Swiss Federal Office for the Environment (FOEN)

EMISSION PATHWAYS TO REACH 2°C TARGET
MODEL RESULTS AND ANALYSIS

Final Report
Zurich, 23 April 2012

Dr. Jürg Füssler, Martin Herren, Madeleine Guyer (INFRAS),
Joeri Rogelj and Prof. Dr. Reto Knutti (ETHZ)

The Swiss Federal Office for the Environment (FOEN) has funded the elaboration of this study that it considers as a valuable contribution to the debate on future greenhouse gas emission pathways. However, the FOEN does not necessarily endorse all the information, analyses, views and comments presented in this study that are the sole responsibility of the authors..

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

INSTITUTE FOR ATMOSPHERIC AND
CLIMATE SCIENCE
ETH ZURICH

UNIVERSITAETSTRASSE 16
CH-8092 ZURICH

WWW.IAC.ETHZ.CH

INFRAS

BINZSTRASSE 23
POSTFACH
CH-8045 ZÜRICH
t +41 44 205 95 95
f +41 44 205 95 99
ZUERICH@INFRAS.CH

MÜHLEMATTSTRASSE 45
CH-3007 BERN

WWW.INFRAS.CH

CONTENT

ACKNOWLEGEMENTS

The authors would like to thank the Swiss Federal Office for the Environment (FOEN) for financial support for this study and for fruitful discussions and inputs. We would also like to thank the members of the Swiss Delegation and OcCC who provided valuable comments and inputs into this project point as well as the research community that develops and maintains the incredibly useful suite of models used – in particular the MESSAGE integrated assessment model (IAM) operated at IIASA and the reduced-complexity climate system and carbon-cycle model MAGICC v.6.

EXECUTIVE SUMMARY

The present study aims at contributing to the discussion about *identifying a global goal for substantially reducing global emissions by 2050 and […] a timeframe for global peaking of greenhouse gas emissions*, a key issue tabled by the Cancun Agreements (2010) that was discussed at COP/MOP 17 in Durban. It builds on earlier studies on pathways (INFRAS 2008, 2010).

1. GLOBAL PATHWAYS TO 2°C

This modelling work analyses different pathways of global greenhouse gas emissions that are consistent with the 2°C target of the Cancun Agreements (2010). The analysis with an Integrated Assessment Model allows to calculate for a given emissions pathway the related least cost energy technology mix. For instance, the prescription of declining greenhouse gas emissions leads to a shift from coal and natural gas based power generation to renewables, energy efficiency and carbon capture and storage compared to the reference scenario.

Not raising the ambition of the 2020 pledges will make reaching the 2°C much more difficult and costly

Our preliminary modelling results indicate that with the current ambitions of the party's 2020 pledges it will be much more difficult (and costly) to reach the 2°C target than if substantial mitigation action is already taken up by all countries and sectors before 2020. The required transition to low carbon economies is difficult; without raising the ambitions significantly, the 2°C goal will be even more difficult to achieve. These findings are in line with similar results in the UNEP GAP report (2010).

Rapid emission reduction in Annex I and swift integration of non-Annex I countries into global mitigation action is instrumental in reaching the 2°C target

Our modelling of pathways indicate that even if Annex I (developed) countries would take swift action to rapidly reduce GHG emissions in the next decades, the 2°C target cannot be reached if non-Annex I (developing) countries do not participate soon in mitigation action but keep following a business-as-usual emissions pathway until 2030.

The results suggest that the room for manoeuvre is narrow. The 2°C target can only be met with likely probability if the integration of non-Annex I countries into international mitigation action can be achieved rather sooner than later. This is in line with the findings of the UNEP Gap report (UNEP 2010).

2. BURDEN SHARING

The work on emissions pathways on a global level identifies the need for very strong cuts in global emissions over the next decades in line with IPCC (2007a). The question on how to share this large global burden in emission cuts between different countries is primarily a political one. Science can only seek to provide relevant data that may feed into the political decisions taking process. The overarching principle of burden sharing is laid down in the Convention (UNFCCC 1992 Art.3): Action should be taken by all countries *on the basis of equity and in accordance with their common but differentiated responsibilities and respective capabilities*, with Annex I countries taking the lead.

The aim of the present modelling work on burden sharing is to illustrate on a conceptual level how different quantitative burden sharing algorithms lead to different emission reduction pathways for countries. Please note that these pathways are subject to high uncertainties and depend heavily on the assumptions made in the modelling. The selection of burden sharing approaches and their operationalization in the model is by no means comprehensive and should be regarded as an illustrative exercise in the quantitative analysis in burden sharing approaches. It is by no means a proposal for actual burden sharing between countries.

The following burden sharing approaches in line with the 2°C target are considered:

BURDEN SHARING APPROACHES		
Approach	**Curve**	**Description of implementation** (simplified, see section 3)
Indian proposal 2008	INDPRO	A developing country has to start mitigation action as soon as it reaches average per capita emissions or a GDP per capita of 20'000 USD.
Equal cumulative per capita emissions	CPC1990	The approach assigns for every country equal cumulative per capita emissions between 1990 and 2100.
Responsibility-Capacity Indicator	RCI	A country's share in mitigation efforts is proportional to the Responsibility-Capacity-Indicator. The indicator is composed of ¾ "polluter pays" (i.e. per capita emissions over last 10 years) and ¼ "ability to pay" (i.e. per capita GDP)

Table 1 Considered approaches to share the burden of emission reductions between countries (see section 3). All approaches are consistent with reaching the 2°C target.

The following figure summarizes the main results of the comparison of the three burden sharing approaches:

COMPARISON OF ANNEX I AND NON-ANNEX I PATHWAYS

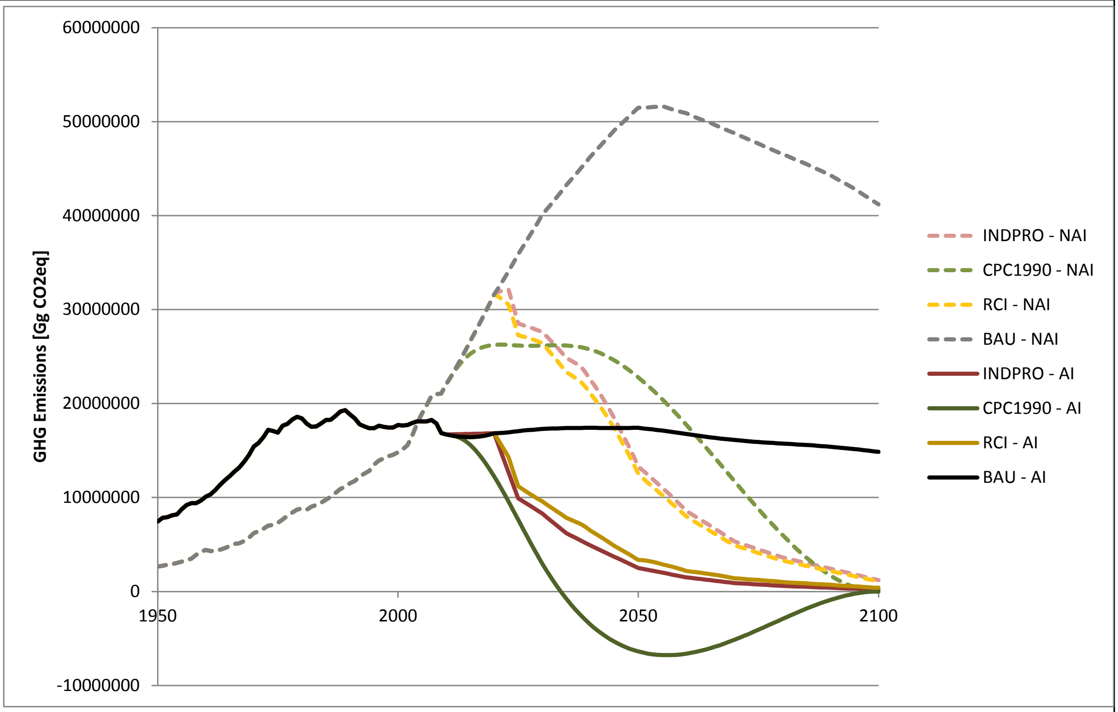

Figure 1 Global emission pathways for Annex I (*AI* – developed countries; *solid lines*) and non-Annex I countries (*NAI* – developing countries, *dashed lines*) for different burden sharing approaches: Indian Proposal 2008 (*INDPRO*), Cumulative per capita emissions since 1990 (*CPC1990*), RC-Indicator (*RCI*) and Reference scenario (*BAU*). All Kyoto-Gases considered excluding LULUCF. Please note that results are preliminary and for illustrative purposes only.

Developed countries have to rapidly reduce their emissions

The model results show that in the Indian Proposal as well as in the RC-Indicator approach, developed countries (Annex I) have to reduce emissions by -85% and -82%, respectively by 2050 (solid yellow and red lines in Figure 1). For individual countries, this rate can go down to lower rates (see Table 2). With the equal cumulative per capita emissions approach the allocation for developed countries goes even negative over many years (solid dark green lines in Figure 1 and Table 2).

Developing countries *on average* have to (stabilize and) reduce their emissions

The emission allocations resulting from the considered burden sharing approaches require also for average developing countries emission allocation to steadily decrease over the 21st century (with the equal per capita emission approach allowing for a period of stabilisation, followed by emission reduction).

The following Table 2 provides examples of results for different countries.

EXAMPLES OF COUNTRY PATHWAYS			
Country (or country group)	**Emissions 2050/1990**		
	INDPRO	**CPC1990**	**RCI**
Examples Developed Countries			
Japan	16%	-30%	4%
Russia, Ukraine, Belarus	7%	-29%	24%
USA	12%	-51%	20%
Western Europe (including Switzerland)	18%	-19%	9%
Examples Developing Countries			
China	68%	15%	136%
India	291%	651%	189%
Oil exporting middle Eastern countries plus Libya	56%	-19%	135%
Sub-Saharan Africa	292%	882%	165%

Table 2 Example results for some developed and developing countries. Percentages provide CO2eq Emissions in 2050 as percentage of 1990 Emissions for different burden sharing approaches: Indian Proposal 2008 (*INDPRO*), Cumulative per capita emissions since 1990 (*CPC1990*), RC-Indicator (*RCI*). Please note that results are preliminary and for illustrative purposes only.

Our modelling results show the following main characteristics of burden sharing approaches:

1. The Responsibility-Capacity-Indicator approach leads to less stringent emission reduction requirements for high emitting developing countries and a higher burden for low-emitting developing countries

The direct comparison of the implemented versions of burden sharing approaches indicate that the linear approach of the RC-Indicator leads to significantly less stringent emission reduction requirements for high emitting developing countries like China than the Indian proposal with its threshold approach, but put a higher burden to developing countries with low per capita emissions and high population growth rates (such as India and Sub-Saharan Africa) in particular in the first half of the 21st century.

2. The Indian proposal reflects different responsibilities and abilities

The Indian proposal allows developing countries with low per capita emissions and high population growth rates (such as India and Sub-Saharan Africa) for significant increases in their emission allocation. One might argue that this is more in line with the principle of equal rights to development. From this perspective, the Indian proposal might seem more adequate to reflect the different responsibilities and abilities of countries to contribute to climate change mitigation than the RC-Indicator approach.

3. Burden sharing based on equal cumulative per capita emissions: It seems not obvious how this approach could be implemented

For developing countries the approach leads on average to larger emission allocations than the two other approaches, in particular for countries with low per capita emissions and projections of strong population growth (e.g. India and Sub-Saharan Africa). Much more stringent emission reduction pathways (with net negative emissions in some years) result for high emitting developing countries such as China.

From a practical point of view it seems less obvious how such a burden sharing with very substantial net negative emission allocations for developed and advanced developing countries could be implemented. This difficulty would become even more pronounced if earlier years than the chosen base year 1990 would be considered.

Please note that these conclusions may only be valid for the implemented version of the burden sharing approaches. Other ways of their operationalization may lead to different conclusions.

Further work is needed to analyse and understand the impact of burden sharing approaches on country's emission pathways

The present study analyses different emission pathways for the 2°C target and illustrates some characteristics of different burden sharing approaches. The work also identified several shortcomings of the considered approaches and the need for further analysis, including the refinement of existing burden sharing approaches, analysis of new and more variants of burden sharing approaches etc.

We hope that in parallel to the scientific work done on this important topic the international negotiations process progresses and converges towards implementing actual quantitative emission limitations and restrictions for all relevant parties.

1. INTRODUCTION

The present study aims at contributing to the discussion about *identifying a global goal for substantially reducing global emissions by 2050 and […] a timeframe for global peaking of greenhouse gas emissions* as requested by the Cancun Accord (2010) for COP/MOP 17. It builds on earlier studies on possible pathways that focussed on one approach to burden sharing, the so called "Indian Proposal" (INFRAS 2008, 2010). The present study seeks to expand this work and in particular looks at several different burden sharing approaches and their impact on countries emissions pathways. Also, this work builds on a new partnership between INFRAS and the Institute for Atmospheric and Climate Science at ETH Zurich which is responsible for the modelling work, in particular with the MESSAGE integrated assessment model (IAM) and the reduced-complexity climate system and carbon-cycle model MAGICC v.6.

Part I provides a short overview of the current status in policy and science (section 2) and discusses different approaches to burden sharing (section 3). Part II presents results from modelling of different global pathways to reach the 2°C target (section 4) and investigates the impact of different burden sharing approaches on resulting emission pathways of countries (section 5). Part III closes with synthesis and conclusions.

PART I: INTERNATIONAL NEGOTIATIONS AND APPROACHES TO BURDEN SHARING

2. STOCKTAKING OF POLICY AND SCIENCE STATUS

2.1. THE STATE OF NEGOTIATIONS

Main outcome of the Copenhagen negotiations in 2009 was a minimal consensus document referred to as the Copenhagen Accord (CA), of which the parties merely “took note of”. However, the CA was eventually annexed with (voluntary) quantitative pledges by 44 developing countries (nationally appropriate mitigation actions of developing country Parties) and 42 developed countries, including aggregated pledges from 27 EU member states (quantified economy-wide emissions targets) for 2020. These pledges are stated as a particular per cent reduction in 2020 (commonly between 17% and 30%) from a certain base year (for example, relative to 1990, 2000, or 2005). Others are stated in terms of reductions in carbon intensity (percent decline in GtCO2e per unit of economic value). These pledges have become the basis for analysing whether the world is being able to achieve the long-term temperature target of limiting global temperature increase to below 2°C relative to pre-industrial and through what kind of pathways this could be reached. For a comprehensive list of pledges by Annex I and non-Annex-I countries (NAMAs) see Annex I.

Due to the deadlocked positions between industrialised, emerging economies and developing countries, negotiations during the COP16, hosted by Mexico in Cancun in December 2010 did not lead to a binding treaty a post-2012 agreement. No progress was made on the legal form of such an agreement including the US or on the establishment of a second commitment period to the Kyoto Protocol. By including the goal of limiting temperature increase to a global average of 2°C relative to pre-industrial levels, the AWG – LCA[1] brings, however, this aspiration into the formal UNFCCC process. However, the pledges that have been included in the Annex to the Copenhagen Accord have not been altered substantially to more stringent ones, neither during the Cancun negotiations, the Bangkok climate talks in April 2011, nor during the Bonn climate talks in June 2011, as mandated in the Cancun Agreement. Only a few countries made some specifications or clarification, e.g. regarding the accounting method used to define their target. The duty for the COP in Durban was therefore, to negotiate emission targets in order to achieve the 2° C target recognized in the Cancun Agreements. Besides the lack of binding quantitative,

1 http://unfccc.int/files/meetings/cop_16/application/pdf/cop16_lca.pdf

global emissions reduction targets until 2020 and/or 2050, also in the issue of the time of global peaking is not tackled yet and remains on the agenda for the next COP.

The pledges made by developed and developing country parties are widely acknowledged to not leading to achieving the 2°C target (SEI 2011, CAT 2011c, UNEP 2010, Rogelj et al. 2010). While analysing the pledges, one has to take into account that there are many factors which are yet needed to be clarified in order to estimate projected emissions in 2020 (REF ClimateAction-Tracker).

