Sharing global CO_2 emission reductions among one billion high emitters

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Contributed by Stephen Pacala, May 19, 2009 (sent for review March 16, 2009)

We present a framework for allocating a global carbon reduction target among nations, in which the concept of "common but differentiated responsibilities" refers to the emissions of individuals instead of nations. We use the income distribution of a country to estimate how its fossil fuel CO_2 emissions are distributed among its citizens, from which we build up a global CO_2 distribution. We then propose a simple rule to derive a universal cap on global individual emissions and find corresponding limits on national aggregate emissions from this cap. All of the world's high CO_2-emitting individuals are treated the same, regardless of where they live. Any future global emission goal (target and time frame) can be converted into national reduction targets, which are determined by "Business as Usual" projections of national carbon emissions and in-country income distributions. For example, reducing projected global emissions in 2030 by 13 $GtCO_2$ would require the engagement of 1.13 billion high emitters, roughly equally distributed in 4 regions: the U.S., the OECD minus the U.S., China, and the non-OECD minus China. We also modify our methodology to place a floor on emissions of the world's lowest CO_2 emitters and demonstrate that climate mitigation and alleviation of extreme poverty are largely decoupled.

climate change | climate equity | climate policy | individual emissions | inequality

The 1992 United Nations Framework Convention on Climate Change (UNFCCC) created a 2-tier world. It called upon the developed ("Annex I") countries to "take the lead" in reducing carbon emissions, and, under the principle of "common but differentiated responsibilities," established no time frame for developing countries to follow. However, a consensus is now emerging in favor of low stabilization targets. These targets cannot be achieved without the participation of developing countries, which today emit about half of global CO_2 emissions and whose future emissions increase faster than the emissions of industrialized countries under "business as usual" scenarios (1).

On what terms should developing countries participate? There are many proposals, each buttressed by some appeal to "fairness." Per capita allocation is widely acknowledged to represent the only equitable goal in the long term, but intermediate steps are required in the short-to-medium term. Uniform percentage reductions in emissions across all countries are rightly rejected by all parties, on the grounds that industrialized countries must create headroom for developing countries. Here, we offer a different approach: An allocation of national targets for fossil-fuel CO_2 emissions derived from a fairness principle based on the "common but differentiated responsibilities" of individuals, rather than nations. Our proposal moves beyond per capita considerations to identify the world's high-emitting individuals, who are present in all countries.

Our approach is designed to blend parsimony, fairness, and pragmatism—treat equally those with the same emissions, wherever they live, and use only national income distributions and economy-wide carbon intensities. National responsibilities are derived by summing the excess emissions of all "high emitter" individuals in a country—"high emitters" are those whose emissions exceed a universal individual emission cap. The scheme does not specify how any nation meets its responsibilities.

Our approach is restricted to future fossil-fuel CO_2 emissions and focuses on the next 2 decades. We do not include biospheric CO_2, other greenhouse gases, and aerosols, because they are not strongly correlated with personal expenditures and national carbon intensities. By imputing national emissions to individuals, we neglect embedded carbon in exports and imports, a component that is relevant for countries with large shares of trade in their economy. We also do not tackle historical responsibility. These are all important topics, and a complete scheme suitable for use in negotiations would need to take them into account.

Baer et al. (2) uses a similar approach, but relies on high incomes rather than high emissions and on a fixed income cap at \$7500 (PPP adjusted). In contrast, our scheme is based on individual emissions rather than income to reward improvements in national carbon intensity. Several others explore allocation regimes based on convergence of national average per capita emissions in the long-term, typically beyond 2050 (3–5), whereas our proposal specifies a transient path that can lead ultimately to long-term convergence.

Individual Emission Distributions. We begin by obtaining a picture of how 26 $GtCO_2$ of global emissions in 2003 were distributed across the world's 6.2 billion people. We first construct national income distributions from World Bank data (6). We then convert these income distributions into individual CO_2 emission distributions, assuming unitary elasticity* and anchoring means using country level emissions data. We use present and projected emissions data from the Energy Information Agency (EIA) (7), a freely available database with geographically disaggregated emissions projections to 2030.

Fig. 1 shows how our method works for 2 representative countries, Australia and France. The upper and lower panels report the probability distributions for income and emissions, respectively. Despite having similar incomes, the emission distribution in Australia is shifted to the right of that of France, because Australia has a higher national carbon intensity. The

Author contributions: S.C., S.P., R.S., and M.T. designed research; S.C., R.S., and M.T. performed research; and S.C., A.C., H.d.C., S.P., R.S., and M.T. wrote the paper.

The authors declare no conflict of interest.

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*The *SI Appendix* presents data sources and categories, methodology, sensitivity analysis of the elasticity of emissions with income, and comments on the poverty emissions floor of 1 tCO_2 per person per year.

This article contains supporting information online at www.pnas.org/cgi/content/full/0905232106/DCSupplemental.

www.pnas.org/cgi/doi/10.1073/pnas.0905232106

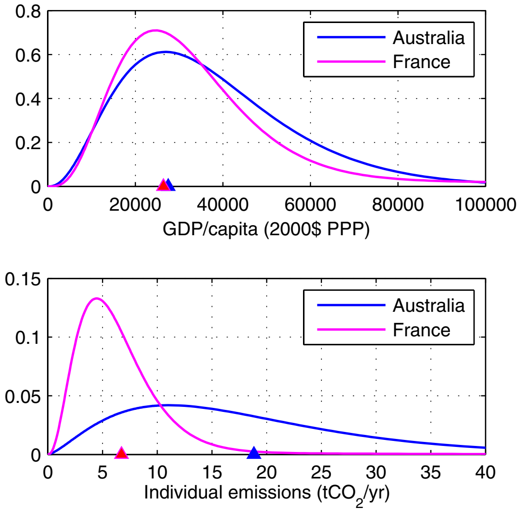

Fig. 1. Income (*Upper*) and emissions (*Lower*) probability density functions for Australia and France in 2003. The triangles on the horizontal axis indicate the means of the distributions.

plot shows that Australia hosts more individuals for every level of annual emissions above 10 tCO_2.

We apply this carbon intensity rescaling procedure to each nation, and we obtain a picture of how individual emissions are distributed globally by summing them up. The global cumulative distribution for 2003 is shown in Fig. 2 *Inset*.[†] To develop our approach, we also need the corresponding national and global CO_2 emission distributions for future dates under BAU. For simplicity, we assume that income inequality at the country level does not change over time. We scale the distributions of individual emissions to the projections of regional CO_2 emissions and population, out to 2030, from EIA (7) and UN (8), respectively. The resulting BAU distribution of the world's 43 $GtCO_2$ emissions in 2030 across 8.1 billion people is also shown in Fig. 2.

Sharing Emission Reductions to Achieve a Global Target. Once the world agrees to a global CO_2 emission reduction target, based on a stabilization target, a framework is needed to arrive at national emission allocations. Our approach provides a consistent rule for determining these allocations. A universal cap is imposed on the global individual emission distribution, such that eliminating all emissions above that cap achieves the target (Fig. 2). The cartoon in Fig. 3 introduces this scheme. The consequences of this cap are country-level emission targets that reflect the number of "high emitter" individuals in that country and their aggregate emissions. The universal emission cap achieves equity and fairness in the climate change context in the sense that: (*i*) countries with a larger proportion of high emitters do more, and (*ii*) countries with similar emission profiles have similar commitments.

Fig. 2 shows how this method works for a specific example: A global fossil-fuel-CO_2 emission target of 30 $GtCO_2$ in 2030. This case requires a 30% global cut in emissions with respect to BAU for that year and essentially the same global emissions as in 2008. The 2030 individual emission cap is 10.8 tCO_2, and 1.13 billion people (less than 15% of the 2030 global population) will be

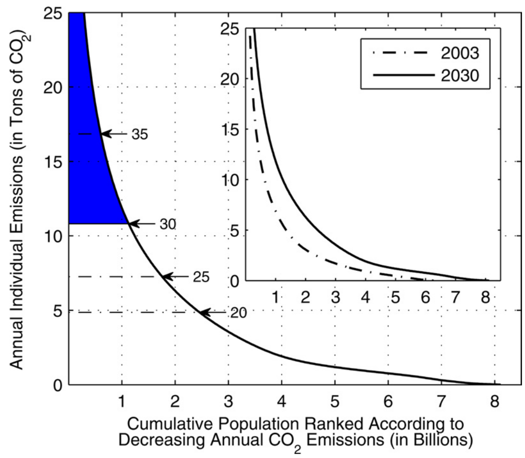

Fig. 2. The world's population in 2030 (8.1 billion) ranked according to decreasing annual emissions. The total area under the curve is the projected BAU emissions in 2030 (43 $GtCO_2$), and the blue region shows the 13 $GtCO_2$ that needs to be removed to meet the 30 $GtCO_2$ ("30" in figure) target. The individual emission cap is 10.8 tCO_2, affecting 1.13 billion people. Also shown are the individual emission caps for global targets of 20 $GtCO_2$ (cap at 4.9 tCO_2), 25 $GtCO_2$ (cap at 7.3 tCO_2), and 35 $GtCO_2$ (cap at 16.8 tCO_2). The *Inset* contrasts the 2003 curve with the 2030 curve.

above the cap.[‡] The shaded area in Fig. 2 shows the total emission reductions, 13 $GtCO_2$. Fig. 2 also shows the individual emission cap for global fossil-fuel-CO_2 emission targets of 20, 25, and 35 $GtCO_2$ in 2030.[§]

Assuming a 30 $GtCO_2$ target for 2030, Fig. 4 disaggregates Fig. 2 into the component emission distributions for 4 regions: U.S., OECD minus U.S., China, and the non-OECD minus China.[¶] At the global cap of 30 $GtCO_2$, the 4 curves are close together, reflecting the roughly 250 million people above the cap in each of the 4 regions. In Fig. 5, we show the trajectories from 2003 to 2030, assuming that global emissions peak at 33 $GtCO_2$ in 2020 and descend linearly to 30 $GtCO_2$ in 2030. Noticeable departures from BAU for China occur later than for the other 3 regions, reflecting the relative paucity of high emitters in China at present. Table 1 provides detailed results for the 30 $GtCO_2$ target for 2030 for the 16 regions EIA uses in its projections. We present a full set of corresponding Tables, for emission targets of 20, 25, 30, and 35 $GtCO_2$, and for 2020 and 2030, in the supporting information (SI) *Appendix*.

The universal carbon emission threshold can be converted into an income threshold for each country/region using the appropriate carbon intensity. In 2030, with BAU projections of 43 $GtCO_2$ of fossil-fuel emissions and a global GDP of 154 trillion

[†]In the *SI Appendix*, we test a power-law relationship between CO_2 emissions and income, seeking a universal exponent β that best fits the historical data. As discussed in the *SI*, it is estimated that $\beta \sim 0.7$. However, in Figs. 1–7 and Table 1 here, we show a linear relationship $\beta = 1.0$, because this value of β is easy to analyze: Each country's emissions distribution is the same as its income distribution with a simple change of units. Also, as seen in the *SI Appendix*, results for $\beta = 0.7$, 0.8, 0.9, and 1.0 are not very different.

[‡]"One billion high emitters" in the title of our paper comes from this example. The actual number depends on the date, the target, and the scenario used for the projection. As seen in the supporting information, 0.60, 1.76, and 2.45 billions high emitters are involved in 2030 if the targets are 35, 25, and 20 $GtCO_2$, respectively, and if the reference scenario from the EIA Annual International Outlook 2007 (7) is used. "One billion high emitters" is our metaphor for a globally coordinated attack on climate change.

[§]A global target for a date as early as 2030 and restricted to fossil fuels cannot be convincingly associated with any specific stabilization target, given the significance of nonfossil fuel emissions, the uncertainty about land sinks, and the many following decades during which the level of effort is unspecified. The 20, 25, and 30 GtCO2 targets for 2030 are intended to be examples of targets that require immediate globally coordinated implementation, thereby making credible the eventual achievement of stringent stabilization targets.

[¶]We group countries using OECD rather than Annex I in this paper because, typically, projections of regional growth and emissions define regions using the OECD/non-OECD distinction. The OECD and Annex I are not the same. Notably, Annex I includes Russia. CO_2 emissions in 2003 were 13.3 $GtCO_2$ for the OECD but 18.4 $GtCO_2$ for Annex I (UNFCCC GHG data).

Table 1. Regional reference emissions, population, emission allocation, and number of people affected for 2030 under a global target at 30 $GtCO_2$, with (P) and without the poverty provision

Region	Emis. [1990], $GtCO_2$	Emis. [2003], $GtCO_2$	Pop. [2003], millions	Emis. (BAU) [2030], $GtCO_2$	Pop. (BAU) [2030], millions	Emis. (30) [2030], $GtCO_2$	Pop. under cap (30) [2030], millions	Emis. (30P) [2030], $GtCO_2$	Pop. under cap (30P) [2030], millions	(30P) change w.r.t [1990], %	(30P) change w.r.t [2003], %	(30P) change w.r.t (BAU), %
U.S.	*5.0*	*5.8*	*291*	*8.0*	*365*	*3.6*	*267*	*3.2*	*285*	*−35*	*−45*	*−60*
Canada	0.5	0.6	32	0.7	39	0.4	29	0.3	31	−27	−40	−53
Mexico	0.3	0.4	101	0.7	129	0.6	14	0.5	16	81	43	−21
OECD Europe	4.1	4.3	529	4.7	561	3.8	139	3.6	175	−11	−16	−23
Japan	1.0	1.2	128	1.3	123	1.1	43	1.0	57	1	−18	−22
South Korea	0.2	0.5	48	0.7	50	0.5	30	0.4	34	81	−9	−37
Australia and New Zealand	0.3	0.4	24	0.6	30	0.3	21	0.3	22	−11	−37	−55
OECD minus U.S.	*6.4*	*7.4*	*861*	*8.7*	*931*	*6.6*	*276*	*6.2*	*336*	*−3*	*−16*	*−28*
Total OECD	11.4	13.3	1152	16.7	1296	10.2	543	9.5	620	−17	−29	−43
China	*2.2*	*4.0*	*1296*	*11.4*	*1442*	*8.5*	*300*	*8.2*	*354*	*264*	*106*	*−29*
Russia	2.3	1.6	145	2.2	125	1.2	77	1.1	85	−54	−33	−51
Transition Economies	1.9	1.1	195	1.6	190	1.3	49	1.2	60	−34	12	−26
India	0.6	1.1	1065	2.2	1442	2.2	1	2.3	2	304	121	7
Other Non-OECD Asia	0.8	1.4	927	2.8	1308	2.2	47	2.5	52	213	85	−9
Middle East	0.7	1.2	175	2.3	282	1.4	56	1.4	64	97	13	−41
Africa	0.6	1.0	854	1.8	1438	1.4	23	2.2	27	244	128	24
Brazil	0.2	0.3	181	0.6	237	0.6	10	0.6	13	161	80	−4
Other South and Central America	0.5	0.6	257	1.2	349	1.0	22	1.0	27	126	59	−16
Non-OECD minus China	*7.6*	*8.3*	*3798*	*14.8*	*5370*	*11.3*	*284*	*12.4*	*330*	*63*	*50*	*−16*
Total Non-OECD	9.8	12.2	5094	26.2	6812	19.8	583	20.5	684	109	68	−22
Total World	21.2	25.5	6245	42.9	8108	30.0	1126	30.0	1304	41	18	−30

Data from the 4 italicized lines are plotted in Figs. 4 and 5.

dollars (PPP, in year 2000 dollars), each ton of fossil-fuel CO_2 emissions is associated with \$3600 of global GDP, and thus the emission cap of 10.8 tCO_2 corresponds to an average global PPP income of about \$39,000. The corresponding national income thresholds vary significantly across countries, reflecting variations in national carbon intensity.‖

Addressing Poverty Alleviation and Carbon Emission Reductions Simultaneously. The approach can be modified to place a floor on individual emissions. For example, a floor of 1 tCO_2/yr per person exceeds the projected emissions of 2.7 billion individuals in 2030 (one-third of the world population). The 1 tCO_2/yr floor is roughly consistent with Millennium Development Goals (http://www.un.org/millenniumgoals/). Establishing such a floor has the consequence of shielding the lowest one-third of the world's emitters from the CO_2 reduction strategies that will need to permeate the activities of the other two-thirds of the world's population to achieve significant global CO_2 emission reductions (9). The world's lowest emitters would not be thwarted from obtaining diesel engines to produce their first electricity for lighting, television, and the charging of batteries; gasoline fuel for their first motorized transport; and liquid petroleum gas for their first modern cooking fuel—where these technologies are the lowest-cost options.

The consequences of a 1 tCO_2 floor for the mitigation required of the other two-thirds of the world's population are small, as Fig. 6 shows. See the cap, labeled "30P," that results when a floor of 1 tCO_2 in 2030 is in place and the 2030 global emission target of 30 $GtCO_2$ is retained. To compensate for the additional 1.5 $GtCO_2$ of reductions by high emitters required to create such a floor, the universal cap is 9.6 tCO_2 (down from 10.8 tCO_2) and the number of "high emitters" is 1.30 billion (up from 1.13 billion). The message of Fig. 6 is that addressing climate change mitigation and meeting the basic energy needs of the global poor are nearly decoupled objectives.

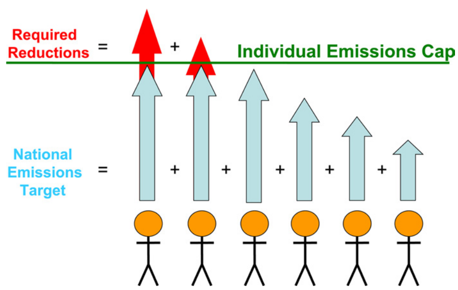

Fig. 3. Cartoon version of the capping scheme for generating national allocations.

‖According to the EIA (7), each ton of fossil-fuel CO_2 emissions in 2003 was associated with \$2000 of global GDP. Accordingly, EIA projects a CO_2 intensity of the global economy (emissions/GDP) that decreases by 43% between 2003 and 2030 in their BAU scenario. This corresponds to a 2.1% reduction per year—faster than the 1.8% per year reduction observed during the 1990–2003 period. Targets for emissions reductions necessitate still faster reductions, achieved by carbon intensity reductions beyond those embedded in BAU. For example, achieving a 30 $GtCO_2$/yr target in 2030 produces a global economy where each ton of fossil-fuel CO_2 is associated with \$5100 of global GDP, i.e., a 3.4% reduction per year in global carbon intensity.

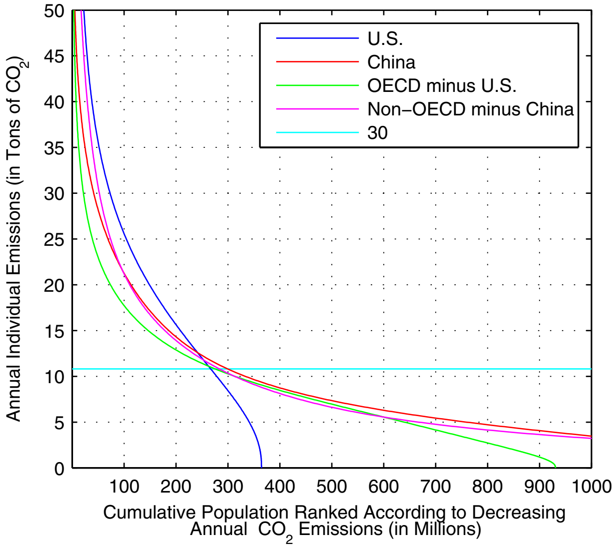

Fig. 4. Regional emission distributions in 2030, revealing the number of individuals above the cap of 10.8 tCO_2/yr (corresponding to a global target of 30 $GtCO_2$ in 2030). The regional efforts are comparable: The U.S. has 270 million people who, relative to "Business As Usual" for 2030, in aggregate reduce emissions by 4.4 $GtCO_2$; the OECD minus U.S. has 280 million who reduce 2.1 $GtCO_2$; China has 300 million who reduce 2.9 $GtCO_2$; and the non-OECD minus China has 280 million who reduce 3.5 $GtCO_2$.

In Table 1, the ninth and tenth columns show the national/regional emission allocations when the 2030 target is modified to include this 1 tCO_2 emission floor. The U.S. target falls by 0.34 $GtCO_2$ (10%) and the African target rises by 0.8 $GtCO_2$ (54%).

Summary of Results. Fig. 7 provides a summary of the national mitigation effort for 7 major regions in 2030. The bars show that the U.S. and China have the 2 highest CO_2 abatement assignments. India mostly gets a free pass, but not Africa, due to high carbon intensity and inequality in South Africa and in North African nations with energy industries. Russia and the Middle East get sizeable mitigation assignments for the same reasons.

