Implications of various effort-sharing approaches for national carbon budgets and emission pathways

Supplementary Information – Climatic Change

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Table S.1 Equations for each effort sharing approach

Effort sharing approach	Equations
Grandfathering (GF*)	$b_i GF^* = \frac{e_{i,t=2010}}{E_{t=2010}} \cdot B$
	$a_{i,t} GF = \frac{e_{i,t=2010}}{E_{t=2010}} \cdot A_t$
Immediate per capita convergence (IEPC*)	$b_i IEPC^* = \frac{\sum_{t=2010}^{2100} pop_{i,t}}{\sum_{t=2010}^{2100} POP_t} \cdot B$
	$a_{i,t} IEPC = \frac{pop_{i,t}}{POP_t} \cdot A_t$
Per capita convergence (PCC*)	$b_i PCC^* = (1-w) \cdot b_i GF^* + w \cdot b_i IEPC^*$
	$a_{i,t} PCC = A_t \cdot \left(MIN\left(\frac{t-2010}{tconv-2010}, 1\right) \cdot \frac{pop_{i,t}}{POP_t} + MAX\left(1 - \frac{t-2010}{tconv-2010}, 0\right) \cdot \frac{e_{i,t=2010}}{E_{t=2010}} \right)$
Equal cumulative per capita emissions (ECPC*)	$Debt_i = \sum_{t=s}^{2010} \frac{pop_{i,t}}{POP_t} \cdot E_t \cdot d_t - e_{i,t} \cdot d_t$
	$b_i ECPC^* = \frac{\sum_{t=2010}^{2100} pop_{i,t}}{\sum_{t=2010}^{2100} POP_t} \cdot B + Debt_i$
Ability to pay (AP*)	Step 1: Reductions before correction factor: $rb_i AP^* = \sqrt[3]{\frac{\sum_{t=2010}^{2100} gdp_{i,t}}{\sum_{t=2010}^{2100} pop_{i,t}} \Big/ \sum_{t=2010}^{2100} \frac{GDP_t}{POP_t}} \cdot \sum_{t=2010}^{2100} \frac{BAU_t - B}{BAU_t} \cdot \sum_{t=2010}^{2100} bau_{i,t}$ Step 2: Global correction factor: $corr\_rb = \frac{\sum_i^N rb_i AP^*}{\sum_{t=2010}^{2100} BAU_t - B}$ Step 3: Budget after correction factor: $b_i AP^* = \sum_{t=2010}^{2100} bau_{i,t} - \frac{rb_i AP^*}{corr\_rb}$
	Step 1: Reductions before correction factor: $ra_{i,t} AP^* = \sqrt[3]{\frac{gdp_{i,t}}{pop_{i,t}} \Big/ \frac{GDP_t}{POP_t}} \cdot \frac{BAU_t - A_t}{BAU_t} \cdot bau_{i,t}$ Step 2: Global correction factor: $corr\_ra_t = \frac{\sum_i^N ra_{i,t} AP^*}{BAU_t - A_t}$ Step 3: Allowances after correction factor: $a_{i,t} AP^* = bau_{i,t} - \frac{r_{i,t} APbc^*}{corr\_ra_t}$
Greenhouse development rights (GDR*)	$b_i GDR^* = \sum_{t=2010}^{2100} bau_{i,t} - \left(\sum_{t=2010}^{2100} BAU_t - B \right) \cdot \left(\sum_{t=2010}^{2100} rci_i / (2100 - 2010) \right)$
	for t < 2031: $a_{i,t} GDR = bau_{i,t} - (BAU_t - A_t) \cdot rci_{i,t}$ for t > 2030: $a_{i,t} GDR^* = ((2100 - t)/70) \cdot bau_{i,t} - (BAU_t - A_t) \cdot rci_{i,2030} + ((t - 2030)/70) \cdot a_{i,t} AP$

