POTSDAM-INSTITUT FÜR
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PIK

Originally published as:

Environmental Research Letters

LETTER

National contributions for decarbonizing the world economy in line with the G7 agreement

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Abstract

In June 2015, the G7 agreed to two global mitigation goals: 'a decarbonization of the global economy over the course of this century' and 'the upper end of the latest Intergovernmental Panel on Climate Change (IPCC) recommendation of 40%–70% reductions by 2050 compared to 2010'. These IPCC recommendations aim to preserve a likely (>66%) chance of limiting global warming to 2 °C but are not necessarily consistent with the stronger ambition of the subsequent Paris Agreement of 'holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5 °C above pre-industrial levels'. The G7 did not specify global or national emissions scenarios consistent with its own agreement. Here we identify global cost-optimal emissions scenarios from Integrated Assessment Models that match the G7 agreement. These scenarios have global 2030 emissions targets of 11%–43% below 2010, global net negative CO_2 emissions starting between 2056 and 2080, and some exhibit net negative greenhouse gas emissions from 2080 onwards. We allocate emissions from these global scenarios to countries according to five equity approaches representative of the five equity categories presented in the Fifth Assessment Report of the IPCC (IPCCAR5): 'capability', 'equality', 'responsibility-capability-need', 'equal cumulative per capita' and 'staged approaches'. Our results show that G7 members' Intended Nationally Determined Contribution (INDCs) mitigation targets are in line with a grandfathering approach but lack ambition to meet various visions of climate justice. The INDCs of China and Russia fall short of meeting the requirements of any allocation approach. Depending on how their INDCs are evaluated, the INDCs of India and Brazil can match some equity approaches evaluated in this study.

1. Introduction

The G7 includes the world's seven largest advanced industrial economies (here we include Canada, Japan, the United States, and the 28 EU countries that are represented by the European Commission within the G7). As a group, the G7 produced over 31% of international greenhouse gas (GHG) emissions in 2010–over 27% including Land-Use, Land-Use Change and Forestry (LULUCF) emissions (Gütschow 2015). The G7's domestic mitigation efforts can therefore have a significant impact on climate change. Moreover, in producing over 65% of

current global Gross Domestic Product (GDP) (World Bank 2014), the G7 has considerable capacity to fund and lead the transition to a zero carbon global economy.

The G8 (G7 plus Russia) first recognized the need for emissions mitigation (Kirton *et al* 2011) in 1979 and in 1992 strongly supported the creation of the United Nations Framework Convention on Climate Change (UNFCCC) (Kirton and Kokotsis 2015, p 107). Five months before the Copenhagen Accord in 2009, the G8 endorsed Intergovernmental Panel on Climate Change (IPCC) recommendations to limit global warming to 2 °C and supported a global

emissions mitigation target of 50% below 1990 levels by 2050 (G8 2009, p 4). Following the Elmau agreement (G7 2015, p 12) in June 2015, the G7 now supports 'the upper end of the latest IPCC recommendation of 40%–70% reductions by 2050 compared to 2010' (G7 2015), intended to preserve a likely (>66%) chance of attaining the UNFCCC objective to limit global warming to 2 °C (Edenhofer *et al* 2014, table 6.3). In Elmau, the G7 also emphasized the requirement of a 'decarbonization of the global economy over the course of the century' and committed to do their part to achieve a 'transformation of the energy sector by 2050'.

