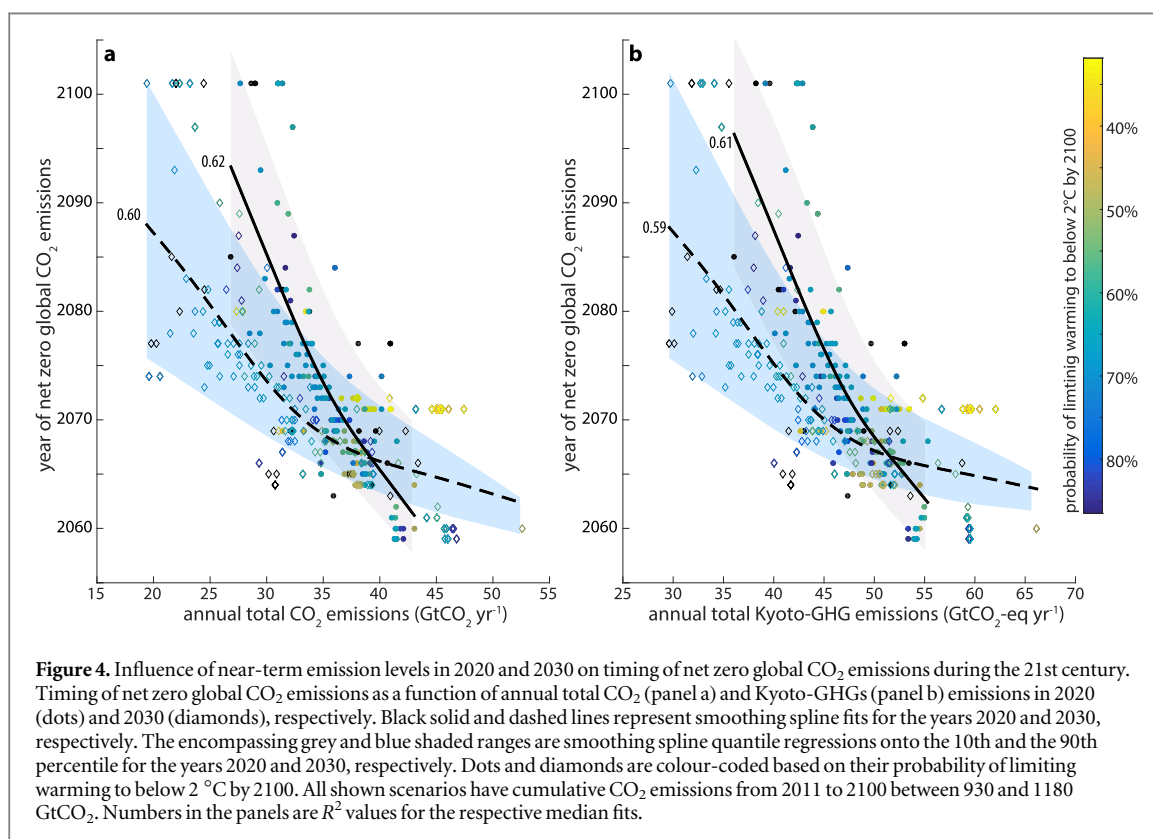
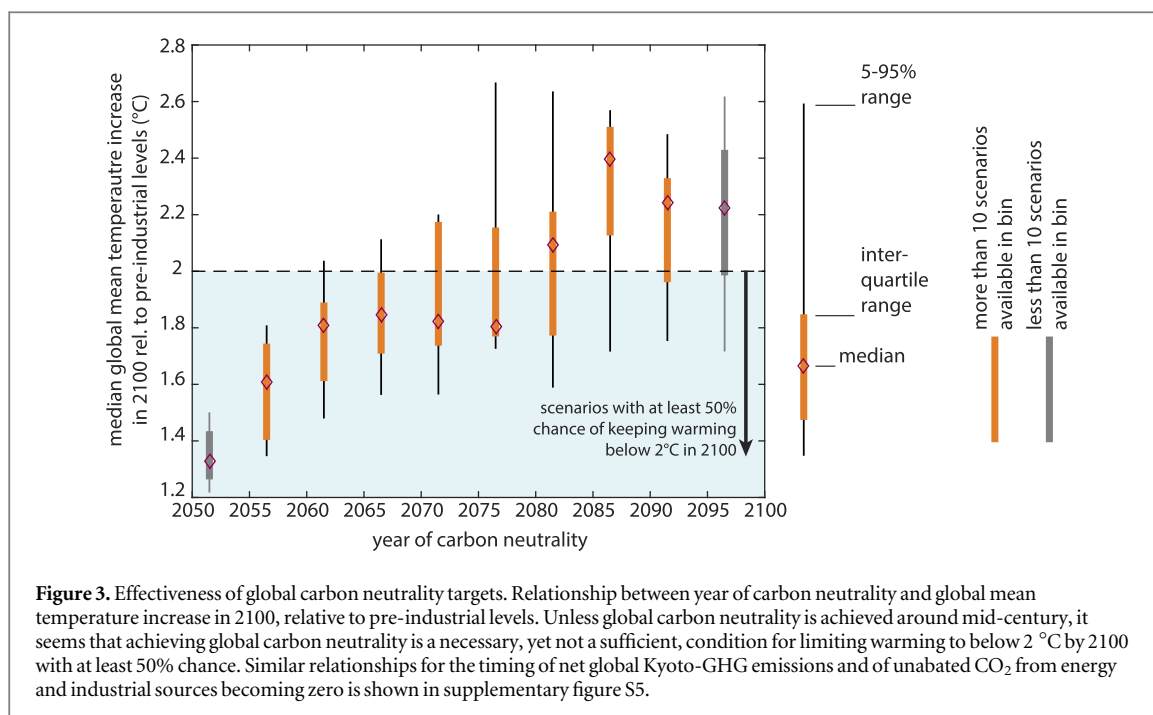
Smoothing spline quantile regressions are computed by first applying a moving window over the dataset and calculating the quantile values per window. Subsequently, a smoothing spline fit was applied to all calculated quantile points. Scenarios that do not reach net zero CO₂ emissions during the 21st 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 CO₂, as well as methane (CH₄), nitrous-oxide (N₂O), hydro-fluorocarbons, perfluorinated compounds, and sulphur-hexafluoride (SF₆). In this study, we use 100 year GWPs as provided in the IPCC Second Assessment report to aggregate CO₂ 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 CO₂ emissions is required to halt global-mean temperature rise to any level and hence implies that annual global CO₂ 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 CO₂ emissions reaching net zero levels as a function of cumulative CO₂ 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