Symbols: t = year; i = region; e = regional emissions; E = global emissions; a = regional emission allowance; A = global emission allowance; b = regional budget allowance; B = global carbon budget; pop = regional population; POP = global population; gdp = regional GDP, GDP = global GDP; bau = regional baseline emissions; BAU = global baseline emissions; w = weighting factor in PCC* approach; $tconv$ = conversion year in PCC* approach; N = Number of regions; rci = regional responsibility capability index; RCI = responsibility capability index summed over all regions; s = historical starting year of ECPC* approach; d = discount factor

Table S.2 Questionnaire on parameter settings

Approach	Fixed variable	Potential variable	Parameters	Explanation	Choice	Reasoning
General		Start year	2010; 2015; 2020	Already started or with a delay		
		End year	2020; 2050; 2100	Short-term or long-term goals		
		Global carbon budget	400; 1000; 1600 $GtCO_2$	1.5°C; 2°C with >66%; >55% likelihood		
		Global reduction target (emission pathway)	1.5°C; 2°C with >66%; >55% likelihood			
		CO_2 category	Incl. LULUCF; only energy; only industry energy	Focus on which emission sources		
GF*		Participation threshold	Yes; no	Paris Agreement		
PCC*	Emission share Population share	Weighting factor (carbon budget)	0.0-1.0	Range from emission share to population share		
	Emission share Population share	Convergence year (emission pathway)	2050-2100	When to converge		
ECPC*	Historical emission share	Historical start year	1850; 1970; 1990	Industrial revolution; increasing research; first IPCC report		
	Population share	Discount factor	1.6-2.8	Technological progress and past emissions out of the atmosphere		
		Future discount factor	Yes; no	Difficult for carbon budget as value is independent of time		
AP*	BAU GDP per capita	Participation threshold	Yes; no	Paris Agreement		
GDR*	BAU	Historical start year	1850; 1970; 1990	Industrial revolution; increasing research; first IPCC report		
	RCI share	Weighting factor RCI	0.0-1.0	Range from capability to responsibility		
Additional comments						

Questionnaire on parameter settings: results

Table S.3 shows the parameter answers that were given in the questionnaires. The default values are shown in bold, based on the number of respondents that chose these parameters. For ECPC*, because combinations of discount rates and historical start years (1.6/1850, 2/1970, and 2.8/1990) were provided, the combination discount rate 2 and historical start year 1970 was chosen as default settings for this approach. These combinations were presented to show the outer ranges of possible parameter settings. Furthermore, additional sensitivity factors were added based on the comments received, such as the inclusion of GDP (MER) in contrast to GDP (PPP).

Alongside the parameter choices, preliminary results were presented to the respondents to give them an idea regarding the sensitivity of parameter settings. These preliminary results showed that the discount rates and start year for historical emissions within the ECPC* approach varied significantly, depending on the parameter setting. Yet, the historical start year for GDR* was less sensitive. The PCC* approach proved to be relatively sensitive to convergence year in emission pathways and weighting factors (towards population share or current emission share) for carbon budgets.

Table S.3 Results from the choices of parameter sets (most selected option in bold)

Approach	Potential variable	Parameter options	Explanation	Range of parameters (# of expert selections)	Reasoning
General	Start year	2010; 2015; 2020	Already started or with a delay	***2010*** (6)	Most-commonly stated by UNFCCC parties; avoids a delay as it would increase the likelihood of triggering adverse positive feedback loops (e.g. permafrost melting)
				2015 (2)	Last year for which emissions data was available
				2020 (1)	End of the 2nd commitment of the Kyoto Protocol and Bali Roadmap, 2030 Paris Agreement
	End year	2020; 2050; 2100	Short-term or long-term goals	2050 (4)	Puts pressure on current emitters to do more; medium-term targets are easier to communicate and are policy-relevant; 2100 too far away allowing too much flexibility to delay
				2100 (5)	Temperature-control target year; a crucial long-time horizon and an easy comparison to other studies; the climate issue is more than a century-scale challenge; temperature targets often refer to 2100
	Carbon budgets Global carbon budget	400; 1000; 1600 $GtCO_2$	1.5°C; 2°C with >66%; >55% likelihood	***1000 or 2°C with >66%*** (7)	400 $GtCO_2$ is too tight of a goal; most-realistic deep de-carbonization target; recognition of 2-degree goal; most discussed and probably the only feasible carbon budget; well-below 2-degree in line with Paris Agreement/ scientific community
	Emission pathways Global reduction target	1.5°C; 2°C with >66%; >55% likelihood		1600 or 2°C with >50% (1)	Gives a 50% chance of achieving a 2-degree target
				400 or 1.5°C (1)	Consistent with medium chance to limit climate change to 1.5 degrees

