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What if negative emission technologies fail at scale? Implications of the Paris Agreement for big emitting nations

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ABSTRACT

A cumulative emissions approach is increasingly used to inform mitigation policy. However, there are different interpretations of what '2°C' implies. Here it is argued that cost-optimization models, commonly used to inform policy, typically underplay the urgency of 2°C mitigation. The alignment within many scenarios of optimistic assumptions on negative emissions technologies (NETs), with implausibly early peak emission dates and incremental short-term mitigation, delivers outcomes commensurate with 2°C commitments. In contrast, considering equity and socio-technical barriers to change, suggests a more challenging short-term agenda. To understand these different interpretations, short-term CO_2 trends of the largest CO_2 emitters, are assessed in relation to a constrained CO_2 budget, coupled with a 'what if' assumption that negative emissions technologies fail at scale. The outcomes raise profound questions around high-level framings of mitigation policy. The article concludes that applying even weak equity criteria, challenges the feasibility of maintaining a 50% chance of avoiding 2°C without urgent mitigation efforts in the short-term. This highlights a need for greater engagement with: (1) the equity dimension of the Paris Agreement, (2) the sensitivity of constrained carbon budgets to short-term trends and (3) the climate risks for society posed by an almost ubiquitous inclusion of NETs within 2°C scenarios.

POLICY RELEVANCE

Since the Paris meeting, there is increased awareness that most policy 'solutions' commensurate with 2°C include widespread deployment of negative emissions technologies (NETs). Yet much less is understood about that option's feasibility, compared with near-term efforts to curb energy demand. Moreover, the many different ways in which key information is synthesized for policy makers, clouds the ability of policy makers to make informed decisions. This article presents an alternative approach to consider what the Paris Agreement implies, if NETs are unable to deliver more carbon sinks than sources. It illustrates the scale of the climate challenge for policy makers, particularly if the Agreement's aim to address 'equity' is accounted for. Here it is argued that much more attention needs to be paid to what CO_2 reductions can be achieved in the short-term, rather than taking a risk that could render the Paris Agreement's policy goals unachievable.

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Introduction

When establishing measures to mitigate greenhouse gas emissions at national and even sub-national scales in line with the Paris Agreement, policy makers are informed, either directly or indirectly, by CO_2 pathways derived from academic research. It is therefore essential that such pathways evolve from a diverse range of inputs and relationships as well as capture differing national circumstances. Yet what is clearly evident is that the analyses informing national energy decision making are dominated by a significant reliance on the large-scale and global implementation of negative emissions technologies (NETs). In theory, such technologies effectively increase the available carbon budget and thereby reduce the rates of actual mitigation of CO_2 emissions necessary to deliver on the commitment under the Paris Agreement to limit warming to 'well below' 2°C. Certainly such NET-based scenarios should be considered as a theoretical possibility. However, and as a complement to the wealth of scenarios with NETs, this article eschews their widespread deployment as technically too speculative, uncertain in terms of efficacy and feedbacks, and with critical issues on the scale and scope of available biomass inadequately understood (Gough & Vaughan, 2015; Mann, 2009). Building on Anderson and Bows (2011), this analysis explores the implications of near-term CO_2 trajectories of the biggest emitters for delivering on the 2°C commitment. Using a cumulative emissions framing, the article highlights how the existing literature typically under-represents socio-technical opportunities for near-term mitigation, and in so doing significantly elevates the risk of potentially irreversible damage to the climate system.

Cumulative emissions and climate sensitivity dictate future temperatures (Allen et al., 2009). Both are important for communicating implications of climate science to decision makers. 'Cumulative emissions' refers to the stock of GHG emissions that can be released into the atmosphere over time, for a given probability of a change in global mean surface temperature, while climate sensitivity is the temperature change associated with doubling atmospheric CO_2 concentration compared with pre-industrial levels. The *transient climate response* is the temperature rise above pre-industrial levels induced when CO_2 concentration doubles following a 1% increase in concentration each year. The *equilibrium climate sensitivity* describes the stabilized temperature at equilibrium, following a sustained long-term doubling of CO_2 concentration. Uncertainty in either leads to uncertainty in the cumulative emissions associated with future temperatures. The likely (>66% probability) range for the transient climate response is 1.0°C to 2.5°C (IPCC, 2013) and 1.5°C to 4.5°C for the equilibrium climate sensitivity, although some studies challenge these ranges (Hansen et al., 2013; Sherwood, Bony, & Dufresne, 2014). It is feasible that temperature changes could be higher, although current consensus is that the empirically measured temperature response makes such changes less likely (Otto et al., 2013).

The *transient climate response to cumulative carbon emissions* (TCRE) is the global mean surface temperature change for every 3670 $GtCO_2$ (1000 GtC)[1] emitted, and provides a preferential measure of the warming response to CO_2 when radiative forcing varies over decadal timescales (Millar, Allen, Rogelj, & Friedlingstein, 2016). Its likely range is 0.8°C to 2.5°C (pp. 17; IPCC, 2013) and important in determining cumulative budgets associated with 2°C. However, even within the Intergovernmental Panel on Climate Change (IPCC)'s Fifth Assessment Report (AR5), including 'summaries for policy makers' (SPM), there remains substantial room for misunderstanding. Table A1 draws attention to the assorted means by which emissions associated with temperature change are communicated, a point made by Rogelj, Schaeffer, et al. (2016). A variety of units, timeframes and probabilities are used throughout AR5 to present a 2°C carbon budget. There are differences in how probabilities of exceeding 2°C are presented: qualitatively (likely, etc.), approximate ranges (>50%, etc.) and precise ranges, and units (e.g. GtC, PgC) vary within and across reports, and different budgets for the same probabilities of staying below 2°C. This variety partly arises from some results being generated by CMIP5 ESM (Coupled Model Inter-comparison Project Phase 5, Earth System Models) ensemble using four Representative Concentration Pathways, with others generated by Integrated Assessment Models (IAMs) using several hundreds of scenarios. Clarity is further hindered by the treatment of non-CO_2 forcings. Such a minefield of potentially confusing information obstructs informed critique by policy makers of the mitigation scenarios forthcoming from the community, and therefore of the scope, scale and deployment rates of energy supply and demand socio-technical options.

Given the implications of exceeding 2°C, there is a responsibility on academics to adhere to scientific evidence and provide clarity for decision makers. Yet when scrutinizing the solution space presented, it can be argued that the community not only offers confusing information, but subjectively chooses to give greater

credence to some options – such as extensive deployment of NETs – over others. The aim of this article is two-fold. Firstly, to complement existing IAM-based outputs commonly informing decision makers, to illustrate the implications of a broader solution space. Secondly, to use this space to illustrate to policy makers, especially within big emitting nations, that overlooking now the full range of mitigation options available, poses a real risk of creating greater lasting damage to the climate system, that may become too late to remedy.

Methods

Applying a carbon budget framing highlights the importance of delivering high (>4% p.a.) mitigation rates and curbing emissions within a plausibly short timeframe (Anderson & Bows, 2011; Rogelj et al., 2010). By contrast, 2°C IAM scenarios typically output global mitigation rates of 2–4% p.a., sometimes made possible by global emissions peaking in 2010 and routinely before 2020 (Anderson, 2015; UNEP, 2014). Moreover, for all scenarios in the IPCC database with a >50% chance of avoiding 2°C, and 'policy delay' to 2020, 'negative emissions' through technologies such as bioenergy with carbon capture and storage (BECCS) are assumed to play a critical role (Anderson, 2015; Gough & Vaughan, 2015; Rogelj et al., 2011; UNEP, 2014; van Vuuren et al., 2011). While some IAM studies draw attention to the importance for avoiding 2°C of long-term technological availability (van Vliet et al., 2014), cost-optimal frameworks point to the alternatives as being simply an issue of technology, cost and potential. They fail to sufficiently address social aspects of technology change (Ackerman, DeCanio, Howarth, & Sheeran, 2009), an issue of deep importance when considering social acceptability in futures with extensive BECCS deployment (Braun, Merk, Pönitzsch, Rehdanz, & Schmidt, 2017; Fuss et al., 2014; Gough & Vaughan, 2015). Although technical efficiency plays a role in IAMs, they are ill-equipped or ill-designed to deliver solutions with substantial socio-economic/demand-side change. Specifically, their economic foundations are mostly based on traditional equilibrium models that cannot capture the complexity of social systems and emergent behavioural patterns (Pahl-Wostl et al., 2013). Thus, current IAM outputs risk delivering overly optimistic, unrealistic and potentially flawed messages about future change (Moss, Pahl-Wostl, & Downing, 2001). This is problematic given their dominance in the literature, underpinning a common view that challenging, but incremental energy policy is sufficient to deliver on the Paris Agreement.

Grouping 'big emitters'

With over 80% of global CO_2 emissions from energy and industry emitted by 25 nations, the largest CO_2 contributors – 'big emitters', are clustered by energy and macro-economic characteristics. Each group's energy and development context is considered, enabling assessment of the sensitivity of decarbonization rates to short-term inertia and lock-in. Although some analyses recognize the importance of approaches grounded in a practical understanding of social, technical and economic factors (for instance, Deetman, Hof, & van Vuuren, 2015), here significant attention is paid to near-term (typically ~5 year) trends. The results present a complementary perspective to the existing literature.

To derive big emitter groups, territorial and consumption-based CO_2 emission inventories were scrutinized to rank nations (Le Quéré et al., 2014). Under both consumption and territorial accounts, the big emitter countries are the same, and contribute over 80% of global emissions (and 65% of the population). They are:

> Australia, Brazil, Canada, China, France, Germany, India, Indonesia, Iran, Italy, Japan, Kazakhstan, Mexico, Poland, Russia, Saudi Arabia, South Africa, South Korea, Spain, Taiwan, Thailand, Turkey, UK, Ukraine and US.