The 5 $GtCO_2$ increments from the weakest to the most stringent global policy are taken up differently by different regions. The mild global target of 35 $GtCO_2$ affects the U.S. more than the other regions; the U.S. has 185 million of the world's 600 million people whose emissions exceed the relatively high (16.8 tCO_2/year) individual cap of this policy. The additional emission cuts to comply with more stringent global targets decline for the U.S. but remain constant for China and Europe,

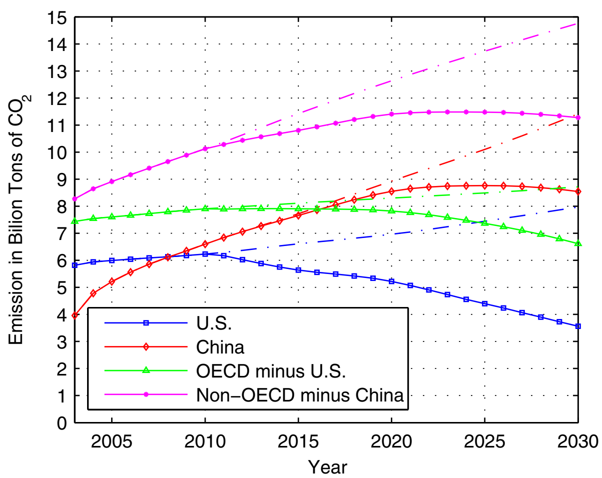

Fig. 5. Regional targets (solid lines) for a global emission trajectory that allows global emissions to peak at 33 $GtCO_2$ in 2020 and to arrive at 30 $GtCO_2$ in 2030. Dashed lines show the regional BAU emissions.

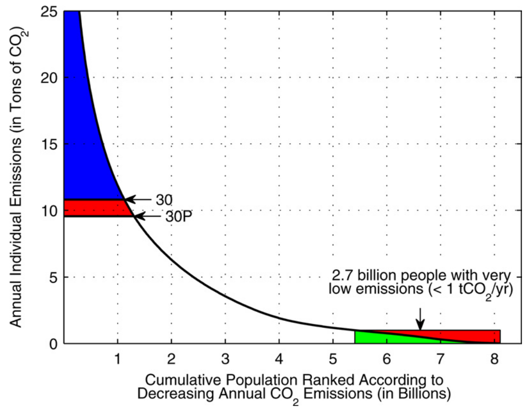

Fig. 6. Individual emissions in 2030 when global emissions are 30 $GtCO_2$ and a poverty provision is included that puts a floor on individual emissions at 1 tCO_2, raising the emissions of 2.7 billion people who emit less than 1 tCO_2 (green area at the right). The red strip at the left between the "30" and "30P" arrows shows the extra reduction required of the high emitters to provide the headroom to achieve this floor. Relative to the same climate goal without a poverty provision ("30"), the cap that includes this poverty alleviation objective ("30P") is lowered from 10.8 to 9.6 tCO_2, and 1.30 instead of 1.13 billion people are under the cap.

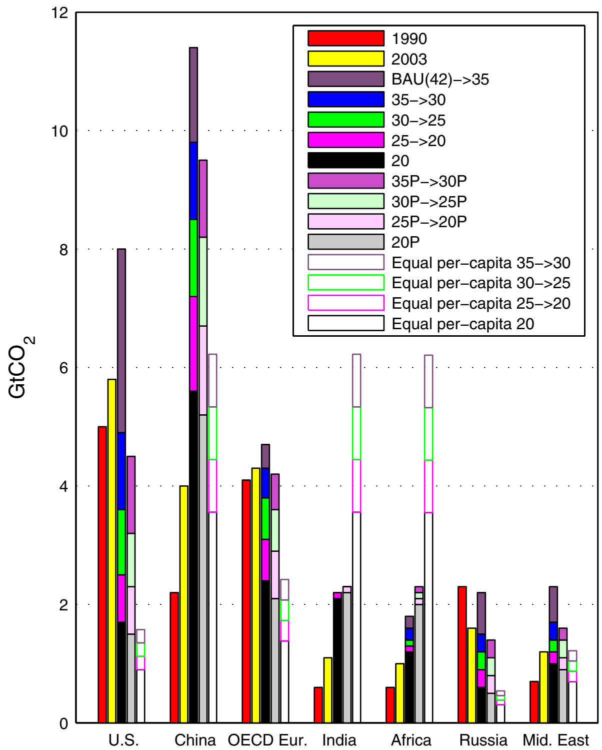

Fig. 7. Emissions in 7 of the 16 EIA regions, in 1990, 2003, and for the global mitigation policies of 35, 30, 25, and 20 $GtCO_2$ in 2030, both with and without poverty provision. The last bar on the right for each region indicates the targets corresponding to an equal per capita allocation scheme and the same 4 global mitigation targets. A table with data for all of the 16 regions can be found in the *SI Appendix*.

reflecting the progressive involvement of all regions as the individual emission cap tightens.

Fig. 7 shows that allowing for the poverty provision of 1 tCO_2 changes most national targets very little. An exception is Africa, which, as a result of its large carbon-poor population, now gets significantly higher allocations.

The regional targets resulting from our poverty floor can be compared to the ones resulting from an equal-per capita (EPC) allocation scheme, where the 30 $GtCO_2$ global emission target for 2030 is divided equally among the world's expected 8.1 billion people, resulting in a universal individual allowance of 3.7 tCO_2. (In the language of our proposal, the EPC allocation scheme lowers the individual emission cap and raises the poverty floor to the same value, here, for 2030, 3.7 tCO_2/person.) Fig. 7 shows that all regions receive a more stringent target in the EPC scheme, with the exception of India and Africa, whose emission targets are significantly larger and roughly equal—due to their similar 2030 populations.

Discussion and Conclusions

The approach presented in this paper is motivated by the reality that emissions from OECD countries and from countries outside the OECD are now roughly equal, and therefore tough global atmospheric stabilization targets require the participation of the developing countries. In our interpretation of fairness, individuals who emit similar amounts of CO_2, regardless of where they live, are expected to contribute to fossil-fuel CO_2 emission reductions in similar ways. In principle, no country gets a pass, because even in the poorest countries some individuals have CO_2 emissions above the universal emission cap.

A well-designed national policy would contain costs and not exacerbate inequalities. Many of the lowest-cost opportunities for CO_2 emission reduction over the next few decades in all countries, especially in the developing countries, will be found in the middle of the emission distribution, associated with billions of people of modest means. Many of them will be moving into cities for the first time and, in a CO_2-responsive economy, would be housed in well-built apartment buildings equipped with efficient appliances and served by efficient mass transit systems. Thus, pursuing CO_2 emission reduction across a wide swath of a country's economy is likely to be preferable to capping the emissions of the high emitters only, as could be inferred from a literal interpretation of the horizontal cutoff in Fig. 2.

Of the countless directions for further work, we note here only a few. It is important to develop more refined tools that reveal the high emitters in developing countries now hidden in the tails of the distributions—for example, in India. Direct measurement of the individual emission distribution using specially designed household surveys may achieve this objective. A better understanding of changes in distributions over time, including the connection between the shape and growth of the emission distribution and the rate (and acceleration) of economic growth, would improve BAU emission projections. The detailed consequences of our scheme for international trading of emission allocations should be investigated and compared with EPC and other schemes.

To review, our scheme requires only a globally agreed emission target and consensus regarding national BAU emissions.[**] Nations derive their obligations from the emissions of their high-emitting citizens, but are left free to decide on implementation policies at national and international levels. It easily accommodates periodic updating as projections of national emissions are revised and improved information about income and emission distributions is obtained. Our scheme does not take into account emissions from land use and non-CO_2 greenhouse gases, emissions embedded in the trade of goods and services,[††] differences in regional climate and country size, inertia restricting rates of change, and prior "legacy" emissions.[‡‡]

Our scheme can be viewed as a step toward allocation on the basis of equal per capita emission rights, but we do not get there in one step. We take into account high emitters above a global cap and low emitters below a global floor, but there is a gap between the cap and the floor. Further application of the underlying principles proposed here would bring about successive reductions of the high-emitter cap and increases of the emission floor, until eventually they converge.

Perhaps our allocation framework can enrich the search for fair and uniform allocation rules governing the international post-2012 regime for climate change mitigation.

**Substantial revisions of emission projections are now underway to take into account the current global recession, see for example http://www.eia.doe.gov/oiaf/aeo/.

††See for example refs. 10 and 11 for estimates of the emissions embodied in international trade of goods.

‡‡Usually, legacy emissions refer to past emissions of nations. In a scheme like ours, which is based on the emissions of individuals, legacy might be incorporated by redefining "high emitters" as those individuals with high lifetime emissions prior to a specific year.

ACKNOWLEDGMENTS. We thank Robert Williams, Sivan Kartha, and John Holdren for useful discussions and Adrian Ross for contributions to an earlier version of this work. S.C., S.P., R.S., and M.T. are supported by the Carbon Mitigation Initiative at Princeton University, funded by BP and Ford Motor Co. A.C. acknowledges support from the Energy Technology Innovation Project, which is financially supported by the David and Lucile Packard Foundation, a gift from Shell Exploration and Production and unrestricted grants from BP Corporation. H.d.C. thanks the Princeton Environmental Institute for its hospitality and numerous colleagues at Energy Research Centre of the Netherlands and participants of COP13 in Bali for fruitful discussions.

1. den Elzen M, Hohne N (2008) Reductions of greenhouse gas emissions in annex I and non-annex I countries for meeting concentration stabilisation targets. *Climatic Change* 91:249–274.
2. Baer P, Athanasiou T, Kartha S, Kemp-Benedict E (2008) *The Greenhouse Development Rights Framework*, 2nd Ed. (Heinrich Böll Foundation, Christian Aid, EcoEquity, and the Stockholm Environment Institute).
3. Agarwal A, Narain S (1991) *Global Warming in an Unequal World: A Case of Environmental Colonialism*. (Centre for Science and Environment, New Delhi, India).
4. Meyer A (2000) *Contraction & Convergence: The Global Solution to Climate Change*. (Green Books, Totnes, Devon). ISBN No. 1–870098-94–3.
5. Aslam MA (2002) in *Building on the Kyoto Protocol: Options for Protecting the Climate*, eds Baumert KA, Blanchard O, Llosa S, Perkaus J (World Resources Institute, Washington, DC), pp 175–202.
6. World Bank (2007) *World Development Indicators 2007* (The World Bank, Washington, DC).
7. Energy Information Administration (2007) *International Energy Outlook* (U.S. Department of Energy, Washington, DC).
8. UN (2006) *World Population Prospects: The 2006 Revision* (United Nations, New York, NY).
9. Shue H (1993) Subsistence emissions and luxury emissions. *Law Policy* 15:39–59.
10. Ahmad N, Wyckoff A (2003) Carbon dioxide emissions embodied in international trade of goods. *OECD Science, Technology and Industry Working Papers* 2003/15 (OECD Publishing, Paris).
11. Peters G, Hertwich E (2008) CO_2 embodied in international trade with implications for global climate policy. *Environ Sci Technol* 42:1401–1407.

Supporting Information for One Billion High Emitters: A New Approach for Sharing Global CO2 Emission Reductions

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May 7, 2009

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Contents

1 Data

Emissions and GDP (expressed in constant 2000 $ PPP) in 2003 form the basis of all subsequent analysis. 2003 is the base year of the International Energy Outlook (IEO) 2007 projections produced by the Energy Information Administration (EIA) of the U. S. The projections go till 2030. Our primary sources of data are:

GDP – current and historical:
Sources, in decreasing order of preference, for current data:

1. World Development Indicators (WDI) 2007 (*http://publications.worldbank.org/WDI*).

2. PWT6.2 (Penn World Tables), Alan Heston, Robert Summers and Bettina Aten, Penn World Table Version 6.2, Center for International Comparisons of Production, Income and Prices at the University of Pennsylvania, September 2006. We use PWT6.2 for historical GDP data. (*http://pwt.econ.upenn.edu/php_site/pwt_index.php*).

3. CIA: The World Factbook (*https://www.cia.gov/library/publications/the-world-factbook/*).

Emissions – current and historical:
EIA is our source for CO_2 emissions data from energy consumption.
(*http://www.eia.doe.gov/emeu/international/carbondioxide.html*).

Historical population data:
PWT6.2

Projections:
We use EIA's International Energy Outlook -IEO 2007 for emissions, population and GDP projections (*http://www.eia.doe.gov/oiaf/archive/ieo07/index.html*). Our analysis is based on the projections of the 'Reference Case'. The population projections used by IEO 2007 are from the United Nations Statistical Division.

Income/Consumption distribution data - current and historical:
We use income (or consumption) distribution data from the most recent survey obtained from the following sources in order of preference:

1. World Development Indicators 2007.

2. World Bank: PovcalNet – for some developing countries (*http://iresearch.worldbank.org/PovcalNet/jsp/index.jsp*).

3. World Income Inequality Database (WIID2b) from the UN University - World Institute for Development Economics Research.
   (*http://www.wider.unu.edu/research/Database/en_GB/database/*
   http://www.wider.unu.edu/research/Database/en_GB/wiid/).
   We also use WIID2b for historical distribution data for income elasticity of CO_2 emissions estimates for select countries.

See the Appendix for details of data coverage and regional definitions used by EIA in IEO 2007.

2 Methodology

We build a global distribution of individual carbon emissions by linking income distributions to national fossil fuel emissions. Three main steps are involved.

- We fit income/consumption distributions using quintiles or deciles data at the country level, for the last available year for which the survey is available in a given country.
- We rescale them to match their nation per capita GDP (in PPP) of 2003.
- Assuming income and emissions are related by a power law, we translate them into emission distributions, ensuring that the averages match the national emission inventories.

In doing so, we attribute all production-based national emissions to their individuals on the basis of their income, although not necessarily in constant proportions. That is, we assume that the emissions generated by government consumption and the investments in the economy are attributed to individuals according to their income, in the same way those deriving directly or indirectly from consumption. The scheme ignores emissions embedded in international (more precisely, inter-regional) trade. The next subsections explore the three steps in some detail.

2.1 Income/Consumption Distributions from Decile Data for Individual Countries

The distribution data from WDI is in the form of income/consumption[1] shares of the five quintiles and the top and bottom deciles. For example, in the case of Indonesia:

Cumulative Population	0	0.1	0.2	0.4	0.6	0.8	0.9	1
Cumulative Income/Consumption	0	0.036	0.084	0.20	0.36	0.57	0.71	1

The relevant data for 2003 are:

Population (millions)	214.7
GDP per capita (2000 $ PPP)	3167

[1]Note that some surveys measure consumption inequality while others measure income inequality. We do not differentiate between the two as both approaches are prevalent in different parts of the world. This is problematic as income distributions tend to have more inequality than consumption distributions. We also anchor the mean of the distribution to the GDP per capita. This has its detractors as the GDP per capita is often larger than the mean income from the surveys. We refer the interested reader to Refs. *(1)* and *(2)* for detailed discussions of issues involved. We use the normalized income distribution to obtain the CO_2 emissions distribution which is insensitive to this issue.

A plot of the cumulative income/consumption share vs. the cumulative population distribution is called the Lorenz curve (see Figure S1). We use a sum of two Gamma probability density functions (PDFs) to model the population distribution as a function of income. Our rationale for using Gamma PDFs is that it facilitates a sensitivity analysis of the simplifying assumptions in the main text. All functions of the form $x^n G(x, a, b)$ of the Gamma PDF $G(x, a, b)$ are also Gamma PDFs (for example, the income distribution is the case where $n = 1$). The population distribution can be obtained by a simple non-linear least square fit of the modeled Lorenz curve with distribution data. We also note that if CO_2 emissions elasticity with respect to (w.r.t.) income is some constant β then the population distribution can be easily converted to a function of CO_2 emissions using generalized Gamma PDFs (see Section 3).

Gamma probability density functions or PDFs ($G(x, a, b)$) and cumulative distribution functions or CDFs ($CG(x, a, b)$) are:

$$G(x,a,b) = \frac{1}{b^a \Gamma(a)} x^{a-1} e^{-\frac{x}{b}} \tag{1}$$

$$CG(x,a,b) = \int_0^x G(x,a,b)dx. \tag{2}$$

where

$$\Gamma(a) = \int_0^\infty x^{a-1} e^{-x} dx \;\; \text{and} \;\; \Gamma(a+1) = a\Gamma(a).$$

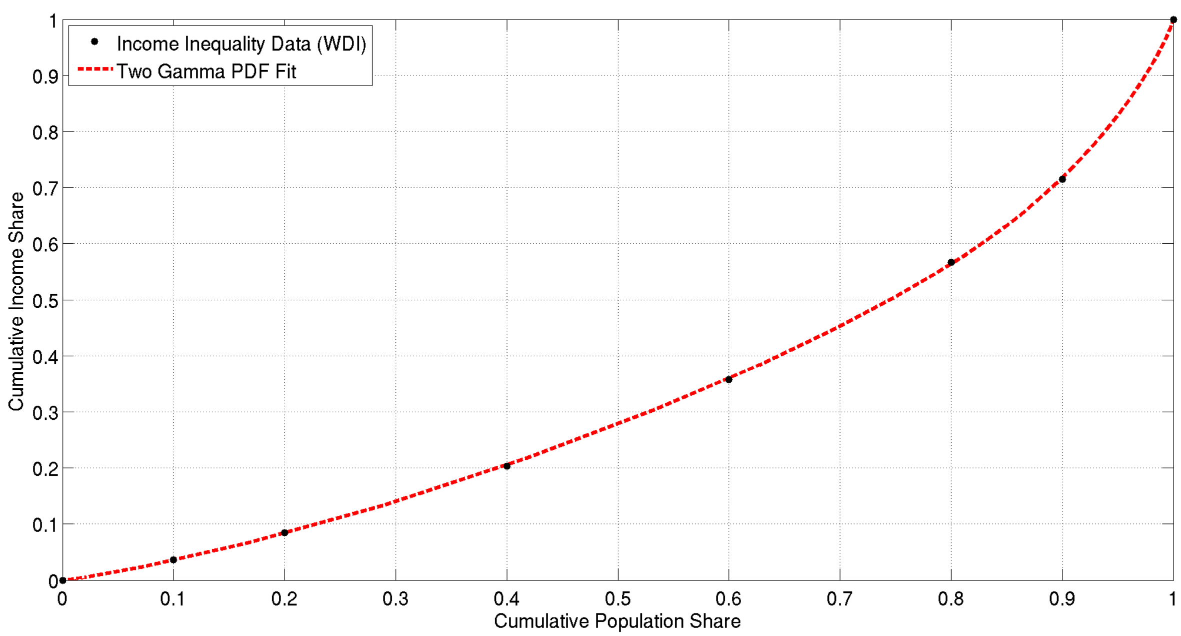

Figure S1: The WDI data and 2-Gamma Fit Lorenz curve for Indonesia.

Recall that we are dealing with probability density functions here, so the CDF should integrate to 1.

$$CG(\infty, a, b) = \int_0^\infty G(x, a, b)dx = 1 \tag{3}$$

The Gamma PDF has an interesting property under scaling of x-axis:

$$x \to z = Ix \quad \Rightarrow \quad G(x, a, b)dx \to G(z, a, bI)dz. \tag{4}$$

This property is very useful as we can fit the Gamma function to income normalized w.r.t. to GDP per capita (I) and then scale the distribution and the x axis to the real income. More importantly, the Lorenz curve is a function of a only. So we can scale b to produce income distributions that have the same inequality (or Lorenz curve) but different GDP per capita. This property is used to project income distributions into the future using projections of GDP per capita and assuming, conservatively, no change in inequality. For the CDF, we have:

$$x \to z = Ix \quad \Rightarrow \quad CG(x, a, b) = CG(z, a, bI). \tag{5}$$

Henceforth, we use x to denote income in units of GDP per capita (I) and $z = Ix$ to denote income in PPP dollars. The income share ($IG(x, a, b)$) and cumulative income share ($ICG(x, a, b)$) are (using (1) and (2)):

$$IG(x, a, b) = xG(x, a, b) = abG(x, a + 1, b), \tag{6}$$

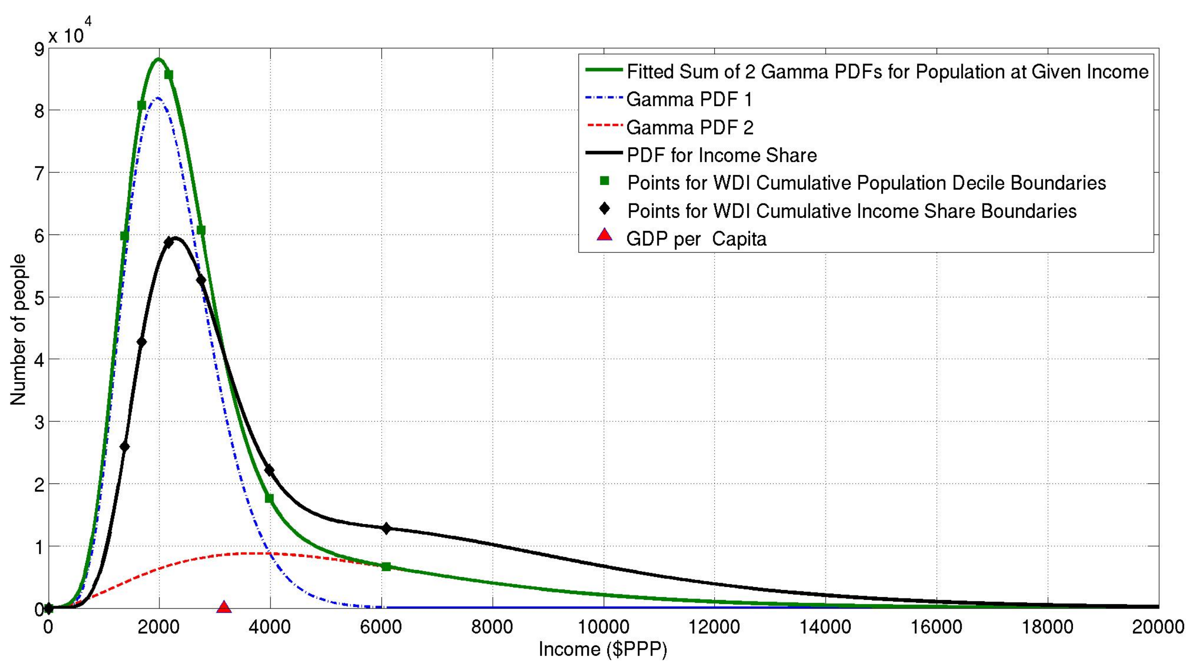

Figure S2: 2-Gamma Fit for Indonesia.

and

$$ICG(x, a, b) = \int_0^x xG(x, a, b) = abCG(x, a + 1, b). \quad (7)$$

We use the trial 2-Gamma PDF for income (normalized w.r.t. GDP per capita I):

$$r_1 G(x, a_1, b_1) + r_2 G(x, a_2, b_2).$$

The 2-Gamma fit after scaling the distribution from normalized income x to real income z using (4) , and multiplying by population N is:

$$F(z) = N[r_1 G(z, a_1, b_1 I) + r_2 G(z, a_2, b_2 I)]. \quad (8)$$

Figure S2 shows the 2-Gamma distribution that we obtain from the fit shown in Figure S1.