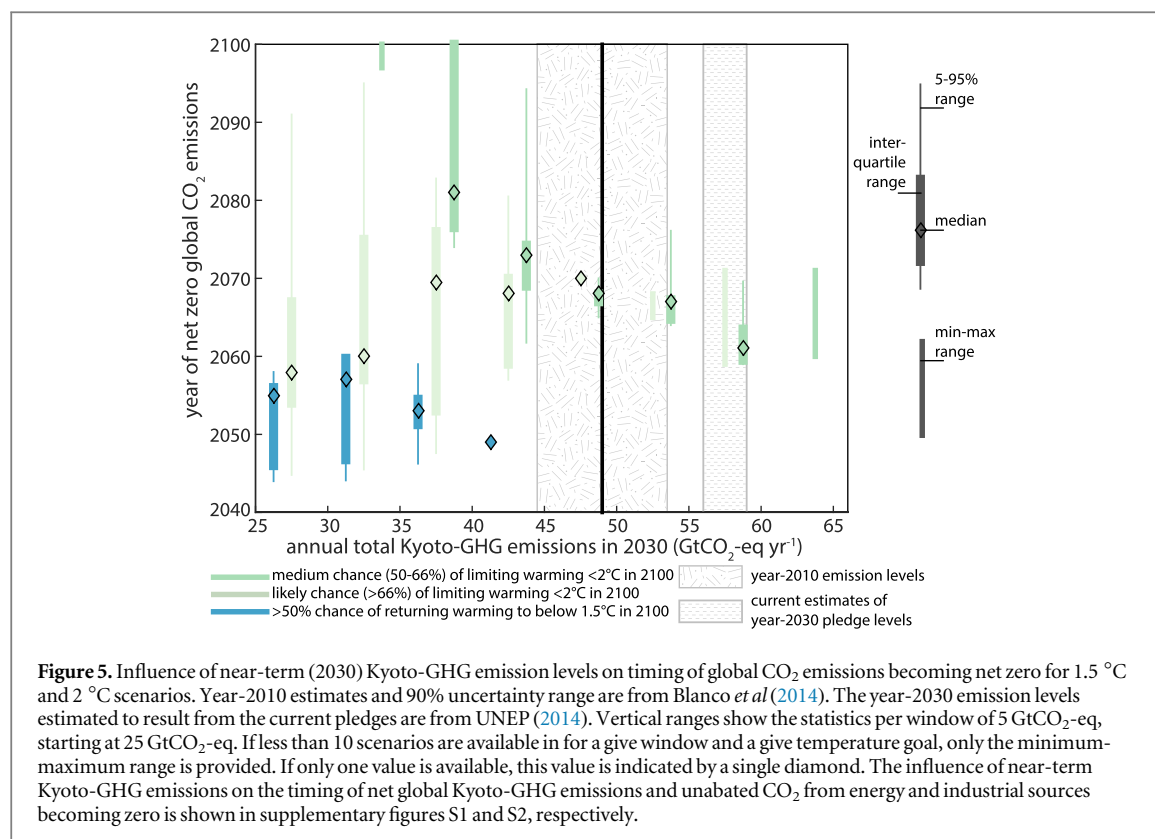


or lower near-term emission levels (in 2020 and 2030) on these zero emission goals (figures 4 and 5).