To build a contextual understanding of these nations, absolute and relative characteristics of energy systems including levels and rates of gross domestic product (GDP)/per capita, CO_2 intensity of energy consumption etc., were compared. These Kaya-type indicators reflect social, economic and environmental aspects of sustainability allowing countries and groups of countries to be assessed in terms of energy system demand- and supply-side characteristics, contextualizing trends in annual CO_2 emissions. Normalizing the indicators for 2000, 2010 and 2012 and absolute CO_2 trends over five year intervals from 1990, the 25 nations[2] were ranked, then expert judgement[3] used to group countries based on if they (a) express similar[4] characteristics, and (b) do not alone exceed >4% of the global budget[5] (Figure 1). The groups are:

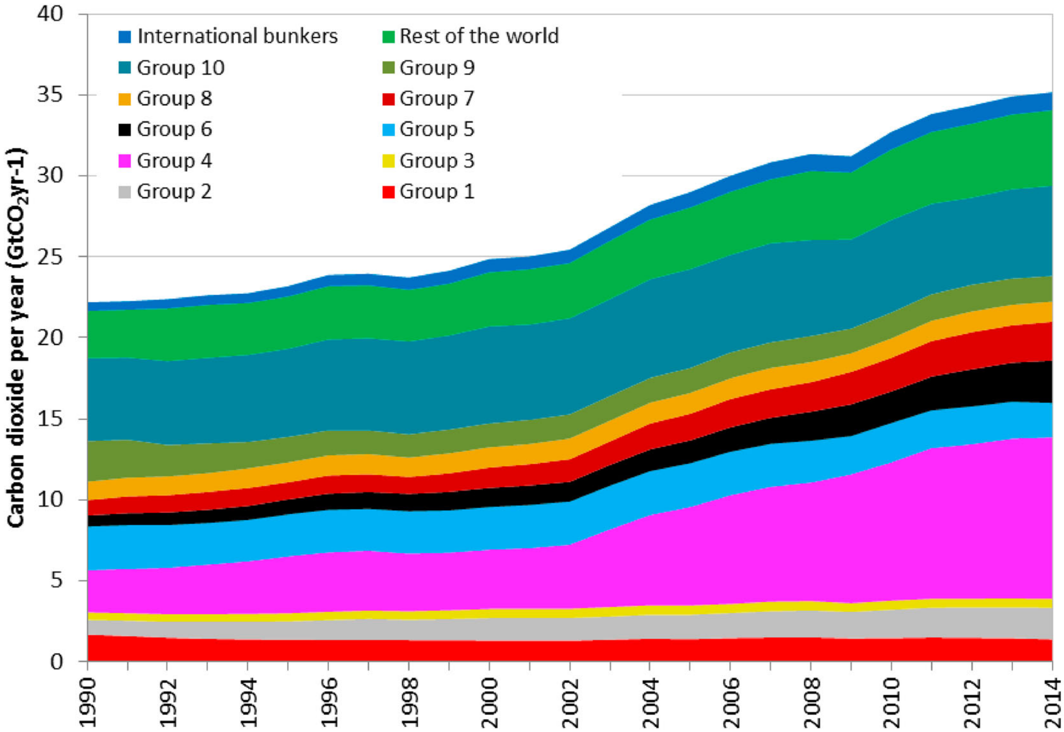

Figure 1. Group annual CO_2 emissions from 1990 to 2014 (equivalent consumption-based figures shown in Appendix Figure A1). Group 1: Australia, Poland, South Africa, Ukraine. Group 2: Brazil, Mexico, South Korea, Turkey. Group 3: Canada. Group 4: China, Hong Kong, Taiwan. Group 5: France, Germany, Italy, Spain, UK; Group 6: India. Group 7: Indonesia, Iran, Kazakhstan, Saudi Arabia, Thailand. Group 8: Japan. Group 9: Russia. Group 10: US.]

- Australia, Poland, South Africa, Ukraine (Group 1)
- Brazil, Mexico, South Korea, Turkey (Group 2)
- Canada (Group 3)
- China, Hong Kong, Taiwan (Group 4)
- France, Germany, Italy, Spain, UK (Group 5)
- India (Group 6)
- Indonesia, Iran, Kazakhstan, Saudi Arabia, Thailand (Group 7)
- Japan (Group 8)
- Russia (Group 9)
- US (Group 10)

Fuel use from international aviation and shipping ('bunkers') is unaccounted for within national budgets. With over 3% of global CO_2 in 2014 (some sources suggest 5%, with ~3% from shipping (Smith et al., 2015)), a share anticipated to grow (Bows-Larkin, 2015), here they are classed as a big emitter. For completeness, all other nations are within a Rest of the World 'RoW' group.

Figure 2 illustrates that CO_2 from China, India, Group 2, Group 7 and 'bunkers' have grown most rapidly since 1990, while Russia's emissions fell dramatically before 1997 growing slowly since. The Western European Group 5, and also Group 1 (heavy coal users) have lower CO_2 emissions in 2014 than in 1990; though consumption emissions were rising prior to the global economic downturn (Figure A2). The US, Canada and Japan have higher CO_2 emissions in 2014 than 1990, although emissions were relatively stable in recent years. As is evident from Figure 1, China, has ~ 30% share of global CO_2 emissions in 2014 (territorial accounting, 25% for consumption based), and its short-term CO_2 growth rate critically influences global CO_2 emissions. Similarly, with ~18% share of emissions (and per capita consumption emissions almost three times that of China),

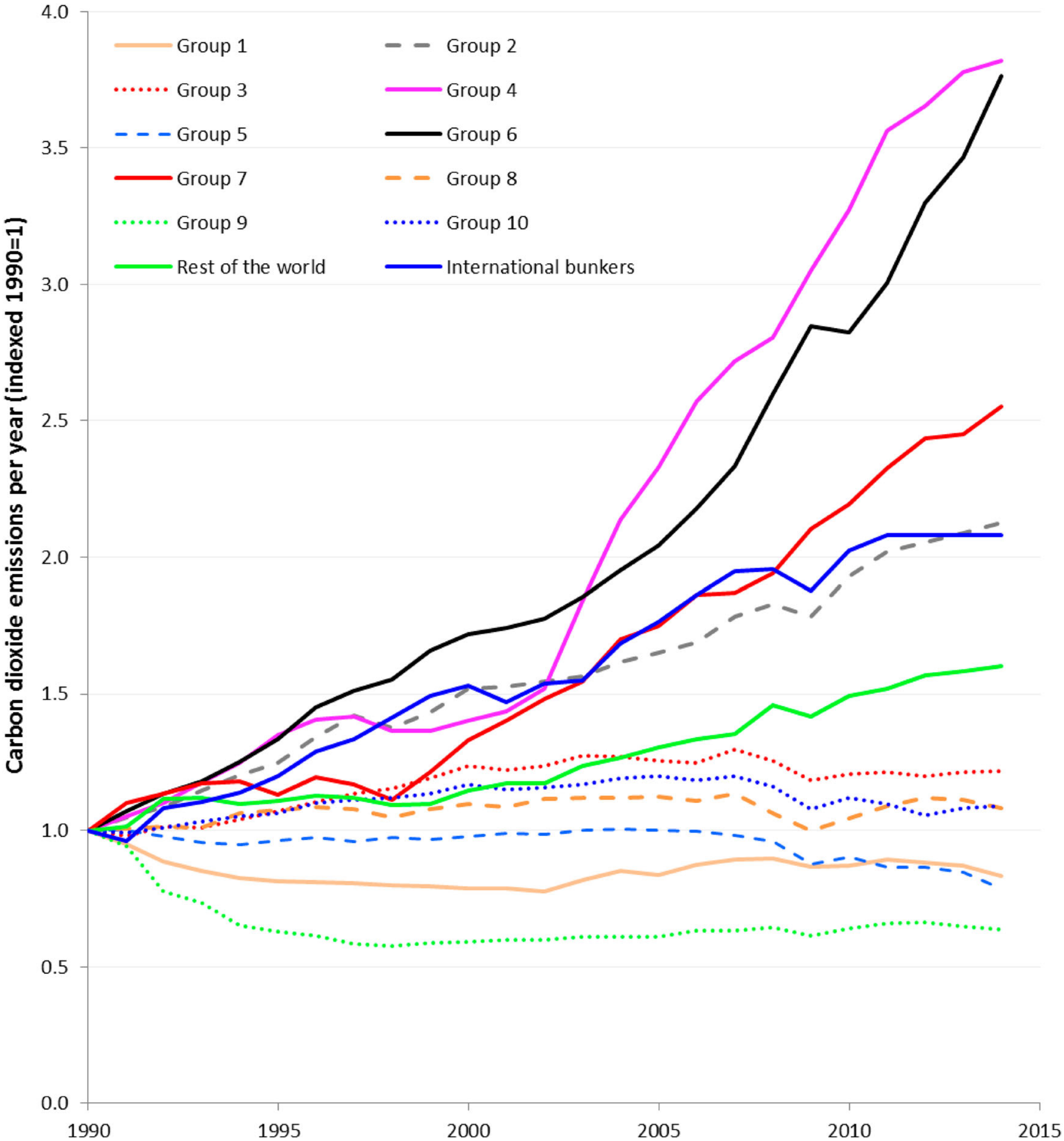

Figure 2. CO_2 emissions from the high emitting groups, bunkers plus RoW, normalized to 1990=1 (consumption-based equivalent in Appendix Figure A2). [Group 1: Australia, Poland, South Africa, Ukraine. Group 2: Brazil, Mexico, South Korea, Turkey. Group 3: Canada. Group 4: China, Hong Kong, Taiwan. Group 5: France, Germany, Italy, Spain, UK; Group 6: India. Group 7: Indonesia, Iran, Kazakhstan, Saudi Arabia, Thailand. Group 8: Japan. Group 9: Russia. Group 10: US.]

emissions from the US strongly influence global CO_2. To explore the implications of current trends, Nationally Determined Contributions (NDCs) submitted by countries in accordance with the Paris Agreement, and issues of energy system lock-in, 'what if?' emission pathways are developed, commensurate with avoiding 2°C.

Developing scenario pathways

The 2°C framing of climate change has emerged as a scientifically informed, but ultimately political 'anchor point' (Jordan et al., 2013) associated with carbon budgets. This was reinforced by the Paris Agreement, with

the additional qualifier of 'well below 2°C', arguably implying a probability of a greater than 50% chance. The emission pathways developed here are premised on budgets constrained by a 50% or 66% probability of avoiding 2°C.

While deforestation emissions are subject to large uncertainties (Houghton et al., 2012; Jain, Meiyappan, Song, & House, 2013; Le Quéré et al., 2015; Saatchi et al., 2011) it is important to estimate twenty-first century cumulative deforestation emissions to determine the remaining CO_2 budget. Here, assumptions around deforestation use historical data from temperate and tropical regions based on the Woods Hole Research Centre (WHRC) book keeping method (Houghton et al., 2012) as the most robust source to 2010 at the time of analysis. Cumulative emissions for deforestation from 1850–2013 are estimated as 571 $GtCO_2$. Land-use change emissions have remained relatively constant at around 1.3 ± 0.5 GtC/yr during 1960–2015, although Federici, Tubiello, Salvatore, Jacobs, and Schmidhuber (2015) suggest there were some decreases during 2011–2015. Here an optimistic assumption is assumed of an on-going 2–3% per year reduction, resulting in a budget for 2000–2100 of 150 $GtCO_2$.