As outlined in the UNEP (2010) report pledges can be classified as conditional vs. unconditional and “lenient” versus “strict” rules. First of all, many countries made lower pledges that are unconditional and higher pledges that are conditional upon certain conditions (such as actions by other Parties or financial and technology support). Some countries also have only one target which is conditional on comparable action by other Parties (UNEP 2010, SEI 2011). However, up to now, there is a lack of clarity on the interpretation of the conditional targets. Developing countries pledges are often contingent on finance or technology transfer. However, the details on the nature and extent of this support required to implement the conditional pledges remain unclear. For most countries also the intended use of carbon offsets to contribute to the conditional targets of developing countries remains to be unclear (CAT 2011a).

Secondly, the international accounting rules for achieving emission reduction targets by 2020 are not clearly defined. For example, surplus emissions (surplus AAUs) arise when countries overachieve their targets during the first commitment period of the Kyoto Protocol. These surplus AAUs can be banked for the period beyond 2012 and could raise the effective emission limits of developed countries to an extent, which would allow them to not implement any further climate policies up to 2020 (CAT 2011b). Options to allow the full, unconstrained use of surplus AAUs from the first commitment period in the period beyond 2012 as well as to fully eliminate them by not allowing banking are included in the current negotiation text. The ultimate impact of all the options regarding a carry-over of the surplus AAUs depends on the willingness of countries to buy the surpluses. Several countries have stated to limit the use of surplus for the attainment of their 2020 pledges. For example, the European Union has stated not to recognize surplus AAUs from the first commitment period (CAT 2011b). Also in Switzerland’s current draft legal text on its national climate policy post 2012 no use of carry-over units and use/purchase of foreign AAUs is expected (see fccc/tp/2011/1).

The accounting rules regarding emissions from the land use, land-use change and forestry (LULUCF) sector for the time period beyond 2012 are also not yet decided upon. This implies that the extent to which LULUCF activities in Annex I countries could be used and help to meet the 2020 targets are still not clear (UNEP 2010). For some countries, an important crux is the choice of the reference level for forest management activities. This aspect is still being negotiated and multiple options are considered. These unresolved issues have the potential to lead to higher actual global emissions in 2020 than pledged [ref UNEP and ref CAT]. There are a range of other factors affecting the accounting of global emissions, such as e.g. how to include bunker emissions into a future agreement.

The timing of global emissions peaking and the definition of a global 2050 emission reduction target were also part of the mandate for COP 17 in Durban, as outlined in the LCA text of Cancun (Cancun Accord 2010):

"… to work towards identifying a global goal for substantially reducing global emissions by 2050, and to consider it at its seventeenth session" and *"… to work towards identifying a timeframe for global peaking of greenhouse gas emissions based on the best available scientific knowledge and equitable access to sustainable development, and to consider it at its seventeenth session*". The discussion in this regard is currently driven by opposing forces and viewpoints, which make the establishment of an equitable allocation of mitigation efforts difficult. On the one hand, arguments for stronger mitigation efforts by developed countries and a later peaking of developing countries are justified by the fact that developed countries have higher historic emissions and the emissions in developing countries that arise from activities that produce goods for consumption in developed counters. Furthermore, developing countries highlight their right for development and therefore argue that a later peaking than developed countries is appropriate. On the other hand, the share of global emissions that come from developing countries is increasing and currently already larger than the share from developed countries. This trend is expected to continue in future, supporting the argument, that most mitigation over the coming decades shall be achieved in developing countries.

In this context, the creation of new market-based mechanisms is another important point to be agreed upon. New market mechanism, such as e.g. sectorial trading, sectorial crediting or crediting of nationally appropriate mitigation mechanisms to enhance and promote the cost-effectiveness of mitigation actions, may have significant influence in the definition of future emission reduction pathways.

On October 2nd 2011, Switzerland has submitted in Panama a Submission to the LCA process aiming at (i) the recognition of a lack in ambition of current pledges, (ii) the evaluation of options in stepping up the pledges to more ambitious levels, (iii) the clarification of the pledges (as mentioned above) and (iv) an Agreement on the goal of a legally binding mid-term climate regime in Durban (Switzerland 2011).

2.2. THE STATE OF SCIENCE

The Fourth Assessment Report (IPCC, 2007a) of IPCC remains the most comprehensive and up-to-date summary on climate change. The Fifth Assessment Report (AR5) drafted by the IPCC is now underway. It will again consist of three Working Group (WG) reports and a Synthesis Report, to be completed in 2013/2014. While results of AR5 are not available yet, an assessment of the recent literature shows that the main conclusions of the physical science part of AR4 have not changed significantly. The evidence accumulates that humans are largely causing the observed warming, and newer model simulations confirm the emission reductions that are needed to stabilize temperature. Recent work highlights that much of the warming, once it is realized, is largely irreversible (e.g (Solomon et al., 2010)), and that the cumulative amount of greenhouse gas emissions approximately defines the long-term global temperature increase(Meinshausen et al., 2009, Matthews et al., 2009, Zickfeld et al., 2009, Allen et al., 2009). In order to achieve the 2°C target, the total amount of greenhouse gases emitted over the course of the century has to be limited to a specified total emission budget. Higher emissions earlier therefore imply lower emissions at a later stage. In the real world, emissions do not change instantaneously, but are dependent on feasibility factors such as economical and/or technological constraints. For example, changes in the energy system and industry that produces the bulk share of current emissions depend on the life time of energy and industry infrastructure (Davis et al., 2010) (for example, about 50 years for a coal-fired power plant) and the rate by which new technologies can be scaled-up. Therefore, specifying well-informed yearly targets at specific time intervals can assure that a technologically and economically feasible path is followed while limiting the total emissions over the century to a maximum budget (UNEP, 2010, Rogelj et al., 2011b).

The emission reduction pledges stated by the countries have not been developed through a quantitative top-down approach to emissions management, in the sense of first defining temperature limits and then negotiating and distributing the burden of emission reduction to the countries. Instead, they are a set of proposals by individual countries, collected in a bottom-up process. Currently, they are unlikely to be sufficient to satisfy a 2° target. The crux will therefore be to negotiate the emission reduction pathways in a way that they will not overburden the technological (refers to whether technologies exist and be scaled-up fast enough), social (refers to whether measures to control emission would be acceptable to society) or economical (refers to whether or not cost is considered prohibitively high) systems (UNEP, 2010, Rogelj et al., 2011b).

While total emissions determine the long term warming, the time evolution determines the rate of climate change, which for certain systems is an important factor (e.g. for the ability of biosphere and humankind to adapt to the change). For targets like 2°C, the required maximum rate of change is similar for any plausible emission path, but the duration of periods of high change differs between different pathways, leading to different time durations of adaptive stress.

3. APPROACHES TO BURDEN SHARING

The above-mentioned mandate urges Parties to find common ground on their pledges as soon as possible, as to avoid a gap between the commitment periods of the Kyoto Protocol. However, current debates about emission reduction pledges are hampered by fundamental discussions about how the burden of global emission reduction should be distributed and ultimately shared by all Parties. A burden-sharing approach determines how emission reductions are allocated to different participating countries according to a variety of rules and principles. Under the UN-FCCC (1992; Article 3.1-5) a variety of principles attempts to lay out the framework conditions for equity among member parties: Action should be taken by all countries *on the basis of equity and in accordance with their common but differentiated responsibilities and respective capabilities*, with Annex I countries taking the lead. This principle of Common but Differentiated Responsibility (CBDR) is a central concept that forms the basis for most burden-sharing approaches. The principle encompasses two aspects: first, there are differences in the contribution of states to current levels of greenhouse gases in the atmosphere and second, countries have varying technical and economic capacities to reduce them. The common responsibility of all states is to protect the climate system, but individual contributions are dependent to respective capabilities. However, the concepts of responsibility and capability are interpreted differently by the different stakeholders. Besides CBDR, further principles, such as the right to develop, precautionary principles, or the adequacy of action make the choice of one single approach even more complex. Most burden-sharing discussions originate from the question whether advanced and major emitting Developing Countries should commit to binding emission reductions and if so, to what extent and financed by whom.

To date a multiplicity of burden-sharing approaches has been discussed in the political and academic domain[2]. In the following, we provide a description of some of the burden-sharing approaches deemed most relevant and describe how they were technically implemented for analysis in the framework of this study. The three approaches analysed in this

[2] For an comprehensive overview of burden sharing approaches see section 13.3.3 in FAR WG3 (IPCC 2007)

study are, (1) the “Indian Proposal”, (2) Equal Cumulative Per Capita Emissions and (3) the Responsibility-Capacity Indicator approach.

Indian Proposal 2008

The Indian Proposal (INFRAS 2008, 2010) uses the level of actual per capita greenhouse gas (GHG) emissions (“polluter pays”) and the per capita gross domestic product (GDP) as a measure of the country’s economic strength and ability to pay. In the context of this study, the proposal is implemented as follows: All countries (parties) are divided into three groups: participating, non-participating and parties in a transitional state. A country changes its status from non-participating to participating in the year when its total greenhouse gas (GHG) per capita emissions reach the average level of all participating countries. Once a country reaches this per capita GHG threshold, it starts participating to the global GHG mitigation effort, and its per capita GHG emissions have to follow the reduction path of all other participating countries from that moment onwards. A transitional regime is implemented for countries that reach a GDP threshold of 20’000 US$/capita (ppp) before they reach the total GHG per capita emissions threshold of the participating countries. Countries that enter this transitional regime, have to stabilize their total emissions, but do not yet have to reduce their absolute amount of emissions. Only once they have reached the total GHG per capita threshold of the participating countries, the absolute emissions start declining. This proposal requires that the initial group of participating countries receives exogenous reduction targets. In this study, the exogenous reduction target, applied to all Annex I-countries, is defined, starting from the Annex I 2020 pledges, in a way such that the global emissions are consistent with the 2°C target. Furthermore, all per capita emissions of Annex I countries converge by 2050 (please note that in contrast this convergence by 2050 is not required in the RC-Indicator approach described below).

Equal Cumulative per Capita Emissions

The Equal Cumulative per Capita Emissions Proposal focuses on historic responsibility of countries and defines that over a given period of time and for all countries the sum of all per capita emissions is equal. As only the sum is defined, this proposal cannot specify one single pathway (or year-to-year evolution of emissions) which complies with the equal cumulative per capita constraint. Many pathways can comply with the overall constraints. Again, we choose our pathways in a way such that the cumulative amount of global emissions until the end of the 21st century are consistent with the 2°C target, and that the cumulative per capita emissions per country are equal from 1990 to 2100. We start to model emission allocation pathways from 2010 onwards. .

Technically, the allocations for each country are computed by optimizing a cubic spline shape over the 21st century in a way such that the cumulative per capita amount of emissions is equal for all countries within the accounting period. The choice of using a cubic spline to compute the pathways is arbitrary and not specified by the proposal itself. Emissions by 2100 are assumed to be zero for all countries.

Responsibility-Capacity Indicator

A third burden sharing approach, in line with an informal statement by the Swiss government, is analysed for this study (Fast Start Finance 2011). The Responsibility-Capacity Indicator approach (RC-indicator) is based on the principle that the effort of emission reductions can be distributed among countries using an indicator based on 2 principles:

(1) the “polluter pays” principle, based on “relative levels of emissions” and

(2) the “ability to pay” principle,

while different weights can be given to one of these two principles.

The “polluter pays” principle is computed in every year and for every country by taking the average per capita emissions per country over the 10 previous years. The “ability to pay” principle is implemented by taking the projected GDP/capita of each country (Van Vuuren et al., 2007). The RC-Indicator is computed as the normalized sum of the values resorting from both principles. The “polluter pays” principle is weighted relatively more (at 75%) and the “ability to pay” relatively less at 25%. The GDP/capita projections at a country level are from the downscaled SRES A1B scenario from (van Vuuren et al., 2006). In this study, the RC-indicator has been used to share the effort between the Infras reference scenario defined in section 4 and a mitigation scenario which mimics the “Pledges” pathway of section 4 until 2020 and that is in line with the 2°C target.

All of these approaches can be regarded as being based on the principle of Common but Differentiated Responsibility. However, further perspectives regarding equity are addressed individually (Table 3).

BURDEN SHARING APPROACHES AND EQUITY					
Approach	**Allocation Equity**	**Outcome equity**	**Historic responsibility**	**Ability to pay**	**Comment**
Indian proposal 2008 (per capita emissions threshold approach)	Per capita emissions	Per capita emissions of AI converge by 2050	The historical level of per capita emissions defines if a country participates from the beginning or not.	Additional transitional regime based on GDP lets more affluent NAI-countries stabilize GHG emissions	Developing countries with large populations participate later. Initial exogenous allocation scheme for Annex I countries consistent with 2°C is crucial.
Equal cumulative per capita emissions	Per capita emissions	Same cumulative per capita emissions for all countries between 1990 and 2100	Cumulative per capita emissions for a specific period of time	Not taken into account	Determination of period per capita emissions are accounted for is considered is crucial.
Responsibility-Capacity Indicator	Per capita emissions (75% weight) and GDP/capita (25% weight)	Ranking according to indicator	Average per capita emission per country in previous 10 years	GDP/capita	Approach is related to Indian Proposal, but more gradual

Table 3 Burden Sharing Approaches as implemented in this study in the light of equity principles.

The table shows that the Indian Proposal and the RC-Indicator approaches are related in that they both build on per capita emissions and GDP to determine the burden sharing. Results for the RC-Indicator approach show that is a more gradual approach than the Indian Proposal. With the RC-Indicator approach, the burden allocated to an individual country (party) steadily increases with increasing emissions and economic development, whereas with the Indian Proposal the burden and therefore emission path of countries shifts suddenly as soon as they make the transition from the group of non-participating to the group of participating countries.

The equal cumulative per capita emissions approach focuses entirely on past emissions and disregards the (economic) ability of countries in engaging in GHG mitigation actions.

This will be further analysed in the model results section 5.

PART II: MODELLING OF EMISSION PATHWAYS

4. MODEL RESULTS: GLOBAL EMISSION PATHWAYS

Several global emissions pathways are conceptually possible that are consistent with achieving the 2°C target. However, they exhibit varying levels of technical and socio-economic feasibility. In the following, we consider on a global level three different pathways reaching the 2°C target (as included in the Cancun Agreement) as well as a pathway consistent with a 1.5°C target (which the Cancun Agreement requires to reconsider in 2015) and analyse their characteristics. The pivotal question is how pathways where fast mitigation action is taken compare to more lenient approaches.

4.1. CHARACTERISTICS OF GLOBAL EMISSION PATHWAYS

The global emission pathways in Figure 2 (left) were computed with the MESSAGE integrated assessment model (IAM) of the International Institute of Applied Systems Analysis (IIASA, Austria). IAMs simulate evolutions of the global energy system and take into account constraints on technological market penetration, technological availability, and resource constraints, amongst other things (see also (O'Neill et al., 2009)). As such IAMs can give insights in the technological and economic feasibility of emission pathways.

Reference scenario

As a basis for the evaluation of global pathways and burden sharing, a reference scenario has been defined. The Reference scenario is constructed based on the latest historical data submitted by Parties to the UNFCCC, the unconditional emission reduction pledges from both Annex I and non-Annex I Parties as assessed in the UNEP "The Emissions Gap Report" (UNEP, 2010), and further uses the projections from the IEA World Energy Outlook 2009 reference scenario. The methodology and sources are similar to the "PRIMAP B" scenario in (Rogelj et al., 2011a), but with the most recent CRF data for Annex I countries and National Communication data for non-Annex I countries. More background on the methodology can be found in (Nabel et al., 2011). It should be noted that emissions data submitted by parties may be of heterogeneous quality, in particular for non-energy related emissions and LULUCF.
The reference scenario assumes that energy efficiency improvements follow historically observed trends. The energy mix is balanced over all supply options (gas, coal, nuclear etc.). As

such, this scenario does not represent a worst case scenario in terms of greenhouse gas emission during the 21st century as they have been assessed in the literature (Sanderson et al., 2008).

Emission Scenarios

Six emission pathways are shown in Figure 2 (left) and Table 3. All but two of the five pathways shown are computed with the MESSAGE IAM. The setup of the pathways is based on (GEA, 2011) and uses a setup similar to (Rogelj, forthcoming).