The objective of the G7 agreement was later strengthened, in Paris, where G7 members and all other UNFCCC parties agreed to 'achieve a balance between anthropogenic emissions by sources and removals by sinks of GHG emissions in the second half of the century' (which basically means net zero GHG emissions sometime between 2050 and 2100) and to hold 'the increase in the global average temperature to well below 2 °C above pre-industrial levels and pursue efforts to limit the temperature increase to 1.5 °C'.
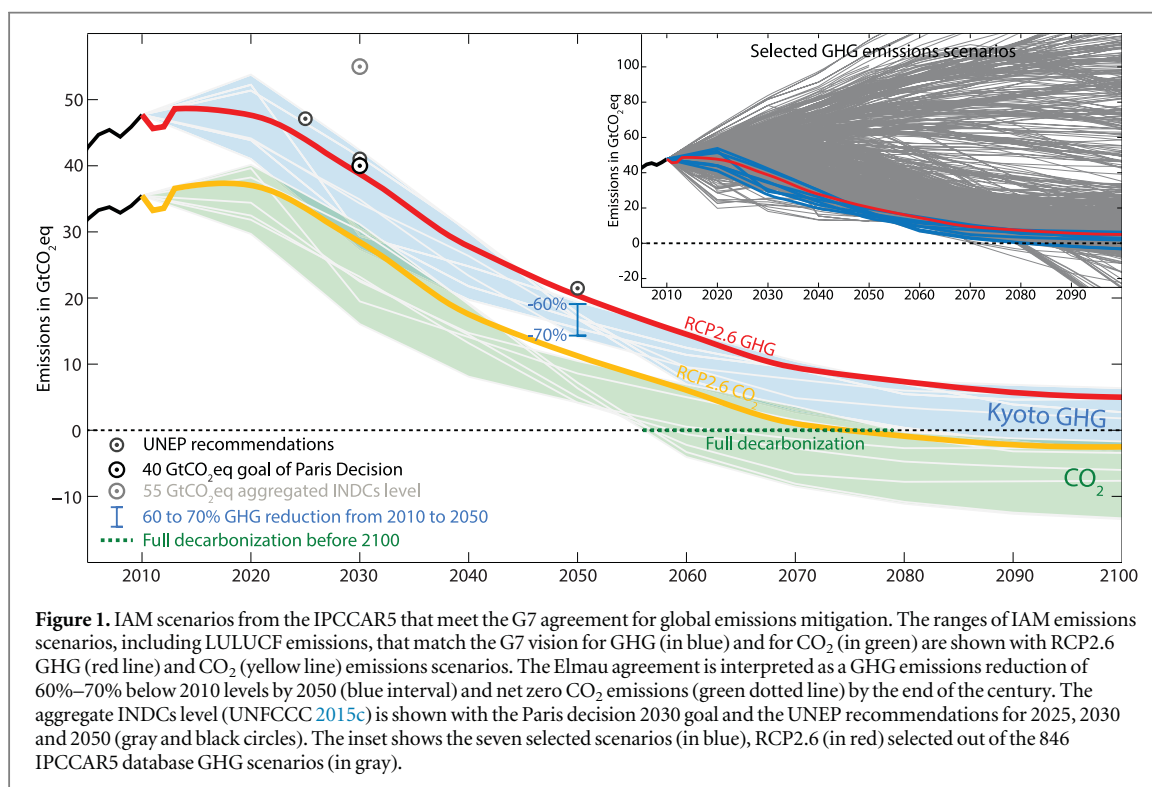
In this study, we interpret the Elmau agreement as a requirement to reduce global GHG emissions by 60%–70% between 2010 and 2050 and fully decarbonize by 2100 at the latest. We note that the term 'decarbonization' is ambiguous, as it can be defined as the process of lowering carbon intensity (Edenhofer *et al* 2014, sec Annex I, Glossary) rather than the endpoint of net zero CO_2 emissions as often interpreted by the public and some governments (Hendricks 2015). We identify the seven cost optimal Integrated Assessment Model (IAM) scenarios from the IPCCAR5 database (https://tntcat.iiasa.ac.at/AR5DB/) consistent with our interpretation of the Elmau agreement (figure 1 and SI). We add to this set RCP2.6, the only one of the four Representative Concentration Pathways employed by the IPCCAR5 that offers a likely chance of limiting global warming to 2 °C (van Vuuren *et al* 2011). While just outside our interpretation of the Elmau criteria, with GHG emissions 57% below 2010 in 2050, RCP2.6 lies within the range of our selected scenarios for most of the century. These eight selected economically optimal scenarios result from mitigation policies starting in 2010 and 2020 and show global GHG emissions between +1% and −28% in 2025 compared to 2010 levels, and between −11% and −43% in 2030 (or between −12% and −55% for CO_2). These mitigation targets are slightly more ambitious than the targets recommended by UNEP, namely −4% in 2025 compared to 2010, −14% by 2030 and −55% by 2050 (UNEP 2014), and are in line with the Paris decision target of 40 $GtCO_2$eq for 2030 (figure 1). The eight selected scenarios reach net negative CO_2 emissions between 2056 and 2080 and some reach net negative GHG emissions after 2080 (see SI). If near-term targets lie at the least ambitious end of the range presented here, achieving the climate objective would

require long-term targets to lie at the most ambitious end of the range.

The question of how mitigation effort, or equivalently emissions rights, should be distributed between countries invokes complex and competing value judgements (Rose *et al* 1998, Ringius *et al* 2002, Bode 2004, Höhne *et al* 2006, Baer *et al* 2008, Jacoby *et al* 2008, Nabel *et al* 2011, Winkler *et al* 2011, Höhne *et al* 2013, Edenhofer *et al* 2014, chapter 6, Raupach *et al* 2014, Winkler and Rajamani 2014, Meinshausen *et al* 2015). In 2009, the G8 supported a differentiated 2050 target for developed countries of at least 80% compared to 1990 or more recent years (G8 2009, p 4) (figure S3 in supplementary information). At Elmau, the G7 stated its determination to adopt an agreement with legal force 'applicable to all parties that is ambitious, robust, inclusive and reflects evolving national circumstances' (G7 2015, p 12) but it has not subsequently provided near-term global targets or national emissions allocations consistent with the 2 °C goal.