CO_2-only budgets used are from the AR5 Synthesis SPM (IPCC, 2014b). Acknowledging debate over greenhouse gas emissions associated with agriculture and non-CO_2 forcers (Bows-Larkin et al., 2014; Calvin et al., 2013; Kyle, Müller, Calvin, & Thomson, 2014; Rogelj, Meinshausen, Schaeffer, Knutti, & Riahi, 2015), the figures used are: >50% of 2°C, 3000 $GtCO_2$[6]; >66% 2900 $GtCO_2$,[7] updating similar analysis (Anderson & Bows, 2011; Anderson, Bows, & Mander, 2008; Bows, Mander, Starkey, Bleda, & Anderson, 2006). Emissions between the 1860–80 mean and 2014 (Le Quéré et al., 2015), along with those from deforestation (Houghton et al., 2012), are removed to leave a CO_2-only budget *for energy and industry* from 2015 to 2100: >50%, 898 $GtCO_2$; >66%, 798 $GtCO_2$, consistent with Rogelj, Schaeffer, et al. (2016). While a next step could allocate shares of the budget to each big emitter, as in Raupach et al. (2014), here the focus is on developing pathways using each group's short-term CO_2 trend, and subsequently 'backcasting' reduction rates to remain within budget. Recognizing the range of burden-sharing frameworks (Höhne, den Elzen, & Escalante, 2014; IPCC, 2014a; Raupach et al., 2014) a very constrained carbon budget raises the question of whether a formal burden-sharing regime for 2°C remains viable (Sharmina, Bows-Larkin, & Anderson, 2015). This study takes a pragmatic approach, contextualizing short-term trends within the global budget available.

Analysis

Three families of scenarios are designed to illustrate the sensitivity of a constrained carbon budget to short-term emission trends of big emitters, when annual CO_2 emissions remain above zero. Consequently, none of the scenarios assume explicit inclusion of NETs to contrast with the majority of 2°C scenarios in the literature.[8] The 'Sustain' pathway family represents a highly inequitable world successfully recovering from the economic downturn, with limited efforts to implement new mitigation policy prior to 2020. Quantitatively, groups sustain post-recession (2009–2014) rates to 2020, decreasing by 1 percentage point p.a. until reaching a peak in emissions (e.g. a 2% rate in 2020 reduces to 1% in the following year, and peaks the year after). Post-peak, the mitigation rate increases year-on-year to the maximum necessary to remain within budget. These pathways are similar to the 'Policy Start in 2020', Table 1 of Fuss et al., 2016. The '*Immediate*' family illustrates another highly inequitable world where the economic downturn resumes and more positive mitigation effort materializes prior to 2020 (closer to Fuss et al., 2016's Table 1 'Policy Start in 2010'). Quantitatively it is similar to the '*Sustain*' family, but with only one year post-recession rate sustained for all groups unless specified (Table 1). The '*Development*' scenario aims to capture a more equitable distribution of mitigation effort, where nations with low per-capita emissions expand fossil energy systems for an extended period. Quantitatively, Groups 6, 7 and RoW maintain post-recession growth rates, reaching a peak in 2030. China's emissions grow at 2% p.a. peaking by 2025. Other groups continue with post-recession rates for one year. All groups have post-peak mitigation rates rising by one percentage point p.a. to remain within the 50% budget. Figure 3 illustrates *Sustain* (50%) and *Immediate* (50%). Other scenarios are illustrated in the Appendix.

Table 1. Scenario names and sustained mitigation rates for the scenario pathways.

Name (probability of exceeding 2°C)	Maximum sustained annual mitigation rate for groups (%)
Sustain (66%)	14.0
Sustain (50%)	8.5
Immediate (66%)	6.0
Immediate (50%)	5.0
Immediate-China-Sustain (66%)	7.5
Immediate-China-Sustain (50%)	6.0
Immediate-China-2% (66%)	6.5
Immediate-China-2% (50%)	5.0
Development	11.0

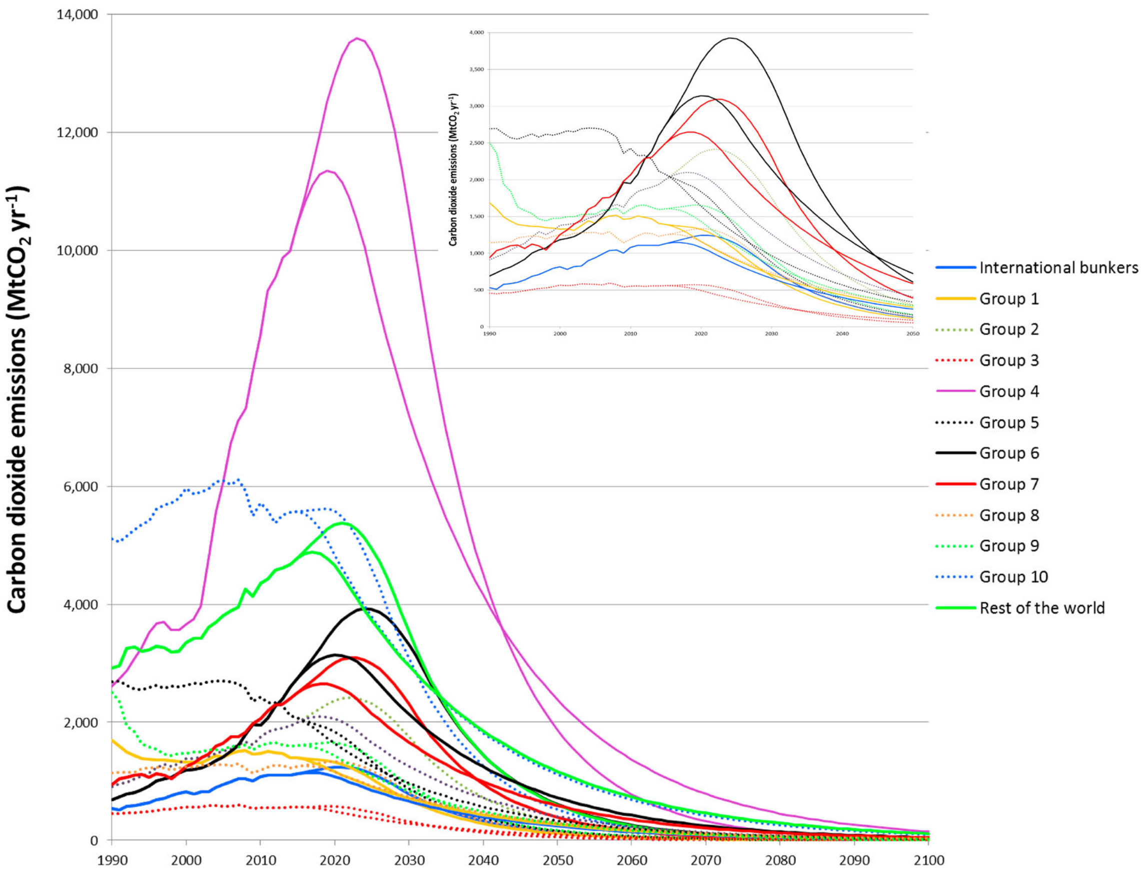

Figure 3. CO_2 from energy and industry under the Sustain (50%) (later peaks for same colour) and Immediate (50%) (early peaks for same colour) scenarios, sustaining either 5-year and 1-year post-economic downturn growth rates respectively. Rates of mitigation are in line with a 50% chance of avoiding 2°C. Inset shows all Groups other than RoW, China and US at a higher resolution. [Group 1: Australia, Poland, South Africa, Ukraine. Group 2: Brazil, Mexico, South Korea, Turkey. Group 3: Canada. Group 4: China, Hong Kong, Taiwan. Group 5: France, Germany, Italy, Spain, UK; Group 6: India. Group 7: Indonesia, Iran, Kazakhstan, Saudi Arabia, Thailand. Group 8: Japan. Group 9: Russia. Group 10: US.]

The scenarios differ by the date when all groups on aggregate start to mitigate. Any group already on a downward trajectory (e.g. Group 5) will continue at that reduction rate for either one (*Immediate*) or five years (*Sustain*) with the rate increasing post-2020. Any group exhibiting a near-term trend of CO_2 growth will start to reduce this growth rate either after one (*Immediate*), or five years (*Sustain*). The difference between the *Immediate* and *Sustain* families demonstrate that for every year's delay in extending or initiating mitigation

effort, there is an increase in the maximum reduction rate required across groups of around 1% p.a. for the 50% budget and nearer 1.5% for the 66% budget. Table 1 in Fuss et al. (2016) suggests no clear signal within IAMs that a delay in policy requires a greater extent of BECCS. Here, with no scope for CO_2 emissions falling below zero later in the century, any delay in policy implementation has a direct impact on the rate of decarbonization necessary in later years.

Immediate-China-Sustain (50%) contrasts a scenario where China's emissions continue to grow at post-recession rates to 2019 with a scenario (*Immediate-China-2% (50%)*) where CO_2 growth reduces to 2% from 2015 to 2019, reducing further thereafter (Figure A3). Comparing this with the scenarios where all groups curb growth rates immediately (e.g. *Immediate (50%)* in Figure 3), illustrates that if mitigation could happen five years sooner in China, or the rate of growth reduced to 2% on average from 2015 onwards, other groups could reduce their sustained reduction rates by 1% to 1.5% per annum under the most constrained budget. A similar analysis can be conducted for the US with its estimated 16% share of global CO_2 emissions in 2015, but the recent low CO_2 growth rate (0.2% from 2009 to 2014) means that mitigation rates for other countries are less sensitive to US pathways than they are to China's.

The *Development* pathways make explicit an allowance for increasing emissions from industrializing nations, while other groups have peaked emissions by 2018. In *Development*, even when constrained by a 50% budget, India, for instance, still needs to decarbonize its energy system such that per capita emissions remain below 4 tonnes of CO_2 per person when emissions peak (compared with the US at 17 tonnes per person, Figure A4).

Even in the *Development* scenario (*Development*, Figure A5), the distribution of cumulative emissions is disproportionately weighted towards wealthier and rapidly industrializing nations. India's 2050 emissions are below 0.6 tCO_2 per person, demonstrating a need to take a much lower-carbon development route than taken by industrialized nations (Lamb & Rao, 2015). All pathways explicitly require industrializing nations to 'leapfrog' carbon intensive development.

Discussion

All scenario pathways illustrated have sustained CO_2 reductions that exceed the 4% p.a. rate typical of 2°C scenarios in the literature, but consistent with budget-focused analysis of Raupach et al. (2014) and Peters, Andrew, Solomon, and Friedlingstein (2015). This divergence arises from three principal factors.

First, all IAM scenarios within the IPCC scenario database for a >50% chance of avoiding 2°C and with a policy delay to 2020, expand the available budget through the large-scale uptake of NETs, specifically BECCS (Gough & Vaughan, 2015). As Peters (2016) notes, in the absence of CCS 'there needs to be a radical reduction in the consumption of fossil fuels for a likely chance to keep global average temperatures below 2°C'. While BECCS may yet prove effective *at scale*, for reasons highlighted below, this is judged as too speculative an assumption to include, providing an important complement to dominant literature.