Approach	Potential variable	Parameter options	Explanation	Range of parameters (# of expert selections)	Reasoning
	CO_2 category	Incl. LULUCF; only energy; only industry energy	Focus on which emission sources	***incl. LULUCF*** (7)	Land use has equity implications; if only energy or energy/industry is chosen, some countries such as Brazil and Indonesia can emit LULUCF; for some developing countries, non-energy CO_2 are the most important emissions (from deforestation); it has become a standard for carbon budgets; all CO_2 contributes, no point in talking about negative emissions without including LULUCF emissions
				only industry and energy (1)	Until LULUCF emission data are clearly harmonized, also indicates the importance of common LULUCF.
				only energy (1)	Less uncertainty on energy CO_2 emissions for both historical and future scenarios
GF*	Participation threshold	Yes; no	Paris Agreement	Yes (4)	Lower-income countries should be allowed to maintain any energy installed capacity; low-income countries should not be penalized for their participation to the Paris Agreement, they should be required to achieve INDCs but not bear burden of GF; although many countries have commitments, some lower-income countries' actions would depend on financial/technological supports, also Paris Agreement is different from budget allocation.
				No (5)	No credible threshold at the moment; if possible, we should try to explore all possibilities; considering the current situation where low-income levels have submitted INDCs, it seems fine to include all countries; recent US exit makes this constraint problematic
PCC*	<u>Carbon budgets</u> Weighting factor	0.0-1.0	Range from emission share to population share	***0.5*** (7)	Ignorant uniform prior; GF* and IEPC* which are extreme and central of them seems reasonable; if we stay in the middle of the road we will be on the safe side; to stay as close as possible to the original idea that goes from 100% emissions to 100% population; equally consider both driving factors
				0.3 (1)	
				0.6 (1)	Should weigh towards population because GF is a poor excuse for continuing to act irresponsibly
	<u>Emission pathways</u> Convergence year	2050-2100	When to converge	***2050*** (3)	Later convergence is hard to defend; slower convergence rate; most close to the 30-year time span in Meyer (2000)
				2060 (1)	Convergence 40 years from now would allow plenty of time for recent capital investments to run their lifetime while making new investments in carbon-intensive technologies more expensive
				2075 (3)	Convergence after the medium-term goal, but before the end of the century; for 2050, time is insufficient, middle of the road between 2050 (earliest year possible) and 2100 (latest year possible)
				2100 (2)	Considering equity, it would be good condition for low-income countries; as the same as the temperature control target