In the absence of international consensus on an effort-sharing approach, scientists and government representatives have employed a range of equity principles when modeling international emissions distributions consistent with holding global warming below 2 °C (Rose *et al* 1998, Baer *et al* 2008, den Elzen *et al* 2008, Jacoby *et al* 2008, Nabel *et al* 2011, Winkler *et al* 2011, Höhne *et al* 2013, Tavoni *et al* 2014, Raupach *et al* 2014, Pan *et al* 2015, Peters *et al* 2015, Meinshausen *et al* 2015). The IPCCAR5 grouped the regional 2030 mitigation targets of over forty studies into five categories according to distributive justice concepts associated with 'capability', 'equality', 'responsibility-capability-need', 'equal cumulative per capita (CPC)' and 'staged approaches' (Höhne *et al* 2013, Edenhofer *et al* 2014, figure 6.28). While the global GHG emissions scenarios of these studies result in the stabilized concentration levels (425–485 ppm CO_2eq) required to have a medium chance (50%–66%) of limiting warming to 2 °C, they do not generally follow trajectories that are—under certain conditions—deemed technologically feasible and economically optimal within IAM modeling worlds (Höhne *et al* 2013).

Under the strict implementation of such a non-optimal allocation approach, countries would have to engage in inter-temporal trading of emission permits (borrowing or banking) in order to achieve realistic mitigation trajectories that minimize aggregate economic costs. Such inter-temporal trading relies on governments that are stable and accountable over time, and on an emission trading system that allows countries to use or sell their future or past emissions permits. Such an arrangement does not appear to be on the horizon in the new post-2020 regime. In this study, we allocate to countries, on the basis of equity approaches, emissions trajectories that add up to global IAM emissions scenarios at any point in time. In addition to domestic mitigation, countries can use

Figure 1. IAM scenarios from the IPCCAR5 that meet the G7 agreement for global emissions mitigation. The ranges of IAM emissions scenarios, including LULUCF emissions, that match the G7 vision for GHG (in blue) and for CO_2 (in green) are shown with RCP2.6 GHG (red line) and CO_2 (yellow line) emissions scenarios. The Elmau agreement is interpreted as a GHG emissions reduction of 60%–70% below 2010 levels by 2050 (blue interval) and net zero CO_2 emissions (green dotted line) by the end of the century. The aggregate INDCs level (UNFCCC 2015c) is shown with the Paris decision 2030 goal and the UNEP recommendations for 2025, 2030 and 2050 (gray and black circles). The inset shows the seven selected scenarios (in blue), RCP2.6 (in red) selected out of the 846 IPCCAR5 database GHG scenarios (in gray).

new mechanisms to match their emissions allocation. The recent Paris Agreement and decision recognized the voluntary 'use of internationally transferred mitigation outcomes towards nationally determined contributions' and encouraged the implementation of 'results-based payments […] for the implementation of policy approaches' (UNFCCC 2015a). While no comprehensive global emissions trading scheme is currently in place, countries can match the emissions allocations derived in this study through a combination of domestic mitigation and financial contributions. These financial contributions could be purchases of mitigation outcomes as part of a global emissions trading scheme or as contributions to global climate finance. An assumption on the pricing, in terms of a contribution to climate finance, of a certain emissions allocation is necessary to compare currents efforts with the allocations derived in this study. The conversion of financial contributions to emissions reductions is beyond the scope of this study.

Our study derives national targets that are consistent with various interpretations of equity and with the aggregate global decarbonization trajectory laid out in the G7 agreement. We model the five IPCC allocation categories as follows (see SI for further details). The 'capability' (CAP) approach, from Jacoby et al (2008), allocates to each country a share of global emissions proportional to its population divided by its per capita GDP—or proportional to its GDP when global net emissions become negative. The 'equal per capita' (EPC) approach, reflecting the 'equality' IPCC category, allocates global emissions shares that are proportional to each country's population. The

'Greenhouse Development Rights' (GDR) approach proposed by Baer et al (2008), reflects the 'responsibility-capability-need' IPCC category, and allocates emissions shares based on the historical and projected business-as-usual emissions, the population and the wealth distribution of each country. The 'equal cumulative per capita' (CPC) approach allocates each country with total cumulative emissions in proportion to its cumulative population over a chosen period. Finally, the 'constant emissions ratio' (CER) approach preserves the relative distribution of GHG emissions across countries from the start of the allocation onwards. This status-quo approach, also referred to as the 'grandfathering' approach (Rose et al 1998, Müller and Höhne 2013) or 'inertia' (Peters et al 2015), is included in the 'equality' category by the IPCC, but is often considered less equitable than other approaches found in the literature (Caney 2009, Peters et al 2015).

2. Methods

We used the Potsdam Real-time Integrated Model for the probabilistic Assessment of emission Paths (PRIMAP) (Nabel et al 2011) to model allocations approaches. This model contains a database with historical and projected data of: national GHG emissions, population and GDP purchase power parity. We used GHG emissions data from the PRIMAP database (Nabel et al 2011) that combines UNFCCC CRF inventories for Annex I (UNFCCC 2014) countries and EDGAR42 data for non-Annex I countries (European Commission 2009). Incomplete historical datasets are extrapolated in the past using the growth rates

of CDIAC data (Boden *et al* 2012) for CO$_2$ and MATCH data (Höhne *et al* 2010) for other GHGs. Country level emissions projections are obtained from downscaled Regional RCP emissions using the Shared Socioeconomic Pathway Two (SSP2) socioeconomic data (O'Neill *et al* 2015) and the assumption of exponential convergence of emission intensities within a region.