The scale and rate of assumed BECCS deployment is typically high in 2°C scenarios, providing the equivalent of up to one third of current global electricity demand by 2040, rising to 50% by 2050.[9] The absence of robust operating costs for a CCS power station, let alone BECCS, also raises concerns given that it is repeatedly found to be a key least-cost policy option in many scenarios.

Second, the potential for socio-technical and socio-economic change to deliver reductions in energy consumption in the near term is something IAMs are ill-equipped to model given their conventional economic frameworks, assumptions and failure to reflect the path-dependent nature of technical change (Ackerman et al., 2009; Pahl-Wostl et al., 2013; Stern, 2016). Third, the inertia constraining the rate of transition to low-carbon energy supply is characterized here by focusing on the dynamics of short-term trends, postulating a mix of both challenging but deliverable, and theoretical changes to these trends.

The essential characteristics of the scenarios draw particular attention to the importance of existing levels of CO_2, and near-term CO_2 growth rates. The groups whose recent emissions rates differ by more than 1% compared with historical rates (Table 2) are Japan and Russia. In Japan's case, emissions are expected to rise at a higher rate than pre-2011, if it continues to move away from nuclear (Crastan, 2014;

Table 2. Comparison between growth/decline rates across groups. Low growth or a reduction: G1, G3, G5, G10; low–medium growth: G8, G9, RoW; medium growth: G2, Bunkers; medium–high growth: G4, G6 and G7.

	G1	G2	G3	G4	G5	G6	G7	G8	G9	G10	RoW	Bunkers	World
	Australia Poland South Africa Ukraine	Brazil Mexico South Korea Turkey	Canada	China	France Germany Italy Spain UK	India	Indonesia Iran Kazakhstan Saudi Arabia Thailand	Japan	Russia	US			
Annual rates of energy & industry CO_2 change 1990–2014	−1%	3%	1%	6%	−1%	6%	4%	0%	−2%	0%	2%	3%	2%
2000–2014	0%	2%	0%	7%	−2%	6%	5%	0%	1%	0%	2%	2%	3%
2009–2014	−1%	4%	1%	5%	−2%	6%	4%	2%	1%	0%	2%	2%	2%
Pledges, NDCs or Kyoto targets as of 2016 interpreted for fossil fuel & industry (UNEP, 2014, Climate Action Tracker 2015) [for a range, the average is used]	Australia: 23–48% above 1990 by 2020; ±5% above 1990 by 2030 Poland: as G5 South Africa: 101% above 1990 by 2020; 20–82% by 2025–2030 Ukraine: 22% below 1990 by 2020, 41% by 2030	Brazil: 60–76% above 1990 by 2020; 116% by 2030 Mexico: 22%–36% below a baseline as defined by the NDC by 2030 (assume recent growth of 1.3% pa to 2020) South Korea: 84% above 1990 by 2020; 81% by 2030 Turkey: 389% above 1990 by 2030 [continue trend to 2020 at 3.4%]	7% above 1990 by 2020; 30% cut from 2005 by 2030	Intensity target of 60–65% below 2005 by 2030. Intention to peak by 2030.	20–30% below1990 by 2020; 40% below by 2030	Intensity targets of 20–25% below 2005 by 2020; 33–35% below by 2030	Indonesia: 330% above 1990 by 2020; 450–540% relative to 1990 by 2030. Iran: 4% below BAU by 2030 Kazakhstan: 19% below 1990 by 2020; 10% by 2030 Saudi Arabia: 600% increase on 1990 levels by 2030 Thailand: 20% below BAU by 2030	+5.2% above 1990 levels by 2020; 15% below 1990 by 2030	6–11% below 1990 by 2030	17% below 1990 by 2025	Assumes recent growth to 2020 then reduced to a peak in 2030	Intensity targets for shipping and potential trading scheme for aviation	
CO_2 change p.a. 2014–2020	5%	−2%	−2%	1%	−1%	6%	1%	0%	4%	−2%	2%	2%	2%
CO_2 change p.a. 2020–2030	−3%	1%	−2%	0%	−2%	0%	4%	−2%	1%	−2%	1%	0%	0%

Huang & Nagasaka, 2012). For Russia, falling oil prices linked to increased production from OPEC and Russia, rising consumption of indigenous shale oil in the US influencing trade, and a highly volatile Russian economy (Connolly, 2015; Korppoo & Kokorin, 2017; Russell, 2015) all add to uncertainty around Russia's CO_2 trends.

How China's shifting economy impacts on CO_2 growth is a key source of uncertainty. With nearly 30% of global CO_2 from fossil fuel and industry, any short-term change in China's CO_2 growth rate has a significant impact on mitigation rates required by all. Recent developments, such as China's reduction in coal consumption, have already influenced global CO_2 growth (Qi, Stern, Wu, Lu, & Green, 2016). A critical issue, is the possibility that data for China for 2000 to 2013 may have underestimated cumulative emissions by nearly 11 $GtCO_2$ (Liu et al., 2015) and that Chinese energy statistics are frequently found to contain large anomalies (Korsbakken, Peters, & Andrew, 2016). Moreover, many IAMs fail to capture near-term issues adequately, as they often involve ten-year time-steps and use modelled, rather than empirical, 2010-to-present data.

India's recent growth rate continued at the 1990 to 2014 average despite the global economic downturn. Its emissions grew by 6% between 2013 and 2014 and 5% 2014–2015, dominating the marginal increase in global emissions. With rising demand for fossil fuels, and India's very low per-capita CO_2, its growth rates might not be expected to fall for at least a decade. India's recent Environment Minister suggested emissions will not peak before 2045, given the need to focus on poverty eradication (Davenport, 2014). This view is buttressed by India's NDC where, even by the start of the NDC period, emissions are estimated at 30% higher than in 2013. In a similar vein, the International Energy Agency concludes that there are few signs of any disconnect between India's energy demand growth and CO_2 emissions out to 2030 (International Energy Agency, 2015).

While not a 'country group', international aviation and shipping (bunkers) are assumed to undertake urgent and rapid decarbonization. This is in contrast to expectations and their exclusion from the Paris Agreement. Stakeholders representing aviation and shipping generally assume that their industries will become net purchasers of emissions rights from others (Bows-Larkin, 2015). This position was reinforced by an International Civil Aviation Organisation agreement to implement its Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) to 'address any annual increase in total CO_2 from international civil aviation' (ICAO, 2016). The analysis here shows that, as a big emitter, emissions from bunker fuels are highly influential. Consequently, there is a clear imperative for this sector to urgently deliver absolute mitigation.

Virtually all nations submitted NDCs for the 2015 Paris Conference of the Parties (COP) 21 meeting. These NDCs, alongside broader energy contexts, are built on (Table 2) to form an NDC-based scenario, constructed for comparison. Using NDCs, other national pledges, targets under the 1997 Kyoto Protocol or the 2009 Copenhagen Accord, or, where none exist, a scenario building on a continuation of post-downturn trend, Table 2 shows emissions mitigation rates for each group for 2014 to 2030. Post-2030, all groups are assumed to accelerate mitigation by one percentage point p.a. to a maximum of 6% (Figure 4). The cumulative budget of this scenario is around 1450 $GtCO_2$ from 2014–2100 for energy and industry only, breaching both the 66% and 50% budgets for staying below 2°C.[10]

Considering the pathways generated here, what stands out is that even a weak consideration of equity[11] (i.e. the *Development* scenario), leaves the 66% chance of avoiding 2°C as arguably infeasible.[12] A similar conclusion can be drawn for the 50% probability of avoiding 2°C, given 11% p.a. reductions would require unprecedented whole-system change. If no allowance is made for equity, the 66% chance of avoiding 2°C is only achievable with a program of deep and immediate mitigation. The Paris Agreement makes no provision for significant pre-2020 efforts. If post-recession emission rates for each country-group continue until 2020, remaining within the 50% budget is practicable, but only with global mitigation rates by 2025 well beyond the aggregated NDCs submitted to the Paris COP. Put simply, failure of the international community to deliver immediate (pre-2020), deep and absolute mitigation from the big emitters, will effectively put the carbon budgets for '*well below*' 2°C (or 'likely' 66–100%, chance) beyond reach, unless NETs are both proved viable at scale and urgently deployed.