PATHWAYS			
Pathway	**Description**	**Target**	**Comment**
Reference	Business as usual including energy efficiency improvements following historical trends	n.a.	See section 0 below
Climate commitment	Sudden stop in global emissions in 2010	n.a.	Purely hypothetical pathway to demonstrate inertia of climate system
Optimal	Globally cost optimal path to target	2°C	Assumes full participation of all sectors in all regions (Annex I and NAI) from *2010*
Pledges	Assumes reaching of emissions pledges 2020	2°C	Assumes full participation of all sectors in all regions (Annex I and NAI) from *2020*
Delayed non-Annex I	Entire mitigation action until 2030 is carried out by Annex I countries	2°C	Assumes full participation of all sectors in all regions (Annex I and NAI) from *2030*
1.5°C target	Full technology scenario leads to return to 1.5°C by 2100 with 50% likelihood.	1.5°C	Pathway overshoots 1.5°C and approaches 1.5°C from top towards 2100

Table 1 Overview on pathways of global GHG emissions considered in this study.

Besides the “reference” pathway characterized above, the “climate commitment” pathway (light blue in Figure 2) represents a sudden stop in global emissions in 2010, and was not modelled with the MESSAGE model. From the other four pathways, three represent pathways with a similar cumulative total greenhouse gas emission budget[3] over the 21st century. The latter three

[3] The emission budget in the model runs has been counted from 2000 until 2110 and amounts to approximately 2400 to 2500 GtCO2e over the entire time frame. This budget has been chosen in a way such that the perfect foresight, full-portfolio energy system simulation from 2010 until the end of the 21st century yields an emission path which has a greater than 66% chance to limit global temperature increase to below 2°C above pre-industrial levels. The applied cumulative GHG emission budgets roughly result in a 1900 to 2000 GtCO2e budget between 2000 and 2050. This is consistent with earlier studies which, at that point, did not yet assume a large potential for negative emissions in the second half of the century. For example: MEINSHAUSEN, M., MEINSHAUSEN, N., HARE, W., RAPER, S. C. B., FRIELER, K., KNUTTI, R., FRAME, D. J. & ALLEN, M. R. 2009. Greenhouse-gas emission targets for limiting global warming to 2°C. *Nature,* 458**,** 1158-1162.

emission pathways have been modelled with the MESSAGE integrated assessment model (IAM) operated at IIASA. These pathways are illustrations of possible and internally consistent evolutions of emissions, but do not represent an in-depth analysis of feasibility of each of the pathways or of the 2020 emission levels. The costs associated with each path differ significantly. For the creation of the pathways we assume that all currently known mitigation technologies will be available in the future but have nuclear energy supply phase-out over the 21st century[4]. Based on the IAM results, the "Optimal" and "Pledges" pathway can be considered "technologically and economically feasible" (see Box 1). The "Delayed non-Annex I" pathway is considered not to be "technologically and economically feasible" by the model.

The "Optimal" pathway (purple) shows the emissions in case a globally cost-optimal path would be followed from today onwards. This is only possible through full and immediate participation of all sectors in all regions. Such early action allows for slower emissions decrease in later decades and allows for positive global emissions in 2100, reducing the need for potentially very costly technologies with negative emissions such as biomass energy combined with carbon capture and storage (CCS). As an example, the mix of energy technologies assumed for the "Optimal" pathway is shown in Annex II (A).

The orange "Pledges" pathway first raises to global emission levels in 2020 in line with the estimate emission levels based on the emission reduction pledges of countries under the Copenhagen Accord and the Cancún Agreements (from (UNEP, 2010)). After 2020 it is assumed that all sectors and all regions participate in the global mitigation effort. The orange pathway can only be considered "feasible" if one assumes major technological breakthroughs such as the advanced decarbonisation of the transportation sector, with the pace of energy efficiency improvements and technology penetration rates lying beyond those observed in the past. This pathway requires a massive upscaling of CCS to reach net negative global emissions at the end of the 21st century.

4 In particular no new investments are made in nuclear energy beyond today. This assumption is made to assure partial consistency with current Swiss energy policy (Bundesrat 2011).

Box 1: What are "feasible pathways" in the context of the Integrated Assessment Model?

The Integrated Assessment Model (IAM) optimizes overall cost to reach a certain global emission level. Besides the existing energy technologies such as fossil fuel based power generation or CCS (and their future improved versions), the model provides the technological option of very expensive (>1000USD/tCO2) yet unknown "backstop" mitigation technologies. Scenarios, where existing technologies are not sufficient to reach required emission levels are characterized by high levels of this "backstop" technology. In general, the amount of unknown backstop technologies allowed by the end of the century should not exceed 5% for a scenario to be considered technologically and economically feasible [ref Chapter 17 GEA].

It should be however noted, that scenarios that are considered technologically and economically feasible in the sense of the IAM may not materialize, because of socio-political barriers. E.g. all scenarios compliant with the 2°C target assume to a large extent the realisation of economically and technically feasible potentials in fossil and biomass based CCS. Given the barriers that current CCS pilot projects face, at this point it seems rather unlikely that such low carbon technologies will be disseminated with sufficient pace to allow for the emission reductions assumed in the considered pathways.

The "delayed non-Annex I" pathway (dark red) represents a pathway in which the entire mitigation action until 2030 is carried out in developed countries and non-Annex-I parties follow a BAU emissions scenario between 2020 and 2030. Developing countries join the global effort to limit global temperature to below 2°C above pre-industrial levels after 2030. Global emissions peak therefore only in 2030 and have to decline very steeply thereafter. Significant net negative global emissions in the last quarter of the 21st century are necessary to reach the 2°C target. This pathway is considered technologically infeasible by the IAM, because not enough technologies are available to generate the steep and sustained decrease in emission after the peak. The only way in which the (technology-rich) MESSAGE model is able to simulate such a path is by assuming that more than a quarter of the total energy demand by 2100 is met by unknown so-called "backstop" technologies (see Box 1). Therefore the "delayed non-Annex I" scenario shown in Figure 2 (left) is considered technologically and economically infeasible.

The "1.5°C" scenario (light green) represents a full technology portfolio scenario with a reduced global total emission budget[5] which allows returning to below 1.5°C by 2100 with at least a 50% chance. According to the IAM results, such a scenario is only feasible, if large investments

[5] In analogy with the approach for the 2°C budget, the 1.5°C cumulative GHG emission budget has been determined in way such that the perfect foresight, full-portfolio simulation yields the desired climate outcome.

at the demand side are combined with policies that promote energy-efficient ways of living (GEA 2011) in order to embark on a future high-efficiency and low-demand path. For example, such a low energy demand future includes a very strong shift to a globally decarbonized transportation sector and an emphasis on public transport. Also this pathway requires considerable net negative global emissions in the last quarter of the 21st century.

This set of possible future emission pathways show very distinct characteristics. All pathways exploit the full allowable potential of biomass combined with carbon capture and storage (BECCS) and all allow the full use of the fossil CCS potential. The “Optimal”, “Pledges”, and “1.5°C” scenario all are able to limit global temperature increase to below 2°C without a future reliance on nuclear energy or other yet unknown “backstop” technologies. For the “1.5°C” scenario a very important shift to energy-efficient modes of living, including a decarbonisation (implying a large-scale electrification) of the global transport sector, would be a requirement.

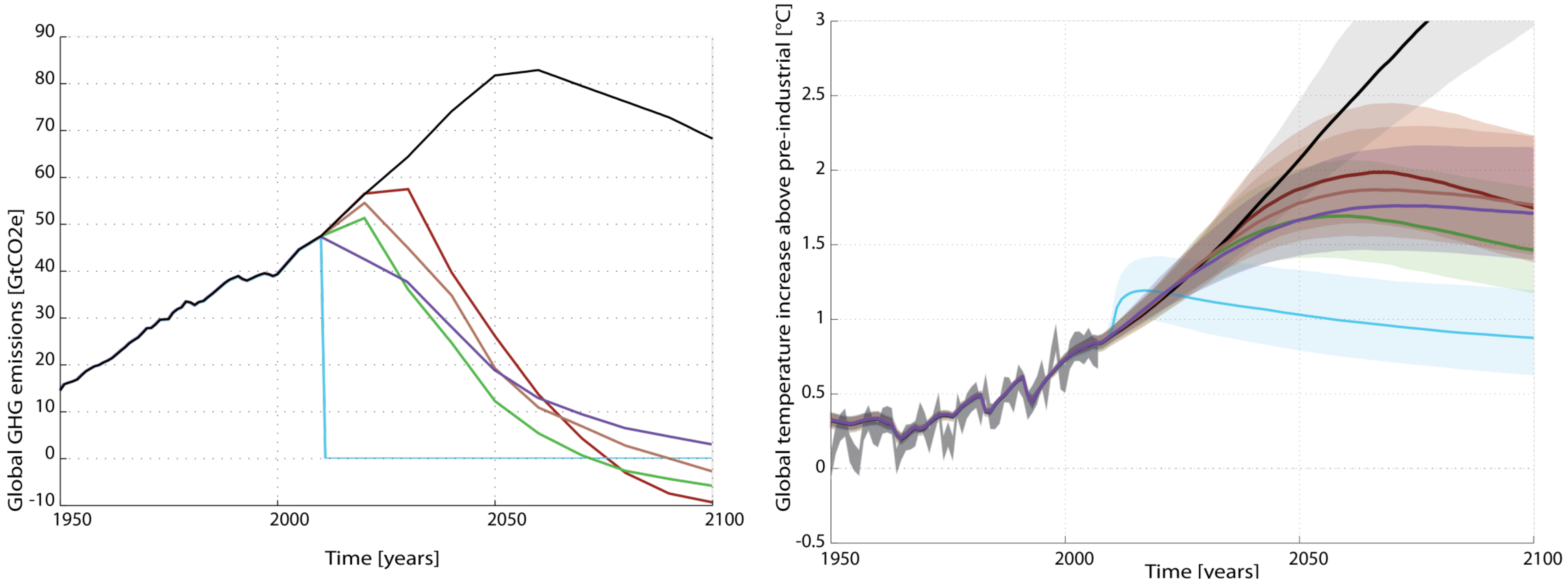

Figure 2 Left: considered pathways for global GHG emissions excluding LULUCF (**Reference**, **Climate commitment**, **Optimal**, **Pledges**, **Delayed non-Annex I**, **1.5°C target** – see Table 1). Right: Resulting probabilistic temperature projections for each of the pathways based on MAGICC model showing median and "likely" (66%) probability ranges.

4.2. GLOBAL TEMPERATURE PROJECTIONS

For each of the global emission scenario described in Table 1, probabilistic temperature projections are computed with the reduced-complexity climate system and carbon-cycle model MAGICC (Meinshausen et al., 2011a), version 6. MAGICC has been calibrated and can reliably simulate atmospheric CO_2 concentrations from emissions following high-complexity carbon-cycle models (Meinshausen et al., 2011b, Meinshausen et al., 2011a). Also its global average near-surface warming projections are closely in line with estimates from the suite of atmosphere-ocean general circulation models, as assessed in the IPCC AR4 (IPCC, 2007b). The model has been constrained with historically observed hemispheric land/ocean temperatures (Brohan et al., 2006) and ocean heat-uptake estimates (Domingues et al., 2008). It further emulates the C^4MIP carbon-cycle models (Friedlingstein et al., 2006) and uses a climate sensitivity probability distribution (Rogelj et al., in review) which closely reflects IPCC estimates (IPCC, 2007b). For each pathway, a 600-member ensemble is calculated to determine its transient temperature probability distribution. The figures show the median and the 66% probability range.
The emission pathways resulting from the “Optimal”, “Pledges” and “Delayed non-ANNEX I” scenario all stay with a likely (greater than 66%) chance below 2°C in the long term (i.e. beyond the 21st century). However, they show very distinct differences in their transient exceedance probabilities. Whereas both the “optimal” and the “pledges” scenario limit global temperature increase to below 2°C with a likely (greater than 66%) chance during the entire 21st century, this probability for the “delayed non-ANNEX I” scenario is reduced to 50%. Despite having the same long-term probability to stay below 2°C, the “delayed non-ANNEX I” shows significantly longer periods in which the rate of temperature change exceeds 0.2°C per decade, a threshold that may being implying increasing amounts of adaptation stress to eco-systems.

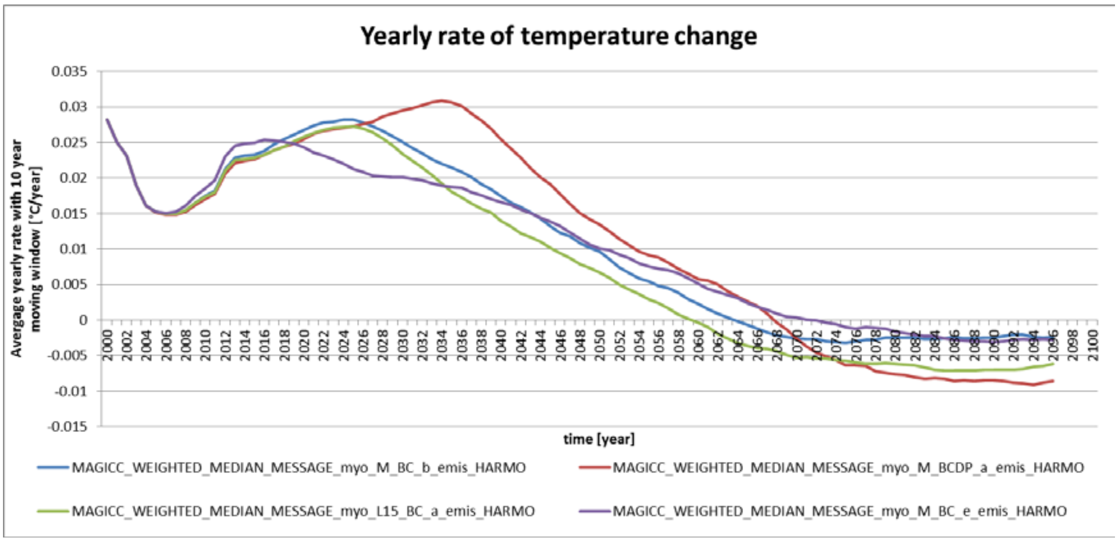

Figure 3 Resulting rate of temperature change per year (10 year moving average) for considered pathways of global GHG emissions (**Optimal**, **Pledges**, **Delayed non-Annex I**, **1.5°C target** – see Table 1).

For comparison, Figure 2 provides also a Reference (BAU) scenario (for definition see section 0). The median temperature estimate in 2100 for the BAU scenario is 3.7°C above rep-industrial, with a 66% confidence range of 3.0 to 4.6°C.

5. MODEL RESULTS: BURDEN SHARING – COUNTRY (-GROUP) LEVEL

In this section, the “Pledges” pathway from section 4 serves as a the basis for exploring three different approaches to sharing the burden of emissions reductions to meet the 2°C target between countries (parties). The three burden sharing approaches considered are described in section 3: (i) Indian proposal, (ii) Equal cumulative per capita emissions, and (iii) Responsibility-Capacity Indicator. For the RC-Indicator based approach, the “burden” of emission reductions to be shared by countries results from the difference between “Reference” and “Pledges” pathways.

In the following, the characteristics of the different burden sharing approaches and their impact on the relative share of emission allowances for different counties or country groups are analysed. It should be noted that underlying assumptions regarding data, models and necessary emission reduction efforts are subject to significant uncertainties and that the results should therefore be considered quantified illustrations of the different concepts rather than exact calculations. The resulting pathways for specific country (groups) are not proposals for the actual burden sharing, but aim at illustrating the dynamic interaction of different approaches and assumptions and highlighting major challenges that lie in such an effort sharing exercise.

5.1. BURDEN SHARING BETWEEN ANNEX I AND NON-ANNEX I COUNTRIES

Figure 4 shows the resulting pathways for both developed countries (Annex I – “AI”) and developing countries (non-Annex I – “NAI”). The reference scenario (BAU) assumes for Annex I countries roughly a stabilisation of emissions, whereas non-Annex I countries from 2010 to 2050 are expected to more than double their GHG emissions to over 50 Gt CO_2eq (black/grey).

