Modelling SkyShares

Technical background

Summary

SkyShares is an interactive and dynamic tool which allows users to visualise the economic and environmental implications of climate agreements. The website is available at http://www.skyshares.org/ and the desktop version is available at http://bit.ly/SkySharesDesktop.

SkyShares calculates the financial flows and costs of countries (chosen by the user) which participate in a cap-and-trade scheme, where the cap is scientifically determined so as to limit warming to the user's chosen temperature target, and where permits are shared according to the allocation rule chosen by the user.

This paper describes the data and methodology which underpin the model. SkyShares can be used to run a variety of scenarios and supports exploration by offering different algorithms and parameters for modelling climate policy.

Alice Lépissier[a], Owen Barder[b] and Alex Evans[c]

[a] Research Associate at the Center for Global Development. Correspondence to alice@skyshares.org.
[b] Senior Fellow and Director for Europe at the Center for Global Development.
[c] Senior Fellow at the Center on International Cooperation, NYU.

Table of Contents

Table of tables and figures 4
Summary of main parameters 6
The carbon budget 6
The allocation rule 6
Trading scenarios 6
Summary of key formulae 7
Box 1: Scientific cap 7
Box 2: Allocation rule 8
Box 3: Market simulation 9
Introduction 10
Charting a way forward for international climate negotiations 10
A dynamic and interactive tool to move forward the negotiations 11
Data 11
Notation, units and measures of conversion 11
Country socio-economic data 12
Country categories 12
Emissions 14
Population 14
Population projections 14
Historical population 15
Currency deflator 15
GDP 16
CEPII's BASELINE dataset 16
MIT's EPPA dataset 17
Marginal abatement cost curves 18
Caveats and limitations of MACCs 20
MACCs derived from top-down models 21
MACCs derived from technological appraisals 24
Business As Usual 28
The scientific cap 31
Limiting warming 31
Relationship between peak warming and cumulative emissions 32
Probabilistic analysis 34
The carbon budget 38

Emissions pathway 38
Integrating to get the allowable carbon budget 40
Finding the rate of mitigation to stay within budget 41
Implications of the date of contraction 42
The allocation rule 44
Per capita 44
Per dollar 46
Equal stocks 48
Historical responsibilities 51
Trading scenarios 53
Modelling trading with marginal abatement cost curves 53
Description of the main variables at play 53
No Trade 55
Full Trade 57
Regulation 61
References 64
Data-sets and software 64
Carbon emissions 64
Population 64
Gross Domestic Product 64
Currency deflator 64
GCAM 4.0 64
EPPA 4.1 65
McKinsey 65
Literature 65
Annex: Graphs 68
Equal stocks rule 68
Historical emissions on a per capita basis 70
Annex: Datasets 71
Proxies for GNI/capita for countries which are missing data in CEPII's BASELINE database 71
Annex: code and data for marginal abatement cost curves 73
Mapping of countries to MACC data-sets 73
Sample case file a $10 carbon price run in EPPA 4.1 78
Configuration file to fed to GCAM 4.0 80
Sample case file for $10 carbon price run in GCAM 4.0 81

Acknowledgements 82

About the Authors 82

Alice Lépissier 82

Owen Barder 82

Alex Evans 82

Table of tables and figures

Table 1. Country categories in SkyShares 13
Table 2. GDP growth rates for income groups, using CEPII's BASELINE GDP series 16
Table 3. GDP growth rates for income groups, using MIT's EPPA GDP series 18
Table 4. Median warming by the end of century with different Business As Usual scenarios 29
Table 5. Peak warming and cumulative emissions of different studies, median warming 33
Table 6. Log-normal probability density function and cumulative distribution function of climate sensitivity λ, defined as the warming resulting from a doubling of CO_2 atmospheric concentrations 35
Table 7. Relationship between climate sensitivity, warming per 1000 GtC, and 2°C carbon budget for different probabilities 37
Table 8. Warming resulting from cumulative carbon emissions in the three SkyShares probability scenarios 38
Table 9. Decarbonisation rates required and emissions peaks with different mitigation start dates 42
Table 10. Allowances per person under different allocation rules (2°C median warming, early mitigation 52
Table 11. Main variables under No Trade scenario 56
Table 12. Main variables under the Full Trade scenario 60
Table 13. Main variables under the Regulation scenario 63
Table 14. Mapping of SkyShares countries to GCAM regions 74
Table 15. Mapping of SkyShares countries to EPPA regions 76
Table 16. Mapping of SkyShares countries to McKinsey regions 78

Figure 1. GDP projections using CEPII's BASELINE model 17
Figure 2. GDP projections using MIT's EPPA model 18
Figure 3. Stylised marginal abatement cost curve 19
Figure 4. Global marginal abatement cost curves generated with GCAM 4.0 23
Figure 5. Global marginal abatement cost curves generated with EPPA 4.1 24
Figure 6. A sample marginal abatement cost curve. Source: McKinsey, 2009. 25
Figure 7. Example of relatively low variance in abatement costs for South Africa in 2025 26
Figure 8. MACCs for South Africa, including outliers 27
Figure 9. Example of relatively high variance in abatement costs for the rest of Africa in 2025 27
Figure 10. MACCs for the rest of Africa, including outliers 28
Figure 11. Business As Usual assumptions for the 3 data-sets included in SkyShares, compared to the IPCC's Representation Concentration Pathways 29
Figure 12. Peak warming trajectories of different studies, median warming (and mean warming for IPCC figures) 34

Figure 13. Log-normal probability density function of climate sensitivity 36
Figure 14. Log-normal cumulative distribution function of climate sensitivity 36
Figure 15. Relationship between peak warming and cumulative emissions for probabilities of 33%, 50%, and 66% 37
Figure 16. Historical emissions and future CO_2 trajectory 39
Figure 17. Carbon dioxide budget for 2°C warming with 50% likelihood 40
Figure 18. Early action, mitigation starts in 2015, 2°C median warming 43
Figure 19. Delayed action, mitigation starts in 2025, 2°C median warming 43
Figure 20. Per capita allowances with a 2030 convergence date (2°C median warming, early mitigation) 45
Figure 21. Distribution of allowances per income group with convergence to per capita entitlements in 2030 (2°C median warming, early mitigation) 46
Figure 22. Per capita allowances under the "per dollar" rule (2°C median warming, early mitigation) ... 47
Figure 23. Distribution of allowances per income group under the "per dollar" rule (2°C median warming, early mitigation) 47
Figure 24. Comparison of equal stocks versus what different income groups actually emitted 49
Figure 25. Emissions on an equal stocks basis, per income group 50
Figure 26. Per capita allowances under the "equal stocks" rule (2°C median warming, early mitigation) 50
Figures 27 and 28. The carbon debt reaches zero at the end of the century. The payback schedule of the debt is linear. 51
Figure 29. Per capita emissions, as they happened in the past, and as they would be under the Historical Responsibilities scenario (2°C median warming, early mitigation) 52
Figure 30. Costs without trading (at time t) 55
Figure 31. Financial flows (adapted from Ellerman and Decaux, 1998) 58
Figure 32. Adding up the costs under trading 59
Figure 33. Gains from trading (adapted from Ellerman and Decaux, 1998) 61
Figures 34, 35, 36 and 37. CO_2 owed and paid back under the equal stocks rule 69
Figures 38 and 39. Comparing historical emissions as they happened to fair historical per capita shares 70

Summary of main parameters

The carbon budget

SkyShares uses the latest scientific evidence to program the relationship between cumulative carbon emissions (all-time) and peak warming relative to pre-industrial levels. The user sets a temperature target, and SkyShares will return the remaining allowable emissions (of CO_2e) in the budget. SkyShares then "spreads" the all-time cumulative emissions budget (a finite quantity) into discrete annual carbon budgets by plotting an idealised emissions pathway. The trajectory is a smooth-capped distribution which increases and decreases exponentially before and after the start of a mitigation scheme. The user can choose to delay the start of the global mitigation regime. SkyShares numerically solves for the required mitigation rate that ensures the planet's emissions trajectory will stay within the confines of the global carbon budget.

The allocation rule

SkyShares offers a variety of algorithms to distribute the yearly carbon budget among the countries the user has chosen to participate in the coalition.

Per capita: Allowances are grandfathered from current emissions shares and converge to per capita entitlements at a date chosen by the user.

Equal stocks: Allowances also converge to equal per capita entitlements, but this takes into account the stock of past emissions. SkyShares computes the carbon owed by each country since 1800 or 1990, and future allowances are adjusted accordingly so that the carbon debt is paid back at the end of the century. The user can choose the repayment schedule for the servicing of that debt (linear, postpone or frontload).

Per dollar: Allowances converge to shares of GDP. This scenario distributes allowances to the richest, and is intended to help visualise the distributional implications of the status quo.

Historical responsibilities: Calculates the share of global emissions that past emitters have been responsible for, and mandates the same rate of mitigation effort in the future. This variant of the equal stocks scenario is more severe in its treatment of past emitters.

Trading scenarios

The market-clearing price of allowances is determined endogenously by matching supply and demand for abatement. SkyShares then maps back the equilibrium price to each country's marginal abatement cost (MAC) curve to determine how much abatement each country provides at the world price. The rest is traded.

Full trade: SkyShares determines the optimal mix of decarbonising at home and of buying allowances on the market so as to minimise total costs. There is a "no banking, no borrowing" rule and the market clears every year. This scenario is a cost-minimising one.

No trade: The user can turn trading off, and countries will be forced to meet their abatement target entirely through domestic emissions reductions.

Regulation: The user can mandate what share of the coalition's abatement target must be decarbonised at home.

SkyShares computes the financial flows and decarbonisation costs of each trading scenario for each country. Whatever scenario is chosen, the coalition will always stay within its carbon budget.

Summary of key formulae

Box 1: Scientific cap

The safe annual carbon budget is given by $E(t)$.

Peak warming equation $$T_p = \frac{\Delta T_1}{2^\alpha - 1} \cdot \left[\left(\frac{Q}{Q_1} + 1 \right)^\alpha - 1 \right]$$

Climate uncertainty $$\Delta T_1 = \Delta T_m \cdot {}^{\lambda}/_{\lambda_m}$$

defined in reference to median warming.

Global carbon budget

$$Q(t) = Q(t_{Hist}) + \frac{E_m - e^{r\cdot(t_{Hist}-t_m)}}{r} + \frac{E_m \cdot \left\{-e^{m\cdot(t_m-t)} \cdot [m \cdot [(m+r)\cdot(t-t_m)+2]+r]+2m+r\right\}}{m^2}$$

Annual emissions pathway

$$E(t) = \begin{cases} observations & \text{for } t \leq t_{Hist} \\ E_m \cdot e^{r\cdot(t-t_m)} & \text{for } t_{Hist} < t \leq t_m \\ f(t) & \text{for } t > t_m \end{cases}$$

with $f(t) = E_m \cdot [1 + (r+m)\cdot(t-t_m)] \cdot e^{-m\cdot(t-t_m)}$

Box 2: Allocation rule

The global annual carbon budget $E(t)$ is distributed among countries in the form of allowances $\bar{q}_{i,t}$.

Convergence parameter $\alpha_t = \frac{\mathrm{t}}{y}$ where y is the number of years until the date of convergence.

Per capita $\bar{q}_{i,t} = E(t) \cdot [\alpha_t \mathrm{FS}_{i,t} + (1 - \alpha_t)\mathrm{GS}_{i,t}]$

with fair shares $\mathrm{FS}_{i,t} = \frac{population_{i,t}}{\sum_i population_t}$

and grandfathered shares $\mathrm{GS}_{i,t} = \frac{q_{i,tHist}}{\sum_i q_{tHist}}$ where t_{Hist} is the last data point for emissions.

Equal stocks $\bar{q}_{i,t} = E(t) \cdot \mathrm{FS}_{i,t} - \left[\mathrm{d}_{i,t-1} - \frac{\mathrm{D}_i}{n}\right]$

with the debt principal

$D_i = \mathrm{FS}_{i,tHist} - \sum_{t=RespDate}^{t=tHist} q_i$

where $RespDate$ is the date at which to start counting past stocks (e.g. 1800 or 1990).

and the starting point of the carbon deficit $\mathrm{d}_{i,t}$ is $\mathrm{d}_{i,0} = \mathrm{D}_i$.

Per dollar $\bar{q}_{i,t} = E(t) \cdot [\alpha_t \mathrm{GDPS}_{i,t} + (1 - \alpha_t)\mathrm{GS}_{i,t}]$

with GDP shares $\mathrm{GDPS}_{i,t} = \frac{GDP_{i,t}}{\sum_i GDP_t}$

and grandfathered shares as above.

Historical responsibilities

$$\bar{q}_{i,t} = \hat{q}_{i,t} - \left[\sum_i \hat{q}_t - E(t)\right] \times \frac{h_i}{H_i}$$

where $\hat{q}_{i,t}$ are Business As Usual emissions,

h_i is a country's stock of historical emissions:

$$h_i = \sum_{t=RespDate}^{t=tHist} q_i$$

and H_i is the coalition's stock of past emissions:

$$H_i = \sum_i h_i$$

Box 3: Market simulation

The optimal level of domestic abatement a^* and the equilibrium price of allowances on the market p^* are determined numerically, subject to the coalition staying within its cap $\sum_i \bar{q}_i$.

Abatement target $\bar{a}_{i,t} = \hat{q}_{i,t} - \bar{q}_{i,t}$

Domestic abatement $a^*_{i,t}$

Equilibrium price p^*_t

Transfers $tf_{i,t} = \bar{a}_{i,t} - a^*_{i,t}$

Discounting $\theta_t = {}^{1}\!/_{(1+d)^{(t-t_1)}}$

where d is the chosen discount rate.

Flows $f_{i,t} = \theta_t p^*_t \cdot (\bar{a}_{i,t} - a^*_{i,t})$

Emissions $q_{i,t} = \bar{q}_{i,t} + tf_{i,t}$

Decarbonisation costs

$$DC_{i,t} = \int_0^{a_{i,t}} country\ MAC\ curve_t$$

Total costs $TC_{i,t} = DC_{i,t} + f_{i,t}$

Introduction

Charting a way forward for international climate negotiations

International climate negotiations on reducing greenhouse gas (GHG) emissions have been fraught with difficulties for the past 20 years. Talks under the auspices of the United Nations Framework Convention on Climate Change (UNFCCC) have yet to deliver a global binding agreement. The forthcoming 21st meeting of the Conference of the Parties (COP-21) in Paris in December 2015 represents a shrinking window of opportunity to be able to limit global average warming to 2 degrees Celsius relative to pre-industrial levels. The world is currently on track for 4°C of warming (World Bank, 2014), which would threaten to roll-back all of the development gains made in the last decades and would disproportionately impact the global poor (Skoufias, 2012). The shape of the agreement in Paris and its level of ambition will determine the prospects for a safe and prosperous world in coming years, and will be make-or-break for the future of the Convention.

We have created an interactive tool, called SkyShares, to aid policy-makers to visualise the economic and environmental consequences of a climate agreement. The tool allows users to set a temperature limit which they deem acceptable, to choose how the resulting safe carbon budget is shared among countries, and to model a trading scheme with varying degrees of trading. This paper describes the data and methodology underpinning SkyShares.

SkyShares supports a conceptual framework which reconciles top-down and bottom-up approaches to international climate policy. The expiry of the Kyoto Protocol and the tepid outcomes of the Copenhagen Accord which rested on voluntary pledges by countries to reduce their emissions signal just how far the current political possibilities are from a universal, ambitious and legally binding climate agreement. The in-built distribution of responsibility within the Convention based on the Annex 1/non-Annex 1 division is obsolete and no longer fit for purpose. Annex 1 parties to the Convention, consisting of industrialised countries, were supposed to and have failed to take the lead on decarbonisation. Non-Annex 1 parties are mostly developing countries which are not expected to bear the brunt of emissions reduction. Yet today the world's largest emitter by volume (China) and rapidly growing and emitting emerging economies such as Brazil and India are considered non-Annex 1 countries.

The negotiations on sharing the burden of decarbonisation are deadlocked. The USA is legally incapable of agreeing to binding emissions reductions unless developing countries also take on decarbonisation commitments, following the passage of the 1997 Byrd-Hagel Senate resolution[1], which means the prospect of a universal and legally binding agreement is dead on arrival. Conversely, developing country negotiators are reluctant to agree to legally binding cuts since they have not been able to reap the benefits of early fossil fuel-intensive industrialisation. SkyShares reframes the question as an asset-sharing one, and offers a variety of algorithms for the user to share a scientifically determined carbon budget among countries.

The world is as far as ever from a top-down treaty on emissions reduction, yet a technological revolution which would rid the world of its dependence on fossil fuels has not materialised. Without a global price on carbon, the private sector has not received a clear and credible market signal to invest in low-carbon and renewable energy resources. The Intergovernmental Panel on Climate Change (IPCC) estimates that an upscaling by a factor of three to four of the share of zero- and low-carbon energy supply from renewables, nuclear and carbon dioxide capture and storage (CCS) technologies by 2050 is needed for a likely chance of hitting the 2°C target, i.e., to stay within concentrations of 450 parts per million (ppm) of CO_2e (IPCC AR5 WG3 SPM, 2014, p. 13). The scale and pace of this upscaling requires a structural transformation of the way humans consume and produce energy and of the way

---

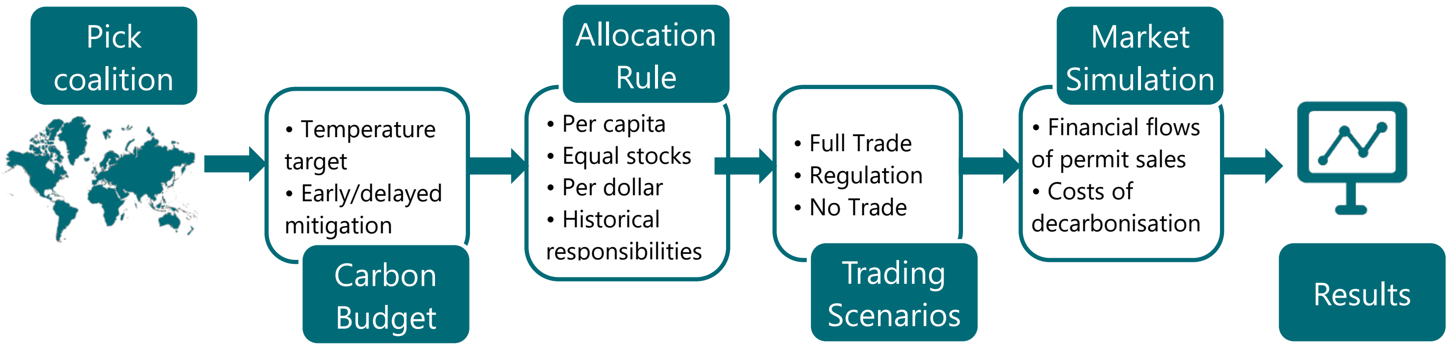
[1] US Senate Journal, 105th Congress, 1997-1998, Senate Resolution 98: https://www.congress.gov/bill/105th-congress/senate-resolution/98/text?q=%7B%22search%22%3A%5B%22international+agreement+on+greenhouse+gas+emissions%22%5D%7D

land systems are managed, if we are to have a chance to avoid dangerous climate change. This necessitates a price on carbon (in the form of an emissions trading scheme or of a carbon tax) in order to internalise the true social and environmental cost of carbon. SkyShares models a cap-and-trade scheme (where the total number of allowances on the market is capped to a desired carbon budget) and allows users to set the degree to which free trade is allowed.

SkyShares allows decision-makers to pragmatically conceptualise a climate agreement where a coalition of progressive and ambitious countries take action unilaterally and participate in such a scheme. Absent a universal and legally binding agreement, and while the green New Deal has yet to cheaply disseminate low-GHG technologies – SkyShares allows users to consider what a plausible way forward would look like by picking and choosing which countries to include in the coalition from the outset.