Approach	Potential variable	Parameter options	Explanation	Range of parameters (# of expert selections)	Reasoning
ECPC*	Historical start year	1850; 1970; 1990	Industrial revolution; increasing research; first IPCC report	**1850** (4)	For most people historical emissions mean emissions from the industrial revolution, we should assume the same. If not, we should use another term instead of historical emissions; if historical, should start pre-industrial; the industrial revolution seems to be more emblematic in this case, choosing any one of the other two years seems to be more subjective, and as such more difficult to justify
				1970 (2)	Until then, the notion of climate change was not widespread. Also, carbon-intensive development allowed for technological improvements that have increased living standards (or at least created the technologies that would allow that to happen), the rules were different then
				1990 (3)	Recognition of climate change; in line with a societal acceptance that human activity causes global warming
	Discount factor (df)	1.6-2.8	Technological progress and past emissions out of atmosphere	0 (1)	Radical, but in terms of fairness considerations, emissions should not be discounted
				1 (1)	Closest to 1990-2010 AEEI
				1.6 (1)	This is consistent with the argument that for fairness (equity, responsibility, capacity), grandfathering needs to be considered. If India and China need to take responsibility for current and future emissions, the past and current emissions of developed countries cannot and should not be ignored.
				2 (4)	Reasoning seems like a good balance; 2.5 as sensitivity for more ambitious technological progress; reasoning is credible, test the entire range; Middle of the road, although not entirely sure
				2.5 (1)	Account for ambitious technological progress
				3 (1)	SRTP = 1 so discount r ate= 3
	Future discount factor	Yes; no	Difficult for carbon budget as value is independent of time	***No*** (6)	The future should not be discounted or, if so, at a very low discount rate, much lower than the 2% agreed upon for the discount factor. If future discounting is included, the discount factor should as well - Stern report
				Yes (1)	Why not? The same arguments apply as for discount factor. The difficulty is that countries would not get a carbon budget, but a time-weighted budget, and this will be difficult to handle
				N/a (2)	
AP*	Participation threshold	Yes; no	Paris Agreement	***Yes*** (6)	some lower countries' actions would depend on financial/technological supports.
				No (3)	Considering the current situation where low-income countries have submitted INDC, it seems fine to include all countries; restrictions seem off

Approach	Potential variable	Parameter options	Explanation	Range of parameters (# of expert selections)	Reasoning
GDR*	Historical start year	1850; 1970; 1990	Industrial revolution; increasing research; first IPCC report	***1850*** (4)	Same as ECPC*
				1970 (2)	Same as ECPC*
				1990 (3)	Same as ECPC*
	Weighting factor RCI	0.0-1.0	Range from responsibility to capability	**0.5** (7)	We can only start from a uniform prior and then consider sensitivity; Basically 0.5 but interested in the sensitivity test, whether it is sensitive or not. From the point of theoretical view, it would be hard to determine a single value other than 0.5; "middle of the road"; also needs a sensitivity case with 0 and 1; no strong preference
				0.6 (2)	Responsibility is more important considering the fair issue