COMPARISON OF ANNEX I AND NON-ANNEX I PATHWAYS

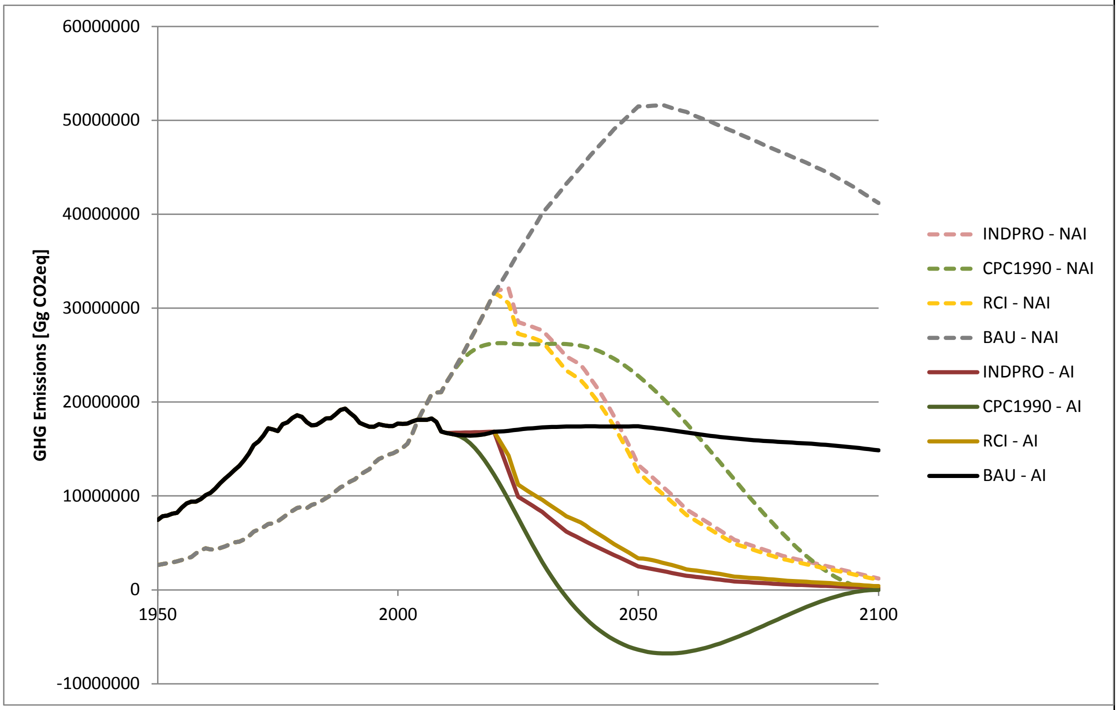

Figure 4 Global emission pathways for Annex I (AI – developed countries; *solid lines*) and non-Annex I countries (NAI – developing countries, *dashed lines*) for different Burden sharing approaches: Indian Proposal 2008 (INDPRO), Cumulative per capita emissions since 1990 (CPC1990), RC-Indicator (RCI) and Reference scenario (BAU). Please note that results are preliminary. All Kyoto-Gases considered excluding LULUCF.

The RC-Indicator approach requires a very rapid decrease in emissions in Annex I countries right after the defined Pledges of 2020 (RCI-AI), because of the high per capita emissions and GDP leading to a high RC-Indicator which requires Annex I countries to shoulder a large amount of the reduction burden. But by 2020 also a significant number of non-Annex I countries *in total* are expected to have reached per capita emissions and GDP levels that trigger immediate strong emission reductions.

On the global level of Annex I vs. non-Annex I countries, the threshold based Indian proposal (INDPRO) leads to rather similar results than the more gradual RC-Indicator approach (RCI), because both approaches mimic the total global emissions (AI plus NAI) of the “Pledges” scenario of section 4. Also, both approaches are primarily driven by actual (INDPRO) or average past emissions during the last ten years (RCI), respectively, resulting in similar shapes. The Indian proposal is somewhat more stringent for total AI emissions in 2050 than RC-Indicator (15% of 1990 emissions instead of 18%) and somewhat less stringent with NAI countries (108% instead of 95%), as shown in Table 4.

BURDEN SHARING APPROACHES					
Approach	**Curve**	**Peaking for NAI**	**2050/1990 ratio for AI**	**2050/1990 ratio for NAI**	**Comment**
Indian proposal 2008	INDPRO	2022	15%	108%	Enforces equal per capita emis-sions in 2050
Equal cumulative per capita emissions	CPC1990	Plateau 2016 - 2034	-27%	192%	Net negative emissions from 2034
Responsibility-Capacity Indicator	RCI	2020	18%	95%	

Table 4 Characteristics of pathways of Annex I (AI) and non-Annex I (NAI) countries under different burden sharing approaches (for approaches see section 3). Please note that results are preliminary.

The pathways resulting from the Equal Cumulative per Capita Emissions proposal since 1990 (CPC1990) display very different characteristics: firstly, both AI and NAI emission paths are by design not bound to the 2020 pledges (as this would lead to even more extreme i.e. net negative curves) but require for AI countries an immediate and rapid reduction after 2010 leading to net negative emissions from 2034 on and reaching -27% of 1990 levels by 2050. NAI countries can still grow their emissions for a few years, and then stabilize on a plateau until about 2034. Then the NAI emissions decrease, converting to zero emissions towards 2100 (by design). Even though NAI countries have also very substantial emissions after 1990, the main driver shaping these burden sharing pathways are population growth in NAI over the entire first halve of the 21^{st} century, whereas population numbers in AI countries stay constant (see population data in Annex II (B)). This approach leads to a strong redistribution of emissions towards countries with growing populations.

Cummulative emissions per approach (billion t CO2)	2010 - 2020				2010 - 2030				2010 - 2050				2010 - 2100			
	IND-PRO	CPC	RCI	BAU	IND-PRO	CPC	RCI	BAU	IND-PRO	CPC	RCI	BAU	IND-PRO	CPC	RCI	BAU
Annex-I	184	167	182	182	293	238	303	353	391	176	429	701	437	-10	500	1501
Non-Annex I	293	273	293	293	588	535	576	656	1015	1039	978	1583	1282	1510	1223	3949

Table 5 . Cumulative emissions for different burden sharing approaches from 2010 until 2020, 2030, 2050 and 2100 for Annex-I and non-Annex-I countries.

The cumulative emissions for different burden sharing approaches from 2010 are provided in Table 5. Again, figures for the Indian proposal (INDPRO) and the RC-Indicator approach (RCI) are rather similar. The Equal Cumulative per Capita Emissions approach (CPC) requires Annex-I countries to neutralize all emissions from 2010 by later negative emissions leading to no net cumulative emissions from 2010 to 2100. In turn, CPC allows for the highest cumulative emissions from non-Annex-I countries until 2100 of the three considered approaches.

5.2. BURDEN SHARING RESULTS FOR SPECIFIC CONTRIES

5.2.1. BURDEN SHARING APPRAOCHES ON COUNTRY LEVEL

In the following, results for the burden sharing algorithms for a number of selected countries are shown. Graphs for all countries or countries are provided in Annex II (C).

Please note that these pathways are subject to high uncertainties and depend heavily on the assumptions made in the modelling. Their aim is not to prescribe emission allocations for specific countries and specific years but to illustrate the main characteristics of the different burden sharing approaches considered for different country circumstances. The model results are by no means meant as a proposal for actual burden sharing between countries. Also it should be noted that there are many more burden sharing approaches that have not been considered in the framework of this study.

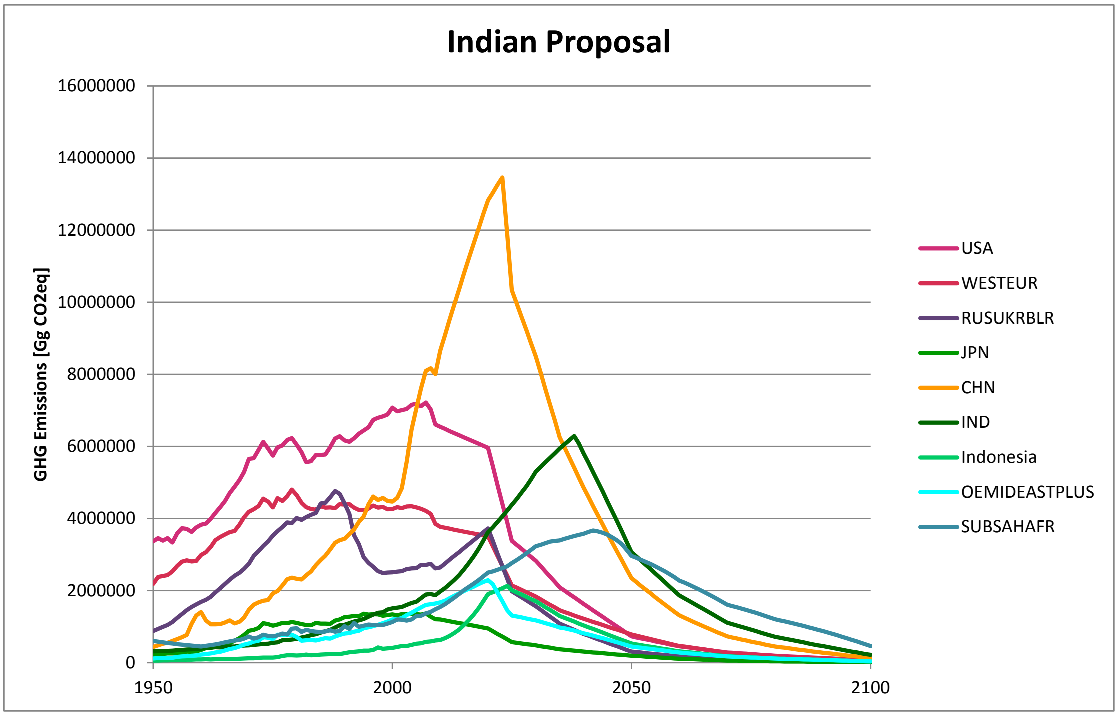

Figure 5 Results for *Indian Proposal 2008*: Emission pathways for countries and country groups. (For all countries/groups see Annex II (C)).

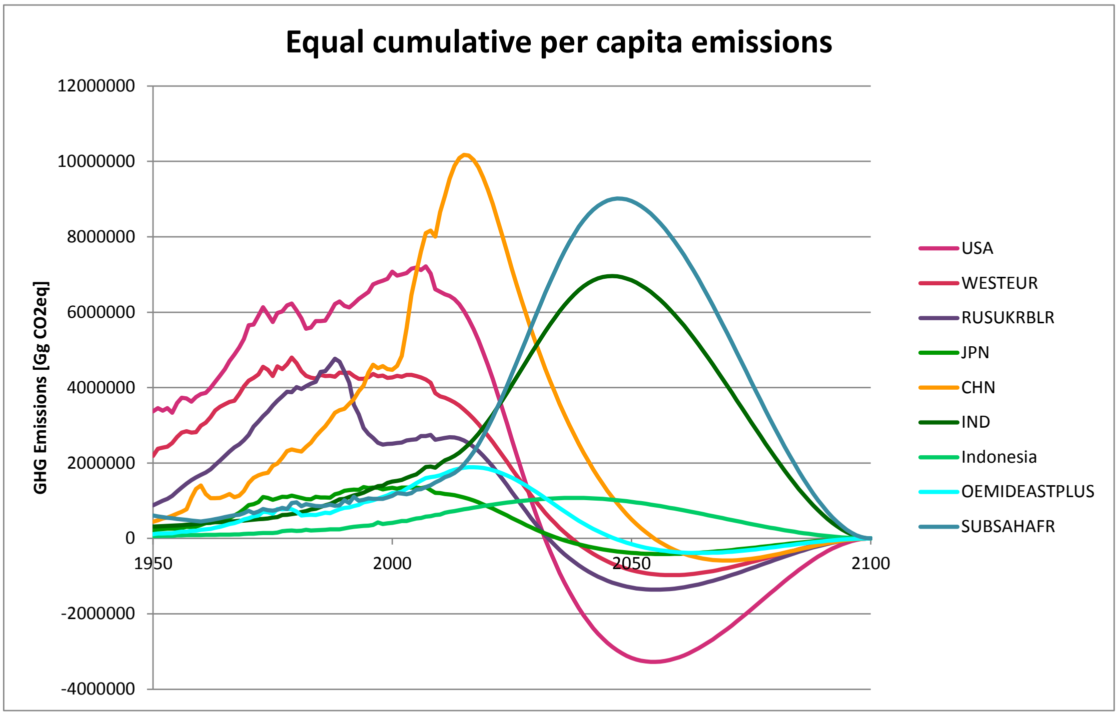

Figure 6 Results for *Equal cumulative per capita emissions*: Emission pathways for countries and country groups. (For all countries/groups see Annex II (C)).

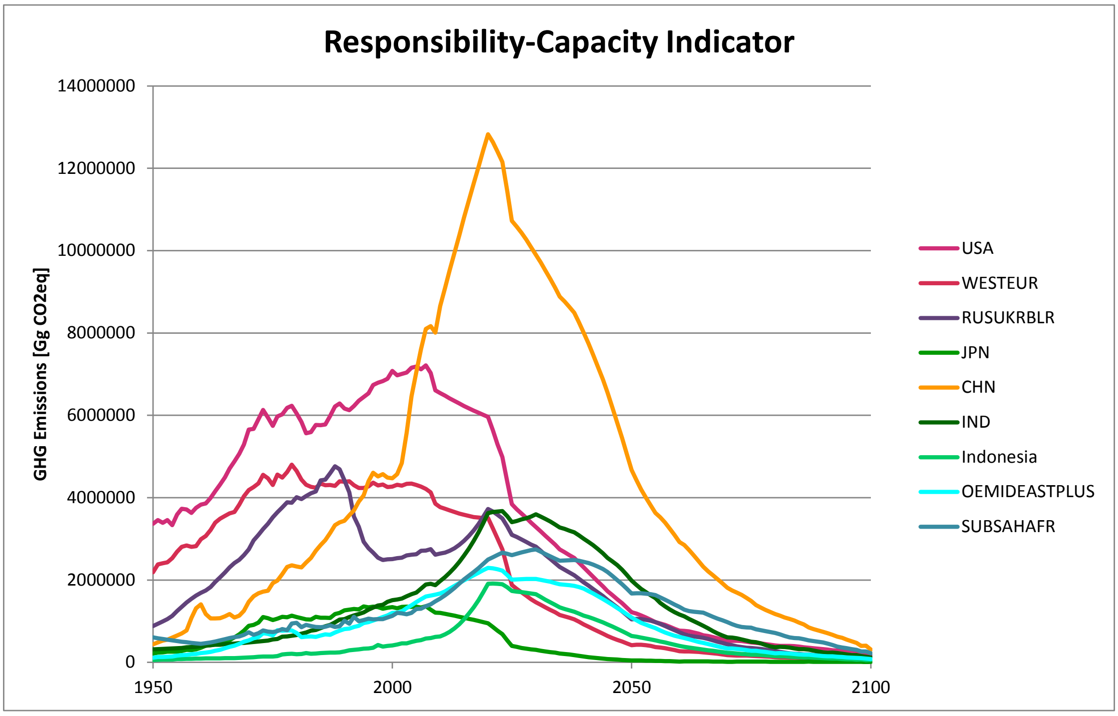

Figure 7 Results for *Responsibility-Capacity Indicator*: Emission pathways for countries and country groups. (For all countries/groups see Annex II (C)).

Figure 5 to Figure 7 provide an overview of the main characteristics of the considered burden sharing approaches on the level of individual countries or country groups. It turns out that the main characteristics of AI and NAI countries under different burden sharing approaches are also mirrored on the level of single countries or country groups, as shown in Figure 5 and Figure 6: The Equal per capita emissions approach (Figure 6) results for AI countries in an immediate and rapid reduction after 2010 leading into net negative emission allocations from around 2030-40 while NAI countries, because of lower historic emissions since 1990, can increase emissions and peak much later. In the Equal per capita emissions approach there is a marked difference within NAI countries with China (yellow) having to almost immediately start rapid reduction (from 2015), similar to the AI countries, whereas NAI countries with much lower emissions since 1990 such as India (dark green) can continue increasing emissions and peaking only around the middle of the century.

With the Indian proposal (Figure 5), it becomes apparent that for some NAI countries, e.g. India (dark green) and China (yellow) this approach leads to a strong increase in emissions until participation (China in 2023, India in 2039), followed by an equally rapid decrease. These steep emission pathways are typical for threshold-based approaches such as the Indian proposal. (A full list of participating years is provided in Annex II (D).)