We combined Kyoto-GHG (carbon dioxide, methane, nitrous oxide, perfluorocarbons, hydrofluorocarbons and sulphur hexafluoride) emissions following the 'SAR GWP-100' (Global Warming Potential for a 100 year time horizon) introduced in the Second Assessment Report of the IPCC and used under the UNFCCC.

We selected from the 846 IAM GHG scenarios available in the IPCCAR5 database those consistent with the G7 Elmau agreement. Scenarios were selected based on their dynamic capacity to achieve emissions reductions of 60%–70% between 2010 and 2050 (including emissions from LULUCF) as well as to reach net zero CO$_2$ emissions by the end of the 21st century (figure S1 in supplementary information). We then removed seven scenarios that showed emissions values almost equal (<2% difference) to others (figure S1 in supplementary information). We further removed two scenarios that featured steep mitigation before 2020, plateauing by 2030, as well as an annual LULUCF emissions sink that exceeds 15 GtCO$_2$ y^{-1} before 2100. Finally, we excluded a scenario that did not offer a likely chance of limiting warming to 2 °C. The seven selected scenarios result from five models involved in three model inter-comparison exercises (table S1 in supplementary information): the LIMITS (Kriegler *et al* 2013), the EMF22 (Clarke *et al* 2009) and the EMF27 (Kriegler *et al* 2014b) studies.

Following this selection, we excluded LULUCF emissions from the global emissions scenarios to be allocated. We also subtracted international shipping emissions (CO$_2$, CH$_4$ and N$_2$O only) and aviation bunker emissions according to scenarios from the QUANTIFY project (Owen *et al* 2010), both following IPCC-SRESB1—a scenario that limits global warming to 1.8 °C compared to the 1980–1999 average (IPCC 2007). In the scenarios used, shipping emissions increase by 288% over the 2010–2100 period and aviation emissions are 101% higher in 2100 after peaking in 2062. More ambitious mitigation from the aviation and marine sectors would create more emissions space for other sectors and countries. A 'fair' contribution from these sectors has not yet been clearly established but would likely require mitigation beyond that assumed here (Anderson and Bows 2012, Cames *et al* 2015). While Article 4 of the Paris Agreement covers global emissions, its lack of specific reference to bunker emissions and the absence of current policies leaves no ground to assume strong mitigation in these sectors.

As the seven selected scenarios are initiated in either 2005 or 2010, we harmonized them to the PRIMAP database's 2010 emissions of 42.5 GtCO$_2$eq excl. LULUCF emissions (see methods). To do so, the scenarios were multiplied by a vector that is an interpolation between the 2010 reported emissions divided by the respective 2010 scenarios values, and 1 in 2040 (Meinshausen *et al* 2011). As the harmonization amended the initial 2010 levels, the harmonized global scenarios (including LULUCF and bunker emissions) do not all exactly meet a 60%–70% reduction in 2050 compared to observed 2010 levels (figure 1). After harmonization, the seven selected global scenarios show instead an emissions reduction of 59%–70% over the 2010–2050 period. We added RCP2.6 to the seven selected IPCCAR5 scenarios.

We calculated emissions allocations for 2011 onwards, since historical emissions are available for all countries only until 2010 (see SI for detailed methods). For the EPC and CAP approaches, a 30 year convergence period allows for a linear transition between initial international emissions ratios and emissions ratios calculated by each approach. Under the CPC and GDR approaches, historical emissions are accounted from 1990, the date of the first IPCC report and second World Climate Conference. Historical emissions are discounted successively by 1.5% each year in the past (Winkler *et al* 2011), starting in 2010, to account for technological improvement. The GDR approach is set to give equal weight to its historical responsibility and its capability components. The mitigation burden of a country is based on the number of its citizens earning more than $7500 (in purchase power parity). Population (KC and Lutz 2014) and GDP (Crespo Cuaresma 2015) scenarios projections follow the SSP2—IIASA implementation (https://tntcat.iiasa.ac.at/SspDb/) that assumes medium population and economic growth, and medium socioeconomic challenges for both mitigation and adaptation. The reference case projections used in the GDR approach are downscaled from RCP8.5—assuming no further mitigation measures. When no absolute target can directly be derived from a country's Intended Nationally Determined Contribution (INDC), we show the range of targets as available from two separate online assessments (Climate Action Tracker 2015, Meinshausen 2015). The national allocations and INDC targets are applied here to 'Kyoto-Annex A' emissions, excluding LULUCF emissions, since proposed accounting rules differ widely across countries.