A dynamic and interactive tool to move forward the negotiations

SkyShares is a web model which offers a dynamic suite of options for the user to model their desired outcome in international climate negotiations. The modelling in SkyShares does not make normative choices about scenarios (though there exist assumptions about efficiency and discounting which are made explicit in this document). The user can choose to set a dangerously high temperature target if they wish. Likewise, they can select a highly unequal distribution of allowances, and can choose economically costly decarbonisation policies if they so desire. The user can choose inequitable distributions of the global shared resource and can "break" economic efficiency, but by construction SkyShares will always model an outcome where the coalition stays within its chosen carbon budget (though of course that cap can be relaxed by choosing a higher temperature target).



Data

Unless otherwise specified, all of the data used in SkyShares comes from publicly available sources. The data-sets can be found in the Documentation tab in the website, or in SkyShares desktop (http://bit.ly/SkySharesv7).

Notation, units and measures of conversion

Formulae in this paper only considers countries which the user has chosen to be part of the coalition. All variables therefore to a country i is which is part of the coalition. A coalition-wide variable is denoted with the subscript COW (to denote a Coalition of the Willing).

1 GigaTonne = 10^9 Tonnes = 1 Billion Metric Tonnes

1 PetaGram of Carbon = 10^{15} g = 1 GigaTonne of Carbon

1 Gram Carbon = 44/12 Gram CO_2

We use different units throughout the paper. To convert a unit of carbon to a unit of carbon dioxide, simply multiply it by 44/12, which is the ratio of the molecular weight of carbon dioxide to carbon.

Country socio-economic data

Country categories

SkyShares has a near-global coverage of 194 territories. Out of the 193 member states of the United Nations General Assembly, SkyShares does not include data for Andorra, the Federated States of Micronesia, Lesotho, Liechtenstein, Monaco, Nauru, San Marino, South Sudan and Tuvalu – usually because of a lack of data on emissions or on population. SkyShares does however include data for the following dependencies of UN sovereign states: Bermuda, Cayman Islands and Turks and Caicos Islands (British Overseas Territories); Faeroe Islands and Greenland (Kingdom of Denmark); Aruba (Kingdom of the Netherlands); French Polynesia and New Caledonia (overseas collectivities of France); and the two Special Administrative Regions of China, Hong Kong and Macau.

Users can choose to include countries in the model either by selecting the countries directly, or by including entire groups of countries at once.

Category	Number of countries	Definition/notes
Income groups	***Total = 194***	World bank definition[2]:
Low-income countries	34	GNI/capita of $1,025 or less
Lower-middle income countries	45	GNI/capita of $1,026 to $4,035
Upper-middle income countries	53	GNI/capita of $4,036 to $12,475
High-income countries	62	GNI/capita of $12,476 or more
World regions	***Total = 194***	
Africa	52	
Americas	40	
Asia	49	
Europe	40	
Oceania	13	
Parties to the UNFCCC		
Annex 1 countries	40	Annex 1 parties include the industrialised economies and economies in transition (EITs) [3].
Non-Annex 1 countries	144	Mostly developing countries[4].
Economic blocs		
G8	31	Includes EU28 member states and excludes Russia[5].
G20	43	Includes EU28 member states.
Group of 77	131	Official membership is 134 countries[6].

Table 1. Country categories in SkyShares

SkyShares allows users to use tags to select groups of countries such as the **Africa Caribbean Pacific** (ACP) countries, the **BRICS**, the **European Union**, and the **EU Emissions Trading Scheme** (EU ETS) countries[7] (includes the EU-28 and the EEA-EFTA states Iceland and Norway).

SkyShares also includes tags for groups of countries which sometimes negotiate together at the UNFCCC: the **Alliance of Small Island States** (AOSIS), an alliance of 34 low-lying coastal and small island countries which are meant to consolidate the voices of Small Island Developing States (SIDS), including a push for an international mechanism for loss and damages; the **BASIC** countries (Brazil, South Africa, India and China) who committed to act jointly at the 2009 Copenhagen climate summit; the **Cartagena Dialogue for Progressive Action** (51 countries, including the EU, which are committed to becoming or remaining low-carbon economies); the group of **Least**

[2] The World Bank uses Gross National Income per capita to classify countries by income groups. We use 2011 figures (GNI per capita ranking, Atlas method and PPP based, World Development Indicators, World Bank. Available at http://databank.worldbank.org/databank/download/GNIPC.xls).
[3] Specifically, it includes the industrialised countries that were members of the OECD (Organisation for Economic Co-operation and Development) in 1992, plus countries with economies in transition (the EIT Parties), including the Russian Federation, the Baltic States, and several Central and Eastern European States. The EU is also a party to Annex 1. SkyShares is missing data for Liechtenstein which is an Annex 1 country.
[4] Non-Annex 1 parties are recognised by the Convention "as being especially vulnerable to the adverse impacts of climate change, including countries with low-lying coastal areas and those prone to desertification and drought". There are 154 Non-Annex 1 parties. We tag Hong Kong and Macau, the two Special Administrative Regions (SAR) of China, as Non-Annex 1. SkyShares does not have data on the following 10 Non-Annex 1 parties: Andorra, Cook Islands, Lesotho, Federated States of Micronesia, Nauru, Niue, San Marino, South Sudan, State of Palestine and Tuvalu. See http://unfccc.int/parties_and_observers/parties/non_annex_i/items/2833.php for the official list of Non-Annex 1 parties.
[5] Russia was suspended from the G8 on March 24, 2014.
[6] SkyShares does have data on the following five G77 members: Lesotho, Federated States of Micronesia, Nauru, South Sudan and State of Palestine. The two Chinese SAR (Hong Kong and Macau) are tagged as part of the G77. See http://www.g77.org/doc/members.html for the official list of G77 members.
[7] Liechtenstein is part of the EU ETS but SkyShares does not have data for it.

Developed Countries (using the UN definition which has a wider coverage than the LIC group with 46 countries[8]); countries from the **Organization of Petroleum Exporting Countries** (12 OPEC members); and the **Umbrella Group**[9] (a loose coalition of non-EU developed countries which formed after the adoption of the Kyoto protocol).

Emissions

SkyShares uses publicly available data from the Carbon Dioxide Information Analysis Center (CDIAC), an authoritative source[10] on emissions from fossil fuels (Andres *et al.*, 2014, p. 1). The data counts carbon emissions from the burning of fossil fuels, cement manufacture and gas flaring. It includes data from the beginning of the industrial period (1751) to the most recent available data (2010). We supplement this data-set with data from the Global Carbon Project on territorial emissions from fossil fuel and cement production to include the years 2011 to 2013. The Global Carbon Project is an international collaborative effort by scientists to keep a yearly tally of emissions which have been emitted so far. The GCP data from 2011 onwards are preliminary and are based on British Petroleum statistics (the "Statistical Review of Word Energy"). Emissions from cement production were estimated by CDIAC based on cement production from the US Geological Survey. We use national data for 194 countries out of the 250 territories[11] included in the CDIAC data-set.

The sum of the national CO_2 emission estimates are less than the global totals, although the difference is small. The sum of territorial emissions generally accounts for 94% of global estimates. The discrepancy is mainly due to the fact that the territorial data excludes emissions from bunker fuels (emissions from fuels used for international aviation and maritime transport), whereas the global figures include emissions from bunker fuels in their estimates. Other reasons for the difference are due to the inclusion of annual changes in fuel stocks in national estimates but not in global ones, and to well-known differences in international statistics where the sum of exports from all exporters is not identical to the sum of imports from all importers[12].

SkyShares uses the territorial level data on emissions when constructing variables such as 'fair shares' or 'grandfathered shares' (so that the total equals 100%), but uses the global estimates when calculating global variables such as the remaining allowable planetary carbon budget.

SkyShares considers 2013 as the last data point for which we have historical information on emissions (t_{Hist}). Global emissions after 2013 are then calculated using the emissions trajectory equation detailed in the section Emissions Pathway on page 38.

Population

Population projections

Population projections out to 2100 are used to construct variables such as countries' per capita 'fair shares'. The data-set has been consolidated for the 194 territories in SkyShares and comes from the United Nations World Population Prospects. We use the medium fertility variant[13].

---

[8] SkyShares does not have data on the following 2 LDC members: Lesotho and South Sudan. The UN uses three criteria to classify countries as Least Developed: gross national income per capita, Human Assets Index, and the Economic Vulnerability Index. See http://www.un.org/en/development/desa/policy/cdp/ldc/ldc_criteria.shtml.

[9] The Umbrella Group usually consists of 9 countries: Australia, Canada, Japan, New Zealand, Kazakhstan, Norway, Russia, Ukraine and the US.

[10] For example, the World Bank's World Development Indicators (WDI) use the CDIAC data to source their data on CO_2 emissions.

[11] The 250 territories include denominations which no longer exist as sovereign states, such as Czechoslovakia, so including all of these would double-count emissions.

[12] See CDIAC Frequently Asked Question number 10 at http://cdiac.ornl.gov/faq.html.

[13] This model uses the April 2011 version. The UN has since published the June 2013 version.

The sum of country totals is not equal to the global estimates provided by the UN, though the difference is on average less than 0.5% between 2013 and 2100. Nonetheless, we use the sum of country estimates to construct variables such as 'fair shares' so that totals equal 100%.

Historical population

Historical estimates of population from the beginning of the Industrial period are used to calculate countries' per capita responsibility for past emissions. We use a data-set developed by Mattias Lindgren of the Gapminder Foundation which collates estimates of past population from a variety of sources, including the UN's World Population Prospects (which we use for future population projections) and the dataset from Angus Maddison. Gaps were then filled with the "International historical statistics" database of Mitchell[14], the US Census Bureau, national sources such as census reports from the statistical bureaus of individual countries and using a variety of other sources and estimation methods[15].

The Lindgren dataset also includes adjustments for missing data by employing geographical interpolation (assuming a territory has had the same population growth rate as the larger area of which it is part), extrapolation (likewise, assuming a country's population grows at the same rate as a neighbouring country). Importantly, the dataset includes recalculations for present borders so that whenever possible, the historical data refer to the present borders of a territory, such as subtracting population from areas which are no longer part of the country. This consolidation work means that we are able to have historical estimates of, for example, the Czech and Slovak Republics' population pre-1993 (i.e. before the dissolution of Czechoslovakia). This allows us yield reasonable estimates of each country's historical responsibility for past emissions which square with current geopolitical borders. Using the Lindgren dataset for the 194 territories of SkyShares, we interpolate between years for each country in order to have an annual time-series and to fill in data for missing years.

Currency deflator

All dollar figures presented in SkyShares are in 2014 dollars. We use the International Monetary Fund's deflator from the World Economic Outlook database (April 2014 version). The IMF's GDP deflator is indexed to 2009, so we first rebase it to the year 2014:

$$Rebased\ deflator_t = {}^{IMF\ deflator_t * 100}\!/\!_{IMF\ deflator_{2014}} \tag{1}$$

We then use this rebased deflator to calculate the multiplier for the series from the year the currency is expressed in to 2014:

$$Multiplier\ for\ rebased\ 2014\ series = {}^{100}\!/\!_{Rebased\ deflator_t} \tag{2}$$

For example, CEPII's BASELINE database for GDP projections is in 2005 dollars, and the IMF's deflator (indexed to 2009) is 92 for 2005 and 108 for 2014. To express the BASELINE data in 2014 dollars, we first rebase the IMF deflator to 2014 which gives $92 * 100/108 = 85$. Therefore, to inflate a series expressed in 2005 dollars to 2014 dollars we multiply it by $100/85 = 1.18$.

[14] Brian Mitchell, "International Historical Statistics", Palgrave Macmillan, 1998.

[15] See the documentation for the dataset "Total population for countries and territories" here: http://www.gapminder.org/documentation/documentation/gapdoc003.pdf.

GDP

SkyShares offers the option to toggle between two datasets for GDP.

CEPII's BASELINE dataset

The BASELINE database is developed by CEPII to provide projections of the world economy until 2050. It projects a long-run growth scenario for 146 countries based on a three-factor production function of labour, capital and energy, plus two forms of technological progress, relying on the model MaGE (Macroeconometrics of the Global Economy). The MaGE model is fitted with United Nations and International Labour Office labour projections, and econometric estimations of capital accumulation, savings rate, relationship between savings and investment rate, education, female participation, and technological progress (which includes energy and total factor productivity).

Since the BASELINE data only includes projections until 2050, we project growth rates for countries until 2100. Projecting this far in the future is an exercise fraught with uncertainties. A reasonable assumption is that countries converge regionally to the same growth rate. Therefore we project GDP series post-2050 using the constant annual growth rate of a country's income group in past years. If a country switches to a higher income category[16] in time, then its growth rate is re-adjusted down (since higher income countries tend to grow slower than lower income countries).

The average annual growth rates for each income group are given below. SkyShares uses the average annual growth rates in the first column (2030-2050 from the BASELINE projections) to project growth rates after 2050. If a lower-middle income country, in the course of growing at 4.6% a year switches to the upper-middle income category (GNI per capita of $4,036 to $12,475), we adjust its future growth rate to 3.36%, and so on. Note that the cut-offs for income group classifications remains constant over time.

	2030-2050	1950-2100	2015-2100
Low income	5.50%	3.70%	4.52%
Lower-middle income	4.60%	2.82%	3.65%
Upper-middle income	3.36%	2.10%	2.71%
High income	2.05%	2.05%	2.13%

Table 2. GDP growth rates for income groups, using CEPII's BASELINE GDP series

The choice of the initial date in which to estimate average annual growth until 2050 has important implications. If we were to choose a longer-time frame, say, 2020, the projections would be smoothed (because averaged over a longer time period), but they would also yield higher GDP figures. We have chosen 2030 so as to project countries' GDP figures post-2050 over a shorter time period and to estimate more conservative GDP figures. Users have the option to switch base years in the Desktop version of SkyShares.

The raw data series from BASELINE is in constant 2005 dollars and is rebased to 2014 dollars using the IMF's deflator (re-indexed to 2014 base year as explained in the section Currency deflator above).

BASELINE does not have coverage for all of the countries in SkyShares, so countries for which data is missing have been proxied by countries with a similar socioeconomic profile. A country with missing GDP data is assumed to have the same GDP per capita as its proxy (using CEPII's GDP per capita series at Purchasing Power Parity Series). Its proxied GDP per capita is then multiplied by its population in the relevant year to recreate the GDP time-series for that country. Proxies have been chosen according to those countries which have the closest GNI per capita, or a combination of geographical proximity and shared sovereignty (e.g. Aruba's proxy is its sovereign state of the

[16] We use the World Bank's definition of income group categories which defines low income (LIC), lower-middle income (LMIC), upper-middle income (UMIC) and high income (HIC) groups. See the section on Country categories on page 12.

Netherlands) when GNI data is missing or when the data for the most preferred proxy is also missing. The complete list of proxies can be found in the Annex on page 71.

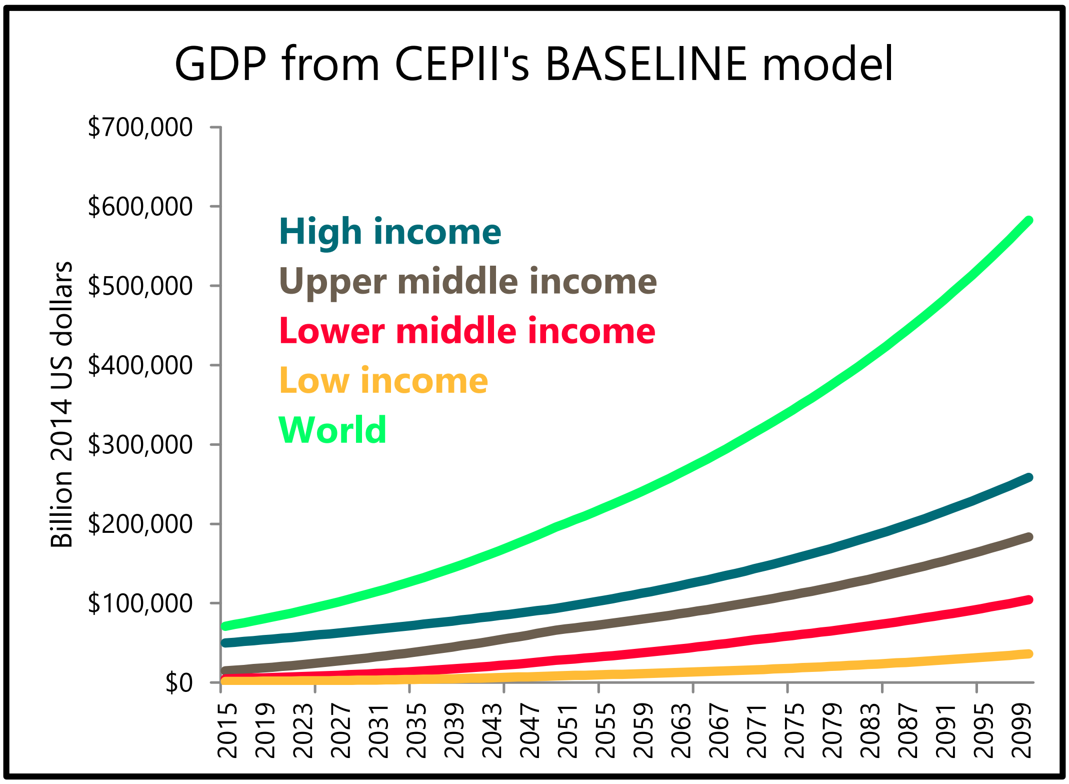


Figure 1. GDP projections using CEPII's BASELINE model

MIT's EPPA dataset

The other GDP dataset available in SkyShares is the one generated by the Massachusetts Institute of Technology's Emissions Prediction and Policy Analysis (EPPA) model. The EPPA model is a technology-rich Computable General Equilibrium (CGE) model which is described in full detail in the section EPPA starting on page 23. The GDP series is taken from the results of a scenario run by EPPA which is consistent with the marginal abatement cost curves also provided by EPPA.

The raw data generated by EPPA is presented in 5 year increments from 2000 to 2100, for the 16 regions in the EPPA model, and is expressed in 1997 US dollars. Transforming this data into a yearly time-series for all of the 194 countries in SkyShares and expressing it in 2014 US dollars involves a few steps.

First, we interpolate data from 5 year increments to annual data by using a spline. We use a Bézier spline which provides a smooth fit to the points.

Second, we reallocate the GDP figures for the 16 regions in EPPA to 194 individual countries. We have tagged each country in SkyShares to one of the 16 regions in EPPA. We then calculate what share of 2014 GDP (using the BASELINE figures) that country had within its EPPA region. For example, Argentina is tagged as belonging to the Latin America region in EPPA, and had a share of 10.8% of Latin America's GDP in 2014 (from the BASELINE figures). We thus use this GDP share to divide up each regional GDP between the countries assigned to it.

Finally, we inflate the data series which is expressed in 1997 dollars to 2014 dollars by using the IMF multiplier (1.39).

	2030-2050	1950-2100	2015-2100
Low income	3.27%	2.35%	2.71%
Lower-middle income	3.16%	2.24%	2.63%
Upper-middle income	3.06%	2.19%	2.55%
High income	2.75%	1.91%	2.24%

Table 3. GDP growth rates for income groups, using MIT's EPPA GDP series

Table 3 shows the average annual growth rates of the EPPA GDP figures for different periods and per income groups. The EPPA figures depict a more homogenous world where there is less variance in the regional GDP growth rates (or what economists would call a world of "sigma-convergence"). By contrast, the BASELINE figures project a world of greater convergence where low income countries grow faster than rich countries and catch up quicker (also called "beta convergence" in the economic growth literature). The EPPA figures project slightly higher growth rates for high income countries over the rest of the century than BASELINE, but they are broadly similar (2.24% for EPPA versus 2.13% for BASELINE).