References

(1) Measuring Poverty in a Growing World (or Measuring Growth in a Poor World), Deaton, A., Review of Economics & Statistics 87(1) (2005), 1-19.
(2) Counting the World's Poor: Problems and Possible Solutions, Deaton, A., World Bank Research Observer 16(2) (2001), 125-147.

2.2 Emissions Elasticities from Surveys

Here we look at the elasticity of energy or emissions vs. consumption expenditure from various studies (See Table S1). These studies consider both direct energy use in households and energy embodied in goods and services consumed in households. The approach, first developed by Robert Herendeen in the 1970s, combines household income and/or consumption expenditure surveys with emissions or energy statistics and input-output table data. Household expenditure in different consumption categories are converted to emissions/ energy use using input-output data. This can be considered a 'bottom-up' approach to the question of the emissions elasticity w.r.t income or consumption expenditure. In the next subsection we consider a 'top-down' approach to the issue using income distributions and emissions data. The elasticity of energy use with expenditure is not strictly comparable with the emissions elasticity. Nonetheless, in most countries both elasticities vary from 0.7 to 1. Emissions in different countries at the same level of household consumption expenditure vary significantly. In the subsequent analysis we will primarily use an elasticity of 1 and consider other elasticities (0.7-1) for sensitivity analyzes. Most results do not vary by more than 20% so the linear elasticity assumption is used to keep the discussion intuitively simple. Note again that we use income distributions anchored to the average GDP per capita instead of the consumption measured in the household surveys.[1]

Country	Reference	Year	Elasticity of energy[a]	Elasticity of CO_2 emissions[a]
Australia	*(1)* Lenzen (1998)	1993-94	0.74	0.7
Australia	*(2)* Lenzen et al. (2006)	1998-99	0.78	
Brazil[b]	*(2)* Lenzen et al. (2006)	1995-96	1	
Denmark	*(3)* Wier et al. (2001)	1995	0.9	0.9
Denmark	*(2)* Lenzen et al. (2006)	1995	0.86	
India	*(2)* Lenzen et al. (2006)	1997-98	0.86	
Japan	*(2)* Lenzen et al. (2006)	1999	0.64	
Netherlands	*(4)* Vringer & Blok (1995)	1990	0.83	
New Zealand	*(5)* Peet et al. (1985)	1980	0.4[c]	
Norway	*(6)* Herendeen (1978)	1973	0.72	
Norway	*(7)* Peters et al. (2006)	1999-2001		0.88
Spain	*(8)* Roca & Serrano (2007)	2000		0.91-0.99[d]
U.S.	*(9)* Herendeen & Tanaka (1976)	1960-61	0.85	
U.S.	*(10)* Herendeen et al. (1981)	1972-73	0.78	
U.S.	*(11)* Weber & Matthews (2008)	2004		0.6-0.8[e]

[a]w.r.t. to consumption expenditure
[b]Survey covers 11 state capitals only.
[c]Low value due to high use of hydroelectric electricity in poor households.
[d]Range depends on assumptions used to convert from household emissions to per capita emissions.
[e]Range depends on the specific model used to fit data.

Table S1: Elasticity of per capita energy consumption and emissions vs. household expenditure

2.3 'Top-down' Estimation of the Income Elasticity of Emissions

We have attempted a 'top-down' analysis of a panel of countries using emission data from EIA, GDP and population data from PWT6.2, and income inequality data from WIID2b. First, we do a simple maximal likelihood analysis where we fit a function of the form

$$c_{it} = A_i \bar{I}_{it}^{\beta} \tag{9}$$

where c_{it} is the per capita emission of country i in year t, A_i is a country specific constant, β is a universal constant, and $\bar{I}_{it}$ is the GDP per capita in country i and year t.There are 43 time series (one for each country) with at least 5 years of data in the period 1980-2004 adding up to 410 'sets'. Each 'set' contains GDP per capita, average annual emissions, and decile income shares for a particular country in a given year. We maximize the loglikelihood function of normally distributed observations with a linearly increasing heteroskedastic standard deviation $\sigma(\bar{I}_{it})$ which is a function of the GDP per capita $\bar{I}_{it}$. $\sigma(\bar{I})$ which is a straight line is parameterized by its values at two points: $\sigma(\bar{I}=0)$ and $\sigma(\bar{I}=50000)$.

$$\ln L = -\frac{1}{2}\sum_{it}[\ln(2\pi) + \ln\sigma^2(\bar{I}_{it}) + \frac{1}{\sigma^2(\bar{I}_{it})}(c_{it} - A_i\bar{I}_{it}^{\beta})^2] \tag{10}$$

The country specific A_i can be derived by setting the derivative of $\ln L$ w.r.t A_i to 0. This substitution significantly reduces the number of variables from 46 (43 A_is, β and two parameters for σ) to 3. The reduced form loglikelihood function $\ln L(x(1), x(2), x(3)$ become a function of the three variables $x(1) = \beta$ and $\sigma(\bar{I})$ parameterized by $x(2) = \sigma(0)$ and $x(3) = \sigma(50000)$. $\ln L$ is maximized at

$$x(1)^* = \beta = 0.718,\ x(2)^* = 0.057 \text{ and } x(3)^* = 2.005$$

with $\max \ln L = -217.244$. This simple analysis is the equivalent of assuming that every country is a representative individual whose income in year t is $\bar{I}_{it}$ with an emissions to income elasticity of β. We repeat the same analysis using income distribution data at the decile level to fit a function of the form

$$c_{it} = B_i \sum_f I_{itf}^{\beta} \tag{11}$$

where I_{itf} is the mean income in fth decile (or quintile). The loglikelihood estimator is

$$\ln L' = -\frac{1}{2}\sum_{it}[\ln(2\pi) + \ln\sigma^2(\bar{I}_{it}) + \frac{1}{\sigma^2(\bar{I}_{it})}(c_{it} - B_i\sum_f I_{itf}^{\beta})^2]. \tag{12}$$

$\ln L'$ is maximized at

$$x(1)^* = \beta = 0.724,\ x(2)^* = 0.055 \text{ and } x(3)^* = 2.007$$

with $\max \ln L' = -215.452$. It is reassuring, that (12) provides a substantially better fit than (10), because this shows that the national-level data carry a substantial signal of the distribution of individual emissions. If we assumed that the two models were equally probable before the analysis (equal prior probabilities), then the data make the model behind (12) approximately six times more likely than the one behind (10) (the posterior probabilities differ by a factor of $e^{1.79}/1$).[2]

It is also reassuring that three different methods give us approximately the same estimated value of β. The most common value from bottom-up household surveys, and the estimates from the top-down methods behind (10) and (12), all are between 0.7 and 1. Nonetheless, it is possible that all of these methods undercount the emissions of the wealthy, primarily due to non-response to surveys and undercounting of indirect emissions from services, dividend income etc. For this reason, we have we performed all of the analyses in this paper for four values of β – 0.7, 0.8, 0.9 and 1.0 (see Sections 3.2 and 3.3) – and found that all of the paper's findings are quite insensitive to β. Also, the case with $\beta = 1$ is easiest to extend to other data sets and to analyze because each country's emissions distribution is then just its income distribution with a simple change of units. For all of these reasons, we present analyses in which $\beta = 1$ in the main text.

[2] 1.79 is the difference between $\max \ln L'$ and $\max \ln L$.

2.4 Emissions Distributions for Different Elasticities

The use of Gamma PDFs also makes it easy to transform the population density w.r.t. income to one w.r.t. to CO_2 emissions. The Gamma PDF is modified to a generalized Gamma PDF. Suppose the CO_2 emissions to income relationship for a given country has the functional form

$$c_\beta(z) = \frac{1}{A_\beta} z^\beta \tag{13}$$

where $c_\beta(z)$ is the annual CO_2 emissions and we assume a power law function of income z. The distribution of emissions as a function of income (using the population distribution $F(z)$, see (8)) is $c_\beta(z)F(z)$. Note that the income distribution is a special case where $\beta = A = 1$. The β moment distribution of a Gamma PDF is another Gamma PDF.

$$x^\beta G(x, a, b) = \frac{\Gamma(a+\beta)}{\Gamma(a)} b^\beta G(x, a+\beta, b). \tag{14}$$

Multiplying both sides of equation (13) with the 2-Gamma fit $F(z)$ (see (8)), and using (3) and (14), we obtain

$$NC = \int_0^\infty c_\beta(z)F(z) = \frac{1}{A_\beta} N[r_1 \frac{\Gamma(a_1+\beta)}{\Gamma(a_1)}(b_1 I)^\beta + r_2 \frac{\Gamma(a_2+\beta)}{\Gamma(a_2)}(b_2 I)^\beta], \tag{15}$$

where, C is the CO_2 emissions per capita and N is the population of the country. The above identity provides us with an explicit value for A_β. This gives us, on changing variables (and dropping the β subscript):

$$z(c) = (Ac)^\gamma \quad \text{where} \quad \gamma = 1/\beta. \tag{16}$$

Substituting z using (16) in (8) will give us the probability density function in terms of CO_2 emissions. This replaces the Gamma function with generalized Gamma functions. A generalized Gamma function $GG(y, \beta, a, \bar{b})$ is

$$GG(y, \gamma, a, \bar{b}) = \frac{\gamma}{\bar{b}^{\gamma a}\Gamma(a)} y^{\gamma a - 1} e^{-(y/\bar{b})^\gamma}. \tag{17}$$

The generalized Gamma function is related to the Gamma function (by definition) as,

$$GG(y, \gamma, a, \bar{b})dy = G(y^\gamma, a, \bar{b}^\gamma)d(y^\gamma). \tag{18}$$

The population density in terms of CO_2 emissions c is

$$\begin{aligned} F(c) &= N[r_1 GG(c, \gamma, a_1, A^{-1}(b_1 I)^\beta) + r_2 GG(c, \gamma, a_2, A^{-1}(b_2 I)^\beta)] && (19) \\ &= N\gamma c^{\gamma-1}[r_1 G(c^\gamma, a_1, A^{-\gamma} b_1 I) + r_2 G(c^\gamma, a_2, A^{-\gamma} b_2 I)], \quad \text{using} \quad \beta\gamma = 1 && (20) \end{aligned}$$

The emissions share probability distribution (emissions at a given annual emissions level) is $C(c) = cF(c)$. The kth moment function (k integer) of a generalized Gamma function is

$$y^k GG(y, \gamma, a, \bar{b}) = \bar{b}^{k/\gamma} \frac{\Gamma(a+k/\gamma)}{\Gamma(a)} GG(y, \gamma, a+k/\gamma, \bar{b}) \tag{21}$$

Using $k = 1$ and (20)

$$C(c) = N\gamma c^{\gamma-1}[s_1 G(c^\gamma, a_1 + 1/\gamma, A^{-\gamma} b_1 I) + s_2 G(c^\gamma, a_2 + 1/\gamma, A^{-\gamma} b_2 I)], \tag{22}$$

where

$$s_i = r_i A^{-1} (b_i I)^\beta \frac{\Gamma(a_i + 1/\gamma)}{\Gamma(a_i)}.$$

We now have all that we need to fit distributions with different elasticities (see Figure S3). Projections that conserve inequality (defined as keeping the Lorenz curve invariant) are easy. Note that changing the b (or $\bar{b}$) parameter in the Gamma (or generalized Gamma) functions does change the Lorenz curve. Projections into the future involve changing GDP per capita I or per capita emissions C to which the Gamma or generalized Gamma functions are anchored and these affect b (or $\bar{b}$) only.

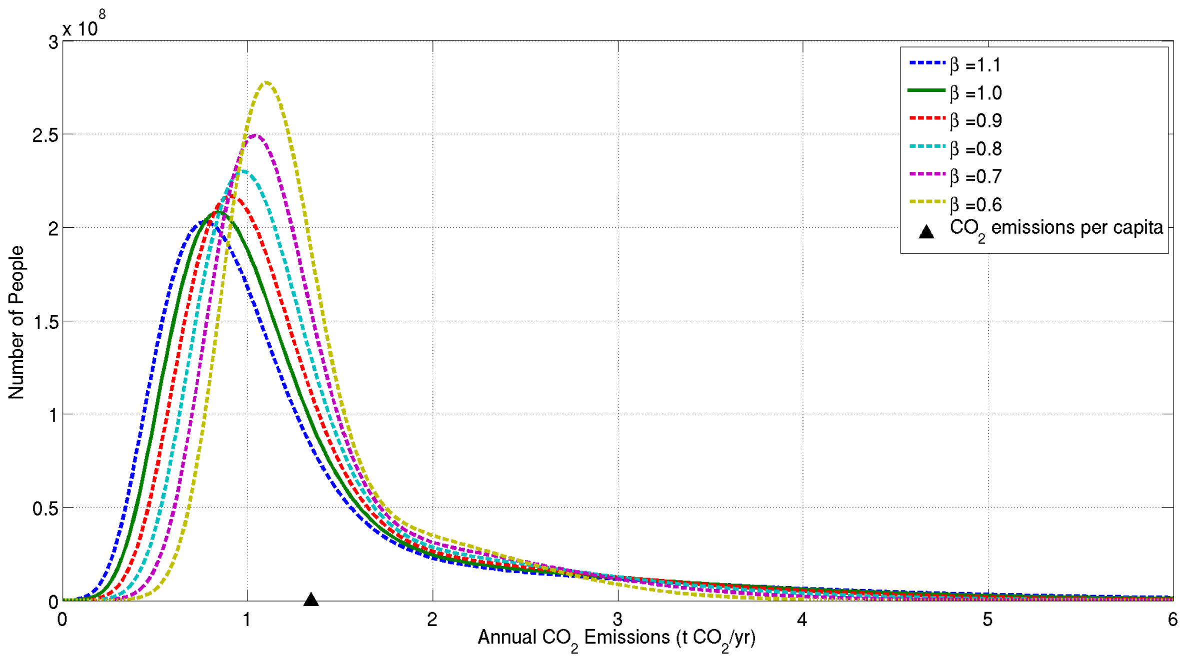

Figure S3: Distribution of emitters vs. annual CO_2 emissions in Indonesia in 2003 for different β's. Note that the curves become more peaked around the emissions per capita as β decreases. In the limiting case of $\beta = 0$, emissions would be independent of income, so every person would emit the same as the average emissions per capita. The area under the curves is the total population of Indonesia in 2003: 214.7 million.

References

(1) The energy and greenhouse gas cost of living for Australia during 1993-94. Lenzen M.

Energy 23 (2006), 497-516.
(2) A comparative multivariate analysis of household energy requirements in Australia, Brazil, Denmark, India and Japan. Lenzel et al., Energy 31 (2006), 181-207.
(3) Environmental effects of household consumption pattern and lifestyle. Wier M. et al., Econ Syst Res 13 (2001), 259-274.
(4) The direct and indirect energy requirements of households in the Netherlands. Vringer K. and Blok K., Energy Policy 23 (1995), 893-910.
(5) Energy in the New Zealand household, 1974-1980. Peet N. J. et al., Energy 10 (1985), 1197-1208.
(6) Total energy cost of household consumption in Norway, 1973. Herendeen R., Energy 3 (1978), 615-630.
(7) Environmental impacts and household characteristics, an econometric analysis of Norway 1999-2001. Peters, G.P. et al, In: Tukker, A. (Ed.), Sustainable Consumption Research Exchange (SCORE!) Launch Conference. Wuppertal, DE, pp. 292-307
(8)Income growth and atmospheric pollution in Spain: An inputoutput approach. Jordi Roca and Mnica Serrano, Ecological Economics 63 (2007), 230-242.
(9) Energy cost of living. Herendeen R, Tanaka J., Energy 1 (1976), 165-178.
(10) Energy cost of living, 1972-1973. Herendeen R et al., Energy 6 (1981), 1433-1450.
(11) Quantifying the global and distributional aspects of American household carbon footprint. Weber C. L. and Matthews H. S., Ecological Economics 66 (2008), 379-391.

3 Projecting Emission Distributions and Caps

This Section explores how we calculate individual caps in the future. It reports first on the projection procedure and then on the way global caps are computed. The importance of the relation between expenditures and emissions is evaluated via sensitivity analysis. Tables at the regional level for 2020 and 2030 for several global emission constraints are provided in Section 3.1 and a few comparisons are made to regional targets currently under discussion.

To obtain a picture of the future, we first need forecasts of regional population and emissions. We use the EIA International Energy Outlook (IEO), as it is a widely used and freely available source of projections. However, the methodology can be straightforwardly replicated using alternative projections, with different regional disaggregation and temporal horizon. Results in this paper are based on IEO 2007.[3] We estimate the country level emissions distributions for 2003 (see Section 2.1) using the most recent income distributions available (as of 2003). We make two main assumptions for emissions projection: 1) no change in income inequality at the country level and 2) a single constant global elasticity of emissions to consumption.[4] Both

[3]While we were finalizing this paper the IEO 2008 was released. Figures at the global scale show little variations with respect to the 2007 version. However, a redistribution mainly from the US to China is foreseen. This reflects recent upwards trends in Chinese emissions and a lower economic growth rate for the US.

[4]We use a constant global elasticity of $\beta = 1.0$ in Section 3.1.

assumptions are crude approximations of reality. Wealth distribution has changed in the past 30 years, especially in countries that have experienced profound economic transformations. However, within-country inequality projections are not available, to our knowledge. Accordingly, we adopt the 'future equals past' rule of thumb. As for emissions/expenditure elasticities, values vary across countries as shown in Table S1, but very few estimates exist for developing countries. In Sections 3.2 and 3.3 we will perform some sensitivity analysis where this elasticity is a parameter.

3.1 Universal Caps

We begin by summing over the country-level emissions distributions (developed in Section 2.2) to obtain regional distributions corresponding to the 16 regions used in EIA's projections (see Appendix A for region definitions). Using EIA's regional emissions growth rates, we project these regional distributions forward in time to obtain a global distribution of emissions. We can then easily compute a maximum individual cap above which all emissions are eliminated. The universal emissions cap for a global emission reduction target is obtained from the Lorenz plot of cumulative BAU emissions vs. cumulative population by finding the tangent to the curve that is consistent with the envisioned target. The linearity of the tangent ensures constant individual emissions, at the rate given by its slope. Figure 4 illustrates the general method for the case explored in the main text, where the date is 2030 and we assume an elasticity of 1.0. Keeping world emissions below the target requires that each of 1.13 Billion people is assigned a 10.8 tCO_2 cap.

The corresponding cap for the '30P' scenario where we provide for an emissions floor of 1 tCO_2 per capita are obtained similarly. The extra emissions required to be set aside for the 1 tCO_2 floor is subtracted from the 30 $GtCO_2$ global target to calculate the new individual emissions cap. From any universal cap, we obtain regional allocations (both the number of people under the regional cap and the required regional emissions reduction) by finding the vertical intercept on the regional Lorenz plot of a line with the slope of the universal cap slope (the same procedure as shown in Figure S4).

In Table S2 we compare the regional target in 2030 for the two schemes proposed in this paper, and the 'equal per capita' approach. In the ' equal per capita' scheme, allocations are based on global emissions divided equally among the 8.1 billion global citizens. This expands on Figure 7 in the paper. In Tables S3-S10, we report projected emissions targets at the regional level for global targets in 2020 and 2030. In 2020 the global targets are 20 $GtCO_2$, 25 $GtCO_2$, 30 $GtCO_2$ and 33 $GtCO_2$. In 2030 the global targets are the global targets are 20 $GtCO_2$, 25 $GtCO_2$, 30 $GtCO_2$ and 35 $GtCO_2$; 30 $GtCO_2$ is the target explored in the main text. All Tables assume an emissions elasticity of 1.0 w.r.t. income. The Tables show results with and without a floor for low-emitters. Inasmuch as the task of creating and raising a floor is likely to be a multi-decade task, we assume a floor for all the worlds individuals of 0.5 tCO_2 for 2020 and 1.0 tCO_2 for 2030.