However, it should be noted that the pathways have to be interpreted as emission allowances and not as actual emissions of a country. Emissions trading and other new market mechanisms would support the gradual technology transition over decades, leading to much less pronounced peaking of actual NAI country emissions than Figure 5 might insinuate.

The Equal cumulative per capita emissions approach (Figure 6) shows again the significant net negative emission allocations for AI countries. The salient feature however are the large allocations for India (dark green) and Sub-Saharan Africa (grey-blue) after 2020 resulting from the expected considerable increase in population and low average per capita emissions.

The Responsibility-Capacity Indicator approach (Figure 7) leads in general to a similar pattern than the Indian proposal (Figure 5), but populous lower income countries such as India (dark green) and Sub-Saharan Africa (grey-blue) receive a much less generous allocation, whereas the burden for AI countries and NAI countries with higher per capita emissions such as China (yellow) are eased. This is based on the fact that the RC-Indicator requires an earlier, even though very small contribution, of low emitting NAI countries, whereas the Indian Proposal allows for more increase of emissions until they hit the threshold of average emissions.

In the following, we discuss specific country cases to deepen the analysis of the characteristics of the considered burden sharing algorithms somewhat further.

5.2.2. DISCUSSION OF SELECTED COUNTRIE'S PATHWAYS

Examples from Annex I countries

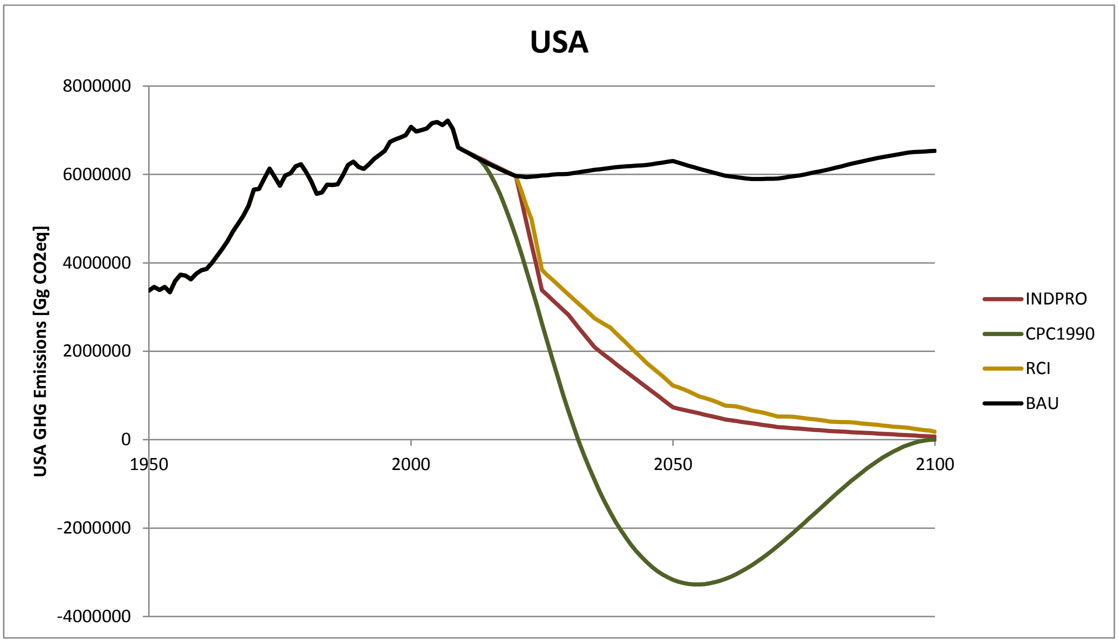

Figure 8 USA – Resulting emission pathways for Indian proposal, Equal cumulative per capita emissions 1990, Responsibility-Capacity Indicator and Reference scenario.

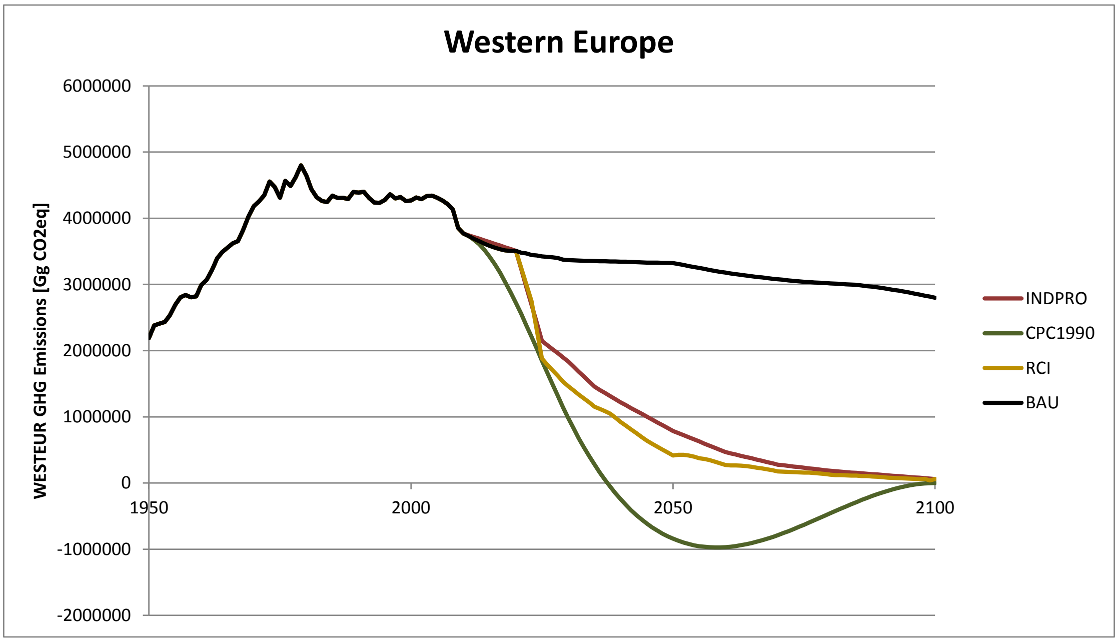

Figure 9 Western Europe (including Switzerland) – Resulting emission pathways for Indian proposal, Equal cumulative per capita emissions 1990, Responsibility-Capacity Indicator and Reference scenario.

The burden sharing pathways for the US and Western Europe are generally similar, while the high historical per capita emissions of the US lead to a much more pronounced net negative emissions allocation with the Equal cumulative per capita emissions in the US (-51% of 1990 emissions in 2050) than in Europe (-19%; see also Table 6).

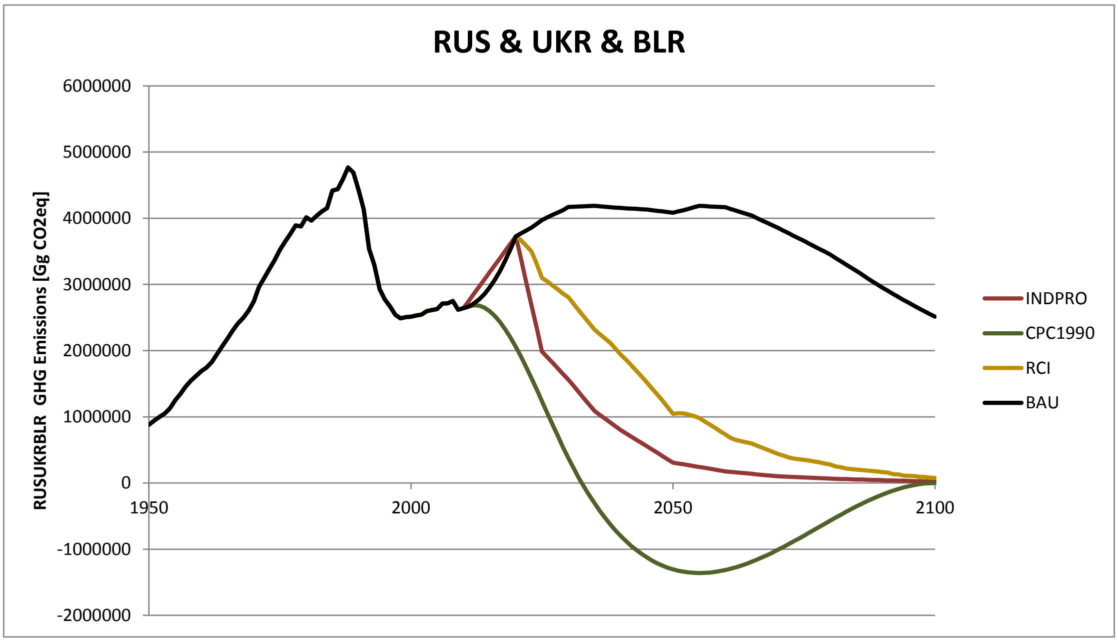

Figure 10 Russia, Ukraine and Belarus – Resulting emission pathways for Indian proposal, Equal cumulative per capita emissions 1990, Responsibility-Capacity Indicator and Reference scenario.

The burden sharing pathways for the country group formed by Russia, Ukraine and Belarus (Figure 10) show typical pattern for AI countries. It turns out, that for high per capita emissions AI countries the RCI approach in its current implementation is much less stringent than the Indian proposal (also for USA, Australia and New Zealand), because the Indian proposal approach in the present implementation imposes per capita emissions convergence by 2050, while RCI doesn't. Please note that also other implementation of the burden sharing approaches could be investigated.

Annex I countries	**(Examples)**		
Country (group)	Emissions 2050/1990		
	INDPRO	CPC1990	RCI
Australia and NZ	14%	-60%	25%
Eastern Europe	15%	-14%	16%
Japan	16%	-30%	4%
Russia, Ukraine, Belarus	7%	-29%	24%
USA	12%	-51%	20%
Western Europe	18%	-19%	9%

Table 6 Results for selected Annex I countries from sharing approaches (see also section 3): CO2eq Emissions in 2050 as percentage of 1990 Emissions. Please note that results are preliminary.

Examples from non-Annex I countries

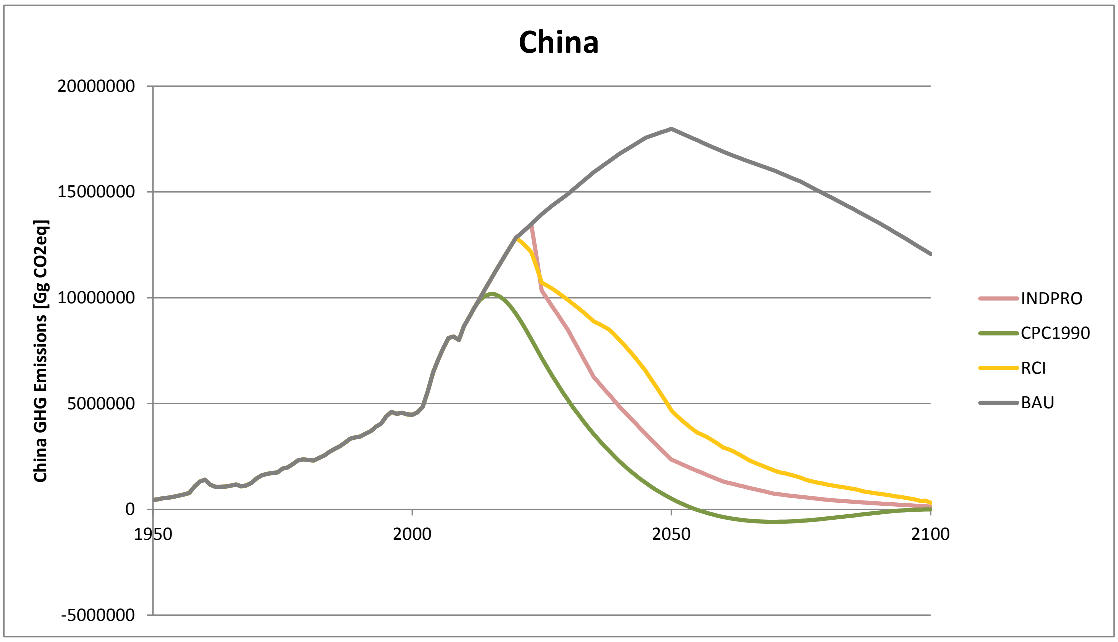

Figure 11 China – Resulting emission pathways for Indian proposal, Equal cumulative per capita emissions 1990, Responsibility-Capacity Indicator and Reference scenario.

The considered burden sharing approaches result for China in a pattern that is somewhere between characteristics of AI and NAI countries (Figure 11). All approaches would require the rapid reduction of emissions, even though the rates of reduction are somewhat less steep than in AI countries. Because the base year for the Equal cumulative emissions is set to 1990, the strong increase in emissions since then leads to China having to reduce emissions also with this approach already from 2015 onwards (see also Table 7), and even go to net negative emissions from 2055.

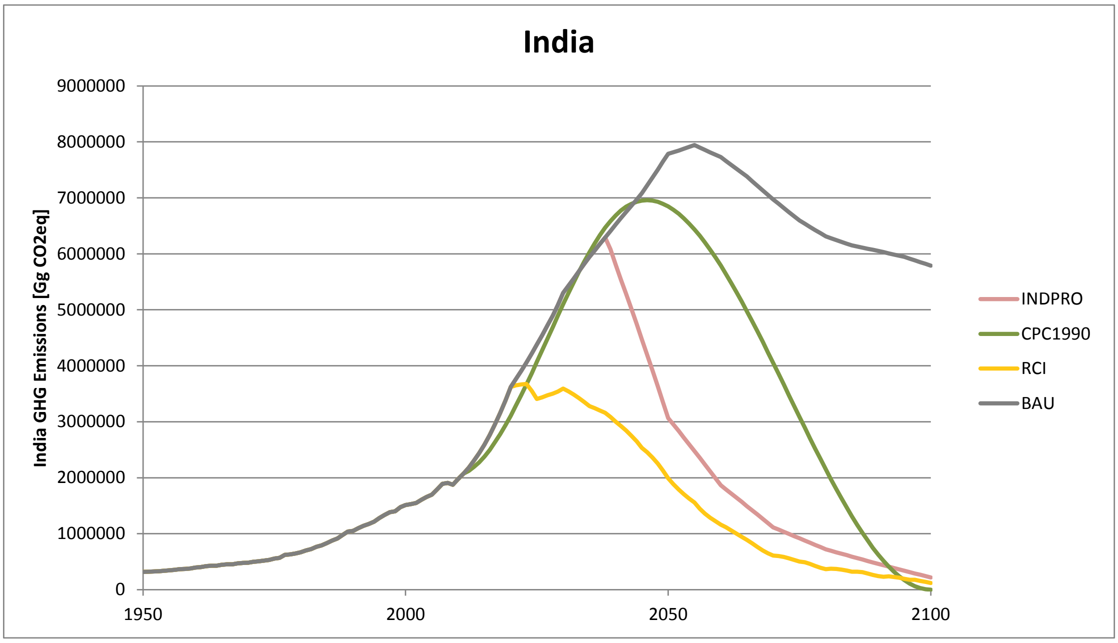

Figure 12 India – Resulting emission pathways for Indian proposal, Equal cumulative per capita emissions 1990, Responsibility-Capacity Indicator and Reference scenario.

As mentioned above, the expected considerable increase in population and low average per capita emissions in countries like India (Figure 12) and the group of countries in Sub-Saharan Africa (Figure 13) results in very large allocations of emissions with the Equal cumulative emissions approach. Countries of Sub-Saharan Africa would receive an allocation that is well above their BAU-scenario.

The Indian proposal allows India to stay until 2038 on the BAU-scenario (when the emissions threshold is reached) than with the RC-Indicator, which requires a stabilisation of emissions from 2020 and decreasing emissions from 2030 (see also Table 7).

The countries of Sub-Saharan Africa would with the Indian proposal be able to grow emissions until 2042 whereas the RC-Indicator would require a stabilization of emissions after 2020 and a (slow) reduction from around 2040.

The pattern of pathways for oil exporting countries of the Middle East (Figure 14) resembles AI countries. All approaches would require a swift reduction in emissions, although necessary emission reduction rates would be somewhat lower than with AI countries.