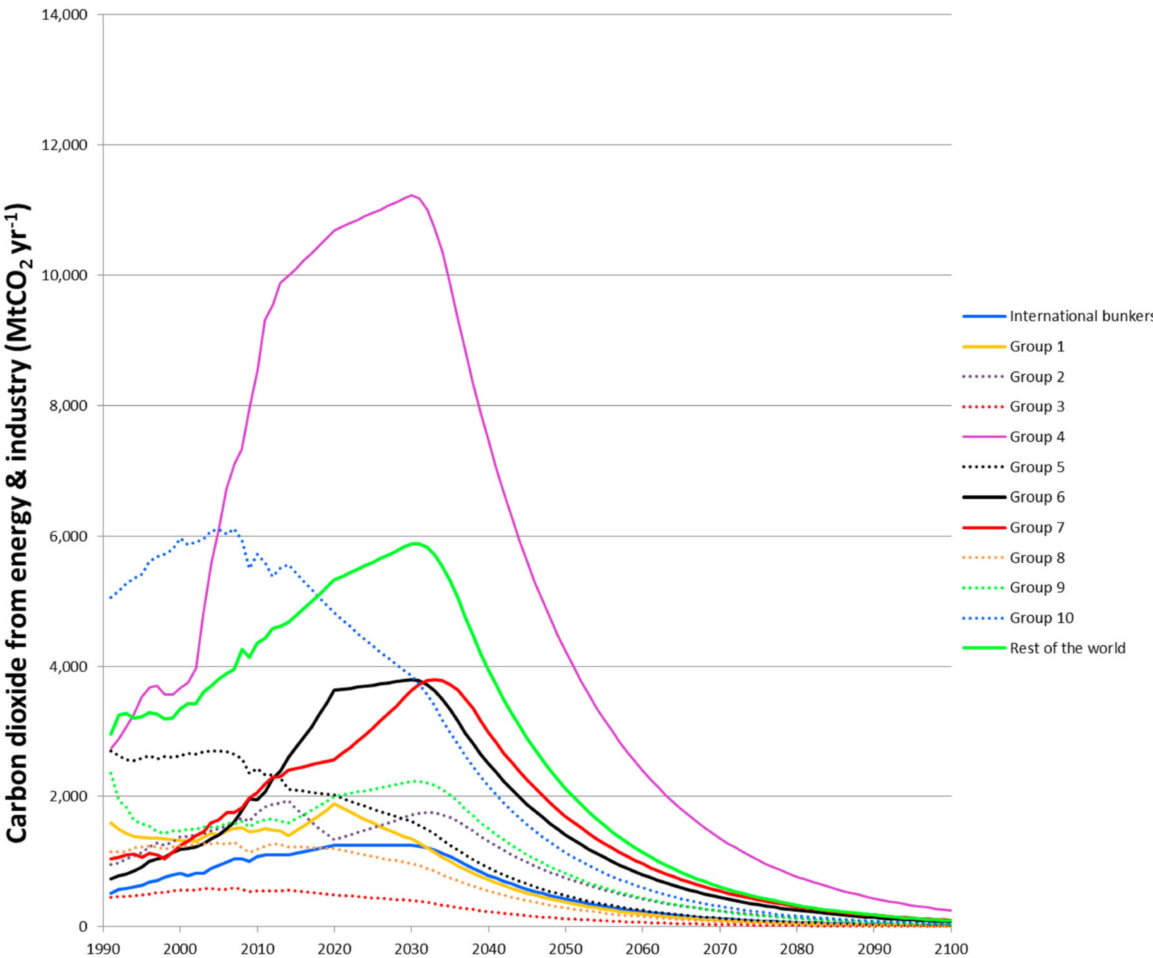

Figure 4. CO_2 from energy and industry pathways for the groups under the NDC scenario where rates are as in Table 2, reducing rapidly from 2030. [Group 1: Australia, Poland, South Africa, Ukraine. Group 2: Brazil, Mexico, South Korea, Turkey. Group 3: Canada. Group 4: China, Hong Kong, Taiwan. Group 5: France, Germany, Italy, Spain, UK; Group 6: India. Group 7: Indonesia, Iran, Kazakhstan, Saudi Arabia, Thailand. Group 8: Japan. Group 9: Russia. Group 10: US.]

Conclusions

This article analyses recent emission trends of big emitting nations, and of the aviation and shipping sectors, and considers these in relation to energy system characteristics, technical, social and political inertia, and issues of development. The analysis explicitly eschews widespread use of NETs, both because there are many major and potentially insurmountable obstacles to their successful uptake *at scale* (Brack, 2017; Fuss et al., 2016; International Energy Agency, 2016; Smith & Torn, 2013; Vaughan & Gough, 2016), and to provide a complement to the wealth of scenarios that do include them.

Bringing together this analysis with the IPCC's carbon budgets leads to challenging and uncomfortable conclusions. First, the on-going failure of any 'big emitter' to begin a comprehensive and rapid transition of its energy systems, suggests that constraining emissions to a carbon budget with a greater than 66% chance of avoiding 2°C, if applying even weak equity criteria, is now infeasible (with the NETs caveat as outlined). A similar conclusion arises for the 50% budget (and again assuming that NETs fails at scale). In essence, there exists a conflict within the Paris Agreement between its temperature and equity commitments.

While big emitting nations and international aviation and shipping are pivotal to delivering early and global-scale mitigation, overlooking how emissions may rise as other nations necessarily improve their

standards of well-being would be a mistake. It is clear that rapidly industrializing nations need to leapfrog the high-carbon infrastructures of their industrialized counterparts, and establish low-carbon alternatives from the outset.

In 2016, global CO_2 emissions were ~60% higher than they were at the time of the IPCC's first report in 1990. Despite a quarter of a century of repeated scientific evidence, there has been limited success in delivering meaningful levels of absolute mitigation. Against this backdrop, and with the successful adoption of the Paris Agreement, it is essential that the academic community captures the breadth of opportunities for constraining emissions within carbon budgets associated with '*well below 2°C*' and, ideally, '*pursuing … 1.5°C*'. While suites of 2°C scenarios exist in the literature, the IAM approach typically underplays the scope and importance of near-term mitigation and in particular the socio-technical opportunities for reducing energy demand as a way to reduce mitigation rates in later years (Anderson & Bows, 2011; Anderson & Peters, 2016). The pathways presented in this article pay greater attention to these issues and the inertia of existing energy-systems (Millar et al., 2016; Otto et al., 2013; Pfeiffer, Millar, Hepburn, & Beinhocker, 2016; Rogelj, den Elzen, et al., 2016) to broaden the view of available mitigation options, and implications thereof for the Paris commitments. They offer a complement to scenarios from the IAMs, virtually all of which have a significant reliance on future NETs to remove hundreds of billions of tonnes of CO_2 directly from the atmosphere in future decades, thereby avoiding a steeper CO_2 reduction pathway.

Providing complementary visions ensures policy makers have a broader solution space than offered by the economically optimized outputs of IAMs. Equipped with this richer portfolio, a more comprehensive assessment of the challenges posed by the Paris Agreement can be readily articulated. Specifically, this article points to how new climate-focused policies in the big emitting nations, and across the aviation and shipping sectors, need to be informed by: (1) the equity dimension of the Paris Agreement, (2) the sensitivity of constrained carbon budgets to short-term trends and (3) the climate risks for society posed by an almost ubiquitous inclusion of NETs within 2°C scenarios. Focusing on the scale of the challenge *without* widespread NETs draws greater attention to how delays to implementing stringent mitigation policy, including curbing energy demand, threatens the feasibility of the Paris commitments. The sooner the scale of the mitigation challenge informs meaningful action to curtail emissions, the greater will be the likelihood of avoiding a 2°C rise in the global mean surface temperature – even if this likelihood is now very low.

Notes

1. This works for CO_2 only, not equivalent, and does not hold beyond 2000 GtC (pp. 17; IPCC, 2013).
2. Taiwan is included in China due to the aggregation of economic indicators for this region.
3. Statistical clustering employed provided no more robust a grouping system than comparison and expert judgment.
4. A gap not greater than 1, where 1 is the difference between two nations if all nations were to be ranked in order across each indicator.
5. More information on the clustering method available in the Appendix.
6. A range of 2900–3200 $GtCO_2$ depending on non-CO_2 drivers.
7. A range of 2550–3150 $GtCO_2$ depending on non-CO_2 drivers.
8. Mitigation technologies or approaches are not specified in the pathways, so in theory some negative emissions technologies could be providing a reduction in absolute CO_2 emissions, but not sufficient to take the pathway below zero.
9. Based on a conversion efficiency of 35% (net of the CCS process), using BECCS primary energy data in Fuss et al. (2016) and background data provided by a co-author.
10. The NDCs formulated in either CO_2 and other GHGs separately, or CO_2 equivalent. Assumptions for CO_2 are either derived directly from information provided, or interpreted using analysis by the Climate Action Tracker, 2015.
11. This is an area where different equity principles (Bretschger, 2013) and interpretations of fairness give different outcomes for carbon budget allocations. However, the Paris Agreement draws particular attention to the importance of ethical issues such as equity and how poorer nations will need a significant grace period to decarbonize energy systems. Specifically, 'peaking will take longer for developing country Parties' (Paris Agreement, Article 4.1). However, as Anderson and Bows (2011) note, even when allowance is made for a delay, current significant differences in CO_2 per capita between wealthy and poorer nations still leaves cumulative emissions per capita within 2°C scenarios larger in wealthier nations. Here, the specific text 'weak consideration of equity' refers to the Development scenario where poorer groups reach a peak in CO_2 at a later date than the other groups (Figure A5).
12. What is or isn't feasible is subjective. Here 'infeasible' is specifically defined as long-run mitigation of over 10% p.a. While such mitigation has not been delivered in practice, and is twice that following the economic breakup of the Soviet Union,

provisional work suggests a combination of supply and demand technologies, allied with policies on behaviour and practices, could deliver mitigation rates of up to 10% p.a. (Anderson, Quéré, & McLachlan, 2014; Watson et al., 2014).

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Appendix

Table A1. Cumulative emission budgets from IPCC AR5.

Cumulative CO_2 emissions parameter	Value	Probability	Source	Notes
2011–2100 for a **1.5°C** target	90–310 $GtCO_2$	A **more likely than not** chance to bring temperature change *back to* below 1.5°C by 2100	WG3 TS, p. 56; WG3 Ch.6, p. 441	'Assessing this goal is currently difficult because no multi-model study has explored these scenarios. The limited number of published studies exploring this goal have produced associated scenarios that are characterized by (1) immediate mitigation; (2) the rapid up-scaling of the full portfolio of mitigation technologies; and (3) development along a low-energy demand trajectory.' (WG3 TS, p. 56) 'Global CO_2eq emissions in 2050 are between 70–95% below 2010 emissions, and they are between 110–120% below 2010 emissions in 2100.' (WG3 TS, footnote 12, p. 56)
2012–2100 for **RCP2.6**	Mean 270 GtC (990 $GtCO_2$). Range 140–410 GtC (510–1505 $GtCO_2$) (Table SPM.3, p. 27)	Warming by 2100 is '**unlikely** to exceed 2°C for RCP2.6' (p. 20)	WG1 SPM (pp. 4, 20, 27).	RCP2.6. Warming by 2100 is unlikely to exceed 2°C. '*Unlikely*' stands for a 0–33% probability (footnote 2, p. 4). Budgets generated by the CMIP5 ESM (Coupled Model Intercomparison Project Phase 5, Earth System Models) ensemble. Same values for cumulative emissions as in the Technical Summary (WG1 TS, p. 93), the Exec. Summary of Ch.6 (WG1 Ch.6, p. 468) and main text of Ch.6 (WG1 Ch.6 Table 6.12, p. 526), although the unit is 'PgC'.
From all anthropogenic sources since the period 1861–1880 *(not discussed till when)*	<1000 GtC (3670 $GtCO_2$)	Probability of **>66%** of limiting warming to less than 2°C	WG1 SPM (p. 27)	This amount decreases to ~**790 GtC** (2900 $GtCO_2$) when accounting for non-CO_2 forcings as in RCP2.6. Note that 515 [445–585] GtC (1890 [1630–2150] $GtCO_2$) was emitted by 2011. Same values for cumulative emissions as in the Technical Summary (WG1 TS, p. 103) and Ch.12 (WG1 Ch.12, p. 1113), although units are 'PgC'. 'These estimates were derived by computing the fraction of CMIP5 ESMs and EMICs that stay below 2°C for given cumulative emissions following RCP8.5 […]. The non-CO_2 forcing in RCP8.5 is higher than in RCP2.6. Because all likelihood statements in calibrated IPCC language are open intervals, the provided estimates are thus both conservative and consistent choices valid for non-CO_2 forcings across all RCP scenarios' (WG1 Ch.12, p. 1113)
2012–2100 for **RCP2.6**	275 PgC	*Not discussed*	WG1 Ch.6 Table 6.12 (p. 526)	These cumulative budgets are generated by IAMs (Integrated Assessment Models) as opposed to the CMIP5 ESM ensemble in the first four rows of this table.
2011–2100 for **RCP2.6**	630–1180 $GtCO_2$	**Likely** to stay below 2°C	WG3 SPM Table SPM.1 (p. 13)	'*Likely*' stands for a 66–100% likelihood (WG3 SPM, footnote 8, p. 13) Same values for cumulative emissions and probabilities for

(*Continued*)

Table A1. Continued.