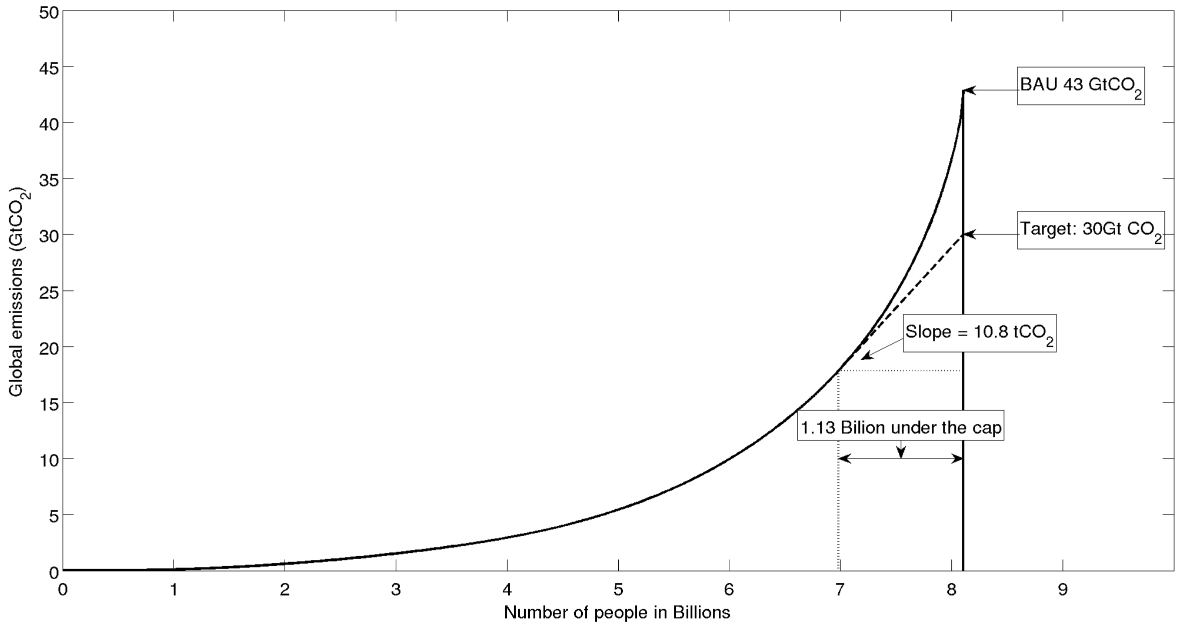

Figure S4: Cumulative emissions vs. cumulative population for 2030. The BAU emissions are 43 $GtCO_2$ and an individual emissions cap of 10.8 tCO_2 (the slope of the tangent) is needed to meet a global emissions target of 30 $GtCO_2$ (the '30' scenario).

We can compare specific results in these Tables to two recently proposed climate policies. The European Commission has proposed a regional target of 3.3 $GtCO_2$ for 2020, a 20% emission reduction with respect to 1990s levels.[5] Associating the European Commission territory with the OECD-Europe region, our Tables reveal that this goal is roughly consistent with the '25P' scenario in 2020. The Lieberman-Warner Security Act envisions long-term emissions reductions for the U.S. that, according to EIA estimates, correspond to 5.5 $GtCO_2$ and 4 $GtCO_2$ targets, 10% above and 20% below 1990 levels, for 2020 and 2030 respectively.[6] These U.S. goals correspond to the demands of a global cap between '30P' and '35P' in the decade 2020-2030. Europe's proposed commitment corresponds to a tighter global target in our allocation scheme than the U.S. commitment does. This is due to the fact that 1) Europe's commitment is an intrinsically tighter regional target compared to the U.S. and 2) our allocation scheme projects more stringent cuts in emissions from the U.S. than Europe as the U.S. has higher average emissions and a higher number of high emitters.

[5] See http://ec.europa.eu/energy/climate_actions/index_en.htm

[6] See http://www.eia.doe.gov/oiaf/servicerpt/s2191/pdf/tbl3.pdf

Region	Emissions [1990]	Em. [2003]	Em. (BAU) [2030]	Population [2030]	Em. (20) [2020]	Em. (20P) [2030]	Em. (20E) [2030]	Em. (25) [2030]	Em. (25P) [2030]	Em. (25E) [2030]	Em. (30) [2030]	Em. (30P) [2030]	Em. (30E) [2030]	Em. (35) [2030]	Em. (35P) [2030]	Em. (35E) [2030]
U.S.	5	5.8	8	364.7	1.7	1.5	0.9	2.5	2.3	1.1	3.6	3.2	1.4	4.9	4.5	1.6
Canada	0.5	0.6	0.7	38.6	0.2	0.2	0.1	0.3	0.2	0.1	0.4	0.3	0.14	0.5	0.5	0.2
Mexico	0.3	0.4	0.7	129.2	0.4	0.4	0.3	0.5	0.5	0.4	0.6	0.5	0.5	0.6	0.6	0.6
OECD Europe	4.1	4.3	4.7	560.6	2.4	2.1	1.4	3.1	2.9	1.7	3.8	3.6	2.1	4.3	4.2	2.4
Japan	1	1.2	1.3	122.8	0.6	0.5	0.3	0.9	0.8	0.4	1.1	1	0.5	1.2	1.2	0.5
South Korea	0.2	0.5	0.7	49.9	0.2	0.2	0.1	0.3	0.3	0.2	0.5	0.4	0.2	0.6	0.6	0.2
Australia and New Zealand	0.3	0.4	0.6	29.9	0.1	0.1	0.1	0.2	0.2	0.1	0.3	0.3	0.1	0.4	0.4	0.1
OECD minus U.S.	6.4	7.4	8.7	930.8	4	3.6	2.3	5.3	4.9	2.9	6.6	6.2	3.4	7.7	7.4	4.0
Total OECD	11.4	13.3	16.7	1295.6	5.7	5.1	3.2	7.8	7.2	4.0	10.2	9.5	4.8	12.6	11.9	5.6
China	2.2	4	11.4	1442.1	5.6	5.2	3.6	7.2	6.7	4.5	8.5	8.2	5.3	9.8	9.5	6.2
Russia	2.3	1.6	2.2	124.7	0.6	0.5	0.3	0.9	0.8	0.4	1.2	1.1	0.5	1.5	1.4	0.5
Transition Economies	1.9	1.1	1.6	189.7	0.8	0.7	0.4	1	1	0.6	1.3	1.2	0.7	1.5	1.4	0.8
India	0.6	1.1	2.2	1441.6	2.1	2.2	3.6	2.2	2.3	4.5	2.2	2.3	5.3	2.2	2.3	6.2
Other Non-OECD Asia	0.8	1.4	2.8	1307.8	1.8	2.1	3.2	2	2.3	4.0	2.2	2.5	4.8	2.4	2.7	5.6
Middle East	0.7	1.2	2.3	282.3	1	0.9	0.7	1.2	1.1	0.9	1.4	1.4	1.0	1.7	1.6	1.2
Africa	0.6	1	1.8	1438.2	1.2	2	3.6	1.3	2.1	4.4	1.4	2.2	5.3	1.6	2.3	6.2
Brazil	0.2	0.3	0.6	236.6	0.4	0.5	0.6	0.5	0.5	0.7	0.6	0.6	0.9	0.6	0.6	1.0
Other South and Central America	0.5	0.6	1.2	349.2	0.8	0.8	0.9	0.9	0.9	1.1	1	1	1.3	1.1	1.1	1.5
Non-OECD minus China	7.6	8.3	14.8	5370.1	8.7	9.7	13.3	10	11.1	16.6	11.3	12.4	19.9	12.5	13.6	23.2
Total Non-OECD	9.8	12.2	26.2	6812.1	14.3	14.9	16.8	17.2	17.8	21.0	19.8	20.5	25.2	22.4	23.1	29.4
Total World	21.2	25.5	42.9	8107.7	20	20	20	25	25	25	30	30	30	35	35	35

Table S2: Comparison of regional emissions for different global targets (20, 25, 30, 35) and allocation schemes. For example, ’25’ and ’25P’ refer to the schemes proposed in this paper whereas ’25E’ is an allocation based on the ’equal per capita’ approach.

Region	Emissions [1990]	Emissions [2003]	Population [2003]	Emissions (BAU) [2020]	Population [2020]	Emissions (20) [2020]	Emissions (20P) [2020]	Population under cap (20) [2020]	Population under cap (20P) [2020]	(20P) change w.r.t. [1990]	(20P) change w.r.t. [2003]	(20P) change w.r.t. (BAU)
U.S.	5.0	5.8	290.8	7.0	336.8	1.9	1.8	303.9	306.3	-63.4%	-68.6%	-73.8%
Canada	0.5	0.6	31.6	0.7	35.6	0.2	0.2	33.6	33.8	-58.6%	-66.3%	-71.4%
Mexico	0.3	0.4	101.0	0.6	121.4	0.4	0.4	25.6	27.1	32.5%	4.3%	-32.1%
OECD Europe	4.1	4.3	528.6	4.6	553.6	2.7	2.6	324.8	335.3	-36.7%	-40.3%	-43.6%
Japan	1.0	1.2	127.7	1.3	126.7	0.7	0.7	112.2	114.6	-31.3%	-44.2%	-46.3%
South Korea	0.2	0.5	47.9	0.6	49.9	0.3	0.3	42.9	43.5	13.1%	-42.9%	-55.8%
Australia and New Zealand	0.3	0.4	23.9	0.5	27.9	0.2	0.2	24.6	24.9	-48.3%	-63.6%	-71.1%
OECD minus U.S.	6.4	7.4	860.7	8.3	915.1	4.4	4.3	563.7	579.1	-32.9%	-42.1%	-48.2%
Total OECD	11.4	13.3	1151.5	15.3	1251.8	6.3	6.1	867.6	885.4	-46.2%	-53.8%	-59.8%
China	2.2	4.0	1295.5	8.9	1420.1	5.6	5.5	496.2	519.5	146.1%	39.3%	-38.3%
Russia	2.3	1.6	144.6	2.0	132.6	0.7	0.7	112.4	114.1	-69.5%	-55.5%	-64.7%
Transition Economies	1.9	1.1	194.6	1.5	193.6	0.9	0.9	100.9	104.7	-53.5%	-20.3%	-41.8%
India	0.6	1.1	1064.6	1.7	1325.2	1.7	1.7	13.7	16.3	200.4%	64.3%	-0.6%
Other NON-OECD Asia	0.8	1.4	926.6	2.3	1177.4	1.6	1.7	70.1	72.9	108.2%	23.2%	-26.9%
Middle East	0.7	1.2	175.4	2.0	243.8	0.9	0.9	90.6	93.6	27.1%	-26.8%	-55.1%
Africa	0.6	1.0	854.4	1.6	1207.2	1.1	1.3	48.1	50.7	107.0%	37.4%	-13.6%
Brazil	0.2	0.3	181.4	0.5	219.5	0.4	0.4	20.0	20.8	85.9%	28.2%	-18.8%
Other South and Central America	0.5	0.6	256.5	1.0	318.7	0.7	0.7	45.2	47.5	57.8%	10.7%	-30.8%
Non-OECD minus China	7.6	8.3	3798.1	12.6	4818.2	8.1	8.4	501.1	520.7	9.9%	1.0%	-33.9%
Total Non-OECD	9.8	12.2	5093.6	21.6	6238.3	13.7	13.9	997.3	1040.2	40.9%	13.4%	-35.7%
Total World	21.2	25.5	6245.1	36.8	7490.1	20.0	20.0	1865.0	1925.6	-5.9%	-21.5%	-45.7%

Table S3: 2020: Global emissions target of 20 $GtCO_2$ with individual emissions caps of 5.8 tCO_2 and 5.6 tCO_2 for the '20' and '20P' scenarios. The '20P' scenario has a poverty floor of 0.5 tCO_2. The three rightmost columns show the '20P' emissions change w.r.t. emissions in 1990, 2003 and under BAU.

Region	Emissions [1990]	Emissions [2003]	Population [2003]	Emissions (BAU) [2020]	Population [2020]	Emissions (25) [2020]	Emissions (25P) [2020]	Population under cap (25) [2020]	Population under cap (25P) [2020]	(25P) change w.r.t. [1990]	(25P) change w.r.t. [2003]	(25P) change w.r.t. (BAU)
U.S.	5.0	5.8	290.8	7.0	336.8	2.8	2.8	261.0	265.7	-44.7%	-52.6%	-60.4%
Canada	0.5	0.6	31.6	0.7	35.6	0.3	0.3	29.5	30.0	-36.7%	-48.5%	-56.3%
Mexico	0.3	0.4	101.0	0.6	121.4	0.5	0.5	14.3	14.9	53.7%	21.1%	-21.3%
OECD Europe	4.1	4.3	528.6	4.6	553.6	3.5	3.4	182.8	194.6	-15.9%	-20.7%	-25.2%
Japan	1.0	1.2	127.7	1.3	126.7	1.0	1.0	59.3	64.3	-2.2%	-20.6%	-23.6%
South Korea	0.2	0.5	47.9	0.6	49.9	0.4	0.4	31.2	32.4	65.3%	-16.6%	-35.4%
Australia and New Zealand	0.3	0.4	23.9	0.5	27.9	0.2	0.2	20.8	21.2	-22.6%	-45.5%	-56.7%
OECD minus U.S.	6.4	7.4	860.7	8.3	915.1	5.9	5.8	337.8	357.4	-9.3%	-21.8%	-30.0%
Total OECD	11.4	13.3	1151.5	15.3	1251.8	8.8	8.6	598.9	623.1	-24.8%	-35.3%	-43.9%
China	2.2	4.0	1295.5	8.9	1420.1	6.9	6.8	269.1	283.7	201.7%	70.8%	-24.3%
Russia	2.3	1.6	144.6	2.0	132.6	1.1	1.0	83.3	86.2	-55.5%	-35.2%	-48.6%
Transition Economies	1.9	1.1	194.6	1.5	193.6	1.1	1.1	53.6	57.2	-39.7%	3.3%	-24.5%
India	0.6	1.1	1064.6	1.7	1325.2	1.7	1.8	0.8	1.0	203.6%	66.1%	0.4%
Other Non-OECD Asia	0.8	1.4	926.6	2.3	1177.4	1.8	1.9	45.3	47.0	131.5%	37.0%	-18.8%
Middle East	0.7	1.2	175.4	2.0	243.8	1.2	1.1	57.6	60.1	61.7%	-6.9%	-42.9%
Africa	0.6	1.0	854.4	1.6	1207.2	1.2	1.5	24.5	25.9	125.1%	49.4%	-6.0%
Brazil	0.2	0.3	181.4	0.5	219.5	0.5	0.5	10.5	11.2	108.9%	44.0%	-8.7%
Other South and Central America	0.5	0.6	256.5	1.0	318.7	0.8	0.8	23.4	24.8	82.5%	28.0%	-20.0%
Non-OECD minus China	7.6	8.3	3798.1	12.6	4818.2	9.4	9.7	299.0	313.4	27.1%	16.9%	-23.5%
Total Non-OECD	9.8	12.2	5093.6	21.6	6238.3	16.2	16.4	568.1	597.1	66.9%	34.3%	-23.8%
Total World	21.2	25.5	6245.1	36.8	7490.1	25.0	25.0	1166.9	1220.2	17.7%	-1.9%	-32.1%

Table S4: 2020: Global emissions target of 25 $GtCO_2$ with individual emissions caps of 9.2 tCO_2 and 8.8 tCO_2 for the '25' and '25P' scenarios. The '25P' scenario has a poverty floor of 0.5 tCO_2. The three rightmost columns show the '25P' emissions change w.r.t. emissions in 1990, 2003 and under BAU.

Region	Emissions [1990]	Emissions [2003]	Population [2003]	Emissions (BAU) [2020]	Population [2020]	Emissions (30) [2020]	Emissions (30P) [2020]	Population under cap (30) [2020]	Population under cap (30P) [2020]	(30P) change w.r.t. [1990]	(30P) change w.r.t. [2003]	(30P) change w.r.t. (BAU)
U.S.	5.0	5.8	290.8	7.0	336.8	4.2	4.1	179.3	187.9	-18.8%	-30.3%	-41.8%
Canada	0.5	0.6	31.6	0.7	35.6	0.5	0.4	19.9	21.0	-5.8%	-23.4%	-34.9%
Mexico	0.3	0.4	101.0	0.6	121.4	0.5	0.5	7.4	8.0	74.7%	37.6%	-10.5%
OECD Europe	4.1	4.3	528.6	4.6	553.6	4.2	4.1	57.5	65.4	0.7%	-5.1%	-10.4%
Japan	1.0	1.2	127.7	1.3	126.7	1.2	1.2	17.1	19.3	18.0%	-4.1%	-7.8%
South Korea	0.2	0.5	47.9	0.6	49.9	0.5	0.5	12.7	14.2	119.8%	11.0%	-14.2%
Australia and New Zealand	0.3	0.4	23.9	0.5	27.9	0.3	0.3	14.2	14.8	12.6%	-20.8%	-37.1%
OECD minus U.S.	6.4	7.4	860.7	8.3	915.1	7.2	7.1	128.8	142.7	11.4%	-4.0%	-14.0%
Total OECD	11.4	13.3	1151.5	15.3	1251.8	11.4	11.2	308.2	330.7	-1.8%	-15.6%	-26.7%
China	2.2	4.0	1295.5	8.9	1420.1	8.0	7.9	121.0	131.7	251.4%	99.0%	-11.8%
Russia	2.3	1.6	144.6	2.0	132.6	1.4	1.4	43.4	46.6	-39.7%	-12.2%	-30.3%
Transition Economies	1.9	1.1	194.6	1.5	193.6	1.3	1.3	19.1	21.2	-28.8%	22.1%	-10.8%
India	0.6	1.1	1064.6	1.7	1325.2	1.7	1.8	0.0	0.0	203.8%	66.2%	0.5%
Other Non-OECD Asia	0.8	1.4	926.6	2.3	1177.4	2.0	2.1	24.6	26.3	156.7%	51.9%	-9.9%
Middle East	0.7	1.2	175.4	2.0	243.8	1.4	1.4	30.7	32.6	97.7%	13.8%	-30.2%
Africa	0.6	1.0	854.4	1.6	1207.2	1.3	1.6	13.5	14.1	141.5%	60.3%	0.8%
Brazil	0.2	0.3	181.4	0.5	219.5	0.5	0.5	2.9	3.4	126.0%	55.8%	-1.2%
Other South and Central America	0.5	0.6	256.5	1.0	318.7	0.9	0.9	9.8	10.7	103.2%	42.5%	-10.9%
Non-OECD minus China	7.6	8.3	3798.1	12.6	4818.2	10.6	10.9	143.9	154.9	43.8%	32.2%	-13.5%
Total Non-OECD	9.8	12.2	5093.6	21.6	6238.3	18.6	18.8	264.9	286.6	91.1%	53.8%	-12.8%
Total World	21.2	25.5	6245.1	36.8	7490.1	30.0	30.0	573.1	617.3	41.2%	17.7%	-18.5%

Table S5: 2020: Global emissions target of 30 $GtCO_2$ with individual emissions caps of 15.2 tCO_2 and 14.6 tCO_2 for the '30' and '30P' scenarios. The '30P' scenario has a poverty floor of 0.5 tCO_2. The three rightmost columns show the '30P' emissions change w.r.t. emissions in 1990, 2003 and under BAU.