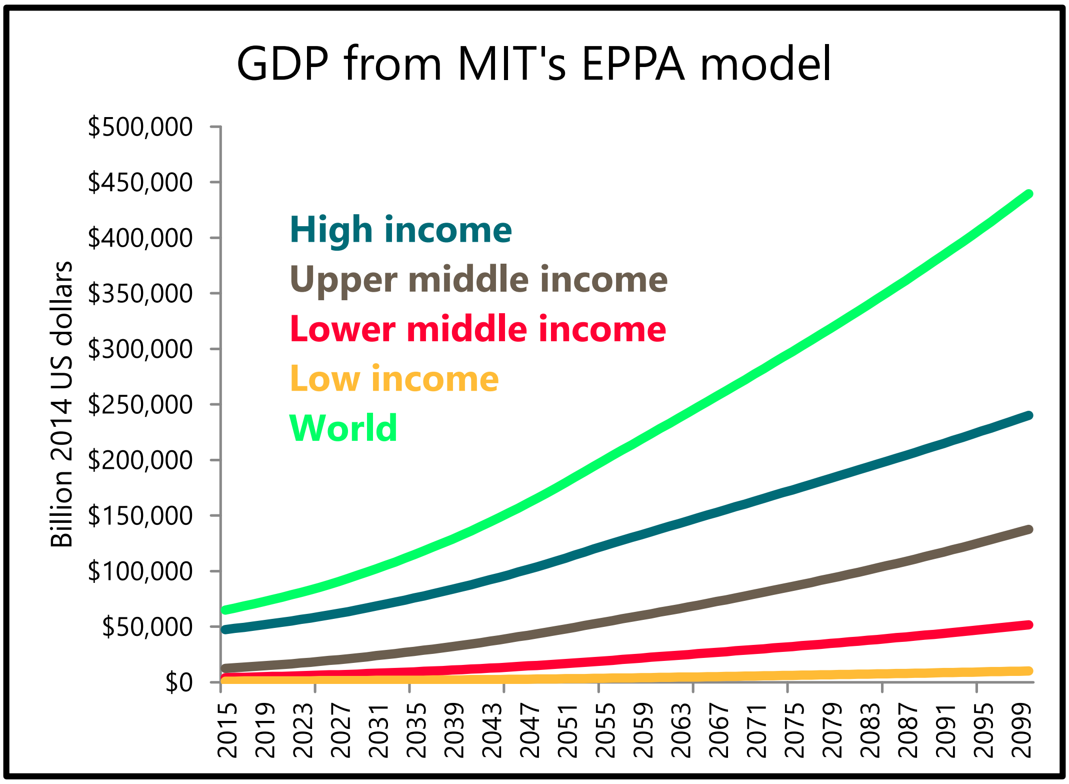


Figure 2. GDP projections using MIT's EPPA model

Marginal abatement cost curves

To get an idea of what costs the different temperature targets entail, SkyShares uses a tool conventionally used in climate economics called a Marginal Abatement Cost (MAC) curve. MAC curves plot the different technologies for emissions reduction, or abatement, against their respective costs. Marginal abatement costs are increasing in the quantity of abatement. The intuition is that one can only retro-fit one's home with climate-friendly insulation once. After most low-hanging fruit technologies are used up, such as switching from incandescent to LED in residential lighting or afforesting pastureland, the remaining avenues to reduce emissions become more expensive, and fast (such as retrofitting gas plants with carbon capture and storage technology). This gives MAC curves their convex shape.

A MAC curve can also be thought of as a 'supply curve for abatement', with its familiar dynamics: as the price rises, the amount of emissions reduction at that price rises. SkyShares uses MAC curves for each country to determine the amount of emissions reduction they will supply at the world price. MAC curves therefore underpin the entire market simulation of the model. This methodology is explained in further detail in the section Trading Scenarios which starts on page 53.

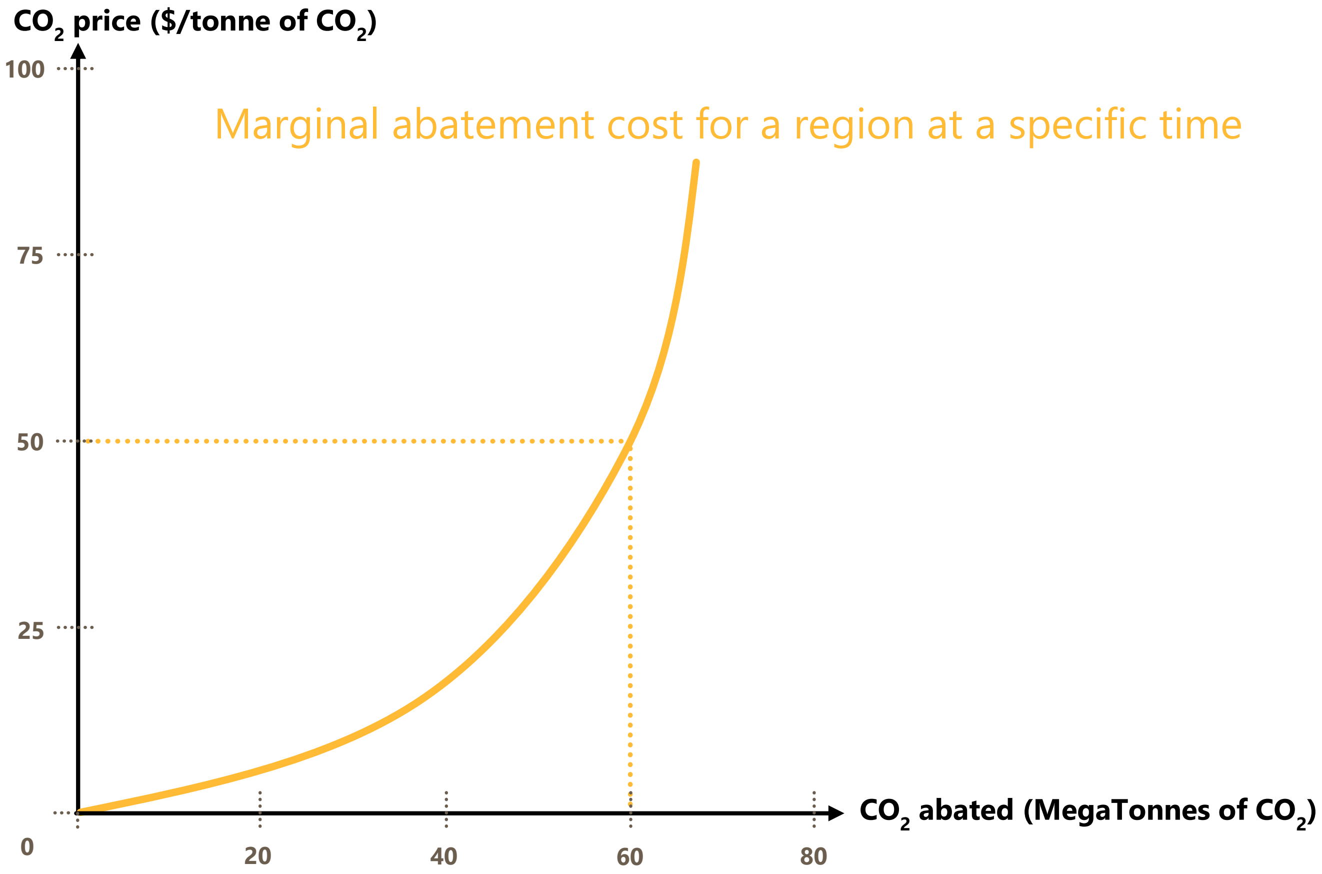


Figure 3. Stylised marginal abatement cost curve

Figure 3 above depicts a stylised marginal abatement cost curve. MAC curves are always represented for a particular region in a particular period. A point on the MAC curve refers to the cost of reducing the last tonne of emissions for a particular quantity of CO_2 abated. This means that MAC curves must be derived using a baseline for what CO_2 emissions are likely to be under a Business As Usual (BAU) scenario, that is, with no policy constraint (such as a carbon tax). In the above example, the cost of reducing the last tonne of CO_2 for an abatement target of 60 MegaTonnes is 50$ per tonne of CO_2. The total cost of abatement can be calculated by taking the area under the MAC curve (the integral). On Figure 3, the total cost of reducing emissions by 60 MegaTonnes compared to BAU levels would be approximately (less than) 60,000,000 tonnes multiplied by 50$, divided by 2 (to approximate the area under the curve, or half of the rectangle drawn by quantity times price), or ≈ $1.5 billion for that specific region in the year that the MAC curve depicts.

MAC curves can be generally derived either from technological appraisals or from models (Kesicki, 2011). SkyShares offers the option to toggle between two model-based curves (GCAM or EPPA), and between a technological appraisal or expert-based MACC (McKinsey). These are described in further detail in the next sections. But first, a few words of caution.

Caveats and limitations of MACCs

Although they are useful tools, MAC curves suffer from several shortcomings, some of which are common to all MACCs and to some degree unavoidable, and others are specific to the type of MACC at hand. First, MACCs are dependent on the baseline chosen. Inconsistent baselines can lead to double-counting of emissions reductions. This is particularly true of MACCs based on expert assessments (such as McKinsey's) which consider the individual abatement potential of each measure. If one abatement option is implemented, this changes the baseline for the remaining mitigation measures. If the baseline is not adjusted properly, this could overestimate emissions reductions. Model-based curves, on the other hand, offer the possibility of consistent baseline emission pathways (Kesicki, 2011, Kesicki and Ekins, 2012)[17].

Second, MACCs are invariably a static snapshot of abatement costs, confined to a specific region and time. The shape of a MAC in a given year will depend on the emissions reduction realised in previous years. MACCs are thus sometimes subject to path dependency. Expert-based MACCs in particular have difficulty accounting for intertemporal dynamics (Kesicki, 2011), whereas intertemporal interactions can be incorporated in model-based curves. For example, energy models can exogenously represent technical learning over time and have MACCs flatten as a result.

Third, MAC curves typically do not include ancillary costs and benefits beyond those of reducing GHG emissions. MAC curves that don't include the co-benefits of mitigation, such as reduced air pollution (the benefits of which can be quantified in terms of public health) or increased biodiversity (the benefits of which are harder to quantify, beyond ecosystem services) can end up overestimating the costs of emissions reduction.

Finally, MACCs are subject to many uncertainties which are embedded in the assumptions made to generate them, such as the rate of technical innovation, the discount rate, or the ease of deployment of a technology. The treatment of uncertainty is hard as often only one MACC is presented for a particular region/time nexus. Uncertainty becomes a particularly vexing problem as curves are generated for many years into the future. Thus care should be taken when interpreting SkyShares results for years after 2030, and especially results for the mid to end of the century.

Model-based curves are also not always robust to general equilibrium effects. Though early findings by Ellerman and Decaux (1998) implied that each country/region's marginal abatement cost curve was independent of the abatement levels in other regions, research by Klepper and Peterson (2006) showed that in a general equilibrium context global abatement levels influence world energy prices, which in turn feed back into each country/region's MAC curve and affect it. This is a particular concern when using MACCs to analyse international emissions trading where term of trade effects could come into play, as in SkyShares.

Moreover, though model-based curves MAC curves are often similar to Marginal Welfare Curves (MWCs), since top-down energy models usually solve by optimising societal welfare (rather than posing it as a single firm maximisation problem), they are unreliable instruments when it comes to deriving estimates of welfare change (Morris *et al.*, 2012).

Despite not offering as much technological detail as expert-based MACCs, model-based curves (such as EPPA and GCAM which are offered in SkyShares) are able to account for sectoral interdependencies, macroeconomic feedbacks, behavioural effects and system-wide interactions. For these reasons, model-based curves (such as EPPA and GCAM which are offered in SkyShares) tend to be preferable than curves based on technological appraisals (such as McKinsey's) for the analysis of incentive-based instruments like carbon pricing policies (Kesicki, 2011). Since SkyShares models a cap-and-trade scheme (an incentive-based policy instrument), we offer GCAM and EPPA as the default options to toggle MACCs in SkyShares. The McKinsey MACC is offered for comparison purposes only,

[17] However, model-based MACCs also need to adjust baselines so that they reflect any changes in world energy prices arising from general equilibrium effects in international emissions trading (Morris *et al.*, 2012).

and we issue a strong call for caution to those who wish to use it to generate costs of emissions trading under different allowance-sharing regimes.

MACCs derived from top-down models

There are two MACCs offered in SkyShares which fall under the category of MACCs generated using top-down[18] Integrated Assessment Models (IAMs) or Computable General Equilibrium (CGE) models. The exercise here is different than the expert-based MACCs which are constructed from the bottom-up by appraising each technology individually. Top-down models such as GCAM and EPPA are systems models which represent the interaction of the climate system with the economy. The representation of the economy itself includes interactions between different sectors and allows modellers to picture the supply and demand responses in various production and consumption sectors of different climate policies.

Models work by creating a stylised representation of the economy and its linkages to other natural systems. They are then calibrated using benchmark data for the economy of the country (region) they represent. Models are powerful tools which allow us to interface the powerful insights gained from microeconomic theory with its broader macro implications in a real economy. Applied to climate change economics, they allow us to see how an economy will respond to a policy, such as the setting of market-based incentives like a carbon tax. These types of top-down models rely on substitution elasticities which capture the behavioural responses of agents switching their consumption or production from one sector to another as a response to a price on carbon.

The exercise to generate MACCs using a model is to shock the economy by applying a carbon tax, for example $10 per tonne of CO_2, and seeing how much abatement the different sectors and countries considered will provide at the shadow price of carbon. We have generated many runs of both the EPPA and GCAM models at different levels of carbon prices in order to derive MACCs for SkyShares.

GCAM

The Global Change Assessment Model (GCAM) model falls under the category of Integrated Assessment Models (IAM). It is developed and maintained by teams at the Joint Global Change Research Institute (operated by the University of Maryland and the Pacific Northwest National Laboratory). The GCAM model is one of the seven models chosen by the IPCC to develop the Representative Concentration Pathways (RCP)[19] – the new family of scenarios developed for the Fifth Assessment Report (AR5). The RCPs replace the previous Special Report on Emissions Scenarios (SRES) which were used in previous IPCC reports. Specifically, GCAM underpins the construction of RCP4.5 (Thomson *et al.*, 2001).

GCAM is an IAM which links a climate model with technology-rich representations of the economy. It is particularly apt to study the interactions between the energy system, water, and land-use sectors. GCAM has global coverage for 31 geopolitical regions, and models their interactions through international trade in energy commodities, agricultural and forestry products and other goods such as emissions permits (GCAM wiki). It is solved with a dynamic-recursive model to reach market equilibrium. Expectations of the representative agent are myopic foresight.

Assumptions on regional population growth and labour productivity drive demand for the energy and land-use systems, and the production sectors include numerous technology options. Technologies modelled by GCAM include: carbon capture and storage, bioenergy, hydrogen systems, nuclear, and renewable energies. The three

[18] MACCs can also be generated using bottom-up engineering models, such as the Targets Image Energy Regional (TIMER) model (see van Vuuren *et al.*, 2004) but these are not offered in SkyShares. MACCs derived from engineering bottom-up models tend to offer greater technological detail, but lack macroeconomic feedbacks.

[19] Intergovernmental Panel on Climate Change (2008), "Report from the IPCC expert meeting towards new scenarios for analysis of emissions, climate change, impacts, and response strategies", IPCC-XXVIII/Doc.8, Twenty-Eighth Session, Budapest, 9-10 April 2008. Available at http://www.ipcc.ch/meetings/session28/doc8.pdf.
GCAM is the successor model to MiniCAM, which is referred to in the IPCC documentation.

end-use sectors are buildings, transportation and industry. Technological change and learning is modelled as an exogenous input. Emissions of greenhouse gases and aerosols are determined endogenously in GCAM as the result of human activities. The climate module in GCAM – the MAGICC model[20] – then calculates the resulting emissions of GHG and aerosols as a result.

GCAM is amenable to the study of various climate policies and targets, such as cap-and-trade, carbon tax and subsidies.

The code of GCAM is available publicly at http://www.globalchange.umd.edu/models/gcam/ and can be run by submitting scenarios in XML files to the model. The JGCRI have built a model interface in Java which allows users to export data and results from the scenarios. We have used the latest version of GCAM released in October 2014: GCAM 4.0.

To generate MACCs using GCAM, we have first run a reference scenario without any climate policies in place, to be used as our Business as Usual (BAU) baseline. Then, we have run GCAM 51 times under carbon tax scenarios, starting from $5 to $500 (in $10 increments from $10 onwards). This allows us to model how the demand for carbon goods, and production of goods which emit CO_2 emissions, react in the 31 geopolitical regions of GCAM – under different carbon prices. We then generated MACCs by subtracting the CO_2 emissions under each price point (e.g. for a scenario where the shadow cost of carbon is $10) from the BAU levels.

To create country-level MACCs from the regional MACCs generated by GCAM, we divide the abatement provided (at each price) among countries of a GCAM region according to the share of current emissions that each country is responsible for within that region. To our knowledge, no single model IAM generates country-level MAC curves for all of the countries of the world, due to data limitations. Proxying the share of abatement that each country will provide according to their share of current emissions (for the particular GCAM region under consideration) is a reasonable way to overcome this.

Figure 5 below depicts the global MAC curves generated by running GCAM using the method described above. The full mapping of countries in SkyShares to regions in GCAM is available in Table 14 in the Annex on page 74.

Prices in GCAM are given in 1990 US dollars so we have converted them to 2014 US dollars using the method described on page 15.

[20] The Model for the Assessment of Greenhouse Gas Induced Climate Change (MAGICC) is a reduced complexity model which includes a terrestrial carbon cycle model and allows for the introduction of variable climate sensitivities (see Meinshausen *et al.*, 2011).

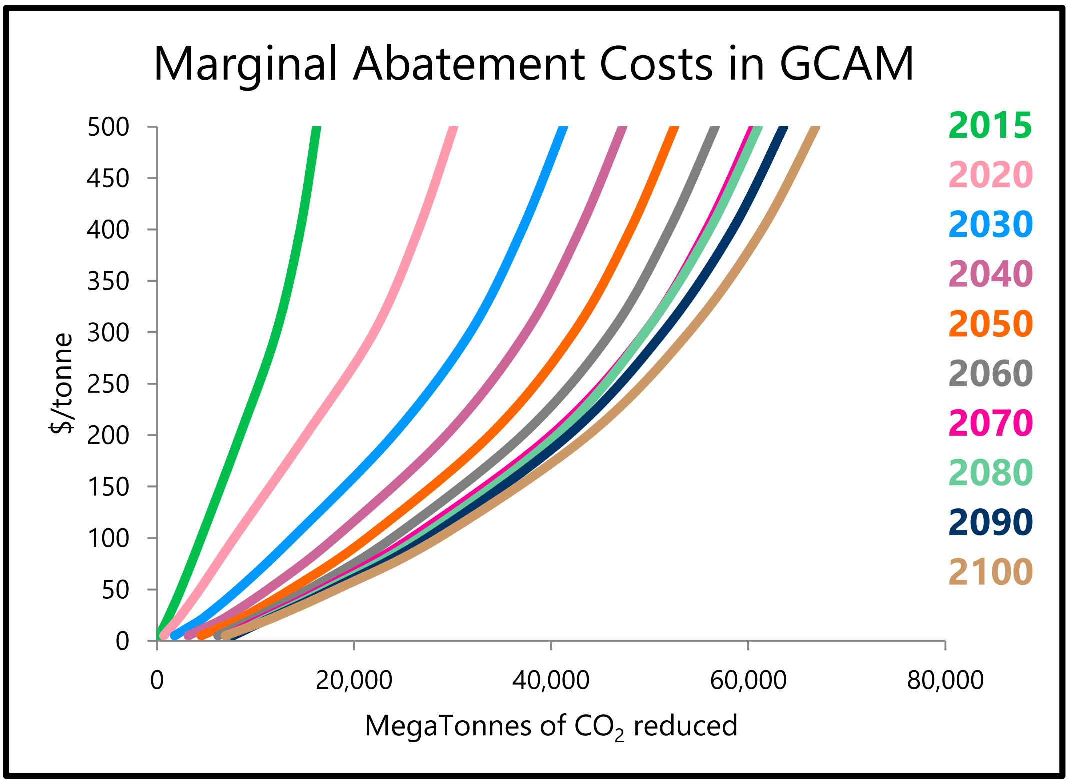


Figure 4. Global marginal abatement cost curves generated with GCAM 4.0[21]

EPPA

The other class of MACCs derived from top-down models is the Massachusetts Institute of Technology's Emissions Prediction and Policy Analysis (EPPA) model. Like GCAM, EPPA forms part of a global IAM when taken as part of MIT's Integrated Global System Modeling Framework (IGSM) which models the interaction between human economies and the climate system. The EPPA model provides the economic model of IGSM, and represents the link between economic activities and GHG emissions.