3. Results

For all G7 parties, allocation approaches can be ranked in the same increasing order of stringency: CER, EPC, CAP, CPC and GDR (figure 2 and table 1). Emissions allocations across the five approaches diverge rapidly for G7 parties, in particular after 2030 when the CPC
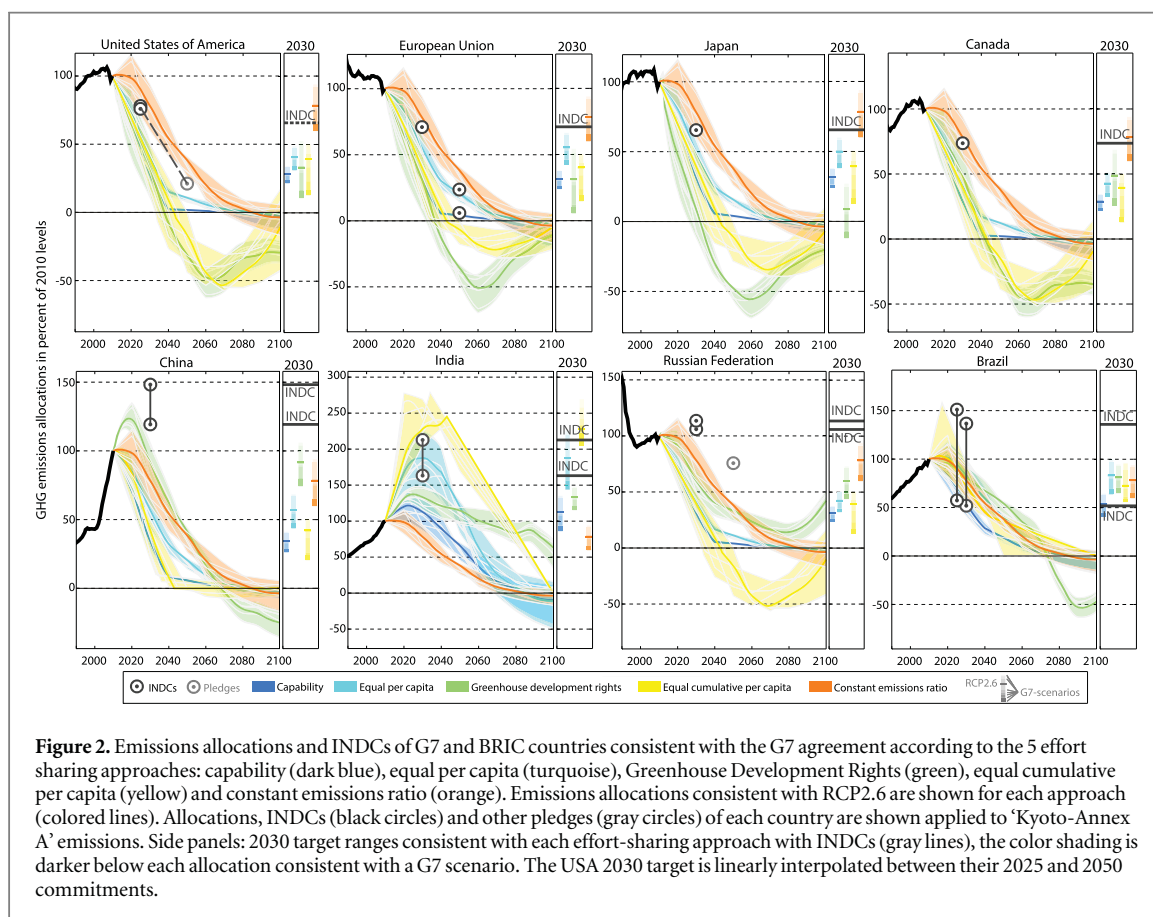
Figure 2. Emissions allocations and INDCs of G7 and BRIC countries consistent with the G7 agreement according to the 5 effort sharing approaches: capability (dark blue), equal per capita (turquoise), Greenhouse Development Rights (green), equal cumulative per capita (yellow) and constant emissions ratio (orange). Emissions allocations consistent with RCP2.6 are shown for each approach (colored lines). Allocations, INDCs (black circles) and other pledges (gray circles) of each country are shown applied to 'Kyoto-Annex A' emissions. Side panels: 2030 target ranges consistent with each effort-sharing approach with INDCs (gray lines), the color shading is darker below each allocation consistent with a G7 scenario. The USA 2030 target is linearly interpolated between their 2025 and 2050 commitments.

and GDR approaches imply net negative emissions. Across the four 'fair' approaches (i.e. all but CER), aggregated emissions allocations over G7 parties are 44%–92% below 2010 levels in 2030, and 84%–144% below 2010 levels in 2050 (figure S3 in supplementary information). By contrast, the INDCs of the G7 parties are consistent only with the CER approach. Only the conditional long-term target of the EU28 matches the reduction of other approaches: EPC and CAP.

Achieving the G7's objectives in a fair way implies the participation of all countries. Other countries can align with the G7 INDCs in one of two ways: either by picking the CER approach, or by picking the approach resulting in the least ambitious national mitigation targets. Assuming that G7 countries do not raise the ambition of their current commitments, only the first of these two options would guarantee a likely chance of limiting global warming to 2 °C (Meinshausen *et al* 2015). All UNFCCC parties would then follow the CER approach and reduce their emissions by the same amount compared to 2010, (6%–40% by 2030 depending on the global target, figure 2). However, such a universal mitigation target is considerably more stringent than other approaches for developing countries.