Region	Emissions [1990]	Emissions [2003]	Population [2003]	Emissions (BAU) [2020]	Population [2020]	Emissions (33) [2020]	Emissions (33P) [2020]	Population under cap (33) [2020]	Population under cap (33P) [2020]	(33P) change w.r.t. [1990]	(33P) change w.r.t. [2003]	(33P) change w.r.t. (BAU)
U.S.	5.0	5.8	290.8	7.0	336.8	5.2	5.1	102.8	114.5	1.6%	-12.9%	-27.2%
Canada	0.5	0.6	31.6	0.7	35.6	0.6	0.6	10.0	11.5	17.2%	-4.6%	-19.0%
Mexico	0.3	0.4	101.0	0.6	121.4	0.6	0.6	2.9	3.5	87.2%	47.4%	-4.1%
OECD Europe	4.1	4.3	528.6	4.6	553.6	4.4	4.4	16.8	20.5	7.0%	0.9%	-4.8%
Japan	1.0	1.2	127.7	1.3	126.7	1.3	1.3	4.2	5.6	25.5%	2.0%	-1.9%
South Korea	0.2	0.5	47.9	0.6	49.9	0.6	0.6	2.9	3.9	143.2%	22.8%	-5.0%
Australia and New Zealand	0.3	0.4	23.9	0.5	27.9	0.4	0.4	8.1	9.0	40.1%	-1.4%	-21.7%
OECD minus U.S.	6.4	7.4	860.7	8.3	915.1	7.8	7.8	44.8	54.0	21.0%	4.3%	-6.6%
Total OECD	11.4	13.3	1151.5	15.3	1251.8	13.0	12.8	147.6	168.6	12.5%	-3.3%	-16.0%
China	2.2	4.0	1295.5	8.9	1420.1	8.6	8.5	47.0	56.3	278.5%	114.3%	-5.0%
Russia	2.3	1.6	144.6	2.0	132.6	1.7	1.6	22.5	25.0	-29.7%	2.3%	-18.8%
Transition Economies	1.9	1.1	194.6	1.5	193.6	1.4	1.4	6.7	8.1	-23.8%	30.5%	-4.7%
India	0.6	1.1	1064.6	1.7	1325.2	1.7	1.8	0.0	0.0	203.8%	66.2%	0.5%
Other Non-OECD Asia	0.8	1.4	926.6	2.3	1177.4	2.1	2.2	11.4	13.2	172.7%	61.4%	-4.3%
Middle East	0.7	1.2	175.4	2.0	243.8	1.6	1.6	17.0	18.7	121.6%	27.6%	-21.8%
Africa	0.6	1.0	854.4	1.6	1207.2	1.4	1.6	8.8	9.5	153.6%	68.4%	5.9%
Brazil	0.2	0.3	181.4	0.5	219.5	0.5	0.5	0.5	0.7	131.3%	59.5%	1.1%
Other South and Central America	0.5	0.6	256.5	1.0	318.7	1.0	1.0	4.3	4.9	114.2%	50.3%	-6.1%
Non-OECD minus China	7.6	8.3	3798.1	12.6	4818.2	11.4	11.7	71.3	80.1	53.8%	41.4%	-7.4%
Total Non-OECD	9.8	12.2	5093.6	21.6	6238.3	20.0	20.2	118.2	136.4	105.0%	65.0%	-6.4%
Total World	21.2	25.5	6245.1	36.8	7490.1	33.0	33.0	265.8	305.0	55.3%	29.5%	-10.4%

Table S6: 2020: Global emissions target of 33 $GtCO_2$ with individual emissions caps of 22.8 tCO_2 and 21.4 tCO_2 for the '33' and '33P' scenarios. The '33P' scenario has a poverty floor of 0.5 tCO_2. The three rightmost columns show the '33P' emissions change w.r.t. emissions in 1990, 2003 and under BAU.

Region	Emissions [1990]	Emissions [2003]	Population [2003]	Emissions (BAU) [2030]	Population [2030]	Emissions (20) [2030]	Emissions (20P) [2030]	Population under cap (20) [2030]	Population under cap (20P) [2030]	(20P) change w.r.t. [1990]	(20P) change w.r.t. [2003]	(20P) change w.r.t. (BAU)
U.S.	5.0	5.8	290.8	8.0	364.7	1.7	1.5	342.5	347.7	-69.2%	-73.6%	-80.7%
Canada	0.5	0.6	31.6	0.7	38.6	0.2	0.2	37.2	37.6	-65.4%	-71.9%	-77.9%
Mexico	0.3	0.4	101.0	0.7	129.2	0.4	0.4	41.1	48.9	33.1%	4.9%	-42.2%
OECD Europe	4.1	4.3	528.6	4.7	560.6	2.4	2.1	378.8	407.9	-47.6%	-50.6%	-54.4%
Japan	1.0	1.2	127.7	1.3	122.8	0.6	0.5	118.3	120.6	-48.4%	-58.1%	-60.1%
South Korea	0.2	0.5	47.9	0.7	49.9	0.2	0.2	46.7	47.7	-11.3%	-55.3%	-69.2%
Australia and New Zealand	0.3	0.4	23.9	0.6	29.9	0.1	0.1	27.6	28.1	-56.9%	-69.7%	-78.3%
OECD minus U.S.	6.4	7.4	860.7	8.7	930.8	4.0	3.6	649.6	690.9	-44.4%	-52.0%	-59.1%
Total OECD	11.4	13.3	1151.5	16.7	1295.6	5.7	5.1	992.1	1038.6	-55.2%	-61.5%	-69.4%
China	2.2	4.0	1295.5	11.4	1442.1	5.6	5.2	779.3	866.9	131.2%	30.9%	-54.6%
Russia	2.3	1.6	144.6	2.2	124.7	0.6	0.5	116.0	118.5	-77.4%	-67.1%	-75.9%
Transition Economies	1.9	1.1	194.6	1.6	189.7	0.8	0.7	126.8	136.6	-61.5%	-34.0%	-56.5%
India	0.6	1.1	1064.6	2.2	1441.6	2.1	2.2	50.1	71.5	285.1%	110.6%	1.6%
Other Non-OECD Asia	0.8	1.4	926.6	2.8	1307.8	1.8	2.1	103.7	120.5	162.9%	55.6%	-23.6%
Middle East	0.7	1.2	175.4	2.3	282.3	1.0	0.9	122.5	135.2	27.0%	-26.9%	-61.6%
Africa	0.6	1.0	854.4	1.8	1438.2	1.2	2.0	70.5	82.7	206.0%	103.2%	9.9%
Brazil	0.2	0.3	181.4	0.6	236.6	0.4	0.5	29.0	33.2	111.6%	45.9%	-22.6%
Other South and Central America	0.5	0.6	256.5	1.2	349.2	0.8	0.8	67.8	78.2	71.9%	20.6%	-36.2%
Non-OECD minus China	7.6	8.3	3798.1	14.8	5370.1	8.7	9.7	686.3	776.4	27.8%	17.4%	-34.2%
Total Non-OECD	9.8	12.2	5093.6	26.2	6812.1	14.3	14.9	1465.7	1643.3	51.3%	21.8%	-43.1%
Total World	21.2	25.5	6245.1	42.9	8107.7	20.0	20.0	2457.8	2681.9	-5.9%	-21.5%	-53.3%

Table S7: 2030: Global emissions target of 20 $GtCO_2$ with individual emissions caps of 4.9 tCO_2 and 4.3 tCO_2 for the '20' and '20P' scenarios. The '20P' scenario has a poverty floor of 1.0 tCO_2. The three rightmost columns show the '20P' emissions change w.r.t. emissions in 1990, 2003 and under BAU.

Region	Emissions [1990]	Emissions [2003]	Population [2003]	Emissions (BAU) [2030]	Population [2030]	Emissions (25) [2030]	Emissions (25P) [2030]	Population under cap (25) [2030]	Population under cap (25P) [2030]	(25P) change w.r.t. [1990]	(25P) change w.r.t. [2003]	(25P) change w.r.t. (BAU)
U.S.	5.0	5.8	290.8	8.0	364.7	2.5	2.3	315.6	325.4	-54.5%	-60.9%	-71.5%
Canada	0.5	0.6	31.6	0.7	38.6	0.3	0.2	34.7	35.7	-48.6%	-58.2%	-67.1%
Mexico	0.3	0.4	101.0	0.7	129.2	0.5	0.5	23.0	27.2	59.6%	25.7%	-30.8%
OECD Europe	4.1	4.3	528.6	4.7	560.6	3.1	2.9	263.5	300.3	-28.8%	-32.8%	-38.1%
Japan	1.0	1.2	127.7	1.3	122.8	0.9	0.8	92.4	103.8	-23.9%	-38.2%	-41.1%
South Korea	0.2	0.5	47.9	0.7	49.9	0.3	0.3	40.9	43.1	30.4%	-34.2%	-54.8%
Australia and New Zealand	0.3	0.4	23.9	0.6	29.9	0.2	0.2	25.0	25.9	-36.6%	-55.4%	-68.1%
OECD minus U.S.	6.4	7.4	860.7	8.7	930.8	5.3	4.9	479.4	535.9	-23.5%	-34.1%	-43.7%
Total OECD	11.4	13.3	1151.5	16.7	1295.6	7.8	7.2	795.0	861.3	-37.1%	-45.9%	-57.0%
China	2.2	4.0	1295.5	11.4	1442.1	7.2	6.7	507.2	583.3	200.7%	70.3%	-40.9%
Russia	2.3	1.6	144.6	2.2	124.7	0.9	0.8	101.8	107.1	-66.9%	-51.7%	-64.6%
Transition Economies	1.9	1.1	194.6	1.6	189.7	1.0	1.0	88.5	100.5	-47.6%	-10.3%	-40.9%
India	0.6	1.1	1064.6	2.2	1441.6	2.2	2.3	10.0	17.5	299.8%	118.7%	5.5%
Other Non-OECD Asia	0.8	1.4	926.6	2.8	1307.8	2.0	2.3	67.8	76.1	188.4%	70.7%	-16.2%
Middle East	0.7	1.2	175.4	2.3	282.3	1.2	1.1	85.9	96.0	62.2%	-6.6%	-51.0%
Africa	0.6	1.0	854.4	1.8	1438.2	1.3	2.1	39.8	47.5	227.1%	117.2%	17.5%
Brazil	0.2	0.3	181.4	0.6	236.6	0.5	0.5	18.7	21.5	137.9%	64.0%	-12.9%
Other South and Central America	0.5	0.6	256.5	1.2	349.2	0.9	0.9	40.4	47.5	101.3%	41.2%	-25.2%
Non-OECD minus China	7.6	8.3	3798.1	14.8	5370.1	10.0	11.1	452.9	513.7	45.8%	34.0%	-24.9%
Total Non-OECD	9.8	12.2	5093.6	26.2	6812.1	17.2	17.8	960.1	1097.0	81.0%	45.7%	-31.9%
Total World	21.2	25.5	6245.1	42.9	8107.7	25.0	25.0	1755.0	1958.3	17.7%	-1.9%	-41.7%

Table S8: 2030: Global emissions target of 25 $GtCO_2$ with individual emissions caps of 7.3 tCO_2 and 6.5 tCO_2 for the '25' and '25P' scenarios. The '25P' scenario has a poverty floor of 1.0 tCO_2. The three rightmost columns show the '25P' emissions change w.r.t. emissions in 1990, 2003 and under BAU.

Region	Emissions [1990]	Emissions [2003]	Population [2003]	Emissions (BAU) [2030]	Population [2030]	Emissions (30) [2030]	Emissions (30P) [2030]	Population under cap (30) [2030]	Population under cap (30P) [2030]	(30P) change w.r.t. [1990]	(30P) change w.r.t. [2003]	(30P) change w.r.t. (BAU)
U.S.	5.0	5.8	290.8	8.0	364.7	3.6	3.2	267.0	284.5	-35.4%	-44.6%	-59.5%
Canada	0.5	0.6	31.6	0.7	38.6	0.4	0.3	29.3	31.3	-26.5%	-40.1%	-53.0%
Mexico	0.3	0.4	101.0	0.7	129.2	0.6	0.5	14.2	16.3	81.1%	42.6%	-21.4%
OECD Europe	4.1	4.3	528.6	4.7	560.6	3.8	3.6	138.9	175.1	-11.0%	-16.0%	-22.6%
Japan	1.0	1.2	127.7	1.3	122.8	1.1	1.0	43.0	57.2	0.8%	-18.1%	-22.0%
South Korea	0.2	0.5	47.9	0.7	49.9	0.5	0.4	29.6	33.6	80.9%	-8.7%	-37.2%
Australia and New Zealand	0.3	0.4	23.9	0.6	29.9	0.3	0.3	20.7	22.2	-10.8%	-37.3%	-55.1%
OECD minus U.S.	6.4	7.4	860.7	8.7	930.8	6.6	6.2	275.7	335.7	-2.5%	-16.0%	-28.3%
Total OECD	11.4	13.3	1151.5	16.7	1295.6	10.2	9.5	542.7	620.2	-16.9%	-28.5%	-43.2%
China	2.2	4.0	1295.5	11.4	1442.1	8.5	8.2	299.7	354.0	264.1%	106.1%	-28.5%
Russia	2.3	1.6	144.6	2.2	124.7	1.2	1.1	76.6	85.4	-54.0%	-33.0%	-50.9%
Transition Economies	1.9	1.1	194.6	1.6	189.7	1.3	1.2	48.9	60.2	-34.4%	12.4%	-25.9%
India	0.6	1.1	1064.6	2.2	1441.6	2.2	2.3	0.7	1.8	303.6%	120.8%	6.5%
Other Non-OECD Asia	0.8	1.4	926.6	2.8	1307.8	2.2	2.5	46.5	52.4	212.6%	85.0%	-9.2%
Middle East	0.7	1.2	175.4	2.3	282.3	1.4	1.4	55.8	64.2	96.9%	13.4%	-40.5%
Africa	0.6	1.0	854.4	1.8	1438.2	1.4	2.2	22.8	26.6	244.0%	128.4%	23.5%
Brazil	0.2	0.3	181.4	0.6	236.6	0.6	0.6	10.1	12.6	161.4%	80.2%	-4.3%
Other South and Central America	0.5	0.6	256.5	1.2	349.2	1.0	1.0	22.3	26.9	126.0%	58.5%	-16.1%
Non-OECD minus China	7.6	8.3	3798.1	14.8	5370.1	11.3	12.4	283.7	330.1	62.7%	49.5%	-16.2%
Total Non-OECD	9.8	12.2	5093.6	26.2	6812.1	19.8	20.5	583.4	684.1	108.5%	67.8%	-21.6%
Total World	21.2	25.5	6245.1	42.9	8107.7	30.0	30.0	1126.1	1304.3	41.2%	17.7%	-30.0%

Table S9: 2030: Global emissions target of 30 $GtCO_2$ with individual emissions caps of 10.8 tCO_2 and 9.6 tCO_2 for the '30' and '30P' scenarios. The '30P' scenario has a poverty floor of 1.0 tCO_2. The three rightmost columns show the '30P' emissions change w.r.t. emissions in 1990, 2003 and under BAU.

Region	Emissions [1990]	Emissions [2003]	Population [2003]	Emissions (BAU) [2030]	Population [2030]	Emissions (35) [2030]	Emissions (35P) [2030]	Population under cap (35) [2030]	Population under cap (35P) [2030]	(35P) change w.r.t. [1990]	(35P) change w.r.t. [2003]	(35P) change w.r.t. (BAU)
U.S.	5.0	5.8	290.8	8.0	364.7	4.9	4.5	184.9	213.6	-10.2%	-23.0%	-43.8%
Canada	0.5	0.6	31.6	0.7	38.6	0.5	0.5	18.9	22.6	2.3%	-16.8%	-34.6%
Mexico	0.3	0.4	101.0	0.7	129.2	0.6	0.6	7.9	9.9	102.4%	59.4%	-12.2%
OECD Europe	4.1	4.3	528.6	4.7	560.6	4.3	4.2	44.7	67.2	2.9%	-2.9%	-10.5%
Japan	1.0	1.2	127.7	1.3	122.8	1.2	1.2	14.2	20.4	18.0%	-4.1%	-8.7%
South Korea	0.2	0.5	47.9	0.7	49.9	0.6	0.6	13.3	18.4	135.4%	18.8%	-18.3%
Australia and New Zealand	0.3	0.4	23.9	0.6	29.9	0.4	0.4	14.1	16.4	22.5%	-13.8%	-38.3%
OECD minus U.S.	6.4	7.4	860.7	8.7	930.8	7.7	7.4	113.0	154.8	15.7%	-0.2%	-14.9%
Total OECD	11.4	13.3	1151.5	16.7	1295.6	12.6	11.9	297.9	368.5	4.4%	-10.2%	-28.7%
China	2.2	4.0	1295.5	11.4	1442.1	9.8	9.5	154.5	193.8	323.0%	139.5%	-16.9%
Russia	2.3	1.6	144.6	2.2	124.7	1.5	1.4	43.4	53.5	-39.2%	-11.4%	-35.0%
Transition Economies	1.9	1.1	194.6	1.6	189.7	1.5	1.4	19.7	27.0	-23.3%	31.5%	-13.4%
India	0.6	1.1	1064.6	2.2	1441.6	2.2	2.3	0.0	0.0	304.0%	121.0%	6.6%
Other Non-OECD Asia	0.8	1.4	926.6	2.8	1307.8	2.4	2.7	26.6	32.7	238.7%	100.4%	-1.6%
Middle East	0.7	1.2	175.4	2.3	282.3	1.7	1.6	31.1	38.0	132.3%	33.8%	-29.8%
Africa	0.6	1.0	854.4	1.8	1438.2	1.6	2.3	14.2	16.4	259.9%	139.0%	29.2%
Brazil	0.2	0.3	181.4	0.6	236.6	0.6	0.6	3.1	4.9	180.2%	93.2%	2.6%
Other South and Central America	0.5	0.6	256.5	1.2	349.2	1.1	1.1	10.2	13.3	147.2%	73.4%	-8.2%
Non-OECD minus China	7.6	8.3	3798.1	14.8	5370.1	12.5	13.6	148.4	185.8	79.2%	64.7%	-7.7%
Total Non-OECD	9.8	12.2	5093.6	26.2	6812.1	22.4	23.1	302.9	379.5	134.7%	88.9%	-11.7%
Total World	21.2	25.5	6245.1	42.9	8107.7	35.0	35.0	600.9	748.0	64.8%	37.3%	-18.3%

Table S10: 2030: Global emissions target of 35 $GtCO_2$ with individual emissions caps of 16.8 tCO_2 and 14.6 tCO_2 for the '35' and '35P' scenarios. The '35P' scenario has a poverty floor of 1.0 tCO_2. The three rightmost columns show the '35P' emissions change w.r.t. emissions in 1990, 2003 and under BAU.

3.2 Sensitivity of the Global Cap to the Emissions Elasticity.

For sake of simplicity, throughout the main text we assume proportionality between emissions and expenditures (an elasticity of 1.0), a world where two persons whose expenditures differ by 10% will also differ by 10% in their emissions. Here we explore the consequences of other relationships between emissions and expenditures by treating the corresponding elasticity as a parameter. An elasticity lower than unity is a situation where the poor spend a higher fraction of their consumption budget on energy and emissions than the rich do, a situation where a flat carbon tax would be regressive. We assume a constant global β but let it take the values, 0.7, 0.8, 0.9 and 1.0.

Figures S5 and S6 show the effect of changing the $\beta = 1.0$ rule on the global population distribution and the global emissions distributions, respectively. For both 2003 and 2030, aggregate emissions of the low emitters increase as β falls, as expected. Note the five-fold change of horizontal scale between Figure S5 and Figure S6, expressing the large share of global emissions coming from the highest emitters. Figure 6 shows the expected high-emitter effect of lower β: Lower values of β are associated with lower aggregate emissions by the emitters above 25 tCO_2/yr in 2030.The effect of various expenditure-emission elasticities on the 2020 and the 2030 universal cap is shown in Table S11. The global emissions target ranges from 20 to 35 $GtCO_2$, and the world does and doesn't have a poverty floor of 0.5 tCO_2 in 2020 and 1.0 tCO_2 in 2030. The individual emissions caps in Table S11 for 2030 are derived from Figure S7 using the method described in subsection 3.1 (see Figure S4).

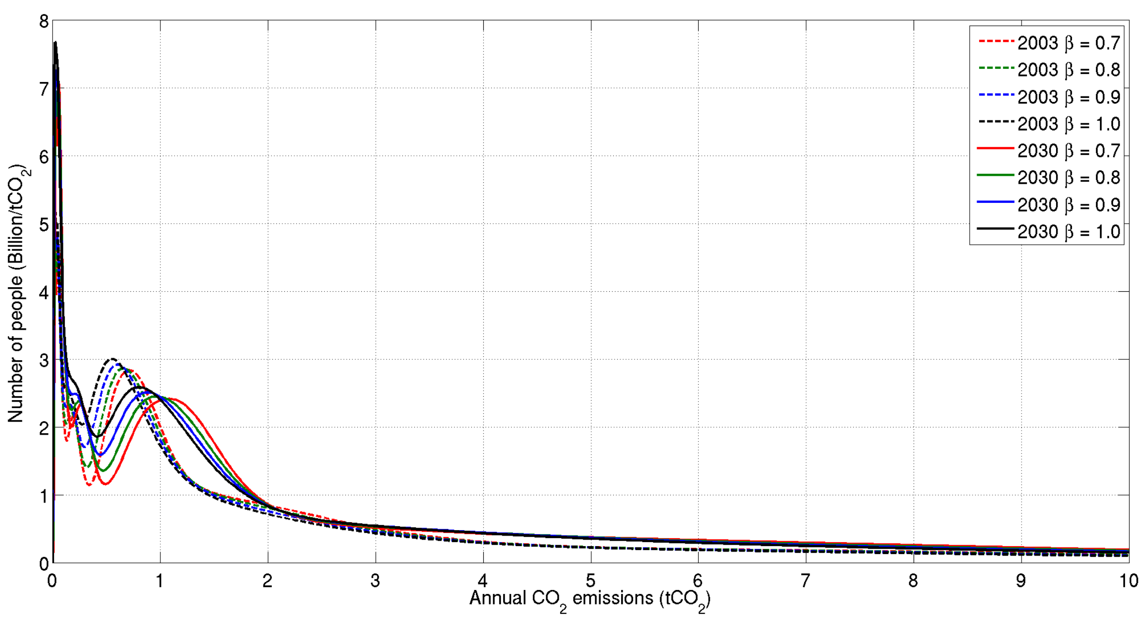

Figure S5: The global distribution of the number of emitters at a given annual individual emissions rate vs. the individual emissions rate in 2003 and 2030 for different values of the elasticity of emissions β.