At its heart, EPPA relies on a Computable General Equilibrium (CGE) model. CGE models provide stylised representations of the economy and its linkages, among different agents (e.g. consumers, producers, and government) and among different sectors (e.g. agriculture and manufacturing). EPPA has global coverage and is composed of 16 geopolitical regions.

The EPPA model has a long history in the literature and is one of the earliest used in the study of climate economics, starting with Ellerman and Decaux (1998) who used EPPA to analyse the benefits of emissions trading to achieve the Kyoto Protocol targets.

EPPA has a rich sectoral disaggregation which includes agriculture, energy intensive sectors, transportation and other services. The EPPA model has numerous technologies for the energy sector, including explicit modelling of renewables (solar, wind and biomass), and the possibility for Carbon Capture Storage and Sequestration (both with the natural gas combined cycle and in the integrated gas cycle) to kick in as new technologies.

Like for GCAM, EPPA is solved with a dynamic-recursive solution and agents are modelled as having myopic expectations (Morris *et al.*, 2008, p. 3). EPPA is written in GAMS (General Algebraic Modeling System), software commonly used for CGE modelling. We have used the core engine of EPPA 4.1 (the latest publicly available version),

[21] Prices are quoted in 2014 US dollars. Coverage includes all of the GCAM regions, except for Taiwan which is not covered by SkyShares.

except for one modification. The file eppaloop2.gms file has been modified to remove the time trend of the carbon price variable (*pcarblag*) in order to run EPPA at fixed carbon prices.[22]

We complete the same exercise as with GCAM: (1) run a reference scenario to project what emissions would be like in the absence of climate mitigation policies; and (2) run various scenarios under different carbon prices to model what the shadow price of carbon and associated emissions reductions would be.

We wrote 51 "case files" (code which we feed to EPPA 4.1 and which tells it which scenario to run) to specify the carbon price, from \$5 to \$500 (in \$10 increments after \$10). The case file specifies the initial carbon price which remains fixed for all of the years considered by the EPPA 4.1 model. We divide our desired carbon price (e.g. \$50) by 27.27 to generate the variable *p_ini*, in order to reconcile with raw MIT values. The EPPA 4.1 model covers the years 1997, and 2000 to 2100 in 5 year increments. We have set the carbon price to kick in from 2010[23] for all carbon tax scenarios to model what the associated emissions reduction would be in all years (this allows us to generate MACCs for the earlier years of SkyShares). A sample case file can be found in the Annex on page 78.

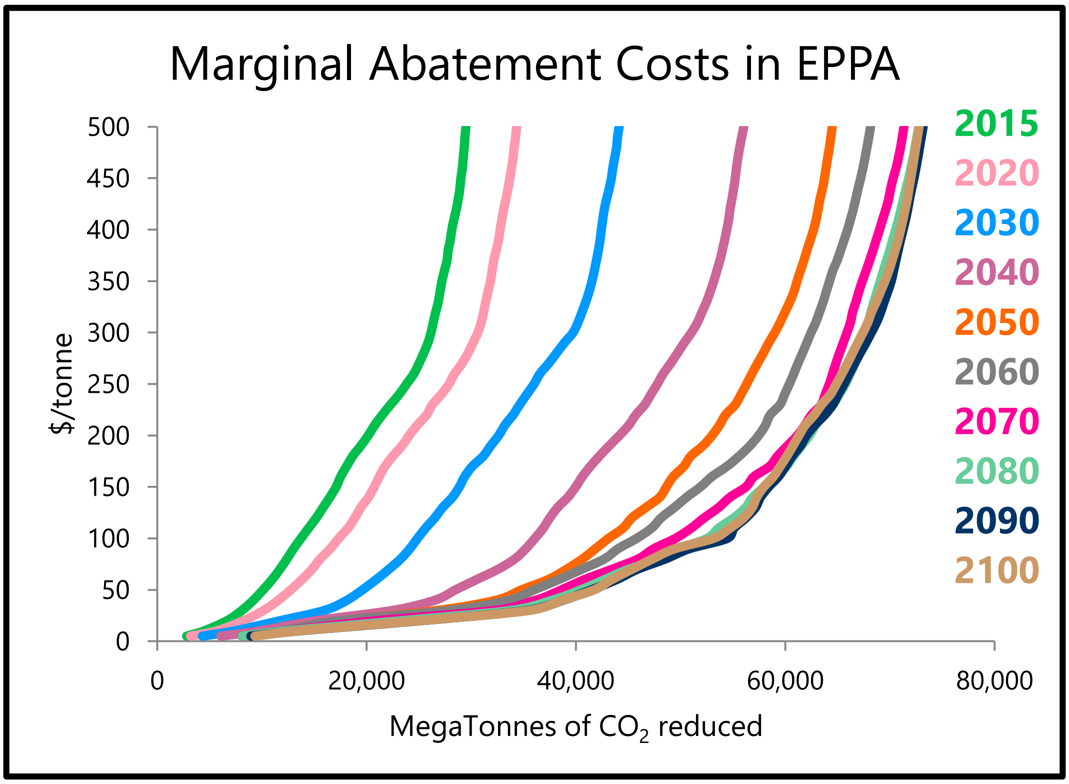


Figure 5. Global marginal abatement cost curves generated with EPPA 4.1[24]

MACCs derived from technological appraisals

McKinsey

This category of MACCs, also called expert-based MACCs (Kesicki, 2011), is created by independently appraising the abatement potential of each technology. McKinsey & Company have developed detailed country-level MACCs, in addition to a global level MAC curve (McKinsey, 2009).

To plot such a MAC curve, one would first calculate the cost per tonne of reducing emissions for each technology. If each 'technology' is represented by a rectangle, the greater the quantity of emissions reduction that is possible, the

---

[22] The time trend in the original EPPA model was parametrised at $*1.04^5$. We keep the USA as the numéraire.
[23] The variable *det_pr* has been set to 4.
[24] Prices are quoted in 2014 US dollars.

wider the rectangle. The cost of that abatement is represented by the height of the rectangle. Then, the different technologies are ordered on the horizontal axis from cheapest to most expensive, and plotted against the cost-per-tonne reduced on the vertical axis.

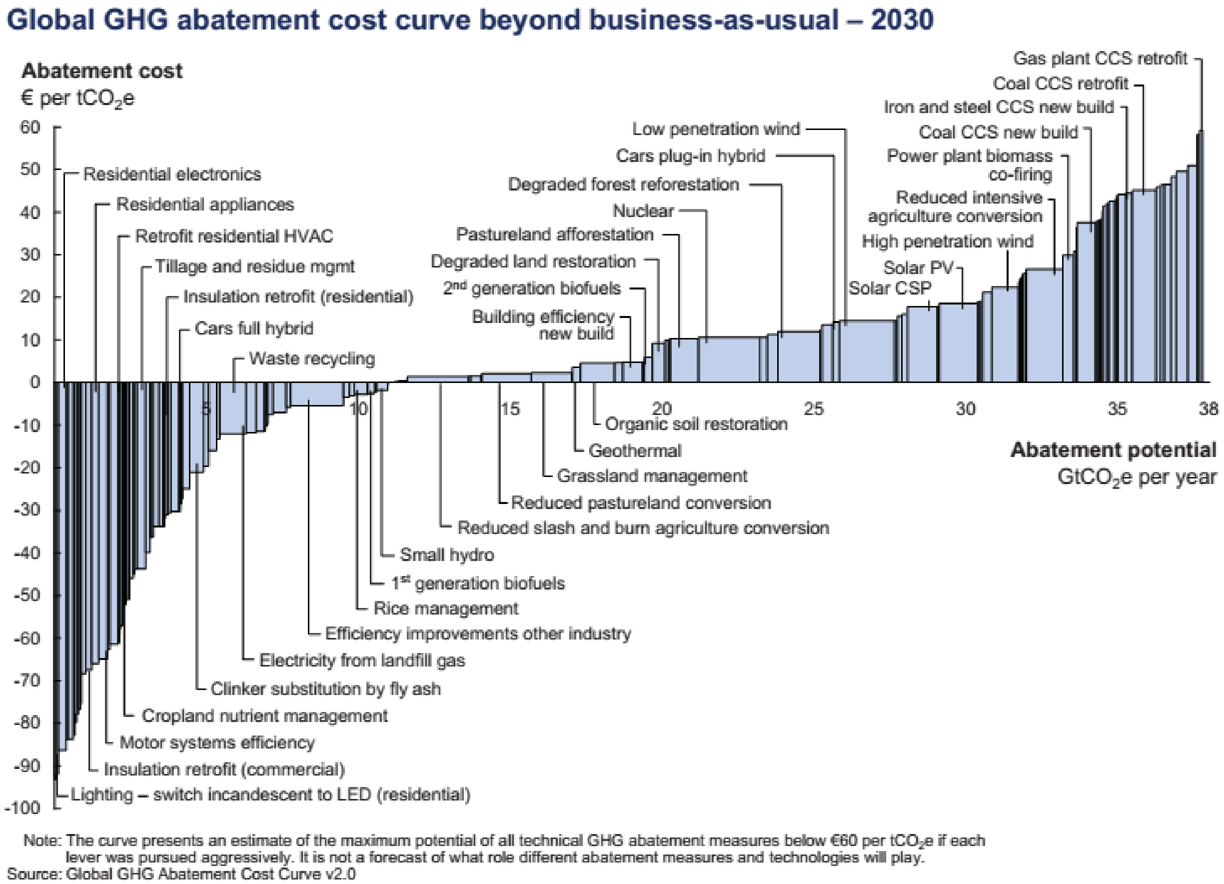


Figure 6. A sample marginal abatement cost curve. Source: McKinsey, 2009.

If one imagines a smooth line connecting the top-right corner of each rectangle on Figure 6, then the expected shape of a marginal abatement cost curve appears.

The main advantage of MACCs based on technological appraisals or expert assessments is the rich detail afforded for each technology. They offer the possibility of accounting for technology-specific market distortions, such as existing subsidies for fuel, or carbon taxes. They however disregard other key drivers which are likely to be important for the analysis or modelling of market-based policies (such as the cap-and-trade system in SkyShares). In particular, they ignore macro-economic feedbacks such as the re-allocation of labour between different sectors, or the impacts on trade. Nor are they able to adequately take into account behavioural changes such as the likely change of demand that would result from changing prices. They aren't able to capture market imperfections such as information asymmetries or split incentives (Kesicki, 2011, p. 5). This explains in part the presence of negative abatement costs, seen on the left of the graph in Figure 6, which represent no-regrets measures but which aren't taken up due to the market distortions described above (e.g. split incentives between a house owner and tenant regarding the installation of insulating materials).

We are grateful to McKinsey & Company for allowing us access to their Global Greenhouse Gas Abatement cost curve. We use version 3.0 of McKinsey's cost curve in SkyShares. This has not been published by McKinsey & Company yet, so this data-set is not publicly available (all other data-sets in SkyShares are).

The McKinsey data provides marginal abatement costs for 21 countries/regions, from 2005 to 2030 in 5 year increments.

Given the nature of MACCs based on technological appraisals such as McKinsey, the raw data displayed a large variance with regards to abatement costs, including negative abatement costs, and maximum abatement costs of 31,770$ per tonne of CO_2e for 2015, and maximums of the order of magnitude of 21,000$/tCO2e for years 2020, 2025 and 2030. Negative abatement costs represent abatement options which are win-win and which should already be implemented as they save money. However, MACCs based on technological appraisals don't capture the behavioural and institutional barriers which would render such options for mitigation unfeasible. Therefore we exclude those from SkyShares. Likewise, expert-based MACCs, since they appraise a wide range of technologies irrespective of the policy context, will invariably find some mitigation options for which the abatement costs are very large per tonne of CO_2 abated (such as the road transport sector in large emerging economies such as India and Brazil). We therefore exclude cost points above the 75th percentile in order to avoid outliers skewing the mean cost of abatement upward.

The variance in abatement costs is generally large, but differs by country/region. For some countries, like South Africa, the variance in abatement costs is relatively low (see Figure 7 below). The resulting MACC plotted in Figure 8 increases (relatively) smoothly, and the price points at the higher end of the distribution are still less than 500$ per tonne.

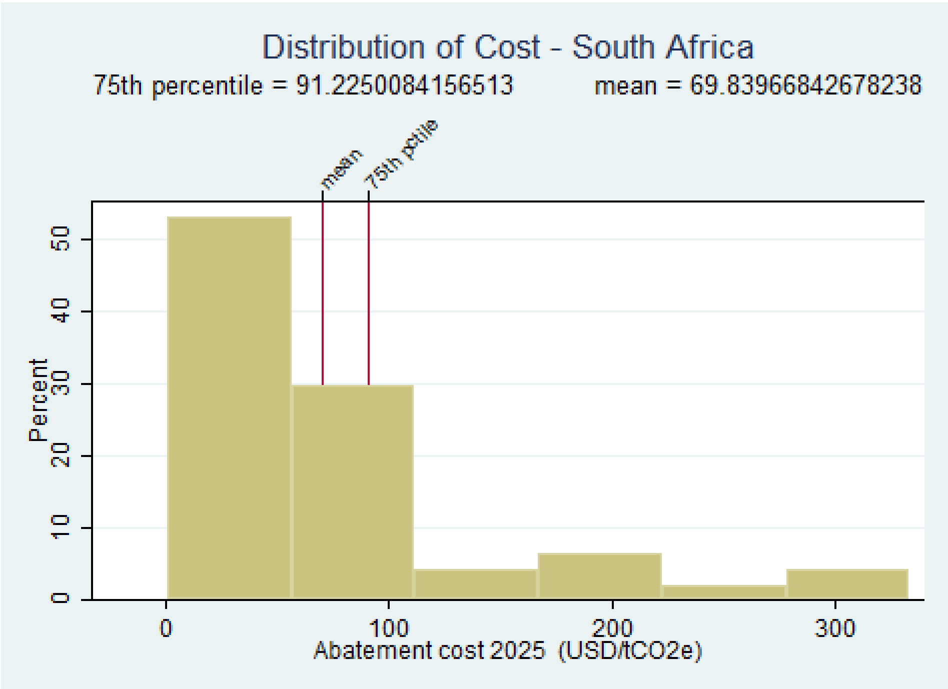


Figure 7. Example of relatively low variance in abatement costs for South Africa in 2025

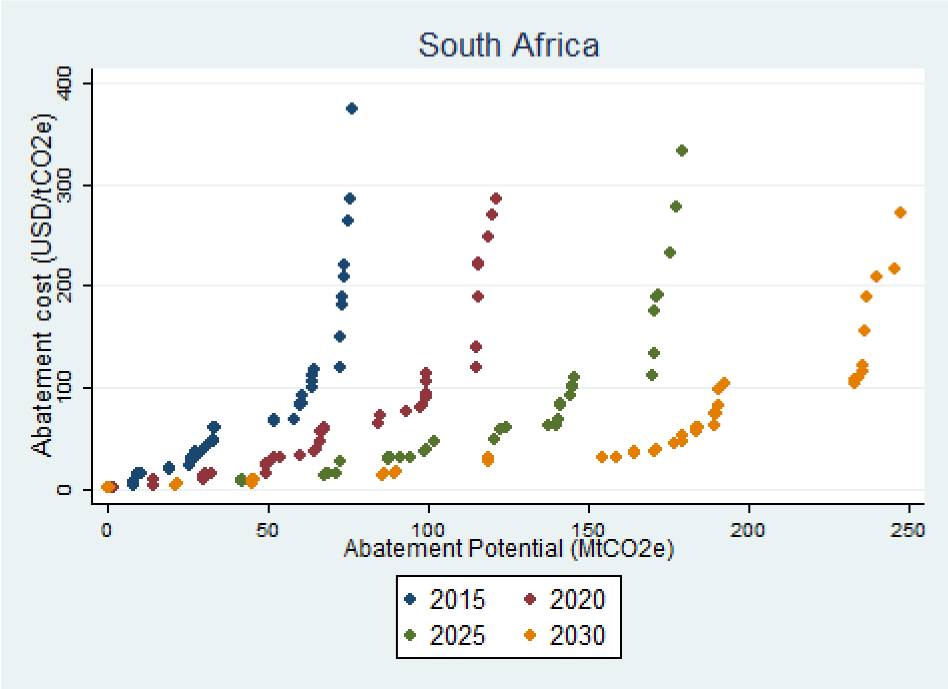


Figure 8. MACCs for South Africa, including outliers

However, for some regions in the McKinsey data like the rest of Africa, the distribution of costs has very long tails to the right. We can see in Figure 9 below that the mean is substantially larger than the median (the mean is greater than the 75th percentile). If we include the outliers, this leads to MACCs which shoot up at a near-right angle to much levels for abatement costs, as shown in Figure 10 below.