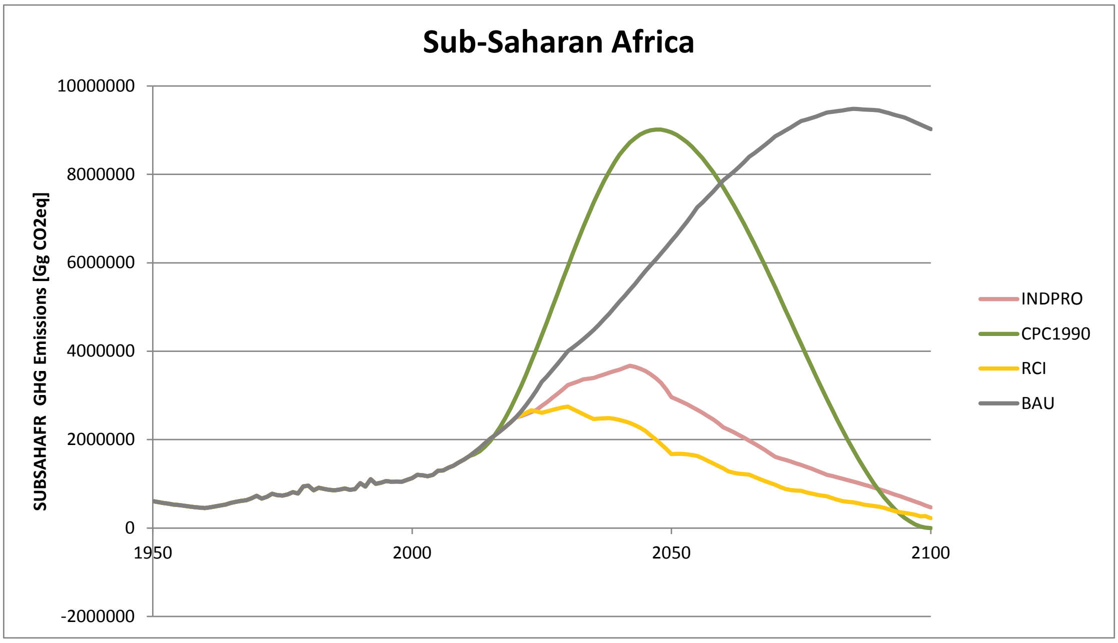

Figure 13 Sub-Saharan Africa – Resulting emission pathways for Indian proposal, Equal cumulative per capita emissions 1990, Responsibility-Capacity Indicator and Reference scenario.

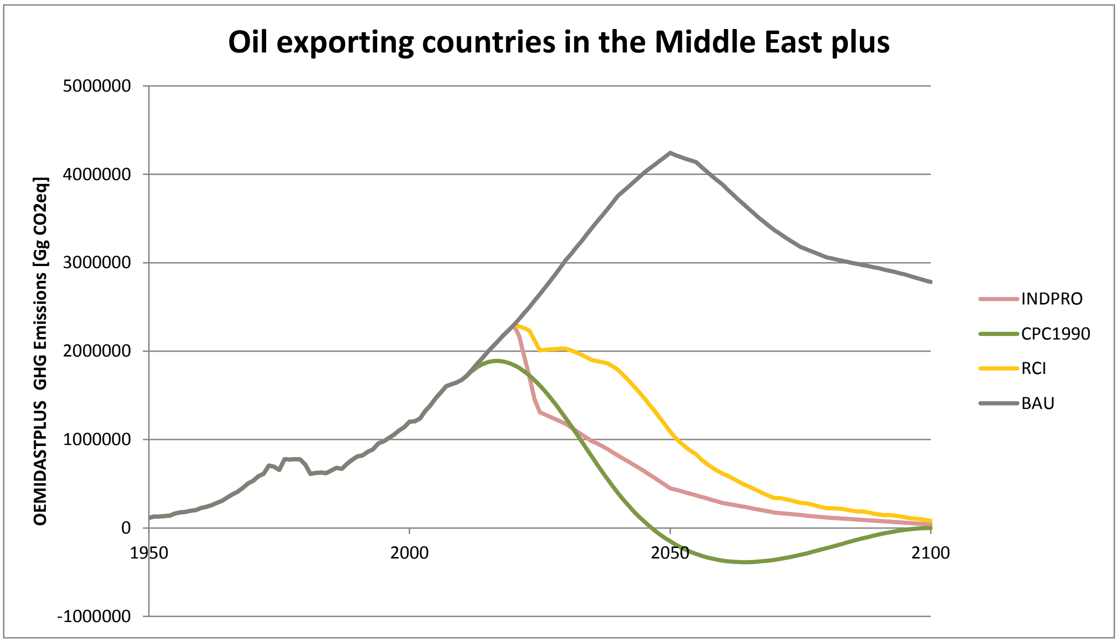

Figure 14 Oil exporting countries in the Middle East plus – Resulting emission pathways for Indian proposal, Equal cumulative per capita emissions 1990, Responsibility-Capacity Indicator and Reference scenario.

Non-Annex I countries (examples)						
Country (group)	Peaking [yr]			Emissions 2050/1990		
	INDPRO	CPC1990	RCI	INDPRO	CPC1990	RCI
China	2023	2015	2020	68%	15%	136%
India	2038	2046	2030	291%	651%	189%
Indonesia	2024	2038	2021	199%	364%	242%
Oil exporting middle Eastern countries plus	2020	2017	2020	56%	-19%	135%
Sub-Saharan Africa	2042	2047	2030	292%	882%	165%

Table 7 Results for non-Annex I countries from sharing approaches (see also section 3): Year of peaking and CO2eq Emissions in 2050 as percentage of 1990 Emissions. Please note that results are preliminary.

PART III: SYNTHESIS AND CONCLUSIONS

6. SYNTHESIS AND CONCLUSIONS

What is the room for manoeuvre in setting targets?

Several different global emission pathways can be projected that are consistent with the 2°C target (UNEP 2010):

i. A pathway, where immediate mitigation action would be taken in all sectors and regions following a globally optimal least cost path to 2°C ("optimal"). Such early action allows for slower emissions decrease in later decades and allows for positive global emissions in 2100, reducing the need for potentially very costly technologies with negative emissions such as biomass energy combined with carbon capture and storage (CCS).

ii. If countries first raise emission to their 2020 pledges, and thereafter all sectors and all regions participate in the global mitigation efforts (pathway "Pledges"), one needs to assume major technological breakthroughs such as the advanced decarbonisation of the transportation sector, with the pace of energy efficiency improvements and technology penetration rates lying beyond those observed in the past. E.g. the pathway requires a massive up-scaling of CCS to reach net negative global emissions at the end of the 21st century. If parties 2020 pledges are not modified by more ambitious quantitative emission targets for 2020, it will be much more difficult (and costly) to reach the 2°C target afterwards.

iii. If the entire mitigation action until 2030 is carried out in developed countries and non-Annex-I parties follow a BAU emissions scenario between 2020 and 2030 ("delayed non-Annex I"), significant net negative global emissions in the last quarter of the 21st century are necessary to reach the 2°C target. The Integrated Assessment Model indicated that this pathway seems infeasible from a technological and economic point of view.

The preliminary results suggest that the room for manoeuvre is narrow and that the 2°C target can only be met with likely probability if the integration of non-Annex I countries into international mitigation action can be achieved rather sooner than later. In line with the findings of the Gap report (UNEP 2010) our results suggest that delaying the start of global mitigation action further makes reaching the target later much more difficult and costly.

Burden sharing

The work on emissions pathways on a global level mentioned above identifies the need for very strong cuts in global emissions over the next decades in line with e.g. IPCC (2007a). The question on how to share this large global burden in emission cuts between different countries is primarily a political one. Science can only seek to provide relevant data that may feed into political decisions taking process. The overarching principle of burden sharing is laid down in the Convention (UNFCCC 1992 Art.3): Action should be taken by all countries *on the basis of equity and in accordance with their common but differentiated responsibilities and respective capabilities*, with Annex I countries taking the lead.

The aim of the present modelling exercise on burden sharing is to illustrate on a conceptual level how different quantitative burden sharing algorithms lead to different emission reduction pathways for countries. Please note that these pathways are subject to high uncertainties and depend heavily on the assumptions made in the modelling. The selection of burden sharing approaches and their operationalization in the model is by no means comprehensive and should be regarded as an illustrative exercise in the quantitative analysis in burden sharing approaches but by no means as a proposal for actual burden sharing between countries.

The following key findings emerge:

- For Annex I countries (AI), the difference between the Indian proposal and the RC-Indicator approach turns out to be rather small overall. All Annex I countries need to initiate rapid action to quickly reduce emissions in both approaches.
- For non-Annex I countries (NAI), the results for the two approaches is more varied between countries:
  - For NAI countries with low per capita emissions and high population growth such as India and Sub-Saharan Africa the Indian proposal allows for growth of emissions until the average emission level of AI countries is reached. With the RC-Indicator approach the emissions allocation to these countries does not grow anymore from 2020; it stabilizes followed by a decrease in emissions allocations from around 2030.
  - For NAI countries with higher levels of per capita emissions and less population growth such as China, both RC-Indicator and the Indian proposal lead to similar, but less rapid decrease in emissions than in AI countries.
- Because the Indian proposal in its present implementation prescribes for countries with high per capita emissions the convergence to equal per capita emissions in 2050, this approach is more stringent these high emitting countries, be it AI or NAI country (e.g. USA, Australia &

New Zealand, China) while for AI countries with lower per capita emissions (Western Europe, Japan) the Indian proposal is less stringent than the RC-Indicator approach.

- The Equal cumulative per capita emissions approach leads to much more stringent emission reduction pathways for AI countries and high emitting NAI countries like China, with AI countries receiving negative emissions allocations from around 2030. NAI countries with low per capita emissions (such as India and Sub-Saharan Africa) would benefit from large allocations of emissions, sometimes surpassing BAU-scenarios. From a practical point of view it seems less obvious how such a burden sharing could be implemented.

The direct comparison of the implemented versions of the RC-Indicator approach and the Indian proposal indicate that the linear approach of the RCI leads to a significantly less stringent emission reduction requirements for AI countries and high emitting NAI like China, but put a higher burden to NAI countries with low per capita emissions high population growth rates (such as India and Sub-Saharan Africa) in particular in the first half of the 21st century than the Indian proposal with its threshold approach.
One might therefore argue that a high emission reduction burden early on for low carbon NAI countries is against the principle of equal rights for development. From this perspective, the Indian proposal might seem more adequate to reflect the different responsibilities and abilities of countries to contribute to climate change mitigation, providing low emitting NAI countries with more room for development. Also, a hybrid approach might be considered, where the possibility for growing emissions for low emissions NAI countries of the Indian proposal may be combined with a RC-Indicator approach applied only to countries with emissions above a certain threshold.

Scope for further work

The present study analyses different emission pathways for the 2°C target and illustrates some characteristics of different burden sharing approaches. The work also identified several shortcomings of the considered approaches and the need for further analysis, including:

- Refinement of existing burden sharing approaches, improvement of data base used.
- Analysis of new and more variants of burden sharing approaches, including above mentioned hybrid approaches or e.g. non-linear RC-Indicators.
- Inclusion of LULUCF emissions (currently not considered for simplification). This is a very important for the analysis of emission schedules in particular for countries like Brazil, Indonesia, Russia etc.

- Receiving and implementing feedback from peers and putting modelling results into the context of other recent work on these topics.

ANNEX I PLEDGES OF ANNEX I COUNTRIES

Country	Target speci-fication	Description	Kyoto Target	Copenhagen Pleges	
				Base year	2020
Australia	high	If the world agrees to an ambitious global deal capable of stabilising levels of greenhouse gases in the atmosphere at 450 ppm CO2-eq or lower.	+8% (1990)	2000	-25%
	middle	If there is a global agreement which falls short of securing atmospheric stabilisation at 450 ppm CO2-eq and under which major developing economies commit to substantially restrain emissions and advanced economies take on commitments comparable to Australia's		2000	-15%
	low	Unconditionally		2000	-5%
Belarus		Which is premised on the presence of and access of Belarus to the Kyoto flexible mechanisms, intensification of technology transfer, capacity building and experience enhancement for Belarus taking into consideration the special conditions of the Parties included in Annex I undergoing the process of transition to a market economy, clarity in the use of new LULUCF rules and modalities.	-8% (1990)	1990	-5%-10%
Canada		To be aligned with the final economy-wide emissions target of the United States in enacted legislation	-6% (1990)	2005	-17%
Croatia		Temporary target. Upon the accession of Croatia to the European Union, the target shall be replaced by arrangement in line with and part of the European Union mitigation effort	-5% (1990)	1990	-5%
EU 27	low	Unconditionally	-7.7% (1990) estimation	1990	-20%
	high	The EU reiterates its conditional offer to move to a 30% reduction by 2020 compared to 1990 levels, provided that other developed countries commit themselves to comparable emission reductions and that developing countries contribute adequately according to their responsibilities and respective capabilities.		1990	-30%
Iceland		In a joint effort with the European Union, as part of a global and comprehensive agreement for the period beyond 2012, provided that other developed countries commit themselves to comparable emissions reductions and that developing countries contribute adequately according to their responsibilities and respective capabilities	+10% (1990)	1990	-30%
Japan		Which is premised on the establishment of a fair and effective international framework in which all major economies participate and on agreement by those economies on ambitious targets.	-6% (1990)	1990	-25%
Kazakhstan		Kazakhstan is a Party included in Annex I for the purposes of the Kyoto Protocol in accordance with Article 1, para-graph 7, of the Protocol, but Kazakhstan is not a Party included in Annex I for the purposes of the Convention		1992	15%
Liechtenstein	low		+8% (1990)	1990	-20%

Country	Target speci-fication	Description	Kyoto Target	Copenhagen Pleges	
				Base year	2020
	high	If other developed countries agree to comparable reductions and emerging economies contribute according to their respective capabilities and responsibilities within a framework of a binding agreement, Liechtenstein is prepared to raise its target up to 30%.		1990	-30%
Monaco		Pour atteindre cet objectif de réduction la Principauté de Monaco entend utiliser des mécanismes de flexibilité comme ceux établis par le Protocole de Kyoto et plus particulièrement le Mécanisme pour un Développement Propre.	+8% (1990)	1990	-30%
New Zealand		If there is a comprehensive global agreement.	0% (1990)	1990	-10%-20%
Norway	low		+1% (1990)	1990	-30%
	high	As part of a global and comprehensive agreement for the period beyond 2012 where major emitting Parties agree on emissions reductions in line with the 2 degrees Celsius target, Norway will move to a level of 40% reduction for 2020.		1990	-40%
Russian Fed.		"The range of the GHG emission reductions will depend on the following conditions: - Appropriate accounting of the potential of Russia's forestry in frame of contribution in meeting the obligations of the anthropogenic emissions reduction; - Undertaking by all major emitters the legally binding obligations to reduce anthropogenic GHG emissions.	0% (1990)	1990	-15-25%
Switzerland		As part of a global and comprehensive agreement for the period beyond 2012, Switzerland reiterates its conditional offer to move to a 30% reduction by 2020 compared to the 1990 levels, provided that other developed countries commit themselves to comparable emission reductions and that developing countries contribute adequately according to their responsibilities and respective capabilities.	-8% (1990)	1990	-20/30%
Ukraine		Ukraine associates with Copenhagen Accord under the following conditions: to have the agreed position of the developed countries on quantified emissions reduction targets of the Annex I countries; to keep the status of Ukraine as a country with economy in transition and relevant preferences arising from such status; to keep the existing flexible mechanisms of the Kyoto Protocol; to keep 1990 as the single base year for calculating Parties commitments; to use provisions of Article 3.13 of the Kyoto Protocol for calculation of the quantified emissions reduction of the Annex I countries of the Kyoto Protocol for the relevant commitment period.	0% (1990)	1990	-20%
USA		In the range of 17%, in conformity with anticipated U.S. energy and climate legislation, recognizing that the final target will be reported to the Secretariat in light of enacted legislation.	-7% (1990) The US has not ratified the Kyoto Protocol.	2005	2020:-17%, 2025: -30%, 2030: -42%, 2050: -83%

Selected pledges of Non-annex I countries.