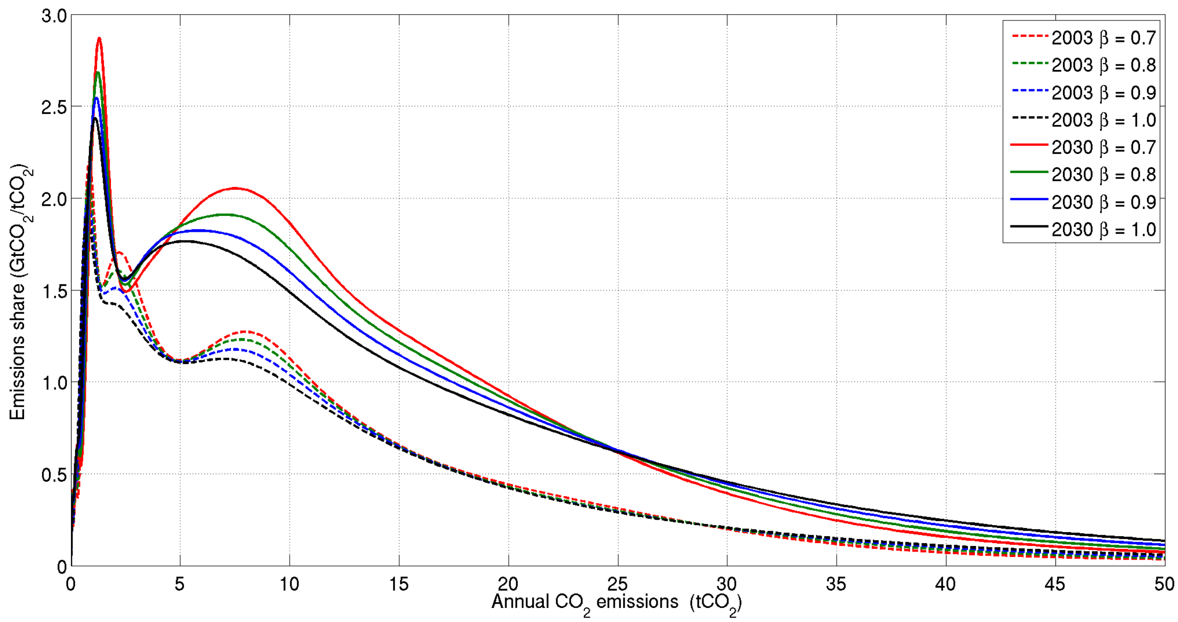

Figure S6: The global distribution of emissions at a given annual individual emissions rate vs. the annual individual emissions in 2003 and 2030 for different values of the elasticity of emissions β.

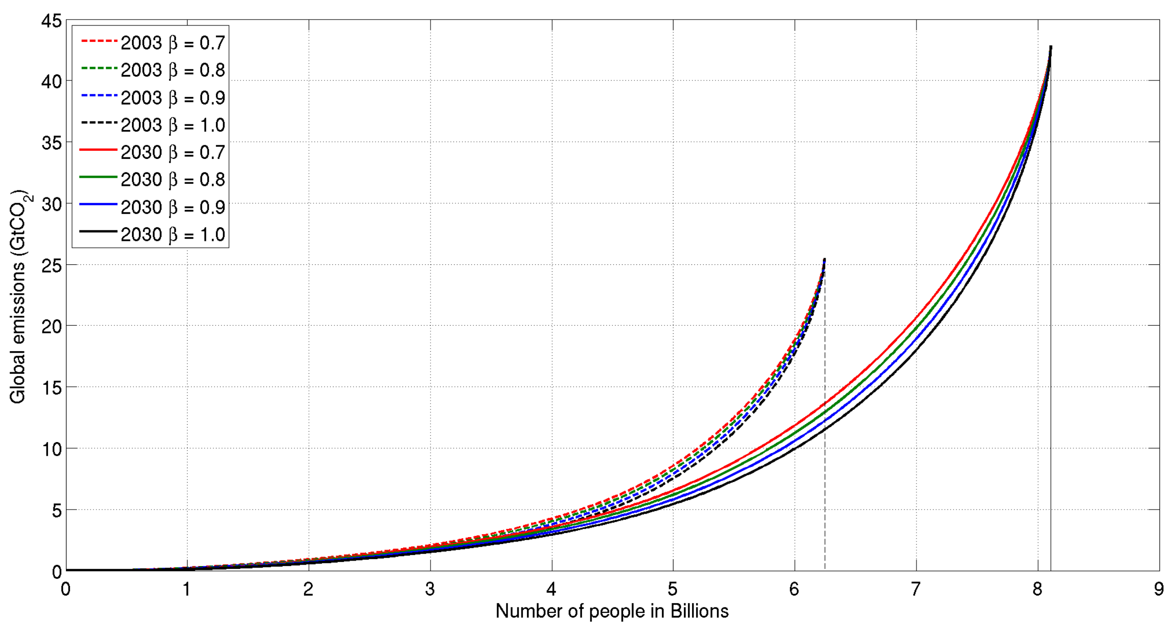

Figure S7: Cumulative emissions vs. cumulative population for 2003 and 2030 for different values of β.

Year	Elasticity (β)	20	20P	25	25P	30	30P	33	33P	35	35P
		[Individual emissions cap in tCO_2/year]									
2020	1.0	5.8	5.6	9.2	8.8	15.2	14.6	22.8	21.4		
	0.9	5.5	5.3	8.6	8.3	14.0	13.4	20.5	19.3		
	0.8	5.3	5.1	8.1	7.8	12.9	12.4	18.6	17.6		
	0.7	5.1	4.9	7.7	7.4	12.0	11.6	17.0	16.3		
2030	1.0	4.9	4.3	7.3	6.5	**10.8**	**9.6**			16.8	14.6
	0.9	4.7	4.1	6.9	6.2	10.1	9.0			15.4	13.6
	0.8	4.5	4.0	6.5	5.9	9.4	8.6			14.2	12.6
	0.7	4.3	3.9	6.3	5.7	8.9	8.2			13.1	11.9

Table S11: The individual cap for different global targets. For example, '20' and '20P' refer to a global emissions target of 20 $GtCO_2$. '20P' also includes a poverty floor of 0.5 tCO_2 in 2020 and 1.0 tCO_2 in 2030. The table shows how the cap changes for different constant elasticities of CO_2 emissions with consumption expenditure. BAU emissions in 2020 and 2030 are projected to be 36.8 $GtCO_2$ and 42.9 $GtCO_2$ respectively. The individual caps for the '30' and '30P' scenario (**10.8** tCO_2 and **9.6** tCO_2, respectively) in 2030 are extensively used in the main text.

We see that the individual cap tightens with a decrease in elasticity. This happens because with a lower elasticity a larger share of emissions comes from the middle of the distribution. The cap for an elasticity of 0.7 is 10% to 25% lower than for an elasticity of 1.0, for the same target.

3.3 Sensitivity of Regional Emissions Projections to the Emissions Elasticity

In Figures S8-S23 we show the variation in regional emissions with change in the elasticity of emissions: β. We show the projections for $\beta = 1.0$, $\beta = 0.9$, $\beta = 0.8$ and $\beta = 0.7$, with β assumed to be the same for all countries. We also show the range of projected emissions with a random β for each country, sampled independently from a uniform distribution in the interval $0.7 \leq \beta \leq 1.0$.

Some broad patterns emerge from the sensitivity analysis. As shown in Figure S3, reducing the elasticity β from 1.0 to 0.7 has the effect of making a country's emissions distribution more equitable, thereby increasing the number of people whose emissions are close to the per capita value, and reducing the number of very low and very high emitters. As a result, the emissions of different regions varies significantly. Regions with a large number of high emitters, especially those whose average emissions are significantly above the cap see a further reduction in total allocated emissions as a higher fraction of the population is under the cap (U.S., Russia, Canada etc.). Regions where most of the people emit significantly below the cap see an increase in total allocated emissions with decrease in β as the number of people above the cap decreases (Africa, India etc.). The results are intermediate for regions between these two extremes. The blue and pink rectangles show the range of regional emissions allocations that may be expected in 2020 and 2030, respectively, if we allow countries to have emissions distributions that have different emissions elasticities (randomly distributed between 0.7 and 1.0).

How to read Figures S8-S23?

The figures are all in same format so we provide some extended notes here. Projected regional emissions in $GtCO_2$ are shown on the Y-axis and the different global scenarios are listed on the X-axis. The four horizontal lines that stretch across the graph are the emissions in 1990, 2003, 2020 BAU and 2030 BAU (labeled likewise on the graphs). The '20', '20P', '25', '25P', '30', '30P' scenarios are for both 2020 and 2030. The '33' and '33P' scenarios are for 2020 only whereas the '35' and the '35P' scenarios are 2030. The numbers refer to the global emissions target in $GtCO_2$ and the 'P' scenarios provide for a 'poverty emissions floor' of 0.5 tCO_2 in 2020 and 1.0 tCO_2 in 2030. This, of course, results in some redistribution of the projected emissions across the different regions. The red, green, blue and black lines show the regional emissions when the elasticity of emissions β is assumed to be 0.7, 0.8, 0.9 and 1.0, respectively. 2020 values are shown using dashed lines and 2030 in bold lines. The light blue and the light pink rectangles show the range of values in 2020 and 2030 for 100 independent runs of the projections with random βs for different countries using uniformly distributed β from the interval $0.7 \leq \beta \leq 1.0$.

The primary difference between the 'P' and the 'non-P' scenarios is that regions with a large number of people who emit below the poverty floor (0.5 $GtCO_2$ in 2020, and 1.0 $GtCO_2$ in 2030) are allowed higher emissions. Since the global target remains the same, the individual cap is lower, and other regions have to make more stringent reductions. So, Africa gets to emit more and the U.S. has more stringent reductions.

We also highlight the difference between the 2020 and 2030 regional emissions targets for the same global emissions target ('25P' in 2020 vs. '25P' in 2030, for example). Regions that already have high emitters as a large fraction of their population in 2003 have 2030 emissions targets that are lower than the 2020 targets (the OECD countries except Mexico, Russia and the Transition Economies). This observation is a consequence of two factors: 1) Stable or declining populations and 2) tighter individual caps for the same global targets in 2030, compared to 2020.

Most of the other regions see higher emissions in 2030 compared to 2020 though they might see a reduction compared to BAU. Most of the individuals in these regions have emissions below the 2020 caps. When emissions are rising at a fast pace as a result of population growth and economic development, the increase in emissions from those below the cap can be much higher than any decrease from those above the cap. This remains true even if the cap in 2030 is lower than the cap in 2020.

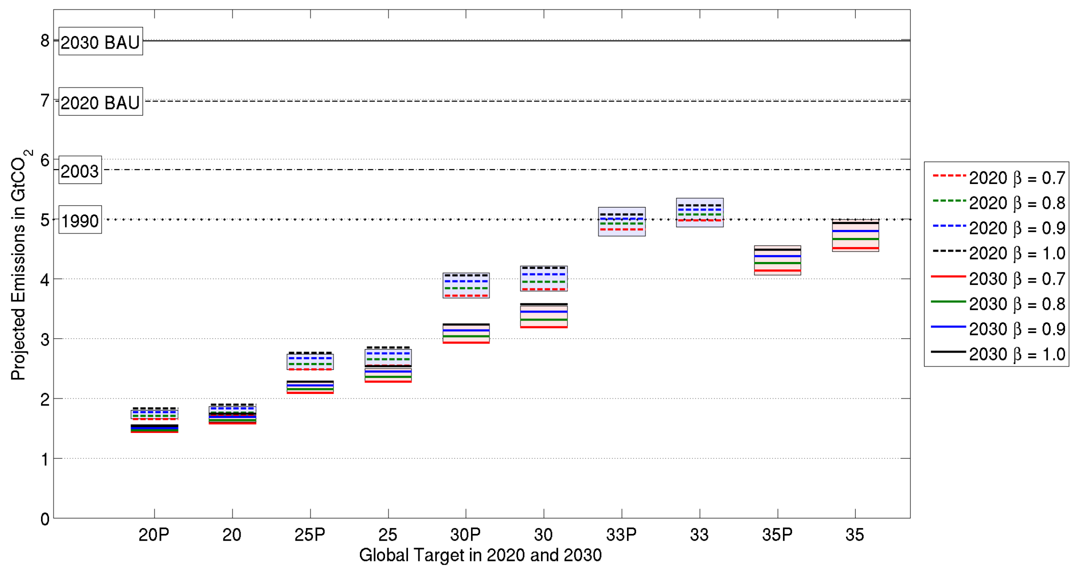

Figure S8: U.S. emissions for different scenarios in 2020 and 2030. The light blue and the light pink rectangles show the range of values in 2020 and 2030 for uniformly distributed β from the interval $0.7 \leq \beta \leq 1.0$. See detailed note on pg. 27.

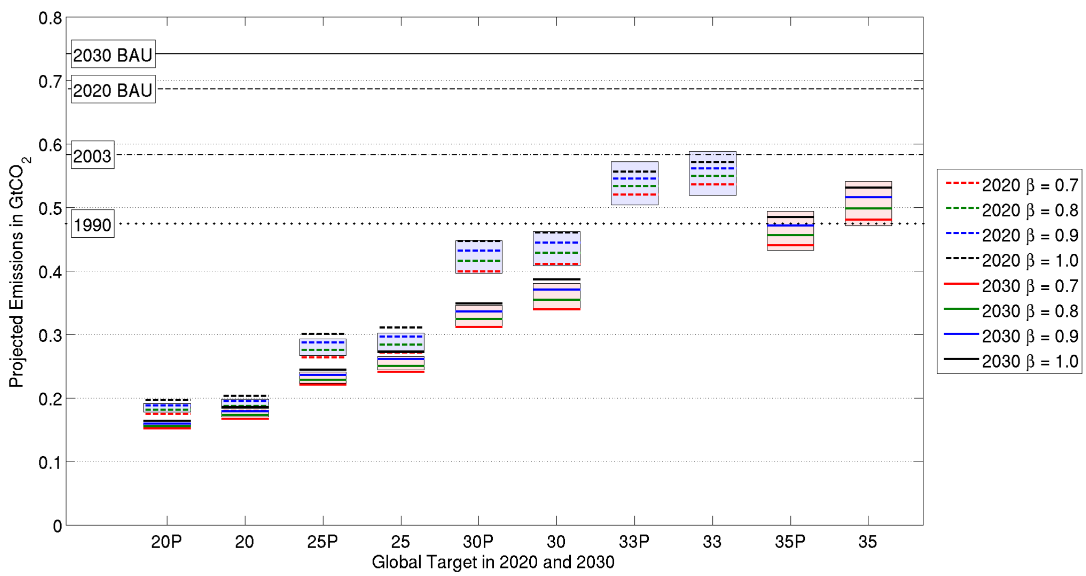

Figure S9: Canada emissions for different scenarios in 2020 and 2030. The light blue and the light pink rectangles show the range of values in 2020 and 2030 for uniformly distributed β from the interval $0.7 \leq \beta \leq 1.0$. See detailed note on pg. 27.

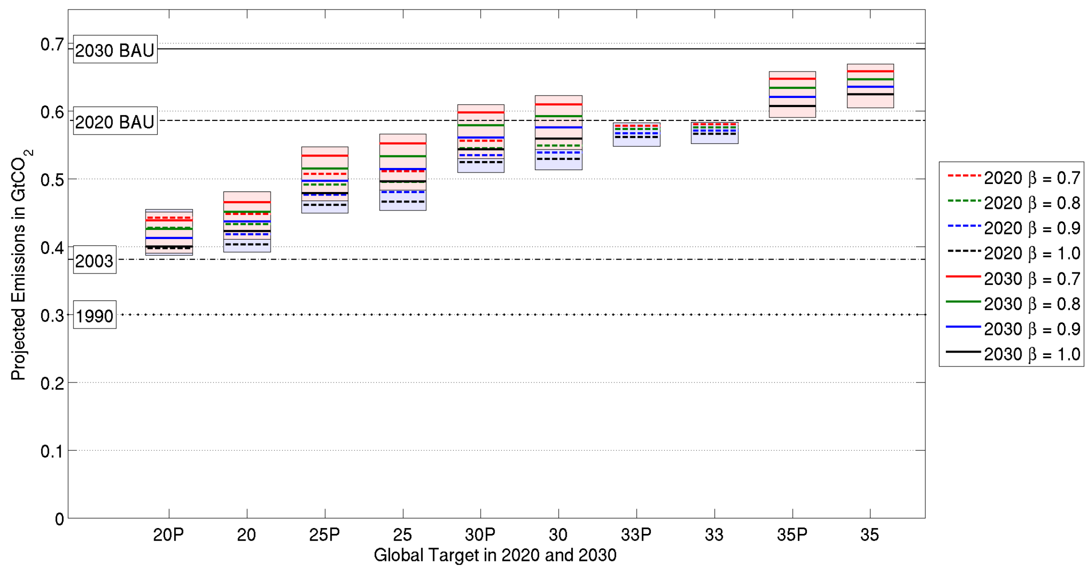

Figure S10: Mexico emissions for different scenarios in 2020 and 2030. The light blue and the light pink rectangles show the range of values in 2020 and 2030 for uniformly distributed β from the interval $0.7 \leq \beta \leq 1.0$. See detailed note on pg. 27.

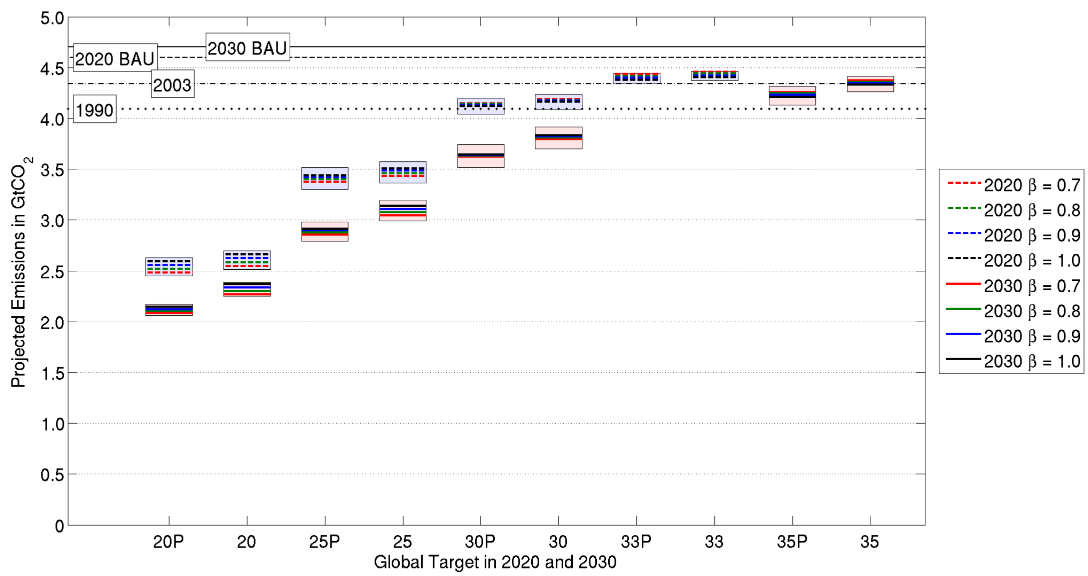

Figure S11: OECD Europe emissions for different scenarios in 2020 and 2030. The light blue and the light pink rectangles show the range of values in 2020 and 2030 for uniformly distributed β from the interval $0.7 \leq \beta \leq 1.0$. See detailed note on pg. 27

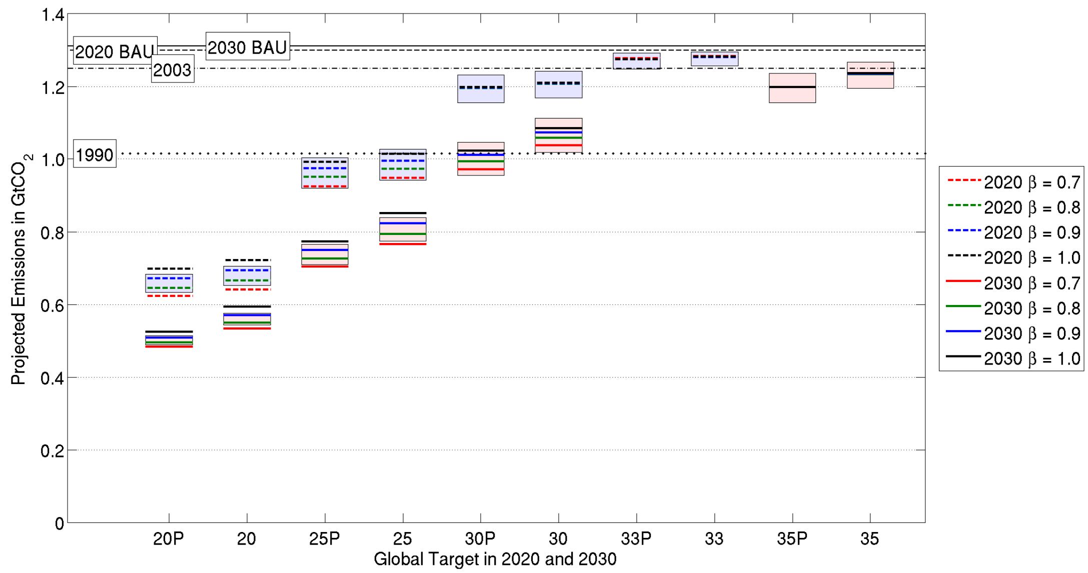

Figure S12: Japan emissions for different scenarios in 2020 and 2030. The light blue and the light pink rectangles show the range of values in 2020 and 2030 for uniformly distributed β from the interval $0.7 \leq \beta \leq 1.0$. See detailed note on pg. 27.