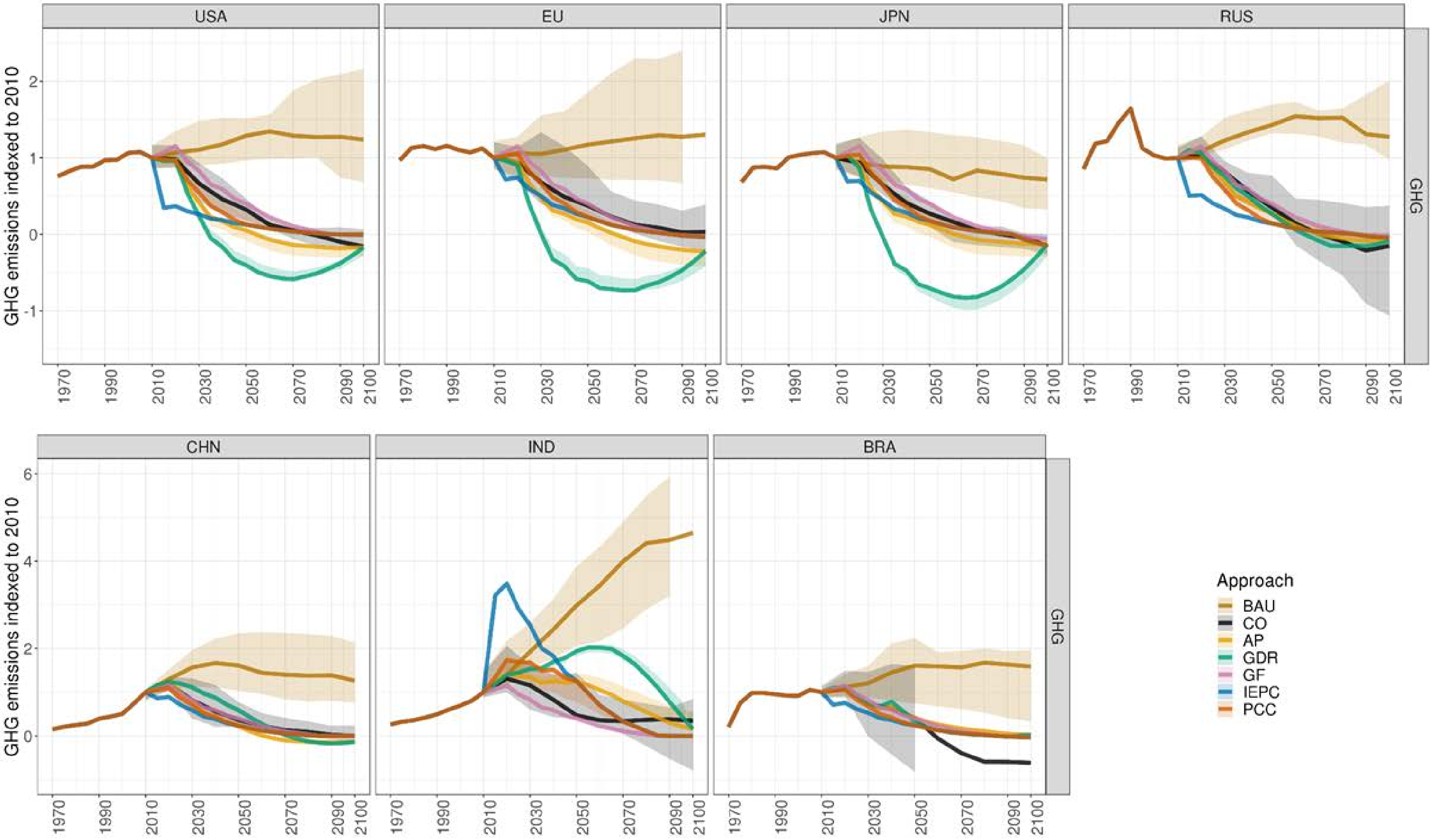

Fig. S.1 GHG emission allowances (including LULUCF) over time of different effort-sharing approaches per country (based on 2°C global target for total GHGs). Default pathways are shown as solid lines, and sensitivity ranges are shown as shaded areas (where for GDR, the default is always shown as part of the sensitivity range, even though default has the most extreme parameter choice, i.e. 1850 vs. 1970-1990 in the sensitivity range). USA: United States of America, EU: European Union, JPN: Japan, RUS: Russian Federation, CHN: China, IND: India, BRA: Brazil. BAU ('no policy' scenario from the CD-LINKS dataset) included for illustrative purposes only