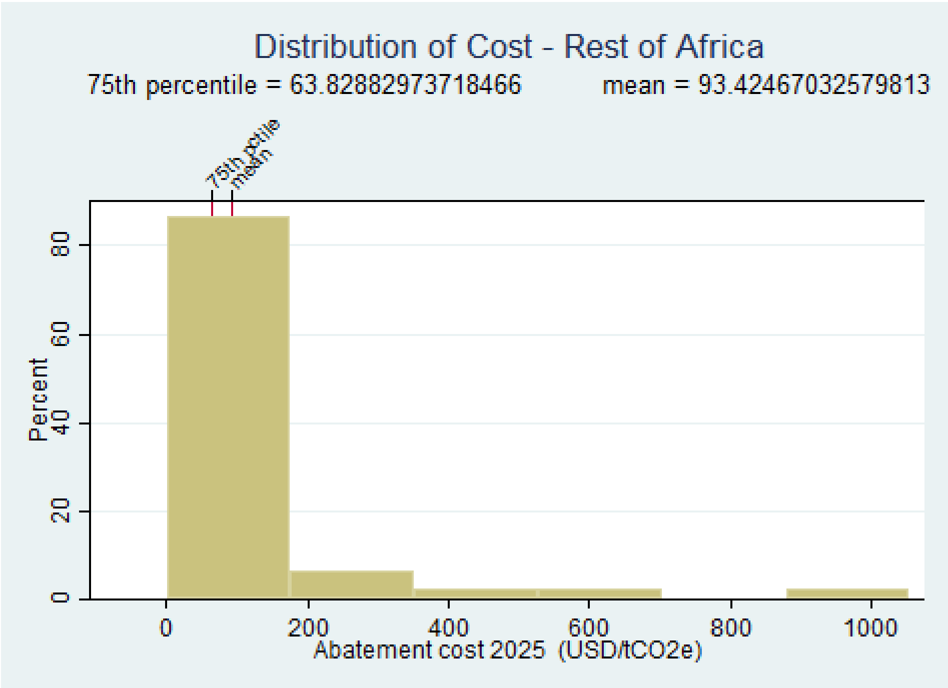


Figure 9. Example of relatively high variance in abatement costs for the rest of Africa in 2025

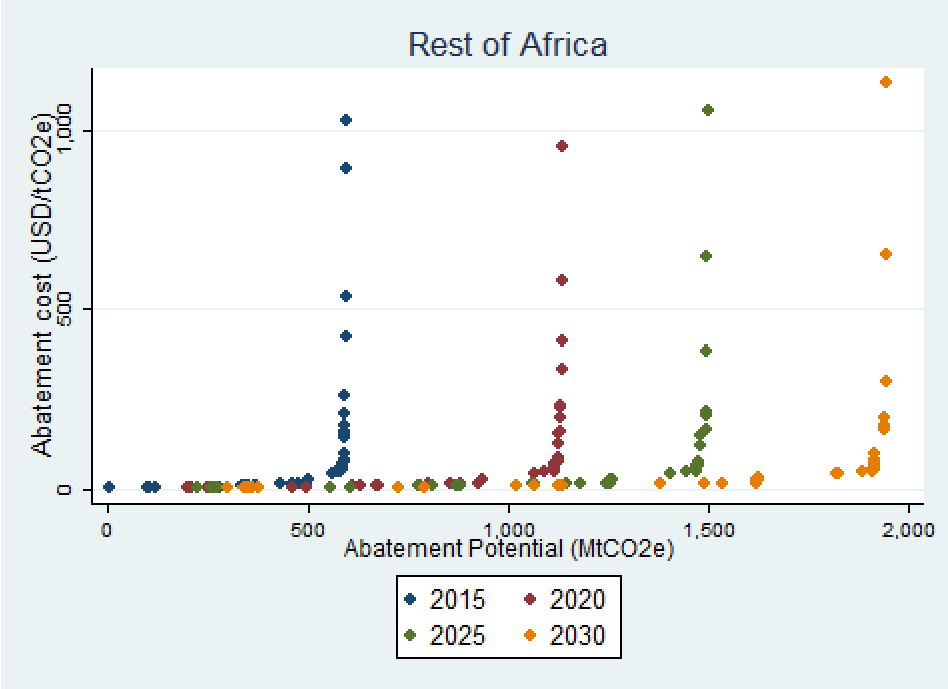


Figure 10. MACCs for the rest of Africa, including outliers

Once we have excluded negative abatement costs and outliers from the McKinsey raw data, we turn our attention to generate the MACCs for 2035 to 2100 that SkyShares requires as inputs (McKinsey only provides data up to 2030). In order to do so, we have first fitted a line of the form $y = ax + b$ to the years 2015 to 2030 for each price point and for each country/region. We then extrapolated the quantity of abatement provided by each country at each price point for the remaining years by applying the coefficients a and b for the remaining years 2035-2100. This led to more conservative (lower abatement quantities) estimates than interpolating.

Finally, we divide these MACCs into country-level MACCs for each of the 194 SkyShares countries by multiplying each country's share of current emissions within a McKinsey group to the abatement provided by each group at each price point. The full mapping of SkyShares countries to McKinsey regions is available in the Annex on page 78.

Business As Usual

Each of the three marginal abatement cost curve data-sets in SkyShares have associated BAU baseline emissions. SkyShares allows users to toggle between MACC data-sets, and the associated BAU data will also be automatically switched. We do offer the possibility to override the standard BAU data associated with its MACC data, and to use the IPCC's Representation Concentration Pathway scenarios instead. These are plotted below in Figure 11.

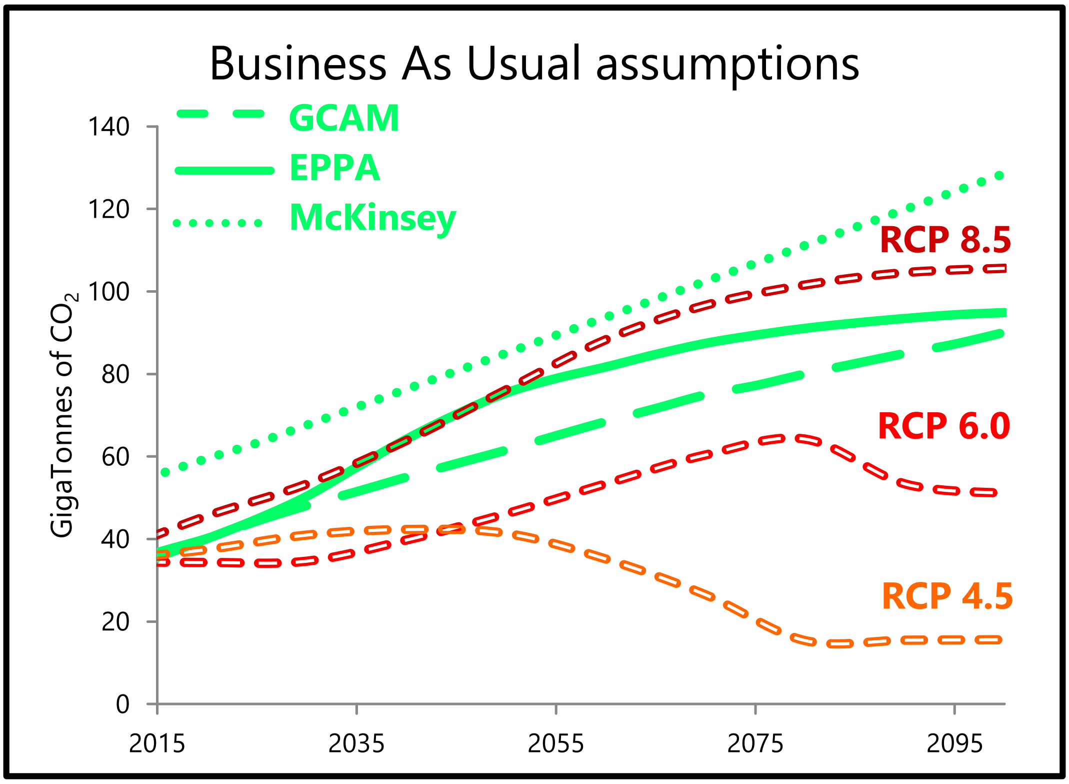


Figure 11. Business As Usual assumptions for the 3 data-sets included in SkyShares, compared to the IPCC's Representation Concentration Pathways

Business as usual emissions under RCP 4.5 entail a global mean surface warming (relative to 1850-1900) of 2.41°C [likely range 1.71°C to 3.21°C]; RCP 6.0 emissions entail warming of 2.81°C [likely range 2.01°C to 3.71°C], and RCP 8.5 emissions lead to mean warming of 4.31°C [likely range 3.21°C to 5.41°C] (IPCC AR5 WG1 SPM, 2013, p. 23).[25]

To provide a rough means of comparison, we have calculated the warming (relative to the pre-industrial period) associated with the three MACC data-sets (GCAM, EPPA, and McKinsey) by summing the cumulative emissions from 2014 to 2100 entailed by each data-set's BAU to the stock of emissions emitted so far. Using the method described in the section Limiting warming, we calculate what the 50% chance of warming by the end of the century would be, as shown in Table 4.

BAU data source	Cumulative emissions to 2100	Associated warming
GCAM	7,602 GigaTonnes of CO_2	3.65°C
EPPA	8,378 GigaTonnes of CO_2	3.91°C
McKinsey	9,644 GigaTonnes of CO_2	4.32°C

Table 4. Median warming by the end of century with different Business As Usual scenarios

It should be noted that the reason that the McKinsey BAU assumptions are much higher than the other data-sets is due to the nature of the modelling (engineering based/technological appraisals, as opposed to top-down modelling for GCAM and EPPA). The version of modelling most heavily used by McKinsey is survival analysis, which excludes taxes and subsidies. They only consider the abatement potential brought by technology, and exclude any transaction costs. Their BAU scenario takes into account how the economy and individual sectors have developed, and only take into account future abatement which has been communicated by policy-makers and put in place.

[25] The table SPM.2 in the IPCC report quotes warming relative to the new IPCC reference period of 1986-2005. We re-adjust the figures to show the warming relative to the period 1850-1900 by adding the observed warming from then to 1986-2005 of 0.61°C.

They don't allow for any future abatement driven by targets. Their BAU is thus higher because it doesn't include any additional improvements, such as changes in policy. Version 3.0 of the McKinsey cost curve does take into account the effects of the 2009 financial crisis, and their BAU outlook is closely aligned with the International Energy Agency's *2010 World Economic Outlook*.[26]

[26] From personal correspondence with Sebastian Schienle, Global Knowledge Manager of the Sustainaiblity and Resource Productivity Practice at McKinsey & Company, 7 July and 31 July 2014.

The scientific cap

Scientific research indicates that warming since pre-industrial times is related to cumulative carbon emissions in a quasi-linear fashion. Starting in 2009, there has been an increasing literature dedicated to the topic of carbon budgets and future warming: Allen *et al.* (2009), Bowerman *et al.* (2011), Gillett *et al.* (2013), Matthews *et al.* (2009), Meinshausen *et al.* (2009), Raupach *et al.* (2011), Smith *et al.* (2012), Stocker (2012), and Zickfeld *et al.* (2009). The IPCC's Fifth Assessment Report also relates cumulative emissions to mean surface temperature change (IPCC AR5 WG1, 2013).

Determining the carbon budget necessary to limit warming to a level deemed acceptable by the user is achieved in two steps:

1. Calculate the cumulative carbon emissions quota associated with a user-chosen temperature target.
2. Spread the all-time safe carbon budget across years in an emissions trajectory and solve for the rate of mitigation required to stay within budget.

SkyShares makes use of the analytical insights of Raupach *et al.* (2011a and 2011b) which provide (1) a quasi-linear equation relating temperature change to cumulative carbon emissions; and (2) a smooth-capped emissions trajectory algorithm to spread the carbon budget across years.

Limiting warming

Changes to the climate system as a result of human activities are expressed in terms of radiative forcing[27]. Other factors such as cloud cover and aerosols also have radiative forcing effects on the climate[28]. Man-made GHG emissions have had a positive radiative forcing which has warmed the atmosphere. The atmospheric concentration of greenhouse gases such as carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) has increased markedly since pre-industrial times as a result of human activities[29]. The global atmospheric concentration of carbon dioxide has increased from a pre-industrial value of 280ppm to 400ppm[30] today. These atmospheric concentrations are at levels unprecedented in at least the last 800,000 years (IPCC AR5 WG1 SPM, 2013, p. 11). Since pre-industrial times, anthropogenic GHG emissions have had a total forcing of 2.29 W m^{-2} [1.13 to 3.33 W m^{-2}] (IPCC AR5 WG1 SPM, 2013, p. 13) leading to a temperature increase of +0.85°C [0.65 to 1.06°C][31] over the period 1880-2012 (IPCC AR5 WG1 Chapter 2, 2013, p. 161).

The extent to which the atmosphere warms as a result of man-made CO_2 emissions can be accelerated by climate change itself through positive carbon-climate feedbacks. Other positive climate feedbacks include ice-albedo and water vapour. These biophysical responses include feedbacks which affect the natural land and ocean sinks of atmospheric CO_2, and those feedbacks which lead to CO_2 releases from previously immobile stores of carbon on land or in the ocean (Raupach *et al.*, 2011a, p. 145).

---

[27] Radiative forcing is a measure of the influence that a factor has in altering the balance of incoming and outgoing energy in the Earth-atmosphere system. It is expressed in watts per square metre (W m^{-2}). Positive forcing tends to warm the surface while negative forcing tends to cool it.

[28] Albedo is the fraction of solar radiation that is reflected (e.g., affected by cloud cover, atmospheric particles or vegetation). Albedo has mostly a negative forcing. Aerosols (primarily sulphate, organic carbon, black carbon, nitrate and dust) tend to have a cooling effect, but remain the dominant uncertainty in radiative forcing. Aerosols also have an indirect cloud albedo effect which has a negative radiative forcing. Anthropogenic contributions to radiative forcing also come from tropospheric ozone changes due to emissions of ozone-forming chemicals such as nitrogen oxides, carbon monoxide, and hydrocarbons.

[29] This is primarily due to fossil fuel and land use change for CO_2 and primarily due to agriculture for CH_4 and N_2O.

[30] 400 ppm means that there are 400 molecules of CO_2 per million molecules of dry air. This data comes from the Keeling Curve data-set (Scripps Institution of Oceanography) at Mauna Loa Observatory, which makes high precision continuous measurements of carbon dioxide levels in the atmosphere. See https://scripps.ucsd.edu/programs/keelingcurve/.

[31] This is the globally averaged combined land and ocean surface temperature data as calculated by a linear trend.

Relationship between peak warming and cumulative emissions

The IPCC does not provide a functional form for the link between peak warming and cumulative emissions. Different studies have provided various functional forms using slightly different methodological approaches. Allen and Stocker (2013) express the approximately linear relationship between cumulative CO_2 emissions and peak warming using the transient climate response to cumulative emissions, or TCRE. They define the TCRE as the warming due to cumulative CO_2 emissions per trillion tonnes of carbon (TtC) released into the atmosphere (Allen and Stocker, 2013, p. 1). Allen *et al.* (2009), Matthews *et al.* (2009) and Stocker (2009) also express that relationship as cumulative emissions over a long time period (up to 2500) to resultant warming, and consider peak warming per trillion tonnes of carbon. Taking a slightly different methodological tack, Meinshausen *et al.* (2009) use a shorter time frame and consider cumulative warming up to 2050 (and emissions levels in 2050) to calculate the probability (using a Bayesian approach) that warming in the 21st century will not exceed 2°C.

Raupach, Harman and Canadell (2011b) have suggested a functional form for the relationship between warming above pre-industrial temperatures (ΔT) and cumulative anthropogenic CO_2 emissions from fossil fuel combustion and net land use change since the start of the industrial revolution. This is not a physically-based expression. For a physically-based functional form, see Raupach, Canadell, Ciais, Friedlingstein, Rayner and Trudinger (2011a) which provides a simple equation for median peak warming and includes physically-based parameters such as the cumulative airborne fraction (CAF) of CO_2, radiative forcing of non-CO_2 agents, and the climate-carbon cycle feedback.

The attractive feature of the Raupach *et al.* (2011b) expression is that it allows the different studies mentioned above to be standardised and compared (even those like the Meinshausen *et al.* study which used a much shorter time period for emissions stocks). Raupach *et al.* (2011b) have empirically fitted the results of the different studies to this expression (for median warming), and provide the calibration values for the relevant parameters.

Furthermore, all of the uncertainty in this expression is carried in the climate sensitivity term λ. The base equation is expressed in terms of median (50%) warming. This expression affords us the possibility to carry out probabilistic analysis for all of these studies by rewriting the climate sensitivity λ to different likelihoods.

The relationship between peak warming $\Delta T(Q)$ as a result of cumulative emissions Q is thus given by this 2-parameter function (Raupach *et al.*, 2011b, p. 47):

$$\Delta T(Q) = \frac{\Delta T_1}{2^\alpha - 1} \cdot \left[\left(\frac{Q}{Q_1} + 1 \right)^\alpha - 1 \right] \tag{3}$$

where

ΔT_1 is the warming at a reference cumulative emission Q_1 (always taken as a trillion tonne of carbon),

α is a dimensionless exponent which gives $\Delta T(Q)$ its logarithmic shape (if $\alpha < 1$).

Raupach *et al.* (2011b) have fitted the results of the different carbon budget studies for median warming to equation (3) and provide the fitted values for α and T_1 (2011b, p. 50). We use this to calculate median warming at different levels of cumulative emissions Q for the studies considered by Raupach *et al.* (2011b), shown in Table 5 below.

Q (in PgC)	Allen *et al.* (2009), simple climate model	Allen *et al.* (2009), C4MIP emulations	Zickfeld *et al.* (2009)	Matthews *et al.* (2009)	Meinshausen *et al.* (2009), all agents	Raupach *et al.* (2011), all agents
0	0	0	0	0	0	0
500	1.185713467	1.023501302	0.791849964	0.774341674	1.239942118	1.154589212
1000	1.97	1.93	1.6	1.55	2.12	2.08
1500	2.547717116	2.75837449	2.420491138	2.326638853	2.802800299	2.865394898
2000	3.000793552	3.529380205	3.250952951	3.104059987	3.360801878	3.554657228
2500	3.371058815	4.255732186	4.089799126	3.88213227	3.832664868	4.173046852
3000	3.682608783	4.945925617	4.935890435	4.66076242	4.241469981	4.736604619

Table 5. Peak warming and cumulative emissions of different studies, median warming

SkyShares uses the peak warming trajectory of the Raupach *et al.* (2011b) for all agents (i.e., including non-CO_2 agents). This calibration for median warming in this specification is $T_{1m} = 2.08$ and $\alpha = 0.353$. The interpretation for is T_{1m} is that a trillion tonnes of carbon will give a 50% chance of staying below 2.08°C warming relative to pre-industrial temperatures.

We plot these relationships in

Figure 12 below, and include the IPCC's Representative Concentration Pathways data on mean warming for comparison (the IPCC does not provide usable data-sets with probabilities attached to them so we do not know what median warming is for the RCPs).

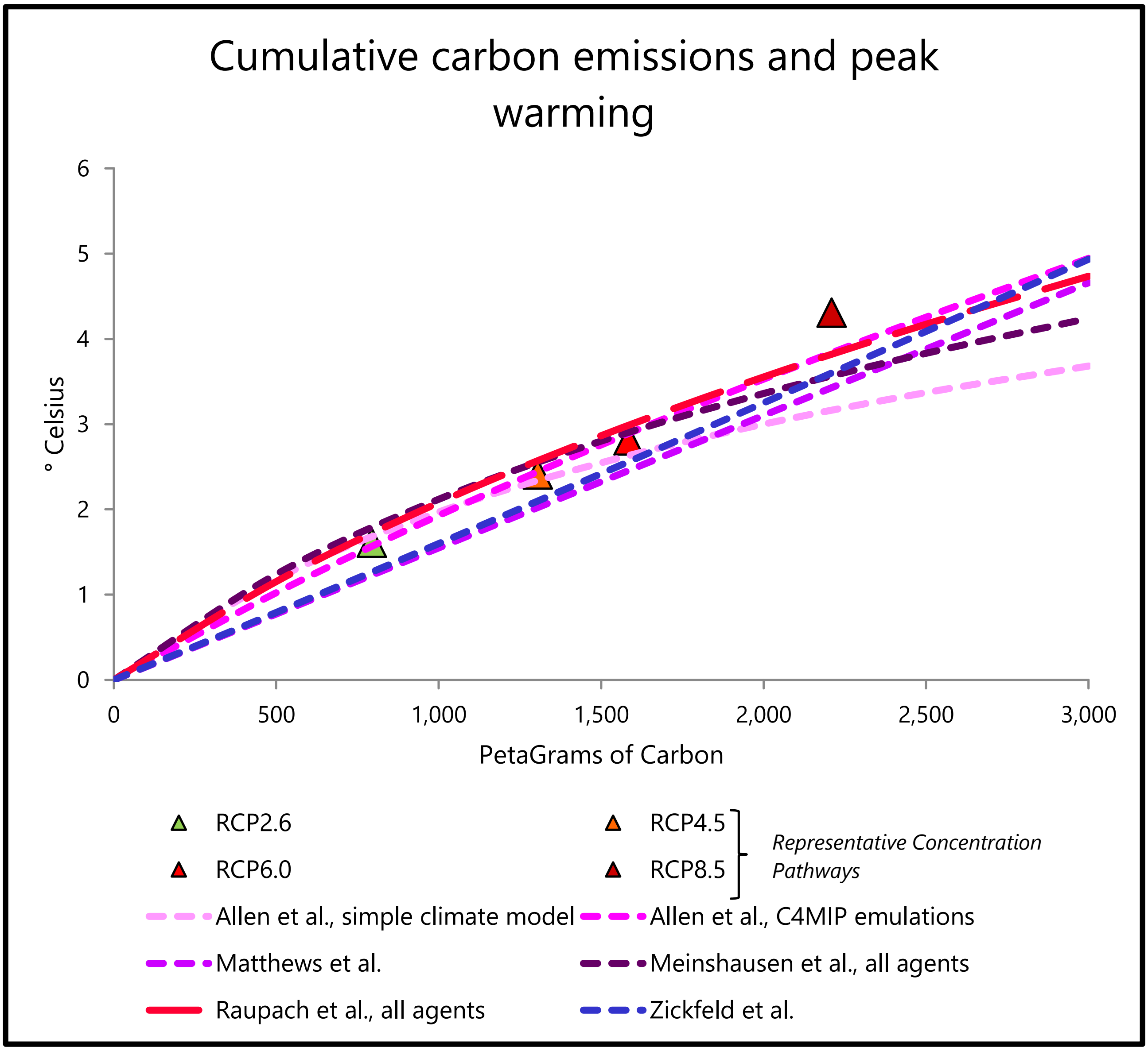


Figure 12. Peak warming trajectories of different studies, median warming (and mean warming for IPCC figures)

SkyShares allows the user to choose a temperature at which they wish to limit warming to. The code then performs a simple goal seek on equation (3) to solve for Q (using the values for $T_1 = 2.08$ and $\alpha = 0.353$ as described above). This will yield the all-time carbon budget for a 50% chance of hitting the chosen temperature target.