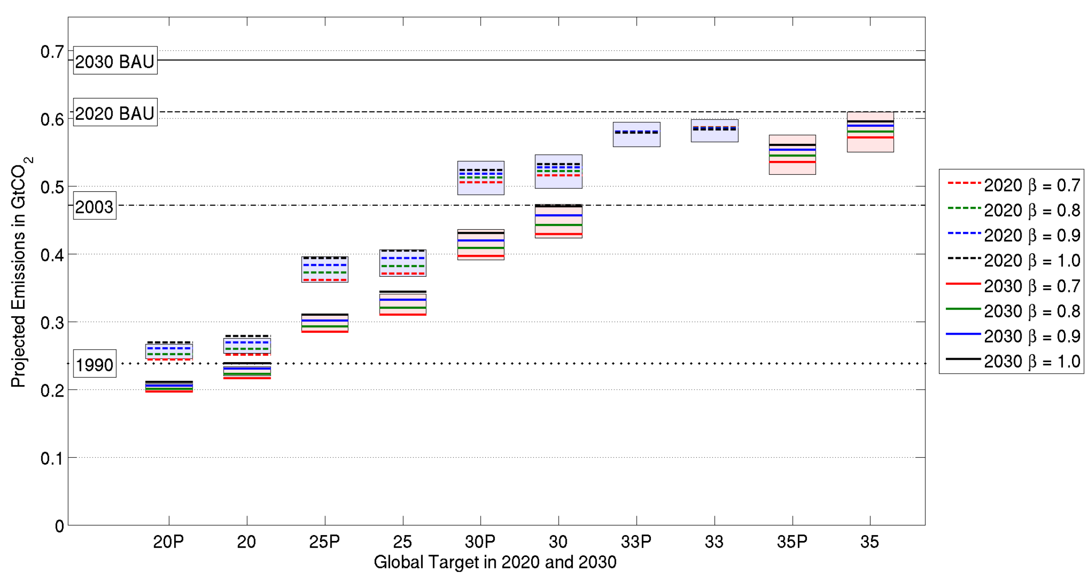

Figure S13: South Korea emissions for different scenarios in 2020 and 2030. The light blue and the light pink rectangles show the range of values in 2020 and 2030 for uniformly distributed β from the interval $0.7 \leq \beta \leq 1.0$. See detailed note on pg. 27.

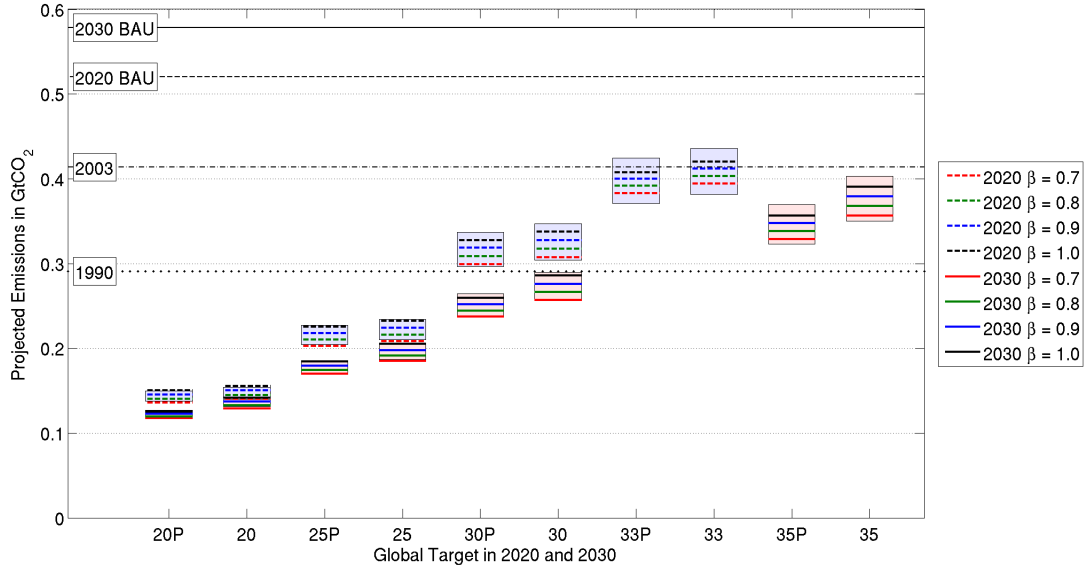

Figure S14: Australia and New Zealand emissions for different scenarios in 2020 and 2030. The light blue and the light pink rectangles show the range of values in 2020 and 2030 for uniformly distributed β from the interval $0.7 \leq \beta \leq 1.0$. See detailed note on pg. 27.

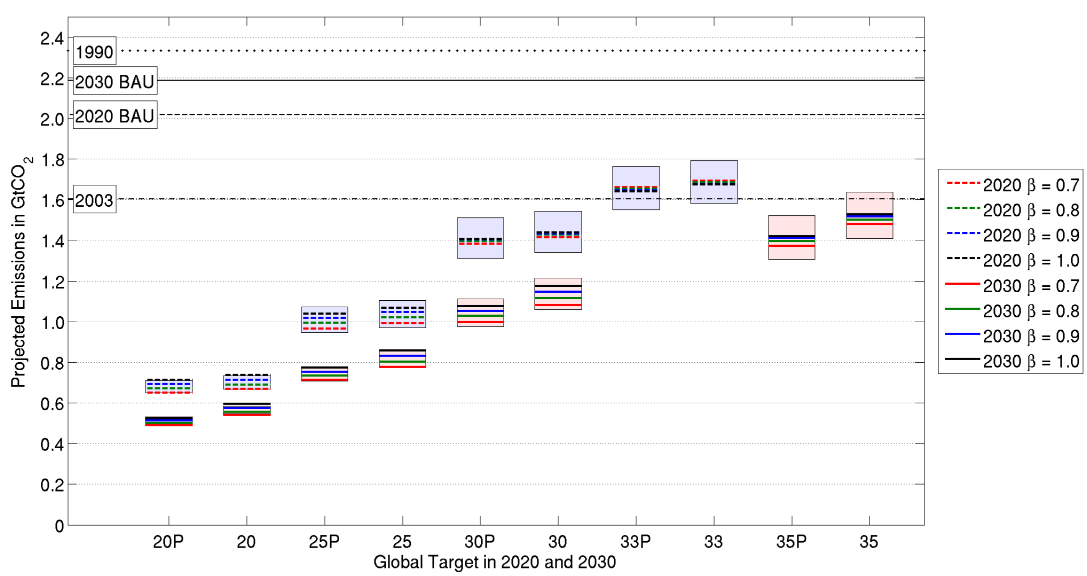

Figure S15: Russia emissions for different scenarios in 2020 and 2030. The light blue and the light pink rectangles show the range of values in 2020 and 2030 for uniformly distributed β from the interval $0.7 \leq \beta \leq 1.0$. See detailed note on pg. 27.

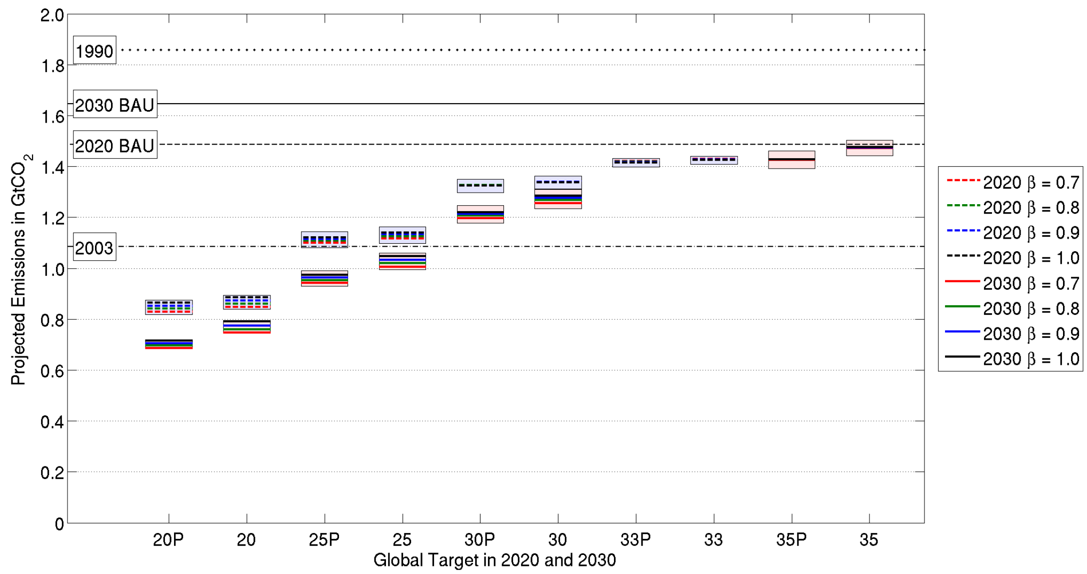

Figure S16: Transition economies emissions for different scenarios in 2020 and 2030. The light blue and the light pink rectangles show the range of values in 2020 and 2030 for uniformly distributed β from the interval $0.7 \leq \beta \leq 1.0$. See detailed note on pg. 27.

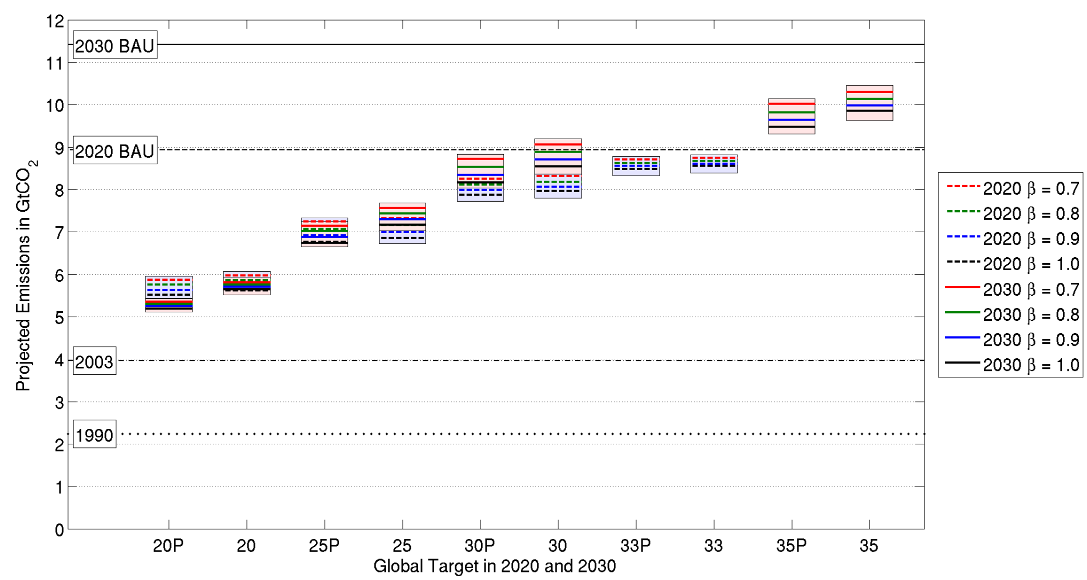

Figure S17: China emissions for different scenarios in 2020 and 2030. The light blue and the light pink rectangles show the range of values in 2020 and 2030 for uniformly distributed β from the interval $0.7 \leq \beta \leq 1.0$. See detailed note on pg. 27.

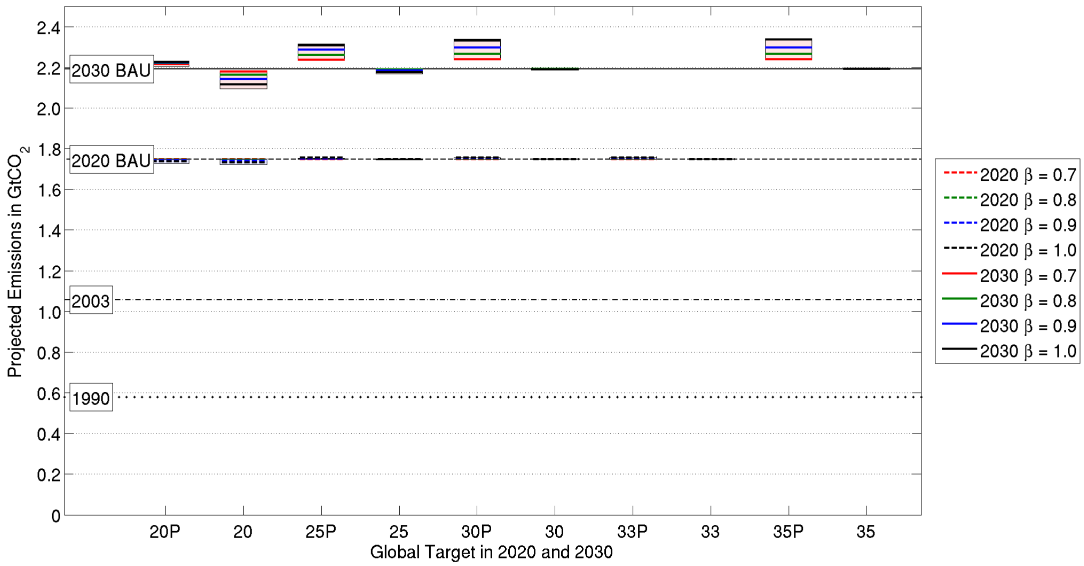

Figure S18: India emissions for different scenarios in 2020 and 2030. The light blue and the light pink rectangles show the range of values in 2020 and 2030 for uniformly distributed β from the interval $0.7 \leq \beta \leq 1.0$. See detailed note on pg. 27.

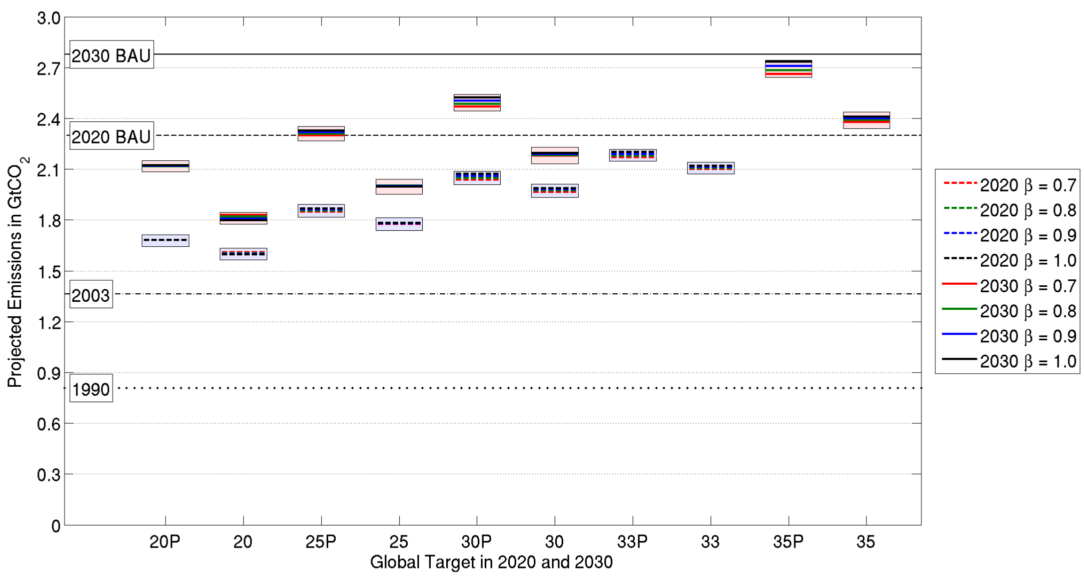

Figure S19: Other Non-OECD Asia emissions for different scenarios in 2020 and 2030. The light blue and the light pink rectangles show the range of values in 2020 and 2030 for uniformly distributed β from the interval $0.7 \leq \beta \leq 1.0$. See detailed note on pg. 27.

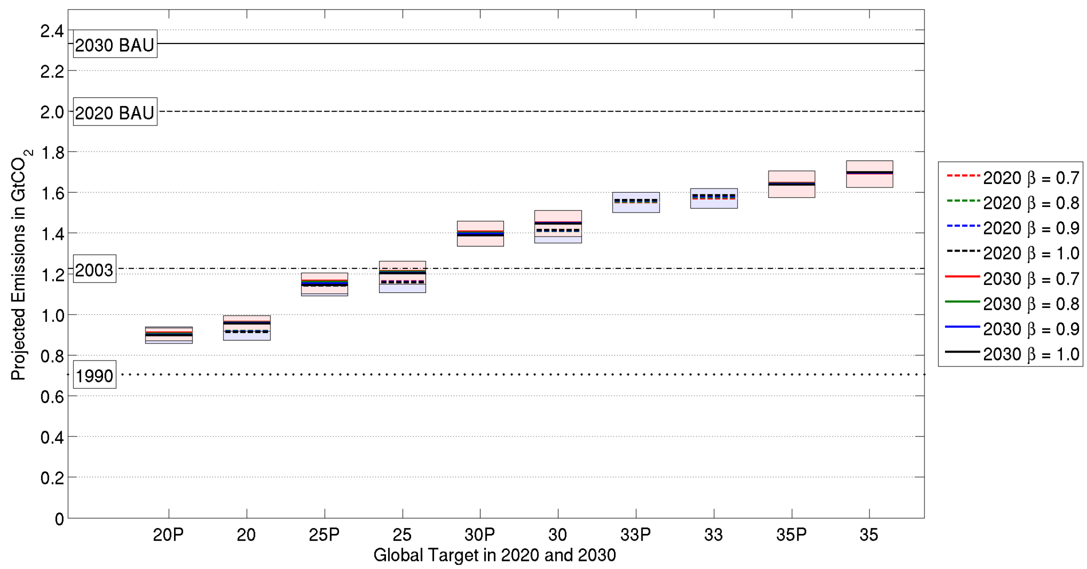

Figure S20: Middle East emissions for different scenarios in 2020 and 2030. The light blue and the light pink rectangles show the range of values in 2020 and 2030 for uniformly distributed β from the interval $0.7 \leq \beta \leq 1.0$. See detailed note on pg. 27.

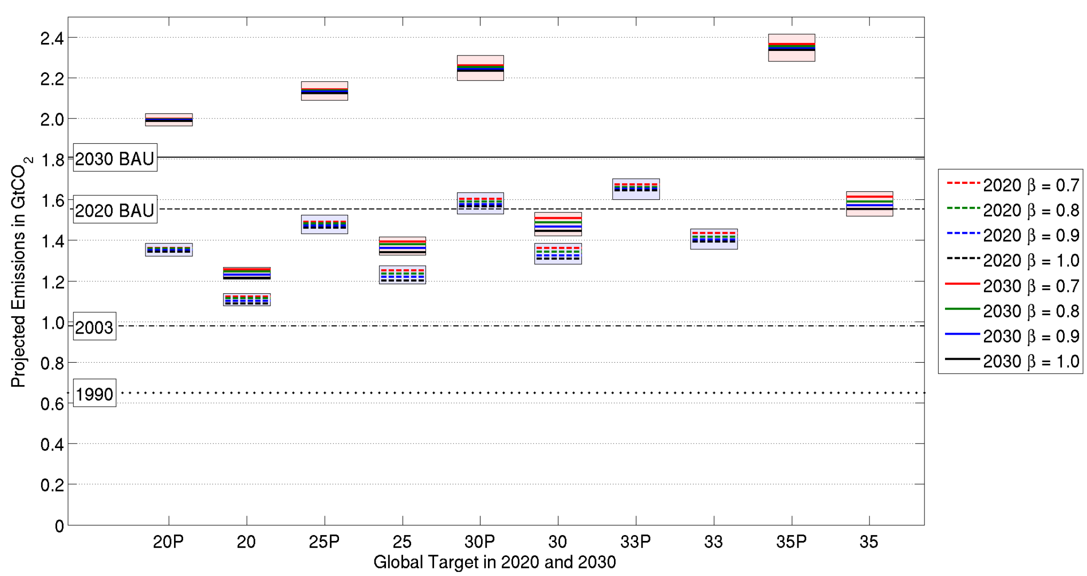

Figure S21: Africa emissions for different scenarios in 2020 and 2030. The light blue and the light pink rectangles show the range of values in 2020 and 2030 for uniformly distributed β from the interval $0.7 \leq \beta \leq 1.0$. See detailed note on pg. 27.