Country	Sector targets /or mentioned targeted areas	Copenhagen Pledges				
		Base year	2020	2025	2030	2050
Brazil	x	BAU, not specified in the pledge	36.1%-38.9%			
Costa Rica	x		carbon neutrality			
China	x	2005	CO2/GDP by -40-45%			
India	NA	2005	Emissions/GDP -20-25%			
Indonesia	x	BAU, not specified in the pledge	-26%			
Maldives	NA		carbon neutrality			
Mexico	NA	BAU, not specified in the pledge	-30%			
South Africa	NA	BAU, not specified in the pledge	-34%	-42%		

ANNEX II ADDITIONAL DATA AND MODEL RESULTS

A) Section 4.1: Example of assumed underlying energy technology mix for "Optimal" pathway

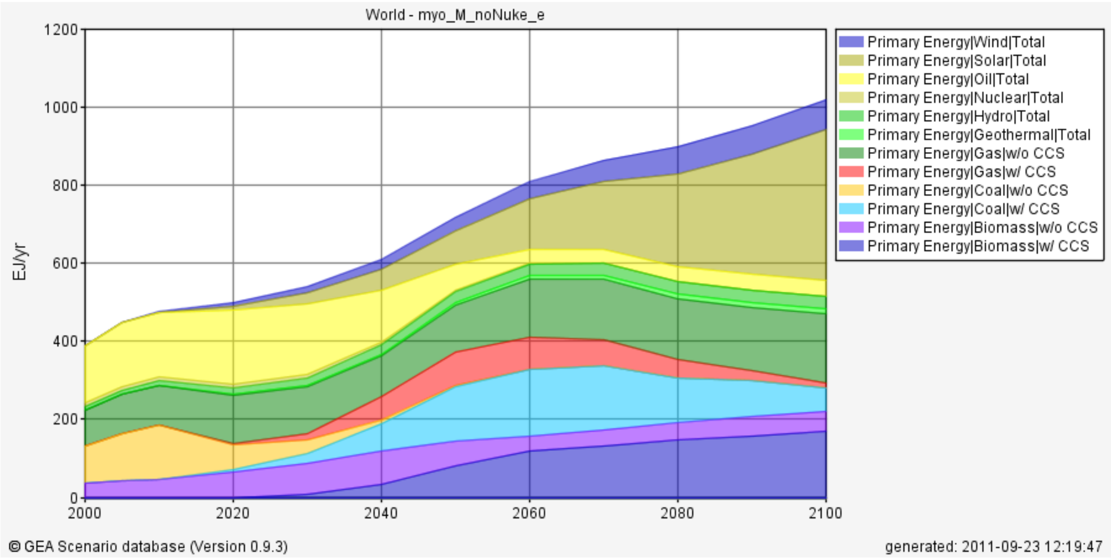

Figure 15 Illustrative example of the energy technology mix for the "Optimal" pathway in line with 2°C target as calculated by the Integrated Assessment Model.

.

B) Section 5.1: Development of population as background to burden sharing between Annex I and non-Annex I countries

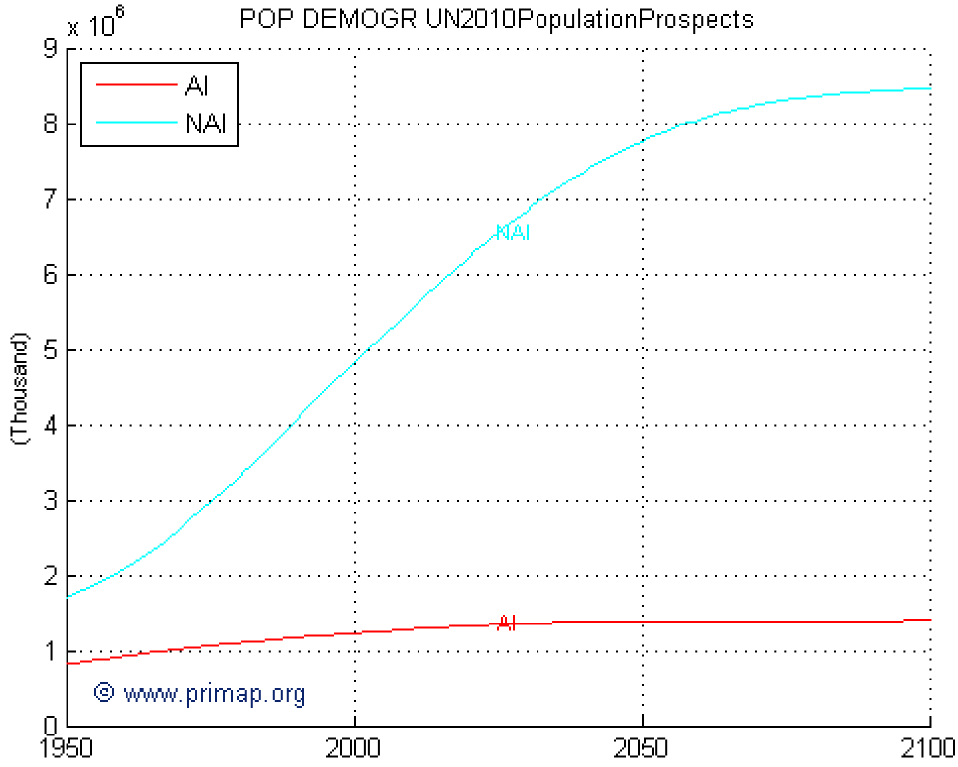

Figure 16 Population scenarios grouped in Annex I (developed countries – AI) and non-Annex I (developing – NAI) countries used for burden sharing appraoches.

C) Section 5.2: Burden sharing results for all countries/groups

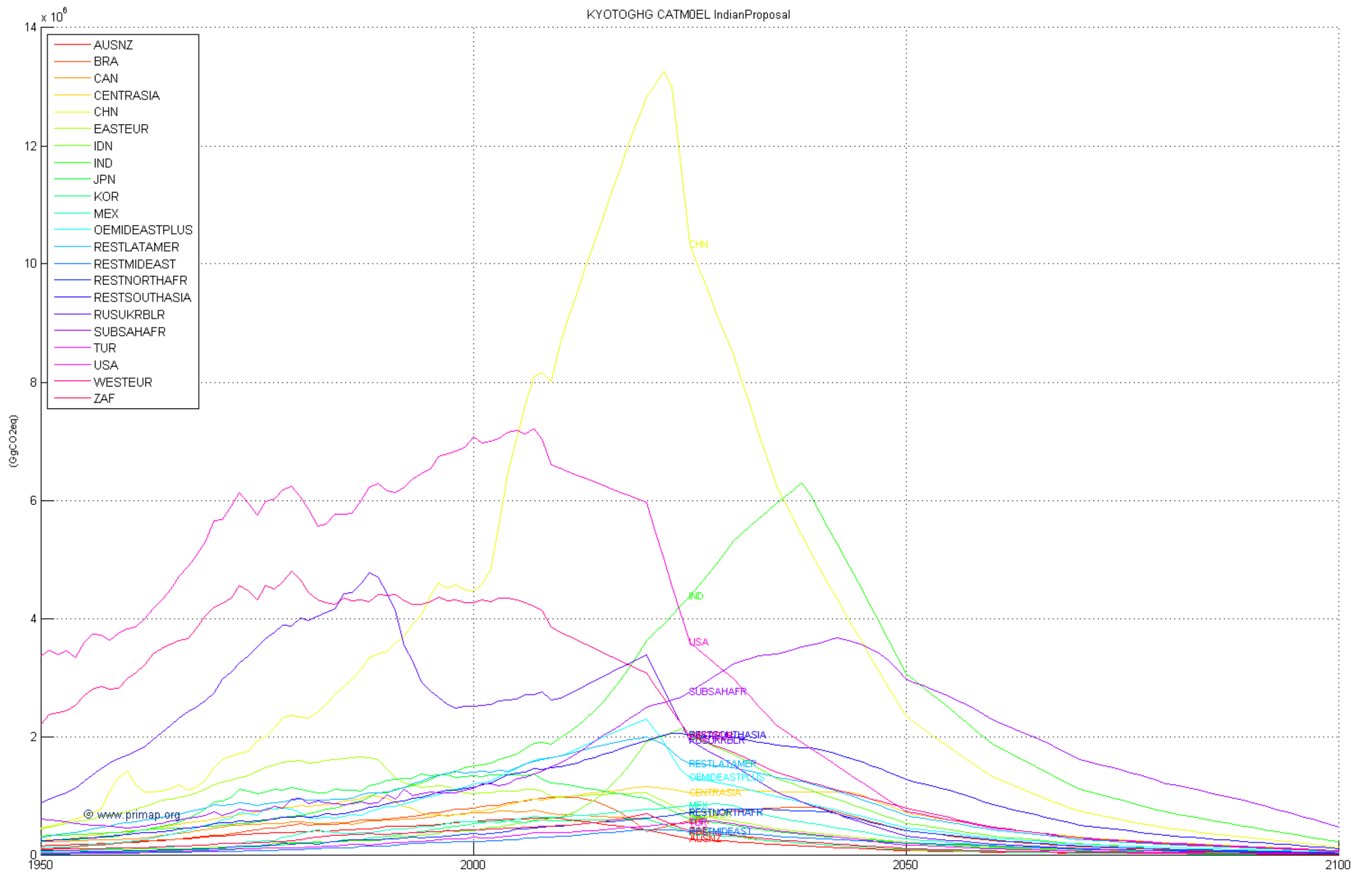

Figure 17 Results for Indian Proposal 2008: Emission pathways for countries and country groups. Please note that results are preliminary.

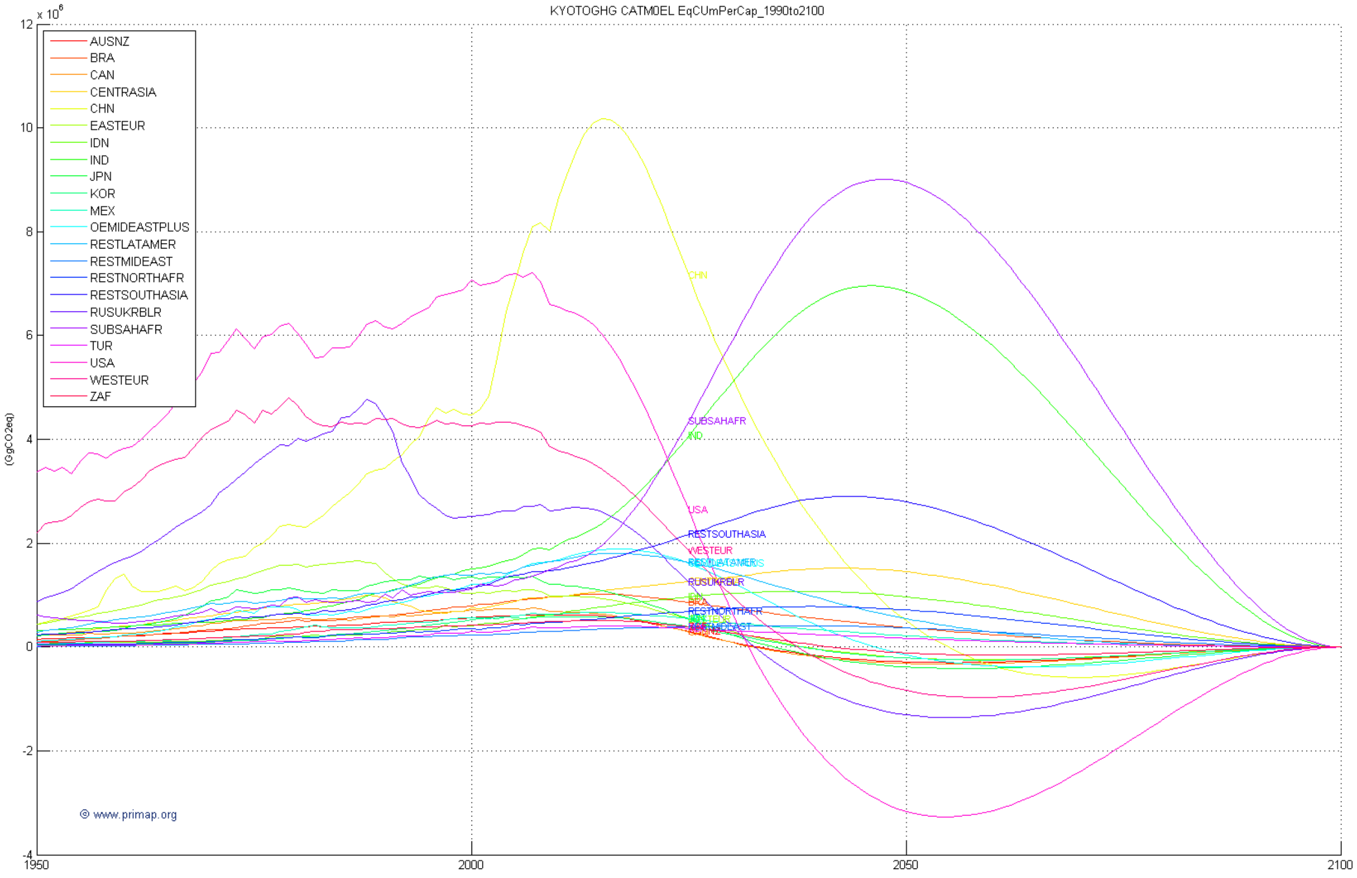

Figure 18 Results for Equal cumulative per capita emissions: Emission pathways for countries and country groups. Please note that results are preliminary.

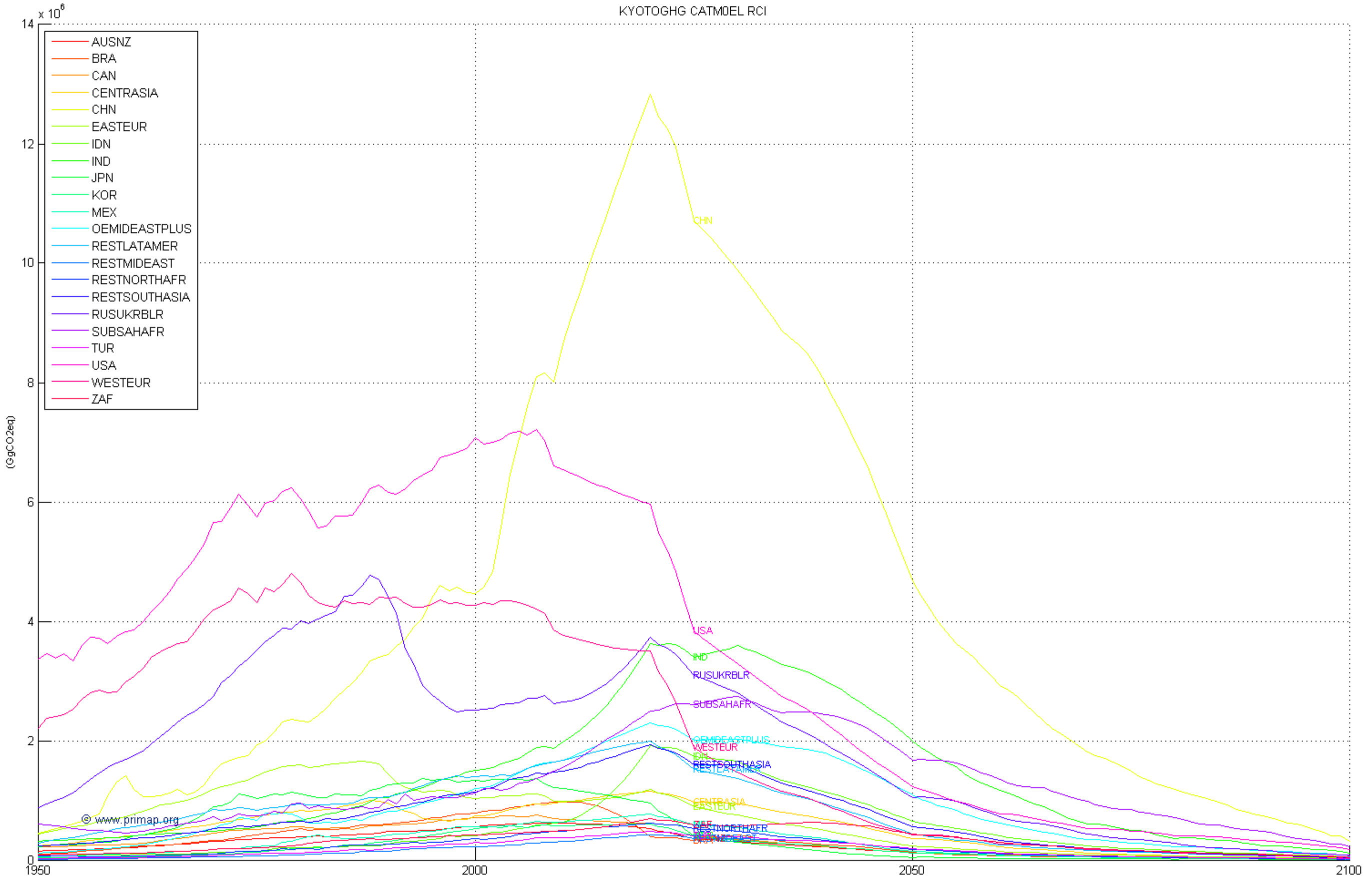

Figure 19 Results for Responsibility-Capacity Indicator: Emission pathways for countries and country groups. Please note that results are preliminary.