Cumulative CO_2 emissions parameter	Value	Probability	Source	Notes
				temperatures as in the Technical Summary (WG3 TS, Table TS1, p. 54)
2011–2100 for **430–480 ppm**	630–1180 $GtCO_2$	12–37% of exceeding 2°C	WG3 Ch.6, Tables 6.2 and 6.3 (pp. 430–431)	**RCP2.6** is 'the corresponding RCP falling within the scenario category based on 2100 CO_2 equivalent concentration' range (WG3 Ch.6, note 3 to Table 6.2, p. 430).
From all anthropogenic sources since 1870 *(not discussed till when)*	<2900 $GtCO_2$ (2550–3150 $GtCO_2$ 'depending on non-CO_2 drivers')	>66% of less than 2°C	SYN SPM (p. 10)	'About 1900 $GtCO_2$ had already been emitted by 2011' (SYN SPM, p. 10). Subtracting these historical emissions from the values in the second column gives a remaining cumulative CO_2 budget of **1000 $GtCO_2$** (range 650–1250 $GtCO_2$ 'depending on non-CO_2 drivers'), from 2011.
From 2011 *(not discussed till when)*	1000 $GtCO_2$ (750–1400 $GtCO_2$)	66% of simulations staying below 2°C ['Fraction of simulations meeting goal', rather than a 'probability']	SYN, Table 2.2 (p. 64)	' … assuming non-CO_2 forcing follows the RCP8.5 scenario. Similar cumulative emissions are implied by other RCP scenarios' (SYN, note (c) to Table 2.2, p. 64) 'Note that the 66% range in this table should not be equated to the likelihood statements in [SYN] Table SPM.1 and [SYN] Table 3.1 and WGIII Table SPM.1. The assessment in these latter tables is not only based on the probabilities calculated for the full ensemble of scenarios in WGIII using a single climate model, but also the assessment in WGI of the uncertainty of the temperature projections not covered by climate models.' (SYN, note (b) to Table 2.2, p. 64)
From all anthropogenic sources since the period 1861–1880 *(not discussed till when)*	<1210 GtC (4440 $GtCO_2$)	Probability of **>50%** of limiting warming to less than 2°C	WG1 SPM (p. 27)	This amount decreases to ~**820 GtC** (3010 $GtCO_2$) when accounting for non-CO_2 forcings as in RCP2.6. Note that 515 [445–585] GtC (1890 [1630–2150] $GtCO_2$) was emitted by 2011. Same values for cumulative emissions as in the Technical Summary (WG1 TS, p. 103) and Ch.12 (WG1 Ch.12, p. 1113), although units are 'PgC'. 'These estimates were derived by computing the fraction of CMIP5 ESMs and EMICs that stay below 2°C for given cumulative emissions following RCP8.5 […]. The non-CO_2 forcing in RCP8.5 is higher than in RCP2.6. Because all likelihood statements in calibrated IPCC language are open intervals, the provided estimates are thus both conservative and consistent choices valid for non-CO_2 forcings across all RCP scenarios.' (WG1 Ch.12, p. 1113)
From all anthropogenic sources since the period 1861–1880 *(not discussed till when)*	<1570 GtC (5760 $GtCO_2$)	Probability of **>33%** of limiting warming to less than 2°C	WG1 SPM (p. 27)	This amount decreases to ~**900 GtC** (3300 $GtCO_2$) when accounting for non-CO_2 forcings as in RCP2.6. Note that 515 [445–585] GtC (1890 [1630–2150] $GtCO_2$) was emitted by 2011. Same values for cumulative emissions as in the Technical Summary (WG1 TS, p. 103) and Ch.12 (WG1 Ch.12, p. 1113), although units are 'PgC'. 'These estimates were derived by computing the fraction of CMIP5 ESMs and EMICs that stay below 2°C for given cumulative emissions following RCP8.5 […]. The non-CO_2 forcing in RCP8.5 is higher than in RCP2.6. Because all likelihood statements in

				calibrated IPCC language are open intervals, the provided estimates are thus both conservative and consistent choices valid for non-CO_2 forcings across all RCP scenarios.' (WG1 Ch.12, p. 1113)
2012–2100 for **RCP4.5**	Mean 780 GtC (2860 $GtCO_2$). (2180–3690 $GtCO_2$) (Table SPM.3, p. 27)	Warming by 2100 is '**more likely than not** to exceed 2°C for RCP4.5' (p. 20)	WG1 SPM (pp. 4, 20, 27).	'*More likely than not*' stands for a >50–100% probability (footnote 2, p. 4) These cumulative budgets are generated by the CMIP5 ESM (Coupled Model Intercomparison Project Phase 5, Earth System Models) ensemble, rather than by IAMs (Integrated Assessment Models). Same values for cumulative emissions as in the Technical Summary (WG1 TS, p. 93), the Exec. Summary of Ch.6 (WG1 Ch.6, p. 468) and main text of Ch.6 (WG1 Ch.6 Table 6.12, p. 526), although the unit is 'PgC'.
From all anthropogenic sources since 1870 *(not discussed till when)*	<3000 $GtCO_2$ (2900–3200 $GtCO_2$)	>50% of less than 2°C	SYN SPM footnote 7 (p. 10)	'About 1900 $GtCO_2$ had already been emitted by 2011' (SYN SPM, p. 10). Subtracting these historical emissions from the values in the second column gives a remaining cumulative CO_2 budget of **1100 $GtCO_2$** (range 1000–1300 $GtCO_2$ 'depending on non-CO_2 drivers'), from 2011.
From 2011 *(not discussed till when)*	1500 $GtCO_2$ (1150–2050 $GtCO_2$)	33% of simulations staying below 2°C ['Fraction of simulations meeting goal', rather than a 'probability']	SYN, Table 2.2 (p. 64)	' … assuming non-CO_2 forcing follows the RCP8.5 scenario. Similar cumulative emissions are implied by other RCP scenarios' (SYN, note (c) to Table 2.2, p. 64)
2012–2100 for **RCP4.5**	735 PgC	*Not discussed*	WG1 Ch.6 Table 6.12 (p. 526)	These cumulative budgets are generated by IAMs (Integrated Assessment Models) as opposed to the CMIP5 ESM ensemble in the first four rows of this table.
2011–2100 for **RCP4.5**	1870–2440 and 2570–3340 $GtCO_2$	**Unlikely** to stay below 2°C	WG3 SPM Table SPM.1 (p. 13)	'*Unlikely*' stands for a 0–33% likelihood (WG3 SPM, footnote 8, p. 13) Same values for cumulative emissions and probabilities for temperatures as in the Technical Summary. (WG3 TS, Table TS1, p. 54)
2011–2100 for **580–650 and 650–720 ppm**	1870–2440 and 2570–3340 $GtCO_2$	74–93% and 88–95% of exceeding 2°C	WG3 Ch.6, Tables 6.2 and 6.3 (pp. 430–431)	**RCP4.5** is 'the corresponding RCP falling within the scenario category based on 2100 CO_2 equivalent concentration' range. (WG3 Ch.6, note 3 to Table 6.2, p. 430)
From 2011 *(not discussed till when)*	1300 $GtCO_2$ (range 1150–1400 $GtCO_2$)	50% of simulations staying below 2°C ['Fraction of simulations meeting goal', rather than a 'probability']	SYN, Table 2.2 (p. 64)	' … assuming non-CO_2 forcing follows the RCP8.5 scenario. Similar cumulative emissions are implied by other RCP scenarios' (SYN, note (c) to Table 2.2, p. 64)
2012–2100 for **RCP6.0**	Mean 1060 GtC or 3885 $GtCO_2$. 840–1250 GtC (3080–4585 $GtCO_2$) (Table SPM.3, p. 27)	Warming by 2100 is '**likely** to exceed 2°C for RCP6.0 and RCP8.5' (p. 20)	WG1 SPM (pp. 4, 20, 27).	'*Likely*' stands for a 66–100% probability (footnote 2, p. 4) These cumulative budgets are generated by the CMIP5 ESM (Coupled Model Intercomparison Project Phase 5, Earth System Models) ensemble. Same values for cumulative emissions as in the Technical Summary (WG1 TS, p. 93), the Exec. Summary of Ch.6 (WG1

(*Continued*)

Table A1. Continued.

Cumulative CO_2 emissions parameter	Value	Probability	Source	Notes
				Ch.6, p. 468) and main text of Ch.6 (WG1 Ch.6 Table 6.12, p. 526), although the unit is 'PgC'.
2012–2100 for **RCP6.0**	1165 PgC	*Not discussed*	WG1 Ch.6 Table 6.12 (p. 526)	These cumulative budgets are generated by IAMs (Integrated Assessment Models) as opposed to the CMIP5 ESM ensemble in the first four rows of this table.
2011–2100 for **RCP6.0**	3620–4990 $GtCO_2$	**Unlikely** to stay below 2°C	WG3 SPM Table SPM.1 (p. 13)	'*Unlikely*' stands for a 0–33% likelihood (WG3 SPM, footnote 8, p. 13) Same values for cumulative emissions and probabilities for temperatures as in the Technical Summary. (WG3 TS, Table TS1, p. 54) 'For scenarios in this category no CMIP5 run […] as well as no MAGICC realization […] stays below the respective temperature level. Still, an unlikely assignment is given to reflect uncertainties that might not be reflected by the current climate models.' (WG3 SPM, footnote 11, p. 13)
2011–2100 for **720–1000 ppm**	3620–4990 $GtCO_2$	97–100% of exceeding 2°C	WG3 Ch.6, Tables 6.2 and 6.3 (pp. 430–431)	**RCP6.0** is 'the corresponding RCP falling within the scenario category based on 2100 CO_2 equivalent concentration' range. (WG3 Ch.6, note 3 to Table 6.2, p. 430)
From all anthropogenic sources since 1870 *(not discussed till when)*	<3300 $GtCO_2$ (2950–3800 $GtCO_2$)	>33% of less than 2°C	SYN SPM footnote 7 (p. 10)	'About 1900 $GtCO_2$ had already been emitted by 2011' (SYN SPM, p. 10). Subtracting these historical emissions from the values in the second column gives a remaining cumulative CO_2 budget of **1400 $GtCO_2$** (range 1050–1900 $GtCO_2$ 'depending on non-CO_2 drivers'), from 2011.
2012–2100 for **RCP8.5**	Mean 1685 GtC or 6180 $GtCO_2$. 1415–1910 GtC (5185–7005 $GtCO_2$) (Table SPM.3, p. 27)	Warming by 2100 is '**likely** to exceed 2°C for RCP6.0 and RCP8.5' (p. 20)	WG1 SPM (pp. 4, 20, 27).	'*Likely*' stands for a 66–100% probability (footnote 2, p. 4) These cumulative budgets are generated by the CMIP5 ESM (Coupled Model Intercomparison Project Phase 5, Earth System Models) ensemble, rather than by IAMs (Integrated Assessment Models). Same values for cumulative emissions as in the Technical Summary (WG1 TS, p. 93), the Exec. Summary of Ch.6 (WG1 Ch.6, p. 468) and main text of Ch.6 (WG1 Ch.6 Table 6.12, p. 526), although the unit is 'PgC'.
2012–2100 for **RCP8.5**	1855 PgC	*Not discussed*	WG1 Ch.6 Table 6.12 (p. 526)	These cumulative budgets are generated by IAMs (Integrated Assessment Models) as opposed to the CMIP5 ESM ensemble.
2011 to 2100 for **RCP8.5**	5350–7010 $GtCO_2$	**Unlikely** to stay below 2°C	WG3 SPM Table SPM.1 (p. 13)	'*Unlikely*' stands for a 0–33% likelihood (WG3 SPM, footnote 8, p. 13) Same values for cumulative emissions and probabilities for temperatures as in the Technical Summary (WG3 TS, Table TS1, p. 54) 'For scenarios in this category no CMIP5 run […] as well as no