To illustrate the second option, we use five approaches to derive allocations (figure 2 and table 1) for Brazil, Russia, India and China (BRIC), which together are responsible for a growing share of international emissions (37% in 2010, 39% incl. LULUCF (Güt-schow 2015)). By picking the least stringent of the five approaches, China would emit −25% to +6% in 2030 compared to 2010 under the GDR approach, India +105% to +169% under the CPC, Russia −6% to −40% under the CER and Brazil −0% to −36% under the EPC. The INDCs of Russia and China (Climate Action Tracker 2015) are inconsistent with any allocation approach applied here. The INDC of India is consistent with the CPC and the EPC approaches (Meinshausen 2015). The indicative 2030 target of Brazil's INDC, 43% below 2005, appears more ambitious than any approach's allocation if applied to non-LULUCF emissions. However, a target 43% below 2005 levels including LULUCF emissions lies far above any approach's allocation. Overall, national results of the 'fair' approaches are consistent with the inter-quartile range of targets (Pan *et al* 2015) aggregated from multiple approaches applied to RCP2.6. However, compared to the Pan *et al* (2015) study, we obtain slightly stricter targets for Japan and Russia, and much stricter targets for China with up to 81% reduction between 2010 and 2030 under the CPC approach.
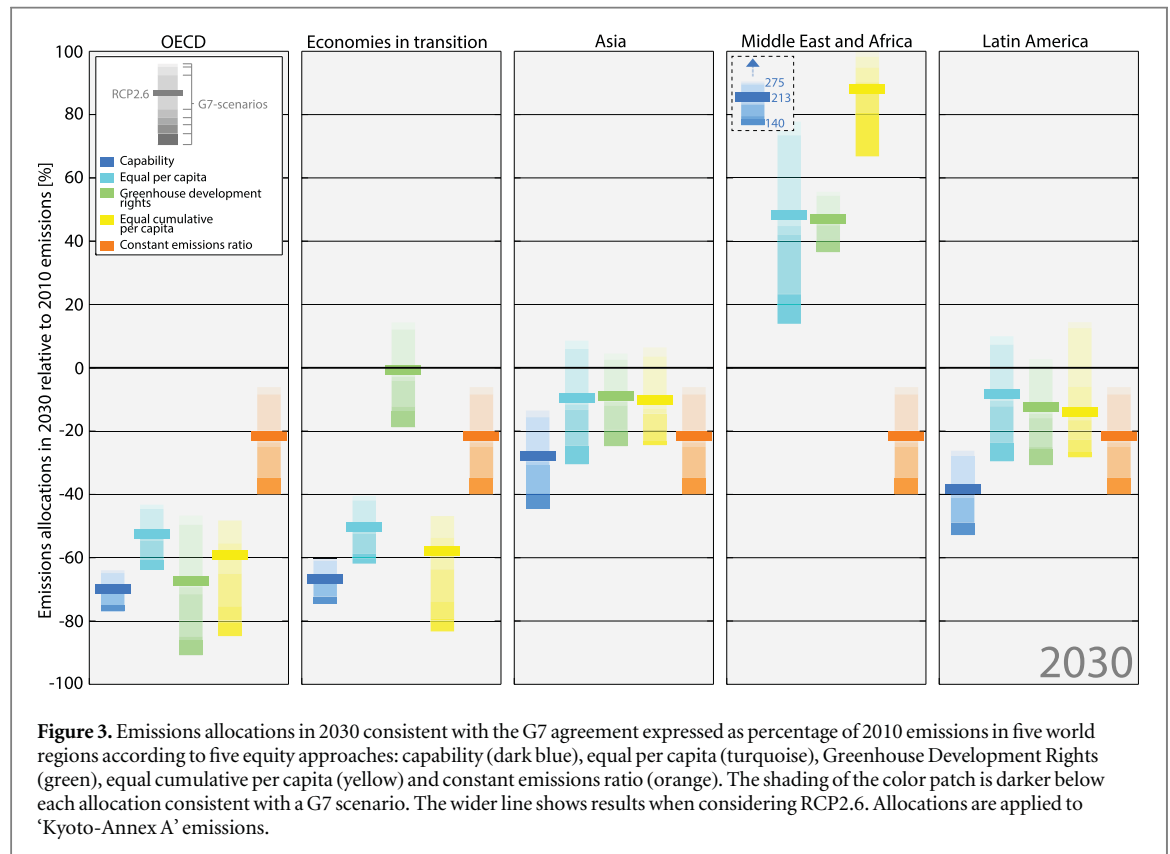
To illustrate the implications of equitable implementations of the G7 agreement for the rest of the world, we derive aggregated 2030 targets for five world regions—OECD, Economies In Transition, Asia, Middle East and Africa, and Latin America—, and compare these with the analysis of the IPCCAR5

Table 1. Emissions reductions consistent with the G7 agreement according the five effort sharing approaches. The INDCs and pledges, the average and complete range (in square brackets) of mitigation targets over the eight selected scenarios are given in percent of 2010 levels.