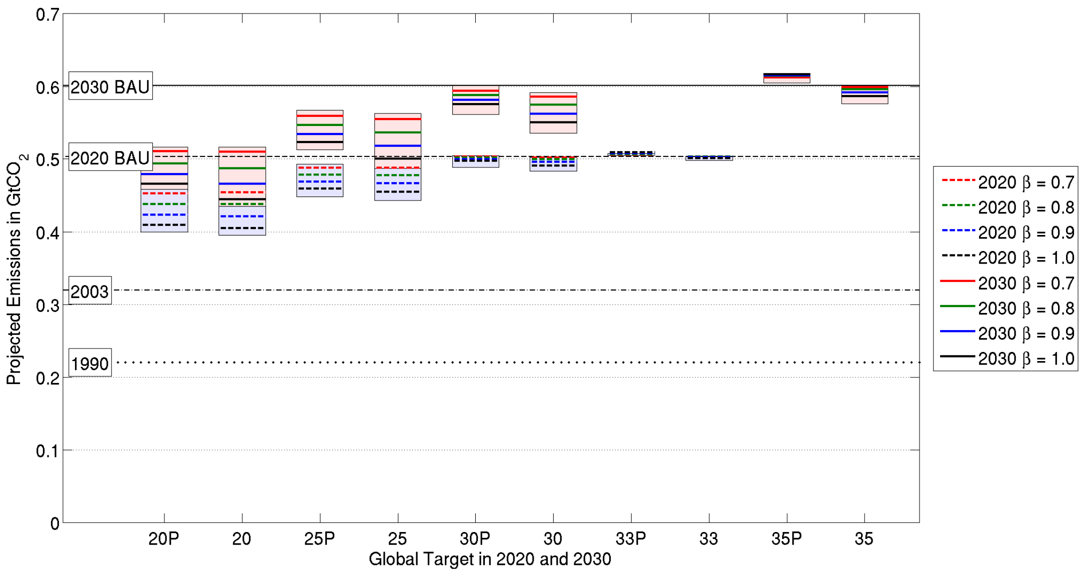

Figure S22: Brazil emissions for different scenarios in 2020 and 2030. The light blue and the light pink rectangles show the range of values in 2020 and 2030 for uniformly distributed β from the interval $0.7 \leq \beta \leq 1.0$. See detailed note on pg. 27.

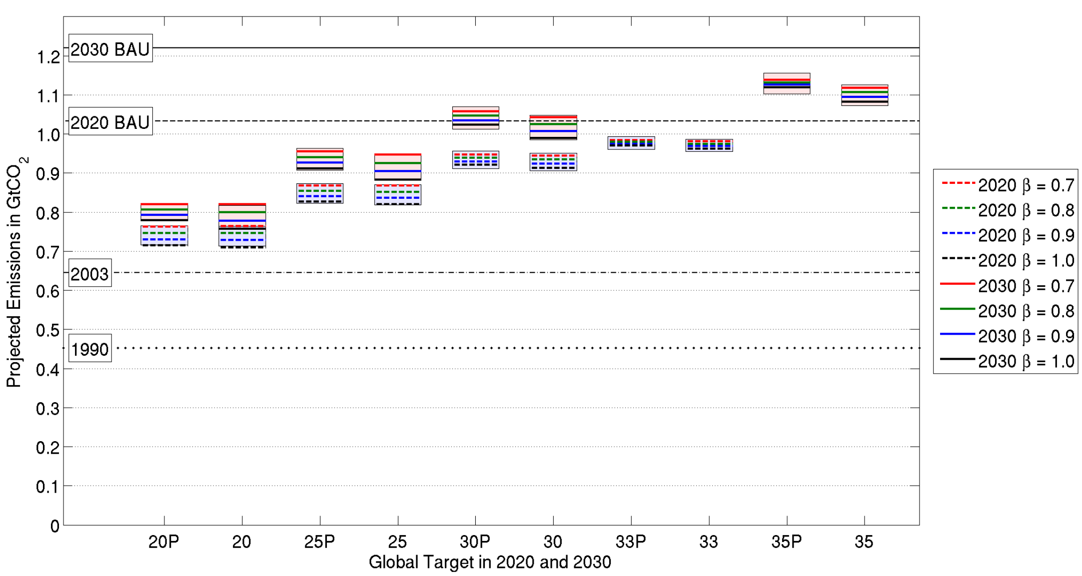

Figure S23: South and Central America emissions for different scenarios in 2020 and 2030. The light blue and the light pink rectangles show the range of values in 2020 and 2030 for uniformly distributed β from the interval $0.7 \leq \beta \leq 1.0$. See detailed note on pg. 27.

4 Poverty floor of 1 tCO_2

The paper introduces an emission floor to allow the 2.7 billion people in 2030 with the lowest personal emissions to increase their annual emissions to 1 tCO2 by 2030. This provision corresponds approximately to a 1.5 $GtCO_2$ decrease in the allowance for the high emitters, or about a 10% increase of the global task of reducing 2030 emissions to 30 $GtCO_2$ relative to BAU. This section aims to show that an emission of 1 tCO_2 per person in a year allows for somewhat more than the standard of living portrayed in the academic literature of Basic Human Needs *(1)*.

We approach the issue from two perspectives. First, we relate 1 tCO_2/person-year to current emissions and future targets from a top-down perspective, relating this emissions level to human development and the stabilization of the atmospheric CO_2 concentration. Second, we provide a bottom-up analysis of what 1 tCO_2 per person per year would provide in terms of energy services.

'Top-down' perspective:

Table S12 shows the number of people who emit less than 0.5 tCO_2 and less than 1 tCO_2 per year, as well as their cumulative emissions, based on the methodology described in the main text, for 2003 and 2030. The Table shows that between 2003 and 2030, under BAU conditions, both the number of low emitters and their total emissions remain roughly the same-indicating that global economic growth has no perceptible impact on the low-emissions tail, which is simply shifted to the right (see the inset to Figure 1 of the main text)-i.e., poverty is not reduced substantially under BAU.

Year	Individual emissions (tCO_2/yr)	Number of people (billion)	Total emissions ($GtCO_2$/yr)
2003	< 0.5	1.3	0.31
	< 1.0	2.4	1.07
2020	< 0.5	1.4	0.30
	< 1.0	2.5	1.11
2030	< 0.5	1.5	0.31
	< 1.0	2.7	1.14

Table S12: Number of people who have individual emissions lower than 0.5 and 1 tCO_2/yr, and their total emissions. Data based on the BAU distributions discussed in the main text.

In this context, it is interesting to compare some indices for national development with per-capita CO_2 emissions. The most commonly used index for development is the UNDP's Human Development Index (HDI). The HDI combines purely economic data (GDP per capita) with data on other development indicators *(2)*, such as adult literacy rate, school enrollment ratios, and life expectancy at birth. In Figure S24 we plot per capita average national CO_2 emissions against HDI for a number of countries and learn that a per capita emission of 1 tCO2 corresponds roughly with the transition into an "inelastic regime," where an increase in emissions gives little gains in HDI *(3)*. In contrast, for countries with per capita average emissions below 1 tCO2, there is a great potential for rapid increases in HDI, and thus in human development, with only a small increase in emissions.

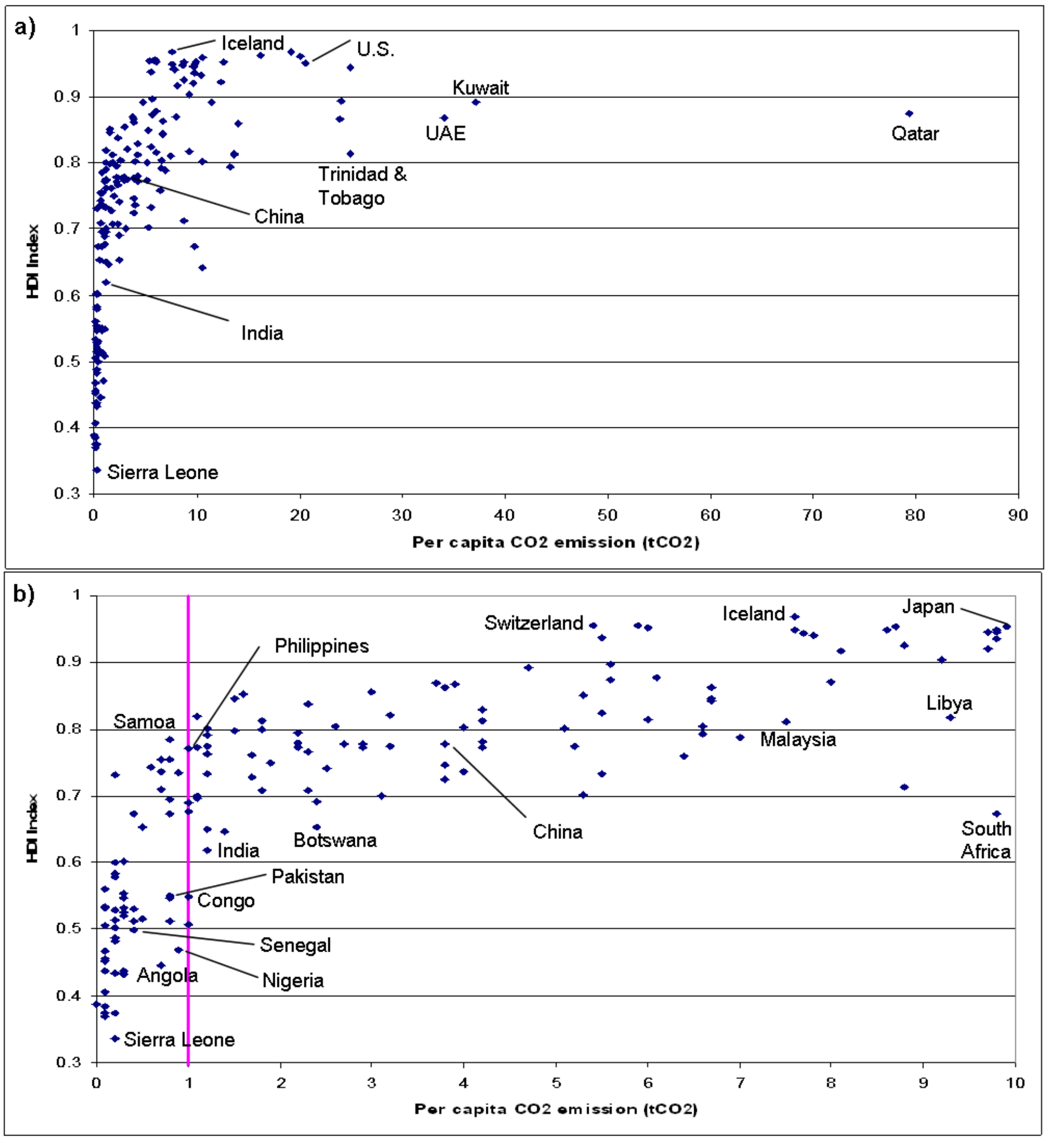

Figure S24: HDI vs. per capita CO_2 emissions. Graphs (a) and (b) show same data with the difference being the scales for the x-axis. The HDI is for year 2005 and per-capita CO_2 emissions are from 2004. The 1 tCO_2 line is also demarcated in (b). Source: Human Development Report 2007/2008 *(2)*

To be sure, achieving a floor of 1 tCO_2/person on the emissions of all individuals in any country guarantees that its per capita emissions will be above 1 tCO_2/capita. Nonetheless, Figure S24 assures us that 1 tCO_2 is a floor on personal emissions relevant to human development. An entirely different way to view 1 tCO_2/capita is to look ahead to the time when the world has stabilized greenhouse gas concentrations. By the end of this century, for a wide range of post-SRES scenarios with CO_2 stabilization targets below twice the preindustrial concentration, global emissions will need to be approximately 10 $GtCO_2$ per year *(4)*, assuming that net CO_2 emissions from land use are close to neutral and direct air capture of CO_2 negligible. Thus, for a world population of approximately 8-10 billion people at the time of stabilization *(5)*, the global per capita emission level should hardly be more than 1 tCO_2/yr.

Accordingly, 1 tCO2 per person per year is the emission level that emerges from many analyses of international convergence. By implication, the energy system must change dramatically in order for stabilization to be compatible with global economic growth.

'Bottom-up' perspective:

The people who are helped by the 1 tCO_2 individual emissions floor are the world's poorest, and it needs to be assessed how 1 tCO_2 relates to an exit from poverty. Whether any specific target group will actually be able to reach an emissions level of 1 tCO_2 depends on a number of issues, including the success of international efforts to achieve the Millennium Development Goals *(6)* and potential successor development targets and the successful implementation of associated domestic policies.

Energy services	Fuel	Rate of use per household	Emission factor	CO_2 emission per household ($kgCO_2$/yr)	CO_2 per person ($kgCO_2$/yr)
Cooking	LPG	14 kg/month	3.12 $kgCO_2$/kg propane (LHV)	532	118
Lighting and appliances	Electricity	200 kWh/yr	0.937 $kgCO_2$/kWh	187	42
Total emission from direct energy use				719	160

Table S13: Basic human needs per person. They consist of low levels of private and some communal electricity use, and about one canister (14 kg) per month for cooking. The household size is 4.5. For electricity, the emission factor is based on IEA's *(7)* estimate of average CO_2 emissions from electricity generation (4.652 $GtCO_2$/yr) and electricity consumption (4966 TWh/yr) in developing countries.

A.K.N. Reddy and his collaborators have assessed energy requirements for "Basic Human Needs" *(1)*. As typical values, we assume one 14 kg canister of liquid petroleum gas (LPG) per household per month and roughly 200 kWh per household per year for electricity (see Table S13). Electricity consumption, for example, could be accounted for by three 11-W compact fluorescent bulbs and a 100-W fan or a small television, all operated 4 hours/day. At this stage, we make no allowance for energy needed for transportation nor for community-level power (e.g., for a school or health clinic). The CO_2 consequences per person, assuming 4.5 persons per household, are shown in Table S13.

Energy services		Rate of use per household	Emission factor	CO_2 emission per household ($kgCO_2$/yr)	CO_2 per person ($kgCO_2$/yr)
Cooking	LPG	14 kg/month	3.12 $kgCO_2$/kg propane (LHV)	532	118
Transport	Two-wheeler	22.5 km/day	57gCO_2/person-km	464	103
	Bus	22.5 km/day	23gCO_2/person-km	189	42
	Shared car	22.5 km/day	39gCO_2/person-km	321	72
Total from Transport		67.5 km/day		974	217
Lighting and appliances	Electricity	794 kWh/yr	0.937 $kgCO_2$/kWh	744	165
Total Emissions from direct energy use				2250	500

Table S14: Extended human energy needs per person. The same cooking demand is assumed as in Table S13, an estimate for transport is added, and the balance is assigned to electricity. As in Table S13, the household size is 4.5 and the emission factor for electricity is 0.937 $kgCO_2$/kWh. The transport assumptions are 113 gCO_2/vehicle-km and 2 passengers/vehicle for the two-wheeler, 920 gCO_2/vehicle-km and 40 passengers/vehicle for the bus, and 196 gCO_2/vehicle-km and 5 passengers/vehicle for the shared car.

The emissions from direct energy use are about 160 $kgCO_2$/person-year. In the Basic Human Needs literature, these estimates of "direct" energy use are multiplied by a factor to take into account the "indirect" energy use associated with energy embodied in the purchases of non-energy goods and services, such as tools, clothing, and other intersections with the market economy *(1,9)*. A factor of 2 for this multiplier was developed in Figure 3.6 of *(1)* and in *(7)*. Using it here gives a total of 320 $kgCO_2$/person year for Basic Human Needs. Evidently, there is considerable room for additional consumption within the quota of 1 tCO_2/person-yr, resulting in a standard of living somewhat better than that of a person who has satisfied only Basic Human Needs.

We illustrate how this gap might be filled in Table S14, first by adding emissions associated with a representative demand for transport and then filling in the balance with electricity. We retain the two-to-one ratio for total vs "direct" emissions. Our estimate is that a little over 200 kg CO_2/person year of direct emissions are associated with transport. This follows from the assumption that, on average, one person in a household will travel 15 km/day (5 km/day each in a motorized two-wheeler, a bus, and a shared car). Vehicle emission factors and load factors are given in Table S14.

After allowing for transport emissions, there is room for an expansion of power consumption from 200 kWh/household-year value in Table S13 to about 794 kWh/household-year in Table S14. Electricity usage of 794 kWh/household-year is consistent with Reference 3 for achieving the "elastic development threshold". Compared to the smaller electricity use for Basic Human Needs in Table S13, it would allow for the operation of more lights, a refrigerator, an additional TV or fan, and some commercial activities.

References

(1) J. Goldemberg, T. B. Johansson, A. K. N. Reddy, and R. H. Williams, 1988. Energy for a Sustainable World. New Delhi: Wiley Eastern Ltd.
(2) UNDP, Human Development Report 2007/2008 (United Nations Development Programme, United Nations, 2007).
(3) A. K. N. Reddy, "Energy Technologies and Policies for Rural Development," in Energy for Sustainable Development: A Policy Agenda, T. B. Johansson, J. Goldemberg, eds. Published by UNDP, The International Institute for Industrial Environmental Economics (IIIEE), and The International Energy Initiative (IEI) (2002).
(4). IPCC, 2007. Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer (eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
(5) UNDESA, World Population to 2300 (United Nations Department of Economic and Social Affairs, 2004).
(6) Millennium Development Goals: See http://www.un.org/millenniumgoals/
(7). IEA, World Energy Outlook 2007 (International Energy Agency, 2007).
(8). Hoen, A., R.M.M. van den Brink, J.A. Annema, 2006. Verkeer en vervoer in deWelvaart en Leefomgeving Achtergronddocument bij Emissieprognoses Verkeer en Vervoer. MNP rapport 500076002/2006: Bilthoven, Netherlands. pp. 119, 132, 145, 158.
(9) R A. Herendeen, C. Ford, and B. Hannon, Energy **6** (12), pp. 1433-1450 (1981).

5 Appendix A

We use the International Energy Outlook 2007 projections for projecting the CO_2 distributions into the future. The EIA divides the world into 16 regions as listed below. We have only included countries which have a population above 1 million. We estimated the income distribution of some countries using the average quintile income shares of the geographical area the belong to. For example, we used the average of the Middle East and North Africa for **Saudi Arabia**. These countries are listed below in boldface. North Korea is missing as we did not have any estimate of its GDP. Our coverage is approximately 99.5% of the world's population (153 countries/territories) in 2003 and almost 100% of the emissions.

OECD

1. USA
2. Canada
3. Mexico
4. OECD Europe:
   Austria, Belgium, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Luxembourg, Netherlands, Norway, Poland, Portugal, Slovak Republic, Spain, Sweden, Switzerland, Turkey, and United Kingdom.
5. Japan
6. South Korea
7. Australia & New Zealand

NON OECD

8. Russia
9. Other NON-OECD Europe & Eurasia:
   Albania, Armenia, Azerbaijan, Belarus, Bosnia and Herzegovina, Bulgaria, Croatia, Estonia, Georgia, Kazakhstan, Kyrgyz Republic, Latvia, Lithuania, Macedonia (Former Yugoslav Rep. of), Moldova, Romania, Serbia and Montenegro, Slovenia, Tajikistan, Turkmenistan, Ukraine, and Uzbekistan.
10. China:
    China, and Hong Kong.
11. India
12. Other NON-OECD Asia:
    Bangladesh, Cambodia, Indonesia, Laos, Malaysia, Mongolia, Nepal, Pakistan, Papua New Guinea, Philippines, Singapore, Sri Lanka, Taiwan, Thailand, Vietnam, **Afghanistan**, and **Myanmar**.
13. Middle East:
    Iran, Israel, Jordan, Yemen, **Iraq**, **Kuwait**, **Lebanon**, **Oman**, **Saudi Arabia**, **Syrian Arab Republic**, and **United Arab Emirates**.

14. Africa:
    Algeria, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Central African Republic, Cote d'Ivoire, Egypt, Ethiopia, The Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Madagascar, Malawi, Mali, Mauritania, Morocco, Mozambique, Namibia, Niger, Nigeria, Rwanda, Senegal, Sierra Leone, South Africa, Swaziland, Tanzania, Tunisia, Uganda, Zambia, Zimbabwe, **Angola**, **Chad**, **Dem. Rep. of Congo**, **Rep. of Congo**, **Eritrea**, **Gabon**, **Liberia**, **Libya**, **Mauritius**, **Somalia**, **Sudan**, and **Togo**.

15. Brazil

16. Other Central & South America:
    Argentina, Bolivia, Chile, Colombia, Costa Rica, Dominican Republic, Ecuador, El Salvador, Guatemala, Guyana, Haiti, Honduras, Jamaica, Nicaragua, Panama, Paraguay, Peru, St. Lucia, Trinidad and Tobago, Uruguay, Venezuela, **Cuba**, and **Puerto Rico**.