Probabilistic analysis

SkyShares also offers the user to toggle between different likelihoods of hitting the temperature target, namely 33% and 66%. In the IPPC lexicon, probabilities between 0% and 33% are termed "unlikely", and probabilities between 66% and 100% are called "likely" (IPCC AR5 WG1 SPM, 2013, p. 4).

The expression for peak warming as a function of cumulative carbon emissions can be included to include climate sensitivity λ. We rewrite ΔT_1 in equation (3) so that it includes a proportional dependence on the climate sensitivity parameter λ, following the methods detailed by Raupach *et al.*, 2011b, p. 47:

$$\Delta T_1 = \Delta T_{1m} \cdot {}^{\lambda}/_{\lambda_m} \tag{4}$$

where λ_m is the median climate sensitivity and ΔT_{1m} is the warming at $Q_1 = 1000\ GtC$ with median climate sensitivity. All of the uncertainty (about aerosols, clouds, feedbacks on carbon pools, etc) is thus carried in λ, which is an attractively self-contained way for SkyShares to grapple with uncertainty.

Raupach *et al*. (2011b) have modelled the probability distributions of climate sensitivity using a log-normal distribution. They take the median climate sensitivity λ_m as 3°C per doubling of CO_2 and a spread parameter of $s = 0.419119$ and find that this gives a 17-83% probability range of 2 to 4.5°C. The parameter in s is the standard deviation of $\ln(\lambda)$ in a log-normal distribution (Raupach *et al.*, 2011b, p. 48). We use the values given in the Raupach study to recreate a log-normal probability density function (PDF) and cumulative distribution function (CDF) for different values of the climate sensitivity parameter λ using s as the spread parameter, shown in Table 6 below.

Values of λ	Log-normal PDF	Log-normal CDF
2	29.81%	16.66%
2.25	33.43%	24.62%
2.5	34.65%	33.17%
2.75	33.88%	41.77%
3	31.74%	50.00%
3.25	28.77%	57.58%
3.5	25.42%	64.35%
3.75	22.03%	70.28%
4	18.80%	75.38%
4.25	15.86%	79.71%
4.5	13.25%	83.34%

Table 6. Log-normal probability density function and cumulative distribution function of climate sensitivity λ, defined as the warming resulting from a doubling of CO_2 atmospheric concentrations

The second and third columns are plotted in Figure 13 and Figure 14, respectively. We can indeed see that the values in the Raupach study give attach a 17% likelihood to a climate sensitivity of 2°C and an 83% chance to a climate sensitivity to 4.5°C.

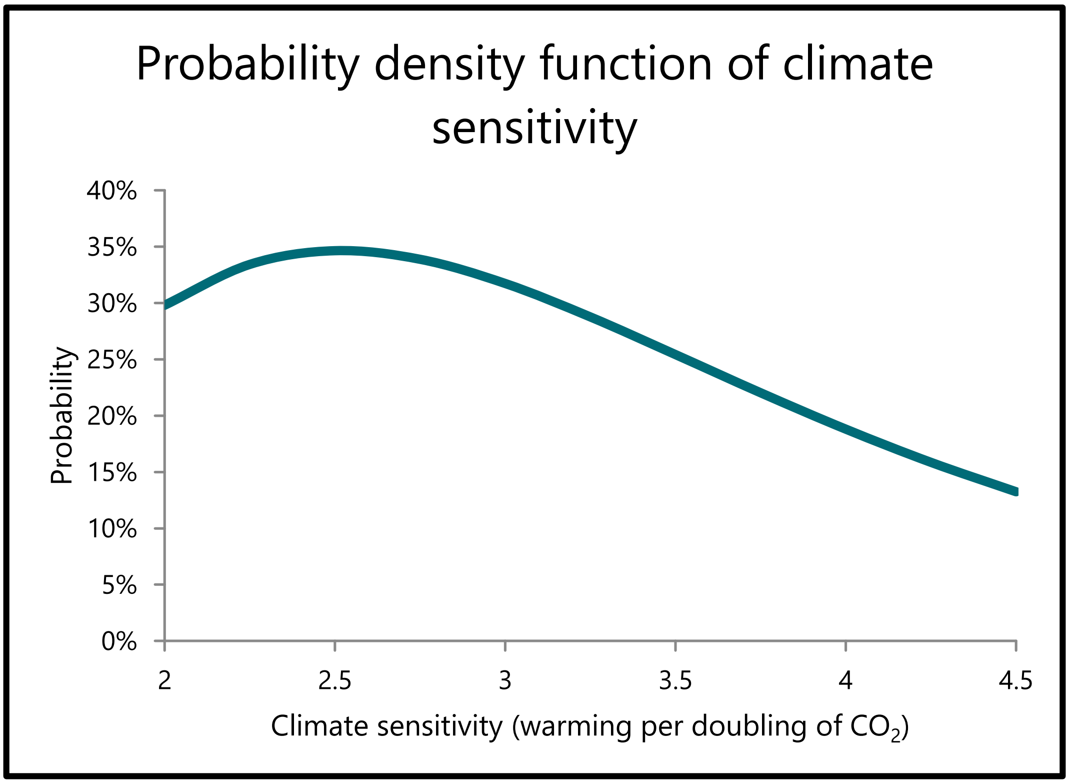


Figure 13. Log-normal probability density function of climate sensitivity

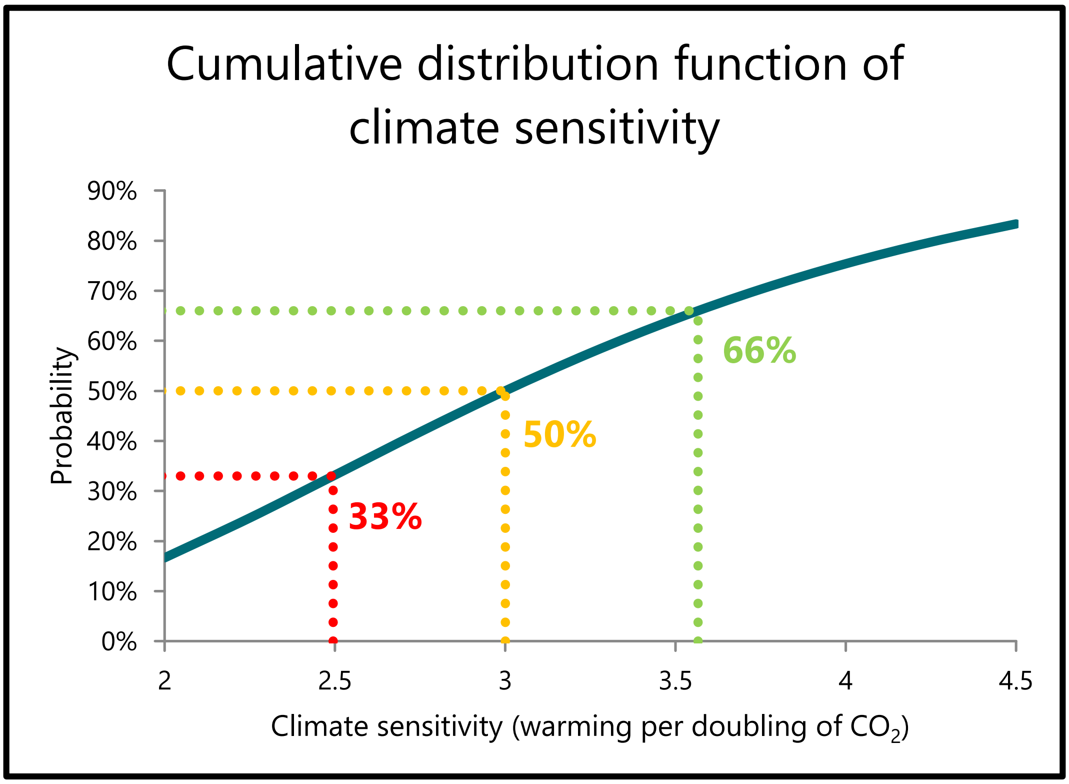


Figure 14. Log-normal cumulative distribution function of climate sensitivity

To get the associated peak warming for a given climate sensitivity value, we replace in equation (4) our chosen values for median climate sensitivity and median warming at a trillion tonnes of carbon (1000 GtC):

$$\Delta T_1 = 2.08 \cdot \lambda/_3 \tag{5}$$

We then replace λ by the climate sensitivity value associated with our chosen probability on the cumulative distribution function (the third column of Table 6, or a point on Figure 14). A simple goal seek gives us the climate sensitivity λ at the chosen probability P. We use that to calculate ΔT_1 for a 33%, 50% and 66% chance of hitting the user's chosen target, which we can then plug in to equation (3). Table 7 summarises how probability, climate sensitivity, and warming fit together.

Probability P	Climate sensitivity λ at P	ΔT_1 at probability P	Carbon budget Q for 2°C at P
0.33	2.504637839	1.736548902	1198.099114
0.5	3	2.08	952.7796392
0.66	3.5665	2.472773333	773.8178881

Table 7. Relationship between climate sensitivity, warming per 1000 GtC, and 2°C carbon budget for different probabilities

To take 33% likelihood as an example, the value in the second column of the table above is the climate sensitivity associated with 33% (see column 2 in Table 6), the value in the third column is given by plugging in the value in the second column into equation (5), and the value in the fourth column is given by plugging in the value of the third column into equation (3) and solving for the carbon budget Q at 2 degrees warming.

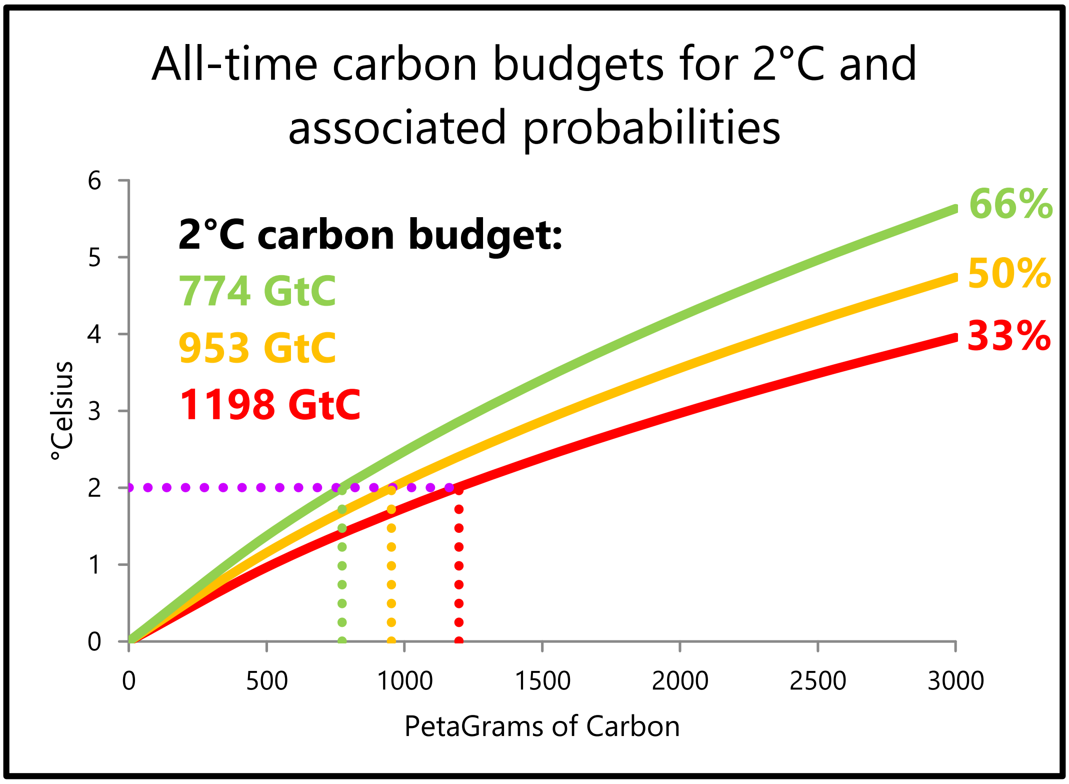


Figure 15. Relationship between peak warming and cumulative emissions for probabilities of 33%, 50%, and 66%

Figure 15 above plots the relationship between peak warming and cumulative carbon emissions for the three different probability scenarios in SkyShares: 33% (unlikely to stay below temperature target), 50% (median chance of hitting target), and 66% (likely to stay below target). Table 8 provides the values for interested readers.

Cumulative emissions (in PgC)	33% chance of warming (in °C)	50% chance of warming (in °C)	66% chance of warming (in °C)
0	0	0	0
500	0.96394261	1.154589212	1.372614142
1000	1.736548902	2.08	2.472773333
1500	2.392258829	2.865394898	3.406476968
2000	2.967709666	3.554657228	4.225895001
2500	3.48399035	4.173046852	4.961057199
3000	3.954493053	4.736604619	5.631033458

Table 8. Warming resulting from cumulative carbon emissions in the three SkyShares probability scenarios

Users of SkyShares can choose which temperature to limit warming relative to pre-industrial temperatures, and with which probability the carbon budget will ensure we stay below that temperature target. SkyShares then plugs in the relevant ΔT_1 associated with the chosen likelihood into equation (3) and solves that equation for Q. This gives us the all-time carbon budget for the user's temperature target.

The carbon budget

Once we have an all-time carbon budget, we plot a yearly emissions trajectory and calculate the rate of mitigation such that the sum of these annual emissions is equal to the safe carbon budget. Most of the literature presents an idealised emissions pathway over time which increases exponentially, peaks at a certain level, and then decreases exponentially after the starting of a global mitigation scheme. We use the same method to "spread" the all-time carbon budget over the time horizon.

Emissions pathway

We use the algorithm given by Raupach *et al.* (2011a) for the emissions pathway. This specification is differentiable and smooth, which offers great advantages in solving for the rate of mitigation, and tractability for policy-making, respectively. The specification of Raupach *et al.* gives a smooth-capped distribution function. It is reasonable to assume that emissions will continue increasing at an exponential rate, and will then decrease after a period of transition, as opposed to declining steeply at the point when mitigation starts.

The system of equations is given by Raupach *et al.* (2011a, p. 148):

$$E(t) = \begin{cases} observations & (t \leq t_{Hist}) \\ E_m \cdot e^{r \cdot (t - t_m)} & (t_{Hist} < t \leq t_m) \\ f(t) & (t > t_m) \end{cases} \tag{6}$$

with

$$f(t) = E_m \cdot [1 + (r + m) \cdot (t - t_m)] \cdot e^{-m \cdot (t - t_m)} \tag{7}$$

where

$E(t)$ is the yearly allowable CO_2 budget to stay below the temperature target
t_{Hist} is the time to which historical observations are available
t_m is the time where mitigation starts
E_m is the amount of CO_2 emissions at t_m
r is the constant rate at which emissions increase exponentially
m is the constant rate at which emissions decrease exponentially

Note that the above system defines allowable emissions in units of CO_2, to ease interpretation for policy-makers.

As discussed in the Data section on emissions data on page 14, historical observations for global CO_2 emissions are available from $t_0 = 1751$ to $t_{Hist} = 2013$.

Users of SkyShares can choose on the website or on the desktop version at which date the world will start reducing its CO_2 emissions. We set the start of the global mitigation regime to $t_m = 2015$ by default, and to provide a worked example here.

Until the start of the global mitigation regime, emissions are assumed to grow exponentially at the constant rate r. We have empirically estimated the historical growth rate of emissions from 1992, which is the date when the UNFCCC was established, to 2010 which is the last data point in the CDIAC emissions data. The coefficient is $y = e^{0.0232x}$ with $R^2 = 0.9465$. We therefore set $r = 0.023242$, which is the constant growth rate of emissions pre-mitigation. Emissions from t_{Hist} to t_m represent future emissions pre-mitigation.

The level of CO_2 emissions E_m at the starting date of mitigation are calculated using a Business As Usual trend where emissions increase at the rate r per year. In the default case, with mitigation starting in 2015, emissions in 2015 are at 37.86 GigaTonnes of CO_2. According to CDIAC, global emissions in 2013 (the most recent year for which they have data) stood at 36.16 $GtCO_2$.

Emissions from t_m to t represent future emissions post-mitigation. They will follow a smooth-capped transition, where they initially grow at rate r and eventually decrease exponentially at mitigation rate m. They are determined by $f(t) = E_m \cdot [1 + (r + m) \cdot (t - t_m)] \cdot e^{-m \cdot (t - t_m)}$.

Figure 16 plots the system of equations (6) with t_m set to 2015. In this case, emissions would peak in 2019 at 39.62 $GtCO_2$ and decrease thereafter. The date of mitigation t_m is the date at which contraction starts, not at which emissions peak. The Raupach *et al.* emissions trajectory algorithm also allows the date at which emissions peak to be analytically ascertained (2011b, p. 52):

$$t_{Max} = t_m + \frac{r}{m(m + r)} \tag{8}$$

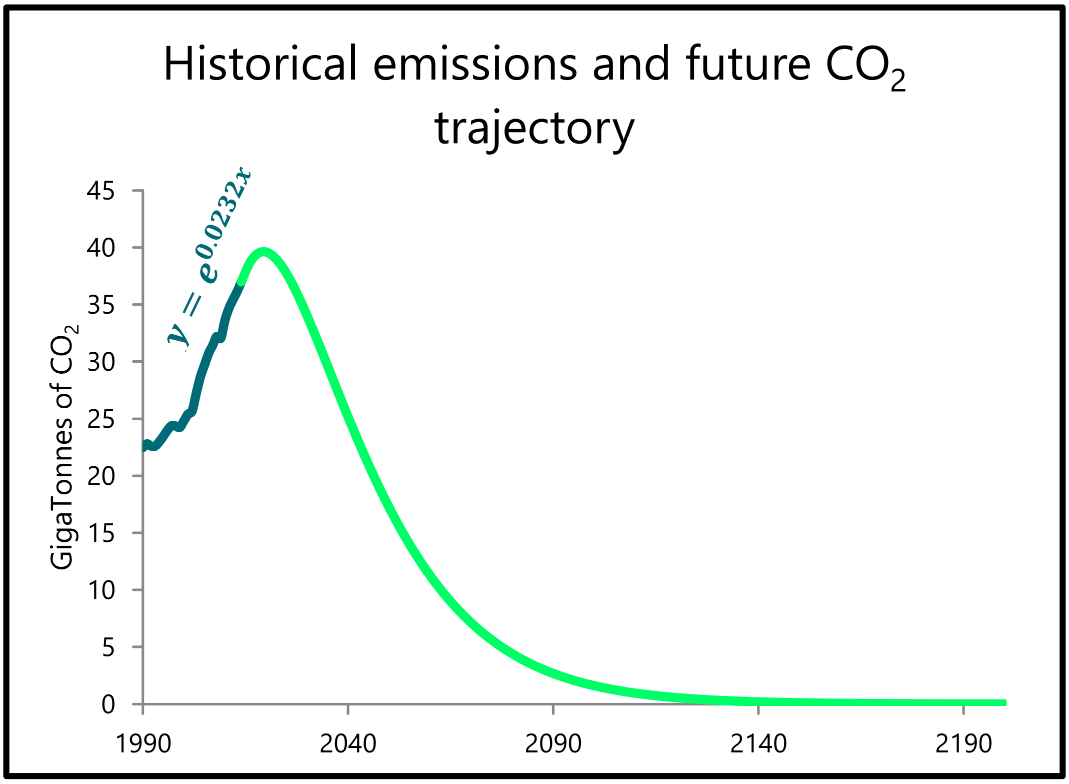


Figure 16. Historical emissions and future CO_2 trajectory

The system of equations $E(t)$ plots a yearly emissions trajectory. Cumulative CO_2 emissions is the area under the curve.