	INDCs and pledges			2025		2030		2050
USA	2025 | −22%	CAP	−54	[−45 to −63]	−73	[−66 to −78]	−98	[−98 to −99]
	2025 | −24% conditional	EPC	−44	[−33 to −54]	−61	[−51 to −69]	−91	[−89 to −93]
	2030 | −34% extrapolated	GDR	−53	[−29 to −75]	−70	[−48 to −89]	−136	[−130 to −141]
	2050 | −79%	CPC	−50	[−37 to −65]	−67	[−50 to −87]	−122	[−100 to −144]
		CER	−12	[5 to −28]	−24	[−6 to −40]	−67	[−59 to −74]
EU28	2030 | −29%	CAP	−51	[−42 to −61]	−70	[−62 to −76]	−96	[−96 to −97]
	2050 | −76%	EPC	−31	[−18 to −44]	−46	[−34 to −57]	−82	[−78 to −86]
	2050 | −94% conditional	GDR	−54	[−26 to −80]	−72	[−46 to −94]	−141	[−133 to −148]
		CPC	−49	[−37 to −64]	−66	[−50 to −85]	−108	[−100 to −118]
		CER	−12	[5 to −28]	−24	[−6 to −40]	−67	[−59 to −74]
Japan	2030 | −35%	CAP	−51	[−42 to −60]	−69	[−62 to −76]	−96	[−96 to −97]
		EPC	−36	[−24 to −48]	−52	[−40 to −62]	−86	[−83 to −89]
		GDR	−75	[−51 to −97]	−94	[−73 to −112]	−151	[−147 to −156]
		CPC	−50	[−37 to −65]	−67	[−50 to −87]	−113	[−100 to −128]
		CER	−12	[5 to −28]	−24	[−6 to −40]	−67	[−59 to −74]
Canada	2030 | −26%	CAP	−54	[−45 to −62]	−72	[−66 to −78]	−98	[−98 to −98]
		EPC	−42	[−31 to −53]	−59	[−49 to −67]	−89	[−87 to −91]
		GDR	−39	[−16 to −61]	−55	[−31 to −74]	−127	[−120 to −133]
		CPC	−50	[−37 to −65]	−67	[−50 to −87]	−119	[−100 to −138]
		CER	−12	[5 to −28]	−24	[−6 to −40]	−67	[−59 to −74]
China	2030 | +19% to +48%	CAP	−49	[−39 to −59]	−67	[−59 to −74]	−95	[−94 to −96]
	(Climate Action Tracker 2015)	EPC	−30	[−16 to −43]	−45	[−32 to −56]	−82	[−78 to −86]
		GDR	8	[23 to −6]	−11	[6 to −25]	−64	[−56 to −71]
		CPC	−46	[−38 to −59]	−64	[−50 to −79]	−97	[−93 to −102]
		CER	−12	[5 to −28]	−24	[−6 to −40]	−67	[−59 to −74]
India	2030 | +63% to +113%	CAP	17	[40 to −5]	9	[35 to −13]	−43	[−30 to −55]
	(Meinshausen 2015)	EPC	80	[115 to 46]	81	[125 to 44]	4	[27 to −17]
		GDR	36	[47 to 24]	31	[48 to 16]	7	[19 to −4]
		CPC	128	[174 to 80]	138	[169 to 105]	93	[111 to 69]
		CER	−12	[5 to −28]	−24	[−6 to −40]	−67	[−59 to −74]
Russia	2030 | +6%	CAP	−52	[−42 to −61]	−70	[−62 to −76]	−96	[−96 to −97]
	2030 | +14% conditional	EPC	−42	[−31 to −53]	−59	[−49 to −68]	−90	[−88 to −92]
	2050 | −24%	GDR	−27	[−12 to −41]	−42	[−27 to −56]	−71	[−65 to −77]
		CPC	−50	[−38 to −65]	−67	[−50 to −87]	−121	[−100 to −143]
		CER	−12	[5 to −28]	−24	[−6 to −40]	−67	[−59 to −74]
Brazil	2025 | +51%	CAP	−33	[−20 to −45]	−48	[−36 to −59]	−83	[−80 to −87]
	2025 | −43% (INDC applied excl. LULUCF)	EPC	−8	[10 to −25]	−19	[0 to −36]	−65	[−57 to −72]
	2030 | +36%	GDR	−13	[2 to −27]	−21	[−5 to −35]	−51	[−44 to −58]
	2030 | −48% (INDC applied excl. LULUCF)	CPC	−7	[20 to −32]	−25	[−4 to −44]	−76	[−58 to −100]
		CER	−12	[5 to −28]	−24	[−6 to −40]	−67	[−59 to −74]

(Edenhofer *et al* 2014, figure 6.28) (figure 3). IPCCAR5 results depend on whether or not the underlying global scenarios allow net negative emissions. Furthermore, differences in the methods used to interpret equity concepts, as well as in the choice of baseline scenario and political parameters, have caused discrepancies between the IPCC's analysis and our own (see SI). Compared to IPCCAR5 results, our capability based results are more stringent for developed countries and less stringent for developing countries (especially in the Middle East and Africa), while GDR based results appear less stringent for developed countries;

this is due to our choice of methodology (Jacoby *et al* 2008) (see SI). According to our analysis, 2030 mitigation targets across all approaches (relative to 2010 levels) range from +9% to −45% for Asia and from +14% to −53% for Latin-America, comparable with IPCC results. Allocations for the Middle East and Africa region vary greatly across approaches with targets between +14% and +108% above 2010 levels under the EPC, GDR, or CPC approaches, and up to +275% under the capability approach. These four 'fair' approaches allow both significant increases of emissions in the Middle East and Africa in line with the

Figure 3. Emissions allocations in 2030 consistent with the G7 agreement expressed as percentage of 2010 emissions in five world regions according to five equity approaches: capability (dark blue), equal per capita (turquoise), Greenhouse Development Rights (green), equal cumulative per capita (yellow) and constant emissions ratio (orange). The shading of the color patch is darker below each allocation consistent with a G7 scenario. The wider line shows results when considering RCP2.6. Allocations are applied to 'Kyoto-Annex A' emissions.

region's needs for economic development, and potential exports of carbon credits to fund later decarbonization of the economy.