The IPCC (2014b) reported that scenarios having a likely (>66%) chance to stay below 2 °C, limit cumulative CO₂ emissions to 630–1180 GtCO₂ over the 2011–2100 period. Our scenario analysis suggests that the vast majority of such scenarios would reach net zero CO₂ before about 2080 (figure 1, all years rounded to the nearest 5). CO₂ budgets are here defined

over the 2011–2100 period, and about 155 GtCO₂ was emitted from 2011 to 2014 (Friedlingstein *et al* 2014, Le Quéré *et al* 2014). Also for higher CO₂ budgets of up to about 1600 GtCO₂ net zero CO₂ 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



approach links temperature objectives to geophysical constraints on cumulative CO₂ 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 CO₂ making up about three quarters of current Kyoto-GHG emissions (Edenhofer *et al* 2014), this implies that cumulative CO₂ 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 CO₂ emissions from 2011 to 2100 are 790 GtCO₂, with an inter-quartile range of 470–1085 GtCO₂ (figure 2(b), table 2; values rounded to the nearest 5 GtCO₂). This range compares well to the abovementioned IPCC range of 630–1180 GtCO₂. 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 GtCO₂ 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 CO₂ budget of 365 GtCO₂, and an interquartile range of 275–425 GtCO₂.

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 CO₂ 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 CO₂ 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 CO₂, the timing of net zero Kyoto-GHG emissions will always be later than the timing of net zero CO₂ emissions. Only when CO₂ 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 CO₂ 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 inter-quartile 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 CO₂ emissions from 2011 to 2100, as well as the time of CO₂ emissions from energy and industrial sources, the time of total global CO₂ 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 GtCO₂-eq/yr) is provided based on figure 5. Values are derived from our full scenario ensemble.

Cumulative CO ₂ emissions ^a from 2011–2100 (GtCO ₂)	Timing of reaching net zero levels (year ^a)			Influence of currently projected near-term (2030) emission levels in line with country pledges
	CO ₂ from energy and industrial sources ^b	Global total CO ₂	Kyoto-GHGs	
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 GtCO₂ or nearest 5 year—format: median [interquartile range] (5th to 95th percentile range).

^b Referring to unabated CO₂ 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 CO₂ 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-CO₂ 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 CO₂ 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 CO₂ emissions peak and the resulting years in which net zero CO₂ emissions would need to be achieved. Our analysis shows for example that for CO₂ budgets in the 930–1180 GtCO₂ range, a delay of two decades in the peak in global CO₂ emissions would imply the need to reach net zero CO₂ emissions about 15 years earlier.

Not only the timing of the global peak in emissions influences when net zero CO₂ emissions are achieved, also the level at which emissions peak plays a role. Figure 4 illustrates this for CO₂ emissions budgets of 930–1180 GtCO₂, roughly consistent with a global warming limit of 2 °C (table 2). Both for near-term CO₂ and Kyoto-GHG emission levels (in the years 2020 and 2030), a clear relationship with the timing of global CO₂ emissions becoming net zero is found.

For instance, to stay within the specified CO₂ emission budget, year-2030 CO₂ emission levels of about 45 GtCO₂ correspond to global CO₂ emissions reaching net zero levels around 2065 (median estimate, 10th–90th percentile range of 2060–2070). Lower 2030 CO₂ levels of about 25 GtCO₂ would correspond to reaching net zero CO₂ later, around 2080 (10th–90th percentile range of 2070–2090). As emission levels of CO₂ and non-CO₂ 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 CO₂ emissions becoming net zero. Later peaking consistently advances the timing of reaching net zero total CO₂ emissions given a specified CO₂ 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 GtCO₂-eq/yr that emissions are lower in 2030, the time of achieving net zero total CO₂ 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 CO₂ 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 GtCO₂-eq/yr range), would postpone the timing of net zero CO₂ 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 CO₂ emissions is generally moved forward with higher near-term emissions given a fixed CO₂ budget, this trade-off is thus less visible in the two most stringent scenario subsets because also the CO₂ 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 GtCO₂-eq/yr. At 2030 emission levels below 45 GtCO₂-eq/yr, also returning warming to below 1.5 °C by 2100 would remain an option—entailing, however, net zero total CO₂ emissions at around 2045–2060.

Finally, besides the level of near-term emissions, the uncertainty in the timing of global CO₂ becoming zero can be influenced by the CO₂ pathway, the

potential for negative emissions, and the non-CO₂ 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. CO₂-related targets (like net zero carbon emissions or full decarbonization) have a compelling direct link to the finding of climate science on CO₂ budgets—the most important anthropogenic radiative forcing agent. These CO₂-related targets can complement targets on the broader Kyoto-GHG emissions basket, so that contributions of non-CO₂ 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 CO₂ emissions. From a climate point of view, capped cumulative CO₂ emissions remain the highest priority for temperature stabilization. Emissions in every year contribute to this CO₂ budget, and delaying mitigation over the coming decades increases the pressure to achieve net zero CO₂ emissions earlier in this century. Once global net zero CO₂ emissions are achieved, also the cumulative CO₂ 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 CO₂ budgets, near-term (2030) global emission levels and a year range for achieving net zero total CO₂ 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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