We clearly note that emissions must got to zero by the end of the century, which is also highlighted by the Intergovernmental Panel on Climate Change (IPCC AR5 WG1 SPM, 2013).

Integrating to get the allowable carbon budget

From the section on Limiting warming, we have derived a finite amount of carbon emissions, with a given probability, that the world must not go over so as to limit warming to the temperature target chosen by the user. This is our carbon budget. We convert our all-time carbon budget Q to units of CO_2 so as to square with the units in the yearly emissions trajectory $E(t)$ by multiplying it by 44/12 (to account for the molecular weight of oxygen).

For a 50% chance of limiting warming to 2°C, the all-time emissions budget is 953 GtC, or 3,494 $GtCO_2$. Therefore, we know that the area under the curve in Figure 16 must be equal to our emissions budget. If we integrate the system $E(t)$, we will get an expression for the cumulative emissions budget as a function of the mitigation rate m. This will allow us to calculate the rate at which emissions must decline by solving for m.

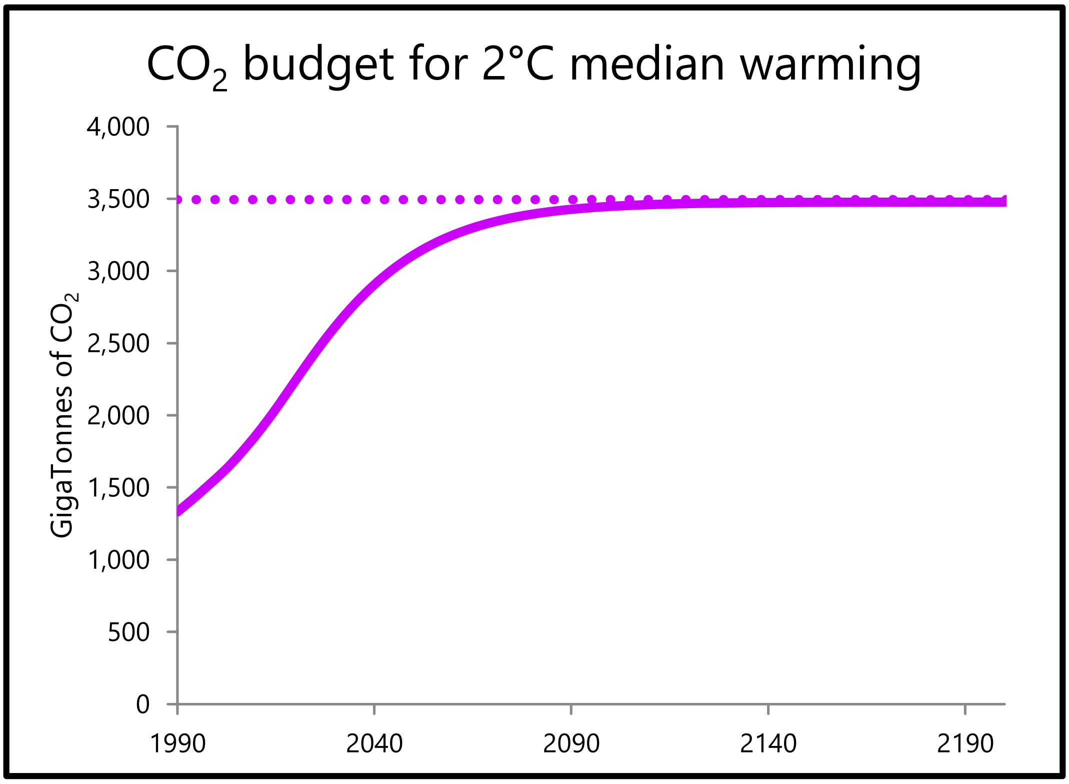


Figure 17. Carbon dioxide budget for 2°C warming with 50% likelihood

The all-time cumulative emissions $Q(t)$ is a finite quantity given by:

$$Q(t) = \int_{t_0}^{t} E(t)dt \tag{9}$$

Note that, contrary to Raupach *et al.* (2011b, p. 51), we use a definite integral as opposed to an indefinite integral, for computational tractability on the website and desktop version of SkyShares. Since we must integrate between definite bounds, we set $t_0 = 1751$ because it is the first year for which we have emissions data. We set $t = 2200$ by default in order to have a long enough time horizon so as not to overshoot the emissions budget. An advanced user can change this, but t must be large enough (must tend to infinity) to ensure that humanity does not go over its allowable CO_2 budget.

We integrate the system $E(t)$ by parts (emissions pre-mitigation, and emissions post-mitigation).

$$Q(t) = Q(t_{Hist}) + \int_{t_{Hist}}^{t_m} E(t)dt + \int_{t_m}^{t} E(t)dt \tag{10}$$

The first term in equation (10) represents historical emissions from $t_0 = 1751$ to $t_{Hist} = 2013$ and is given by historical data. Cumulative emissions $Q(t_{Hist})$ are equal to 1969 $GtCO_2$, with 1443 Gt CO_2 of emissions from fossil fuels (CDIAC) and 526 $GtCO_2$ from land use and land use change (Raupach *et al.*, 2014, p. 874). This means we have 1525 Gt CO_2 left in our emissions budget.

We take the anti-derivatives of the second and third terms and arrive at:

$$Q(t) = Q(t_{Hist}) + \frac{E_m - E_m \cdot e^{r\cdot(t_{Hist}-t_m)}}{r} + \frac{E_m \cdot \{-e^{m\cdot(t_m-t)} \cdot [m\cdot[(m+r)\cdot(t-t_m)+2]+r]+2m+r\}}{m^2} \tag{11}$$

We all-time allowable global emissions budget has been determined in the previous section. We know that for a median chance of limiting warming to 2°C, it is equal to 3494 $GtCO_2$. The exercise then is to set $Q(t)$ in equation (10)(22) equal to 3494 $GtCO_2$ and to solve for the rate of mitigation m at which emissions must decline is humanity is to operate within safe planetary boundaries. All of the values apart from m are given. They are either historical observations [$Q(t_{Hist})$, r] Business as Usual projections [E_m] or set by SkyShares [t].

Finding the rate of mitigation to stay within budget

We cannot offer a closed-form analytical solution to equation (11)(22) because it includes expressions of the form $x \cdot \log(x)$. We approximate a solution for m by using the Newton-Raphson method.

The Newton-Raphson is a root-finding algorithm which converges to the roots of a function after k iterates. It is implemented as follows:

$$m_{k+1} = \frac{f(m_0)}{f'(m_0)} \tag{12}$$

where

k is the number of iterations
m_0 is the starting "guess" for m
$f(m_0)$ is the equation for which we want to find the root (i.e. find m such that $f(m_0) = 0$)

Using the default case to illustrate (50% chance of limiting warming to 2°C, 0.0232 historical growth rate, 2200 long-term horizon, 2015 contraction date), we need to find the mitigation rate such that $Q(t_{2200}) \approx 3{,}494$ Gt CO_2.

We re-write equation (11) as:

$$\begin{aligned} f(m) = {} & Q(t_{Hist}) \\ & + \frac{E_m - E_m \cdot e^{r\cdot(t_{Hist}-t_m)}}{r} \\ & + \frac{E_m \cdot \{-e^{m\cdot(t_m-t)} \cdot [m \cdot [(m+r)\cdot(t-t_m)+2]+r]+2m+r\}}{m^2} - Q(t) = 0 \end{aligned} \tag{13}$$

$Q(t_{Hist})$ is the total emissions that have been emitted between 1751 and 2013, and is approximately equal to 1,969 Gt CO_2.

The second term on the right-hand side (RHS) represents future emissions pre-mitigation, and the third term on the RHS represents future emissions post-mitigation.

$Q(t_{Hist})$ and the second term on the RHS are constants, as the mitigation rate m only appears in the third term on the RHS. Therefore, we see that solving $f(m) = 0$ is akin to finding the mitigation rate for future emissions post-mitigation.

We derivate equation (13) and write:

$$f'(m) = \left(-\frac{1}{m^3}\right) \cdot E_m \cdot \{(t_m - t) \cdot (t - t_m) \cdot m^3 \cdot e^{m \cdot (t_m - t)} + (t_m - t) \cdot m^2 \cdot e^{m \cdot (t_m - t)} \cdot [(t - t_m) \cdot r + 2] + m \cdot \left[e^{m \cdot (t_m - t)} \cdot [(t_m - t) \cdot r - (t - t_m) \cdot r - 2] + 2\right] - 2 \cdot r \cdot \left(e^{m \cdot (t_m - t)} - 1\right)\} \quad (14)$$

We plug equations (13) and (14) into equation (12) and program the Newton-Raphson algorithm into over $k = 10$ iterates for a starting value of $m_0 = 0.0000001$.

The Newton-Raphson will converge to a value of m such that $f(m) = 0$ when $Q(t) = Q$. In the reference case, the algorithm converges over 8 iterates and finds a value $m \approx 0.0619$.

This means that, in order to limit median warming to 2°C, and if a global mitigation regime starts in 2015, emissions must decline at 6.19% per annum.

SkyShares plugs the value of m found back in the system $E(t)$ given by equation (6), which plots a yearly emissions trajectory. Therefore, this emissions pathway will give a yearly allowable amount of emissions that the world can emit and still stay within the carbon budget.

Implications of the date of contraction

Due to the exponential nature of the emissions pathway, the date of contraction t_m has severe implications for the world's potential to mitigate climate change. Delaying mitigation effort by an additional year will require larger emissions reduction later to maintain the same target. Every year counts, and the starting date of mitigation will have important implications for the allowable emissions trajectories. The later the world waits, the steeper the decline, and the more expensive it will be to cut CO_2 emissions.

A 2015 date for the start of emissions reduction requires decarbonisation rates of 6.2% per year. Delaying the starting date of mitigation by 5 years only would require mitigation rates of 7.8% per annum. This is fast stretching the envelope of economic and political possibilities. Apart from perhaps the digital economy, no other sector in the economies of industrialised nations has managed to sustain such rates of productivity growth for such long periods of time (Nordhaus, 2013).

	2015 mitigation date	2020 mitigation date	2025 mitigation date
Remaining CO_2 budget for median 2°C	1,525 Gt CO_2		
Decarbonisation rate (per year)	6.2%	7.8%	10.3%
Year at which emissions peak	2019	2023	2027
Level of emissions peak	40 Gt CO_2	44 Gt CO_2	49 Gt CO_2

Table 9. Decarbonisation rates required and emissions peaks with different mitigation start dates

Table 9 shows that in addition to requiring much higher subsequent rates of emissions reduction, delaying the start of a mitigation regime would also lead the world to peak later, and at higher emissions levels. The level of yearly emissions is also a strong predictor of the feasibility of reaching a temperature targets. The IPCC finds that models with annual 2030 emissions higher than 55 Gt CO_2eq could not produce scenarios that would make it "as likely as not that temperature change will remain below 2°C relative to pre-industrial levels" (IPCC AR5 WG3 SPM, 2014, p. 14). We can see that a 2025 start date for mitigation is close to approaching the limit, as emissions peak at 49Gt CO_2 in 2027.

Delaying mitigation will also require us to peak faster after we start reducing our emissions, relatively. An immediate mitigation start date allows us 4 years to implement a low-carbon transition, whereas a 2020 start date shortens our transition period to 3 years, and a 2025 start date affords us only 2 years until our emissions must peak in order to remain within our carbon budget.

Figures Figure 18 and Figure 19 illustrate how steeply our emissions must decline if we delay the start of a global mitigation regime. The policy implication is clear: procrastinating on reducing emissions increases moral hazard and the likelihood that policy-makers will renege on emissions pledges, since the required decarbonisation rates are beyond what domestic electorates would consider economically palatable.

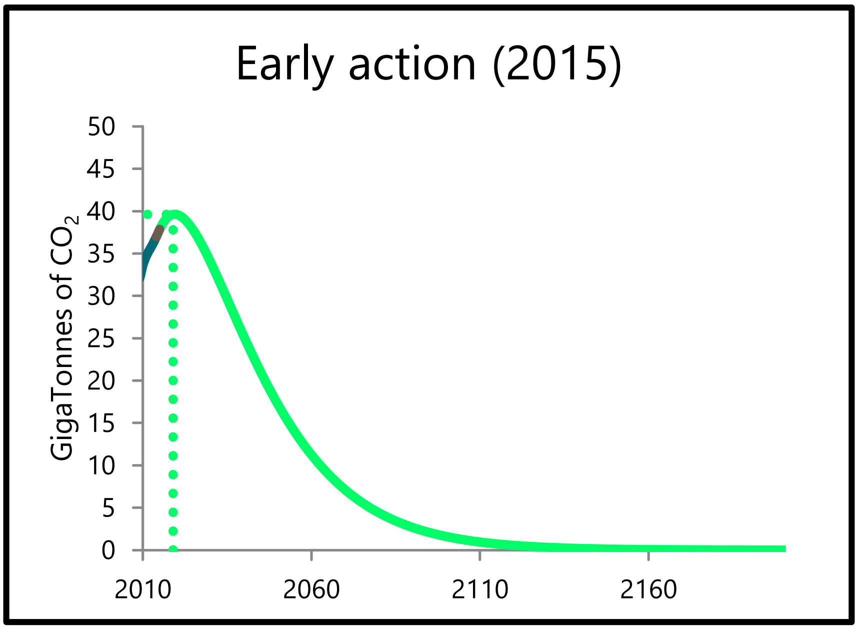


Figure 18. Early action, mitigation starts in 2015, 2°C median warming

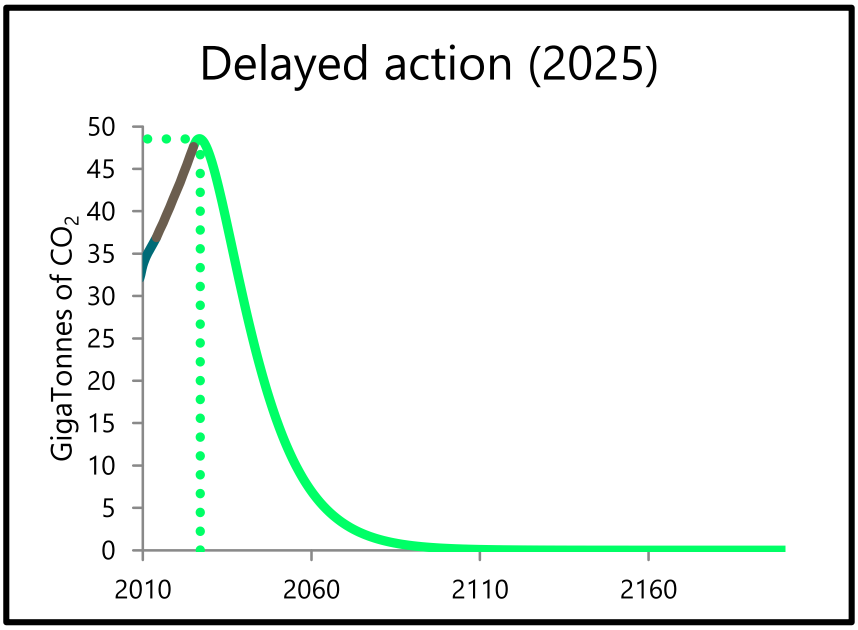


Figure 19. Delayed action, mitigation starts in 2025, 2°C median warming

The allocation rule

The previous section details the methods used to calculate a yearly carbon budget which is consistent with limiting warming to the temperature chosen by the user. This annual global emissions budget $E(t)$ is then fed into the part of the model which offers different algorithms to distribute the carbon budget into yearly allowances $\bar{q}_{i,t}$ for countries of the coalition.

The different allocation rules differ in their treatment of past emissions and equity.

We note, for all countries i of the coalition:

q_t historical emissions
$\hat{q}_t$ business as usual emissions
$\bar{q}_t$ allowances

Per capita

This allocation rule converges to a per capita allocation of entitlements at a date chosen by the user. During the convergence period, allowances are grandfathered from past emissions.

The allowances (measured in tonnes of CO_2) are given by:

$$\bar{q}_{i,t} = E(t) \cdot \left[\alpha_t \mathrm{FS}_{i,t} + (1-\alpha_t)\mathrm{GS}_{i,t}\right] \tag{15}$$

with

$E(t)$ the annual carbon budget
$\mathrm{FS}_{i,t}$ the "fair share" of country i at time t
$\mathrm{GS}_{i,t}$ the "grandfathered share" of country i at time t
α_t the weight given to both shares

By definition, fair shares are constructed so as to be proportional to a country's current and future population (using the UN population projections):

$$\mathrm{FS}_{i,t} = \frac{population_{i,t}}{\sum population_{i,t}} \tag{16}$$

Allowances converge from current levels of emissions in a process called "grandfathering", with t_{Hist} as the latest year for which we have data on emissions (2013):

$$\mathrm{GS}_{i,t} = \frac{q_{i,tHist}}{\sum_i q_{tHist}} \tag{17}$$

The linear convergence parameter is given by:

$$Max\left(\alpha_t = \frac{\mathrm{t}}{y}, 1\right) \tag{18}$$

where y is the number of years until the date of convergence chosen by the user. At the date of convergence chosen by the user, α will be equal to 1, and thereafter by definition.

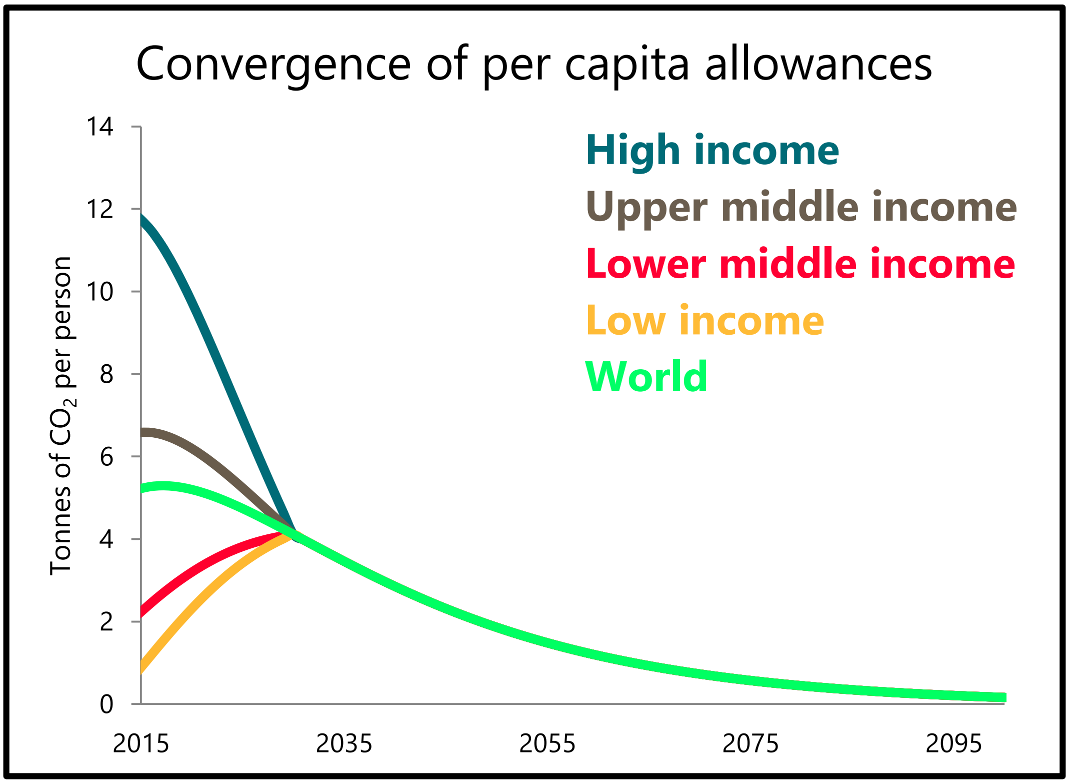


Figure 20. Per capita allowances with a 2030 convergence date (2°C median warming, early mitigation)

Figure 20 shows the distribution of per capita allowances under the reference scenario (50% likelihood of staying below 2°C, with mitigation starting in 2015) between different income groups. The global average of per capita emissions is 5.16 tonnes of CO_2 per person, with high income countries emitting significantly more (11.7 tCO_2/capita) than poor countries (1.2 tCO_2/capita). By 2030, all countries will be allocated 4.1 tonnes of CO_2 per person, which will decrease to 1.9 tCO_2 by 2050, and 0.2 tCO_2 by the end of the century.