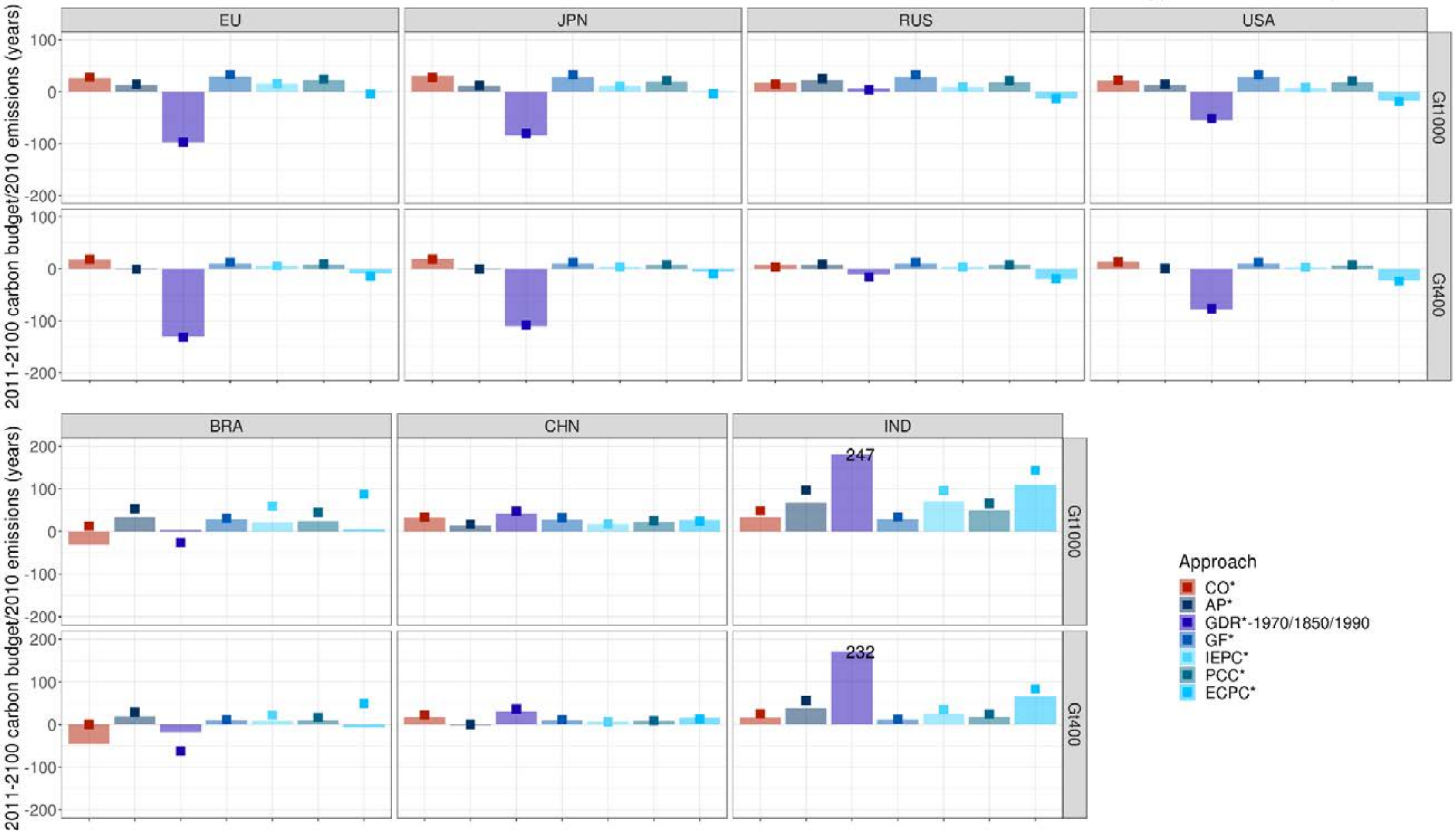

Fig. S.2 Carbon budgets of different effort-sharing approaches per country. The carbon budgets (2011-2100) are given in 2010 emission years. First and third row: based on 1075 $GtCO_2$ global carbon budget, second and fourth row based on 400 $GtCO_2$ global carbon budget. Default values are shown as filled bars for total CO_2, square for CO_2 from energy and industrial processes. One combination of parameter choices for GDR* is shown: sensitivity analysis on start year only (1970/1850/1990) with RCI at 0.5 (default), where the default is always shown as part of the sensitivity range, even though default has the most extreme parameter choice, i.e. 1850 vs. 1970-1990 in the sensitivity range. USA: United States of America, EU: European Union, JPN: Japan, RUS: Russian Federation, CHN: China, IND: India, BRA: Brazil. Note that India's emission years for energy and industrial processes CO_2 under GDR* are out of range, and therefore indicated by their values