				MAGICC realization […] stays below the respective temperature level. Still, an unlikely assignment is given to reflect uncertainties that might not be reflected by the current climate models.' (WG3 SPM, footnote 11, p. 13)
2010–2100, without 'any explicit mitigation efforts'	'potentially well over 4000 $GtCO_2$'	*Not discussed*	WG3 TS (p. 50)	The exact phrase: 'the scenarios strongly suggest that absent any explicit mitigation efforts, cumulative CO_2 emissions since 2010 will exceed 700 $GtCO_2$ by 2030, 1500 $GtCO_2$ by 2050, and potentially well over 4000 $GtCO_2$ by 2100' (WG3 TS, p. 50) AN ENIGMATIC PHRASE: 'Note that cumulative CO_2 emissions are presented here for different periods of time (2011–2050 and 2011–2100) while cumulative CO2 emissions in WGI AR5 are presented as total compatible emissions for the RCPs (2012–2100) or for total compatible emissions for remaining below a given temperature target with a given likelihood.' (WG3 TS, footnote 3 to Table TS1, p. 54)
2011–2100 for **>1000 ppm**	5350–7010 $GtCO_2$	100–100% of exceeding 2°C	WG3 Ch.6, Tables 6.2 and 6.3 (pp. 430–431)	**RCP8.5** is 'the corresponding RCP falling within the scenario category based on 2100 CO_2 equivalent concentration' range (WG3 Ch.6, note 3 to Table 6.2, p. 430).

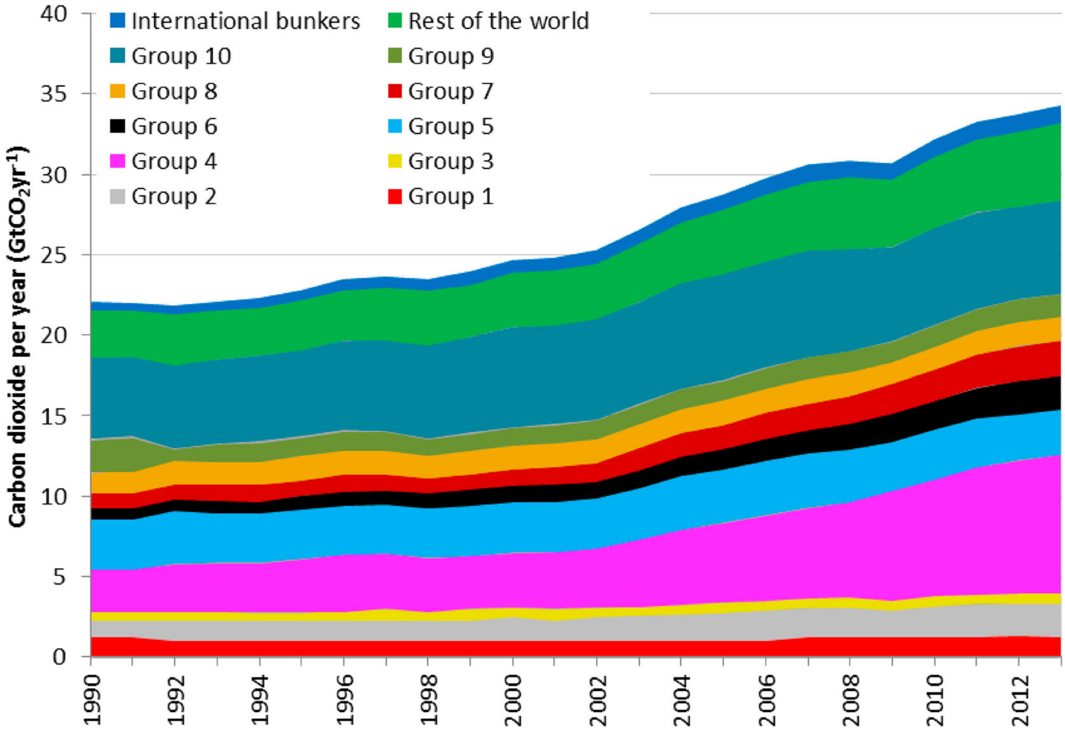

Figure A1. Group annual CO_2 emissions 1990–2014 for consumption-based accounts. [Group 1: Australia, Poland, South Africa, Ukraine. Group 2: Brazil, Mexico, South Korea, Turkey. Group 3: Canada. Group 4: China, Hong Kong, Taiwan. Group 5: France, Germany, Italy, Spain, UK; Group 6: India. Group 7: Indonesia, Iran, Kazakhstan, Saudi Arabia, Thailand. Group 8: Japan. Group 9: Russia. Group 10: US.]

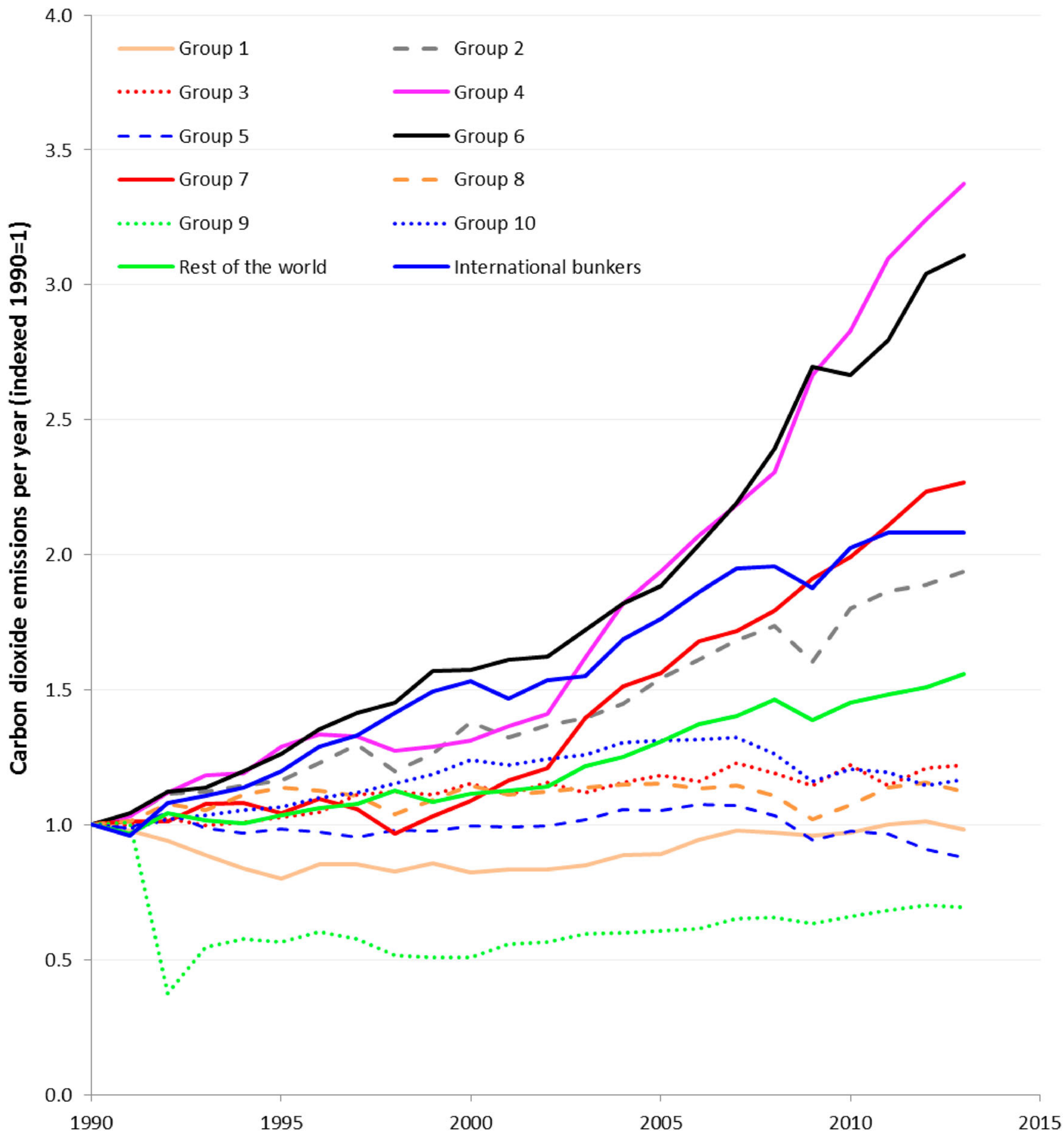

Figure A2. CO_2 emissions from the high emitting groups, bunkers plus RoW, normalized 1990=1 for consumption-based accounts. [Group 1: Australia, Poland, South Africa, Ukraine. Group 2: Brazil, Mexico, South Korea, Turkey. Group 3: Canada. Group 4: China, Hong Kong, Taiwan. Group 5: France, Germany, Italy, Spain, UK; Group 6: India. Group 7: Indonesia, Iran, Kazakhstan, Saudi Arabia, Thailand. Group 8: Japan. Group 9: Russia. Group 10: US.]