4. Discussion

Our analysis shows that the mitigation commitments announced by the G7 members to the UNFCCC are consistent with the Elmau agreement only if they are enhanced by additional mitigation (or substantial financial support pledges), or if all other countries preserve their current share of global emissions throughout the decarbonization phase. The latter approach is considered by many to be inconsistent with the principle of 'common but differentiated responsibilities and respective capabilities' (CBDR + RC) enshrined in Article 3 of the UNFCCC treaty (UNFCCC 1992, Art. 3.1), but also seems inconsistent with some declarations and positions of G7 members themselves. The EU, for example, uses a capability-based approach to distribute mitigation efforts internally (Commission of the Europeans Communities 2008, p 9) and Japan supported considering 'the impacts of GHG emissions of each Party on global warming' (Japan 2014, p 2). Separately, non-G7 members supported different concepts of fairness that appear incompatible with current G7 commitments under a 2 °C warming limit: China, India and Brazil support concepts that emphasize historical responsibility for climate change (Winkler *et al* 2011)

and the Least Developed Countries support a comprehensive approach similar to the GDR (Nepal on Behalf of the Least Developed Countries Group 2014, p 5). Here we presented approaches consistent with each of these visions of fairness and compatible with a 2 °C limit, provided that all parties adopt the same approach. The global emissions scenarios used in this study rely on cost-optimal and technical feasibility considerations within the IAM models used to produce them. Real world policy implementation will likely alter the global, and consequently national, emissions scenarios. Such real world global emissions scenarios can however not differ substantially from the IAM scenarios in the context of the physical imperative to rapidly reduce global emissions in order to stabilize global temperature.

Further limiting global warming to 1.5 °C, as aspired to in the Paris Agreement, requires emissions of 27–31 GtCO$_2$eq in 2030 and 13–17 GtCO$_2$eq in 2050 (UNEP 2014). These ranges are in the lower end of the range of scenarios consistent with the Elmau agreement used in this study (27–42 GtCO$_2$eq for 2030 and 14–19 GtCO$_2$eq for 2050, figure 1). Future studies can apply the allocation framework developed here to determine, on the basis of equity, the further emissions reduction each party should undertake by 2030, to limit global warming to 1.5 °C.

The global scenarios selected and presented in this study represent physically realistic emissions trajectories. However, all of the allocated national scenarios imply strong mitigation in all world regions except the

Middle East and Africa. Applying such emissions scenarios domestically is not always politically acceptable given the economic and technological momentum of major emitting parties. The national emissions scenarios presented here should rather be seen as a basis for the allocations of emissions mitigation and financial or technological transfers, as encouraged in the Paris Agreement.

5. Conclusions

The global emission goals agreed in Elmau represent long-term milestones in line with a 2 °C global warming limit. However, current INDCs are projected to lead to global emissions around 55 GtCO$_2$eq in 2030 (UNFCCC 2015c), inconsistent with cost-optimal scenarios that limit global warming to 2 °C (figure 1), and more so to 1.5 °C (Rogelj *et al* 2015, tables 1–2). The five year revision cycle of the Paris Agreement, which will begin by 2020, requires parties to regularly update their mitigation ambition in order to close the gap with least cost mitigation scenarios. At the national level, our results suggest that all G7 parties need to increase their mitigation efforts in order to contribute meaningfully to the global goals agreed in Elmau and Paris while respecting a range of visions of climate justice and the principle of CBDR + RC. Commitments from China, Russia, and Brazil are also clearly incompatible with the agreed 2 °C warming limit.

Nevertheless, despite the inadequacy of the 2 °C warming limit as a safe 'guardrail' against climate change's adverse effects (UNFCCC 2015b) and the deficiency of G7 parties' commitments in relation to that goal, the G7 agreement should be seen as a major step forward. Achieving global decarbonization over the course of this century is essential to halting warming and is a necessary step to achieve the Paris Agreement's ambition of achieving 'a balance between anthropogenic emissions by sources and removals by sinks of GHGs in the second half of the century, on the basis of equity'. The global decarbonization decided in Elmau, and in particular the decarbonization of developed countries, is to occur well ahead of the net-zero GHG target of the Paris Agreement. Therefore the Elmau agreement, understood as full decarbonization of the world economy and transformation of the energy sector, could be the crystallizing focal point that galvanizes joint mitigation action towards the Paris Agreement's goals and averts the most unfair solution of all: unmitigated climate change.

Acknowledgments

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