D) Years of participation for Indian proposal

Additional results for section 5.2. Year of exceeding 20’000USD pppGDP threshold (“Transition start”, if applicable) and year of exceeding average per capita emissions of participating countries

Country name	Transition start [year]	Full participation [year]
ARUBA	2020	2020
AFGHANISTAN	2075	2085
ANGOLA		2043
ANGUILLA	2039	2045
ALBANIA	2041	2047
NETHERLANDS ANTILLES		2020
UNITED ARAB EMIRATES	2020	2020
ARGENTINA		2023
ARMENIA		2031
AZERBAIJAN		2032
BURUNDI		2050
BENIN		2024
BURKINA FASO		2071
BANGLADESH		2058
BAHRAIN		2020
BAHAMAS	2020	2025
BOSNIA AND HERZEGOVINA		2023
BELIZE		2020
BERMUDA	2020	2024
BOLIVIA		2037
BRAZIL	2036	2040
BARBADOS		2020
BRUNEI DARUSSALAM	2020	2020
BHUTAN		2042
BOTSWANA		2025
CENTRAL AFRICAN REPUBLIC		2020
CHILE		2030
CHINA		2023
COTE D'IVOIRE		2035
CAMEROON		2020
CONGO, Democratic Republic of (was Zaire)		2059

Country name	Transition start [year]	Full partici-pation [year]
CONGO, People's Republic of		2057
COOK ISLANDS		2042
COLOMBIA		2039
COMOROS		2050
CAPE VERDE		2041
COSTA RICA	2037	2043
CUBA		2033
CAYMAN ISLANDS	2020	2079
CYPRUS	2020	2032
DJIBOUTI		2048
DOMINICA		2037
DOMINICAN REPUBLIC		2040
ALGERIA		2034
ECUADOR		2037
EGYPT		2042
ERITREA		2043
WESTERN SAHARA	2053	2064
ETHIOPIA		2049
FIJI		2049
FALKLAND ISLANDS (MALVINAS)		2020
FAROE ISLANDS	2020	2020
MICRONESIA, FEDERATED STATES OF		2043
GABON		2023
GEORGIA		2032
GHANA		2047
GIBRALTAR	2020	2020
GUINEA		2051
GUADELOUPE	2031	2069
GAMBIA		2031
GUINEA-BISSAU		2038
EQUATORIAL GUINEA		2020
GRENADA		2020
GUATEMALA	2046	2059
FRENCH GUIANA	2024	2100
GUYANA		2034
HONG KONG	2020	2091
HONDURAS		2048

Country name	Transition start [year]	Full partici-pation [year]
HAITI	2067	2067
INDONESIA		2025
INDIA		2039
IRAN (ISLAMIC REPUBLIC OF)		2021
IRAQ		2037
ISRAEL	2020	2020
JAMAICA		2020
JORDAN		2024
KAZAKHSTAN		2020
KENYA		2048
KYRGYZSTAN	2048	2048
CAMBODIA		2049
KIRIBATI		
SAINT KITTS AND NEVIS	2034	2034
KOREA, REPUBLIC OF	2020	2021
KUWAIT	2020	2020
LAO PEOPLE'S DEMOCRATIC REPUBLIC		2047
LEBANON		2025
LIBERIA		2060
LIBYAN ARAB JAMAHIRIYA		2020
SAINT LUCIA		2024
SRI LANKA		2040
LESOTHO		2045
MACAU	2020	2044
MOROCCO		2041
MOLDOVA, REPUBLIC OF		2035
MADAGASCAR		2049
MALDIVES		2036
MEXICO		2029
MARSHALL ISLANDS		2056
MACEDONIA, THE FORMER YUGOSLAV REPUBLIC OF		2029
MALI		2060
MALTA	2024	2036
MYANMAR		2043
MONGOLIA		2030
MOZAMBIQUE		2069

Country name	Transition start [year]	Full partici-pation [year]
MAURITANIA		2036
MONTSERRAT	2044	2044
MARTINIQUE	2026	2069
MAURITIUS		2024
MALAWI	2074	2091
MALAYSIA		2023
NAMIBIA		2031
NEW CALEDONIA	2020	2066
NIGER		2077
NIGERIA		2042
NICARAGUA		2049
NIUE		2020
NEPAL		2055
NAURU		2037
OMAN		2020
PAKISTAN		2044
PANAMA	2038	2038
PERU		2043
PHILIPPINES		2050
PALAU		2024
PAPUA NEW GUINEA		
KOREA, DEMOCRATIC PEOPLE'S REPUBLIC OF		2025
PARAGUAY		2020
FRENCH POLYNESIA	2020	2084
QATAR	2020	2020
REUNION	2034	2088
RWANDA		2058
SAUDI ARABIA		2024
SUDAN		2033
SENEGAL		2046
SINGAPORE	2020	2023
SAINT HELENA		2070
SOLOMON ISLANDS		2027
SIERRA LEONE		2050
EL SALVADOR		2044
SAN MARINO	2020	2027
SOMALIA		2089

Country name	**Transition start** [year]	**Full partici-pation** [year]
SAINT PIERRE AND MIQUELON	2020	2022
SAO TOME AND PRINCIPE		2043
SURINAME		2024
SWAZILAND		2025
SEYCHELLES		2020
SYRIAN ARAB REPUBLIC		2027
CHAD		2039
TOGO		2039
THAILAND		2025
TAJIKISTAN	2054	2058
TURKMENISTAN		2020
TIMOR LESTE		2057
TONGA		2050
TRINIDAD AND TOBAGO		2020
TUNISIA		2033
TURKEY		2028
TUVALU	2060	2092
TANZANIA, UNITED REPUBLIC OF		2061
UGANDA		2045
URUGUAY		2022
UZBEKISTAN		2024
SAINT VINCENT AND THE GRENADINES		2027
VENEZUELA		2023
VIRGIN ISLANDS (BRITISH)	2038	2066
VIET NAM		2040
VANUATU	2067	2087
WALLIS AND FUTUNA ISLANDS		2044
SAMOA		2037
YEMEN	2056	2058
SOUTH AFRICA		2021
ZAMBIA		2046
ZIMBABWE		2044

Table 8 Year of participation of individual countries in “Indian Proposal” burden sharing approach (see section 3). Please note that results are preliminary.

ACRONYMS

AI	Annex I countries to the Kyoto Protocol, i.e. “developed countries”
CCS	Carbon capture and storage
CPC1990	Burden sharing “Equal cumulative per capita emissions” (see section 3)
GHG	Greenhouse gas
IAM	Integrated assessment model
INDPRO	Burden sharing “Indian proposal 2008” (see section 3)
LULUCF	Land use, land use change and forestry
MAGICC	A climate system and carbon-cycle model (see section 4.2)
MESSAGE	An integrated assessment model (see section 4.1)
NAI	Non-Annex I countries to the Kyoto Protocol (“developing countries”)
OcCC	Advisory body on climate research to the Swiss federal government
RCI	Burden sharing “Responsibility-Capacity Indicator” (see section 3)

REFERENCES

Reports and decisions

Bundesrat 2011: Federal Council decides to gradually phase out nuclear energy as part of its new energy strategy. Federal Department of the Environment, Transport, Energy and Communications (DETEC) media release of 25.5.2011. http://www.uvek.admin.ch/dokumentation/00474/00492/index.html?lang=en&msg-id=39337 (accessed 9.11. 2011).

CAT 2011a: No move to close the gap at Bangkok Climate Talks. Climate Action Tracker briefing paper, 6 April 2011. Climate Analytics, PIK, Ecofys.

CAT 2011b: Emissions and CO_2 concentrations at record highs: Developed countries ambition stalled while developing countries gearing up to act. Climate Action Tracker Update, 16 June 2011.

CAT 2011c: Climate Action Tracker [Online]. Ecofys-ClimateAnalytics-PIK. Available: http://www.climateactiontracker.org/ [Accessed 2 November 2011].

Cancun Agreements 2010: Decision 1/CP.16. The Cancun Agreements: Outcome of the work of the Ad Hoc Working Group on Long-term Cooperative Action under the Convention. FCCC/CP/2010/7/Add.1

Fast start finance 2011: Contributing Countries – Switzerland. http://www.faststartfinance.org/contributing_country/switzerland (accessed 9.11.2011)

INFRAS 2008: Per capita emission paths for developed and developing countries. A Swiss contribution to discussion in AWG-LCA. Summary of results of a study on the implications of the "Indian Proposal".

INFRAS 2010: Emission Paths for developed and developing countries. Schedules for reaching the 2°C target. 29. November 2010.

SEI 2011: Comparison of Annex 1 and non-Annex 1 pledges under the Cancun Agreement, Stockholm Environmental Institute (SEI), 11 June 2011.

Switzerland 2011: Submission from Switzerland. Mitigation Pledges - steps to be taken in Durban. AWG-LCA 3.2.1. FCCC/AWGLCA/2011/CRP.24. 4 October 2011. http://unfccc.int/resource/docs/2011/awglca14/eng/crp24.pdf

UNEP 2010: The Emissions Gap Report; Are the Copenhagen Accord Pledges sufficient to limit global warming to 2°C or 1.5°C? A preliminary assessment, November 2010.

UNFCCC 1992: United Nations Framework Convention on Climate Change.

Scientific papers

ALLEN, M. R., FRAME, D. J., HUNTINGFORD, C., JONES, C. D., LOWE, J. A., MEINSHAUSEN, M. & MEINSHAUSEN, N. 2009. Warming caused by cumulative carbon emissions towards the trillionth tonne. Nature, 458, 1163-1166.

BROHAN, P., KENNEDY, J. J., HARRIS, I., TETT, S. F. B. & JONES, P. D. 2006. Uncertainty estimates in regional and global observed temperature changes: A new data set from 1850. Journal of Geophysical Research-Atmospheres, 111, D12106.

DAVIS, S. J., CALDEIRA, K. & MATTHEWS, H. D. 2010. Future CO2 Emissions and Climate Change from Existing Energy Infrastructure. Science, 329, 1330-1333.

DOMINGUES, C. M., CHURCH, J. A., WHITE, N. J., GLECKLER, P. J., WIJFFELS, S. E., BARKER, P. M. & DUNN, J. R. 2008. Improved estimates of upper-ocean warming and multi-decadal sea-level rise. Nature, 453, 1090-U6.

FRIEDLINGSTEIN, P., COX, P., BETTS, R., BOPP, L., VON BLOH, W., BROVKIN, V., CADULE, P., DONEY, S., EBY, M., FUNG, I., BALA, G., JOHN, J., JONES, C., JOOS, F., KATO, T., KAWAMIYA, M., KNORR, W., LINDSAY, K., MATTHEWS, H. D., RADDATZ, T., RAYNER, P., REICK, C., ROECKNER, E., SCHNITZLER, K.-G., SCHNUR, R., STRASSMANN, K., WEAVER, K., YOSHIKAWA, C. & ZENG, N. 2006. Climate–Carbon Cycle Feedback Analysis: Results from the C4MIP Model Intercomparison. Journal of Climate, 19, 3337-3353.

GEA 2011. Global Energy Assessment. IIASA, Laxenburg, Austria and Cambridge University Press, Cambridge, UK.

IPCC 2007a. Climate Change 2007: Synthesis Report. Cambridge, UK and New York, USA: Intergovernmental Panel on Climate Change.

IPCC 2007b. Climate Change 2007: The Physical Science Basis. Working Group I Contribution to the Intergovernmental Panel on Climate Change Fourth Assessment Report., Cambridge, UK and New York, USA, Cambridge University Press.

MATTHEWS, H. D., GILLETT, N. P., STOTT, P. A. & ZICKFELD, K. 2009. The proportionality of global warming to cumulative carbon emissions. Nature, 459, 829-832.

MEINSHAUSEN, M., MEINSHAUSEN, N., HARE, W., RAPER, S. C. B., FRIELER, K., KNUTTI, R., FRAME, D. J. & ALLEN, M. R. 2009. Greenhouse-gas emission targets for limiting global warming to 2°C. Nature, 458, 1158-1162.

MEINSHAUSEN, M., RAPER, S. C. B. & WIGLEY, T. M. L. 2011a. Emulating coupled atmosphere-ocean and carbon cycle models with a simpler model, MAGICC6 – Part 1: Model description and calibration. Atmos. Chem. Phys., 11, 1417-1456.

MEINSHAUSEN, M., WIGLEY, T. M. L. & RAPER, S. C. B. 2011b. Emulating atmosphere-ocean and carbon cycle models with a simpler model, MAGICC6 – Part 2: Applications. Atmos. Chem. Phys., 11, 1457-1471.

NABEL, J. E. M. S., ROGELJ, J., CHEN, C. M., MARKMANN, K., GUTZMANN, D. J. H. & MEINSHAUSEN, M. 2011. Decision support for international climate policy – The PRIMAP emission module. Environmental Modelling & Software, 26, 1419-1433.

O'NEILL, B. C., RIAHI, K. & KEPPO, I. 2009. Mitigation implications of midcentury targets that preserve long-term climate policy options. Proceedings Of The National Academy Of Sciences Of The United States Of America, 107, 1011-1016.

ROGELJ, J., CHEN, C., NABEL, J., MACEY, K., HARE, W., SCHAEFFER, M., MARKMANN, K., HÖHNE, N., KROGH ANDERSEN, K. & MEINSHAUSEN, M. 2010. Analysis of the Copenhagen Accord pledges and its global climatic impacts—a snapshot of dissonant ambitions. Environmental Research Letters, 5, 034013

ROGELJ, J., HARE, W., CHEN, C. & MEINSHAUSEN, M. 2011a. Discrepancies in historical emissions point to a wider 2020 gap between 2°C benchmarks and aggregated national mitigation pledges. Environmental Research Letters, 6, 9.

ROGELJ, J., HARE, W., LOWE, J., VAN VUUREN, D. P., RIAHI, K., MATTHEWS, B., HANAOKA, T., JIANG, K. & MEINSHAUSEN, M. 2011b. Emission pathways consistent with a 2°C global temperature limit. Nature Clim. Change, 1, 413-418.

ROGELJ, J., MEINSHAUSEN, M. & KNUTTI, R. in review. Global warming under old an new scenarios using IPCC climate sensitivity range estimates.

SANDERSON, B. M., KNUTTI, R., AINA, T., CHRISTENSEN, C., FAULL, N., FRAME, D. J., INGRAM, W. J., PIANI, C., STAINFORTH, D. A., STONE, D. A. & ALLEN, M. R. 2008. Constraints on Model Response to Greenhouse Gas Forcing and the Role of Subgrid-Scale Processes. Journal of Climate, 21, 2384-2400.

SOLOMON, S., DANIEL, J. S., SANFORD, T. J., MURPHY, D. M., PLATTNER, G.-K., KNUTTI, R. & FRIEDLINGSTEIN, P. 2010. Persistence of climate changes due to a range of greenhouse gases. Proceedings of the National Academy of Sciences, 107, 18354-18359.

VAN VUUREN, D. P., LUCAS, P. L. & HILDERINK, H. B. M. 2006. Downscaling drivers of global environmental change. Enabling use of global SRES scenarios at the national and grid levels. Bilthoven, The Netherlands: Netherlands Environmental Assessment Agency.

VAN VUUREN, D. P., LUCAS, P. L. & HILDERINK, H. 2007. Downscaling drivers of global environmental change: Enabling use of global SRES scenarios at the national and grid levels. *Global Environmental Change,* 17**,** 114-130.

ZICKFELD, K., EBY, M., MATTHEWS, H. D. & WEAVER, A. J. 2009. Setting cumulative emissions targets to reduce the risk of dangerous climate change. Proceedings of the National Academy of Sciences, 106, 16129-16134.