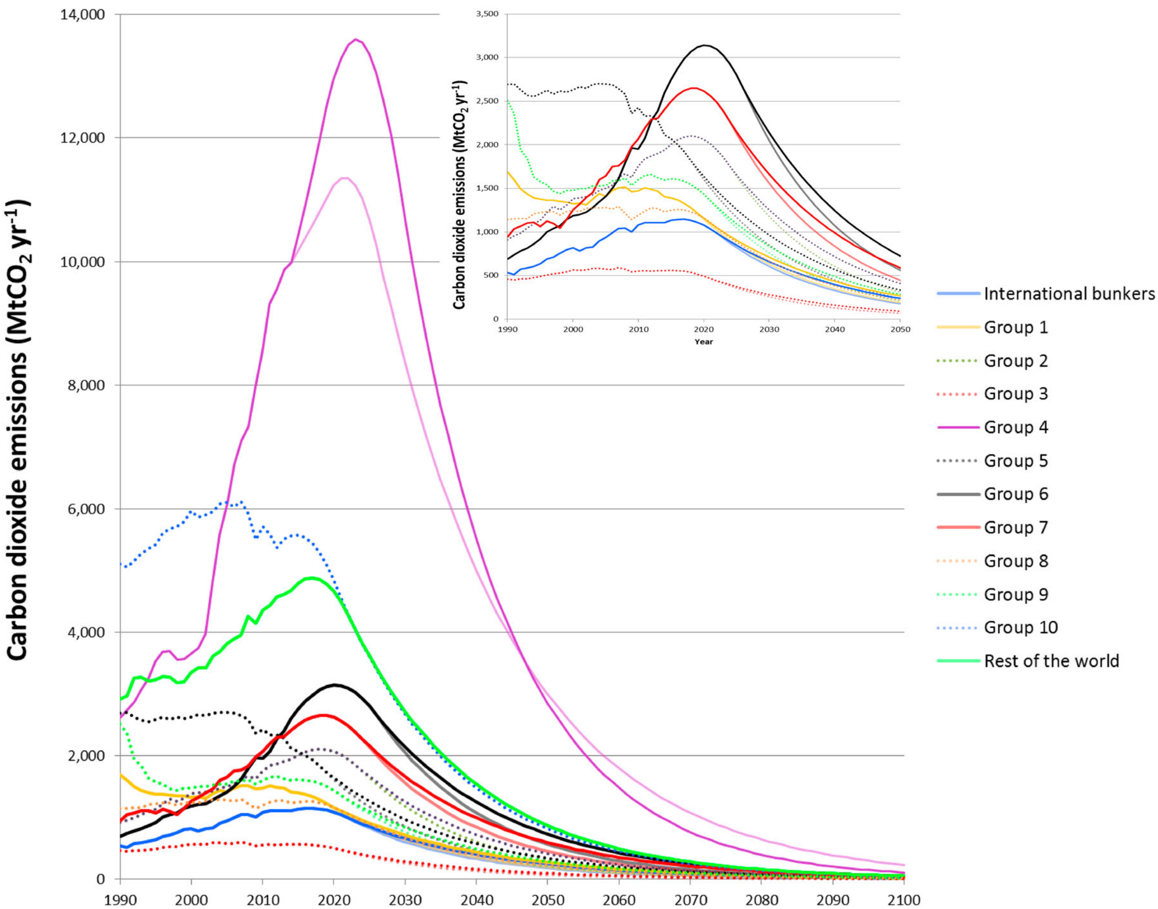

Figure A3. CO_2 from energy and industry pathways for *Immediate-China-Sus (50%)* (strong lines) and *Immediate-China-2% (50%)* (weaker coloured lines) scenarios with 1-year's post-economic downturn rate continued towards a peak for all groups apart from in China, where post-recession rates continue for 5-years in '*Sustain*' and 2% growth assumed to 2020 in '2%'. Both have a 50% chance of avoiding 2°C. [Group 1: Australia, Poland, South Africa, Ukraine. Group 2: Brazil, Mexico, South Korea, Turkey. Group 3: Canada. Group 4: China, Hong Kong, Taiwan. Group 5: France, Germany, Italy, Spain, UK; Group 6: India. Group 7: Indonesia, Iran, Kazakhstan, Saudi Arabia, Thailand. Group 8: Japan. Group 9: Russia. Group 10: US.]

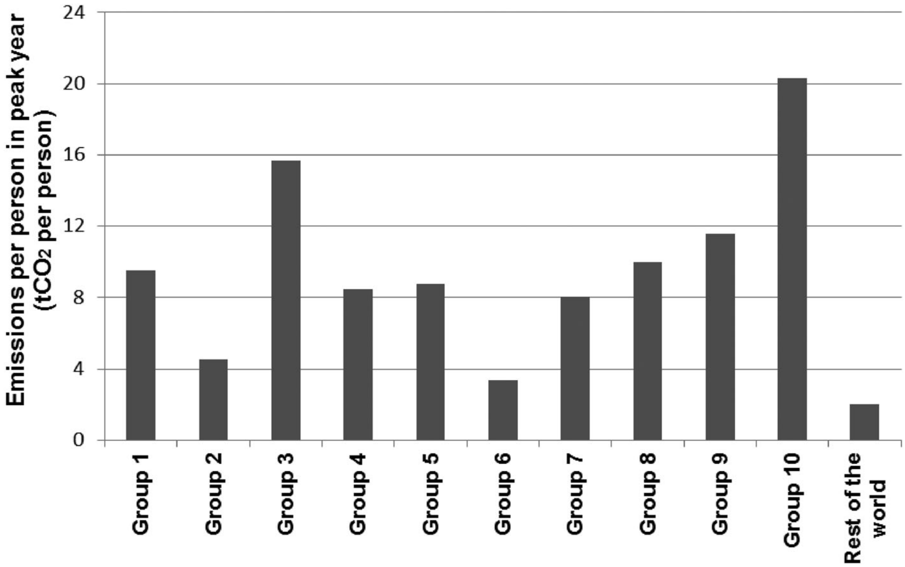

Figure A4. CO_2 emissions per capita in each group's emission peak year for '*Development*'. [Group 1: Australia, Poland, South Africa, Ukraine. Group 2: Brazil, Mexico, South Korea, Turkey. Group 3: Canada. Group 4: China, Hong Kong, Taiwan. Group 5: France, Germany, Italy, Spain, UK; Group 6: India. Group 7: Indonesia, Iran, Kazakhstan, Saudi Arabia, Thailand. Group 8: Japan. Group 9: Russia. Group 10: US.]

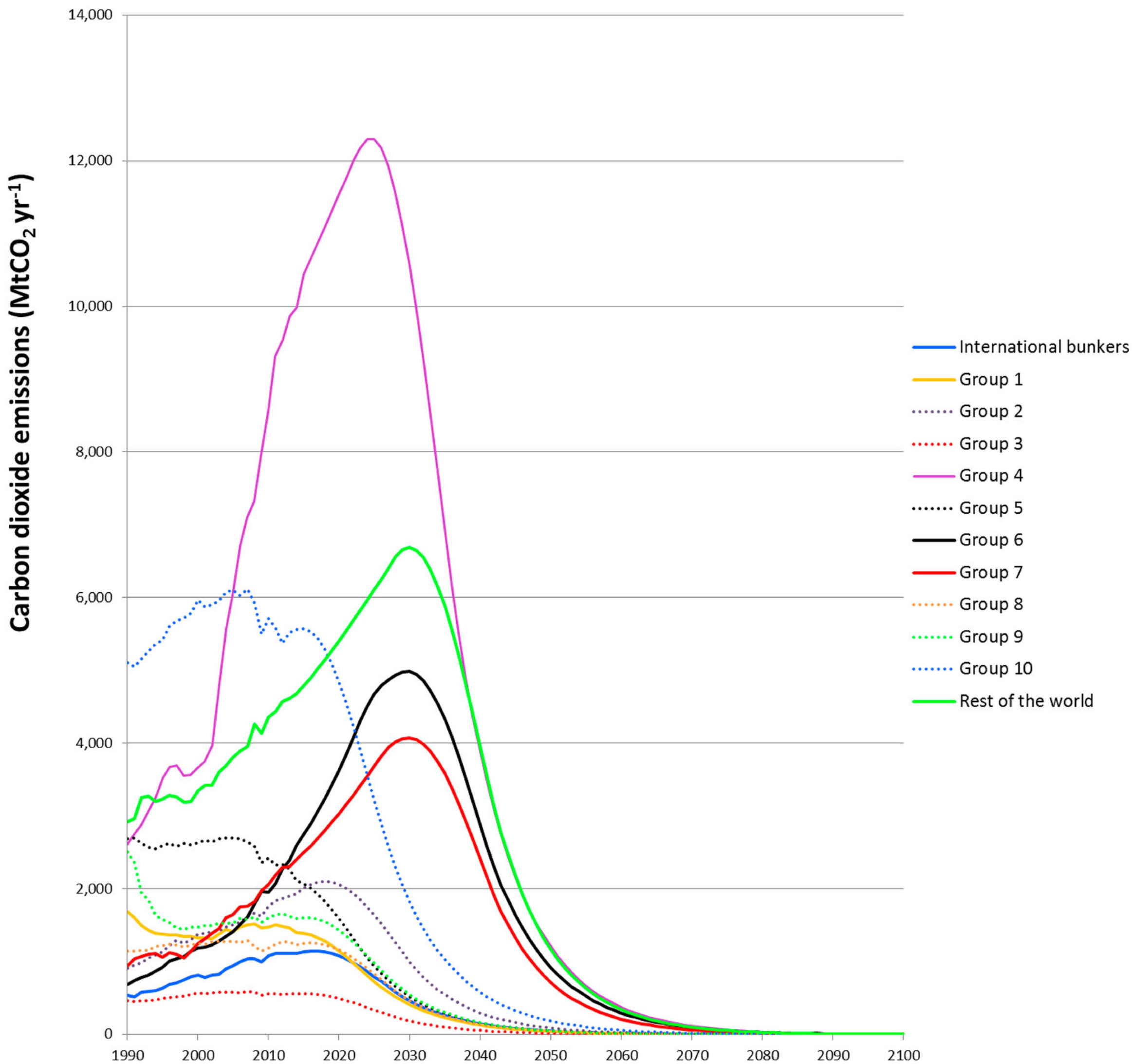

Figure A5. CO_2 from energy and industry pathways under the *Development* scenario where CO_2 in the RoW, India and Group 7 grow until a peak in 2030, with all other groups mitigating after only 1 year of post-recession CO_2 rate. The CO_2 budget is commensurate with a 50% chance of avoiding 2°C. [Group 1: Australia, Poland, South Africa, Ukraine. Group 2: Brazil, Mexico, South Korea, Turkey. Group 3: Canada. Group 4: China, Hong Kong, Taiwan. Group 5: France, Germany, Italy, Spain, UK; Group 6: India. Group 7: Indonesia, Iran, Kazakhstan, Saudi Arabia, Thailand. Group 8: Japan. Group 9: Russia. Group 10: US.]