Figure 21 below illustrates the distribution of the yearly emissions budget among different income groups under the same reference scenario.

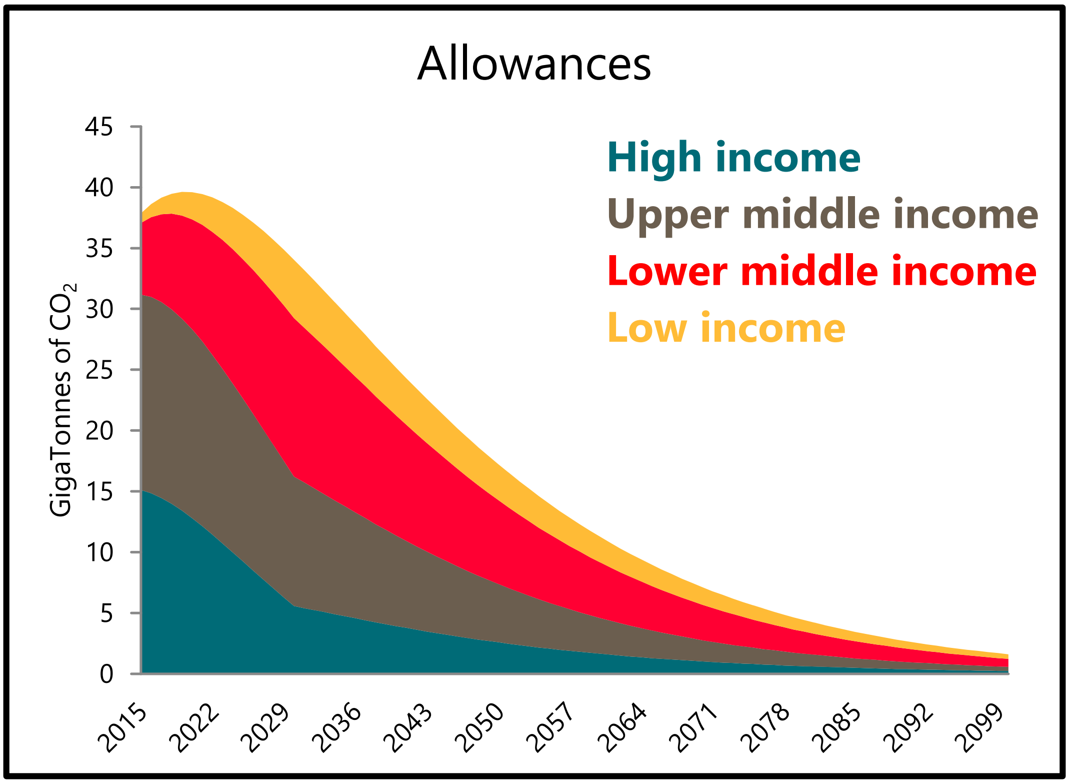


Figure 21. Distribution of allowances per income group with convergence to per capita entitlements in 2030 (2°C median warming, early mitigation)

Per dollar

The "per dollar" allocation rule is skewed towards countries with higher levels of wealth. The algorithm distributes one allowance (1 tonne of CO_2) per 1 dollar of GDP. The convergence period follows the same pattern as the per capita allocation rule and grandfathers emissions from current emission patterns.

$$\bar{q}_{i,t} = E(t) \cdot \left[\alpha_t \mathrm{GDPS}_{i,t} + (1 - \alpha_t)\mathrm{GS}_{i,t}\right] \tag{19}$$

with GDP shares defined as:

$$\mathrm{GDPS}_{i,t} = \frac{GDP_{i,t}}{\sum_i GDP_t} \tag{20}$$

and grandfathered shares as above.

The figures below illustrate how much the distribution of allowances would change under this allocation rule, compared to the per capita entitlements detailed in the previous allocation rule.

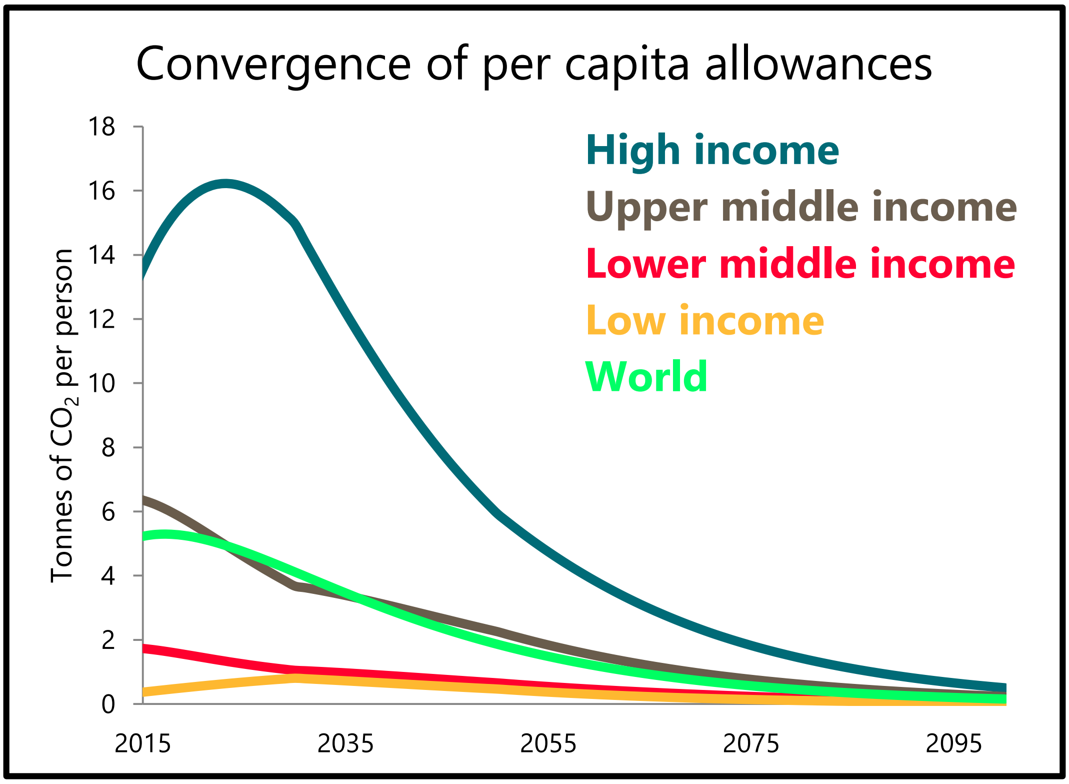


Figure 22. Per capita allowances under the "per dollar" rule (2°C median warming, early mitigation)

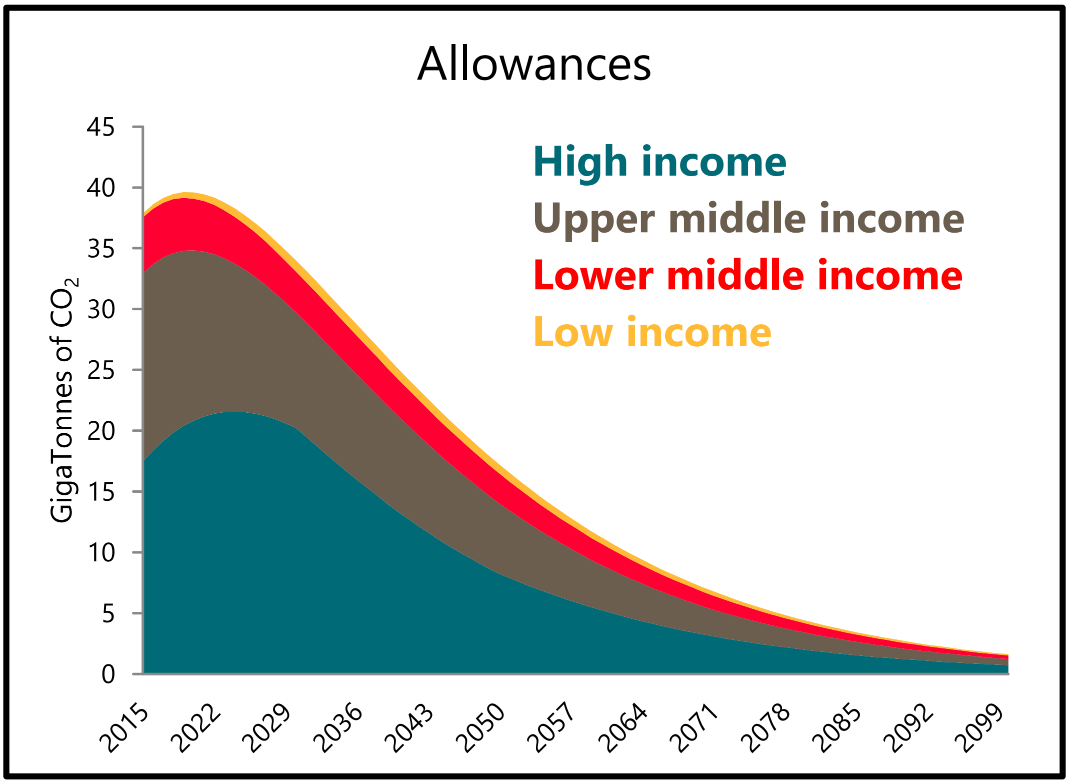


Figure 23. Distribution of allowances per income group under the "per dollar" rule (2°C median warming, early mitigation)

Equal stocks

This algorithm is designed to replicate a "carbon debt" approach to international climate policy-making. It considers that the global emissions budget should be allocated on the basis of stocks rather than flows of emissions (which is what the "per capita" rule does).

The equal stocks allocation rule calculates what each country *would have been entitled to* of the stock of past emissions Q_{tHist} (emissions from 1751 to 2013), according to their present share of world population. In this case, the present share of world population is calculated using 2013 figures (the last data point for which we have historical emissions data). The rationale behind using present shares of population rather than past shares is that equity is defined in terms of present rather than past generations. Note that this allocation rule just considers emissions from fossil fuels combustion in the stock past emissions, due to data constraints.

This allocation rule calculates each country's yearly allowances using the per capita rule defined above, but re-adjusts the quota according to how much CO_2 they are "owed".

$$\bar{q}_{i,t} = E(t) \cdot \mathrm{FS}_{i,t} - \left[\mathrm{d}_{i,t-1} - \frac{\mathrm{D}_i}{n}\right] \tag{21}$$

The debt principal D_i is defined as:

$$D_i = \mathrm{Q}(t_{Hist}) \cdot \mathrm{FS}_{i,tHist} - \sum_{t=RespDate}^{t=t_{Hist}} q_i \tag{22}$$

where $RespDate$ is the date at which to start counting past stocks. SkyShares offers the possibility to choose between two starting dates at which to start calculating the carbon debt: 1800 or 1990. The former considers that equity in the share of the global atmospheric commons is intemporal (i.e., we consider all of the emissions since the start of the Industrial period). The latter considers that carbon debts can only be accrued if there is pre-existing knowledge of tort being inflicted. The start of the 1990s is the period at which scientific evidence started to show that anthropogenic emissions were warming the climate, and that policy-makers should have known better.

The starting point of the carbon deficit $\mathrm{d}_{i,t}$ is $\mathrm{d}_{i,0} = \mathrm{D}_i$.

This algorithm ensures that all "carbon debts" are paid equalised or "paid back" at the end of the century. The Annex on page 68 provides four graphs which illustrate how the equal stocks rule would work under a reference scenario (2°C median warming with early mitigation), and if the carbon debt was counted from 1800.

Figure 24 compares what proportion of the all-time emissions budget (from 1800 to 2100) each income group would have been entitled to on a "fair stocks" basis, to what they actually emitted. Using the same colour key as the graphs above, low income countries are in yellow, lower-middle income countries are in pink, upper-middle income countries are in brown, and high income countries are in teal. We can see that high income countries, if their emissions were in proportion to their share of the world population, should emit only 17% of the all-time carbon dioxide budget. In reality, they emitted 42% of it. Therefore, they "owe" 730 Gt CO_2 to the rest of the world. All other income groups emitted less than their "fair stocks", with low income countries in particular having emitted much less (relatively) than their share of population would entail.

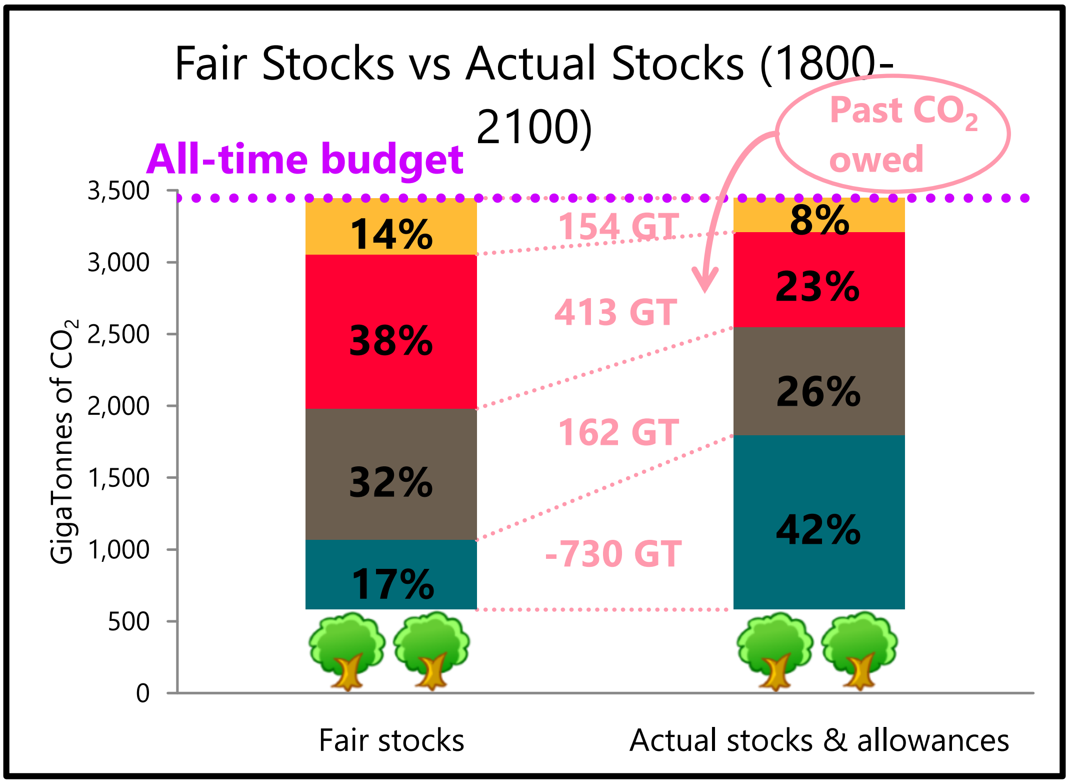


Figure 24. Comparison of equal stocks versus what different income groups actually emitted

Figure 25 shows what emissions would be on an equal carbon space basis. Note that historical emissions in this graph do not show what actually happened, rather what they would have been if each country had emitted their per capita share (at that time) of the yearly emissions total. To do this, we have created a data-set (available in SkyShares desktop), which shows how much each country would have emitted if the yearly total flow of emissions had been shared on a per capita basis. Further details can be found in the Annex on page 70.

Figure 26 then shows what the per capita allowances of each country would be under the equal stocks rule, with all other climate parameters set to the default scenario (2°C median warming, mitigation starting in 2015). Since some countries are in surplus and others are in deficit (according to our carbon debt calculations detailed above), some past high emitters will have negative future allowances because their yearly allowance has been adjusted for them to pay back the debt.

The debt reaches zero at the end of the century, and the pay-pack of the debt principal is linear. Figures 27 and 28. The carbon debt reaches zero at the end of the century. The payback schedule of the debt is linear.SkyShares desktop offers the option to either front-load or postpone the debt service.

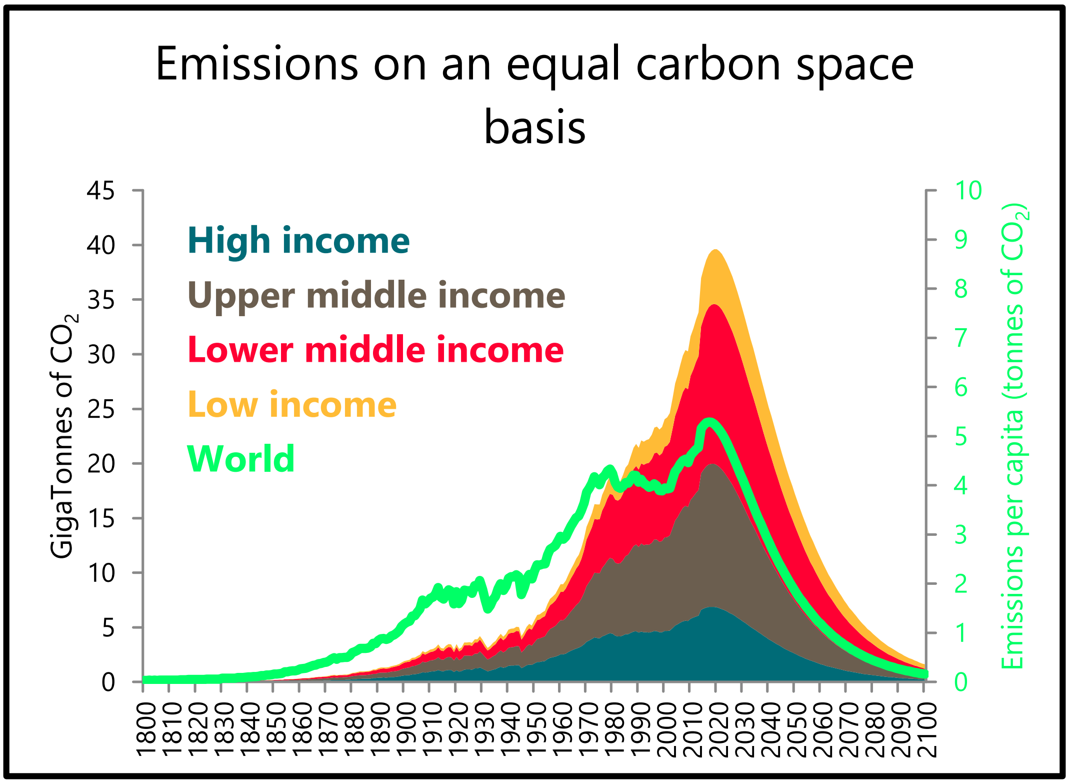


Figure 25. Emissions on an equal stocks basis, per income group

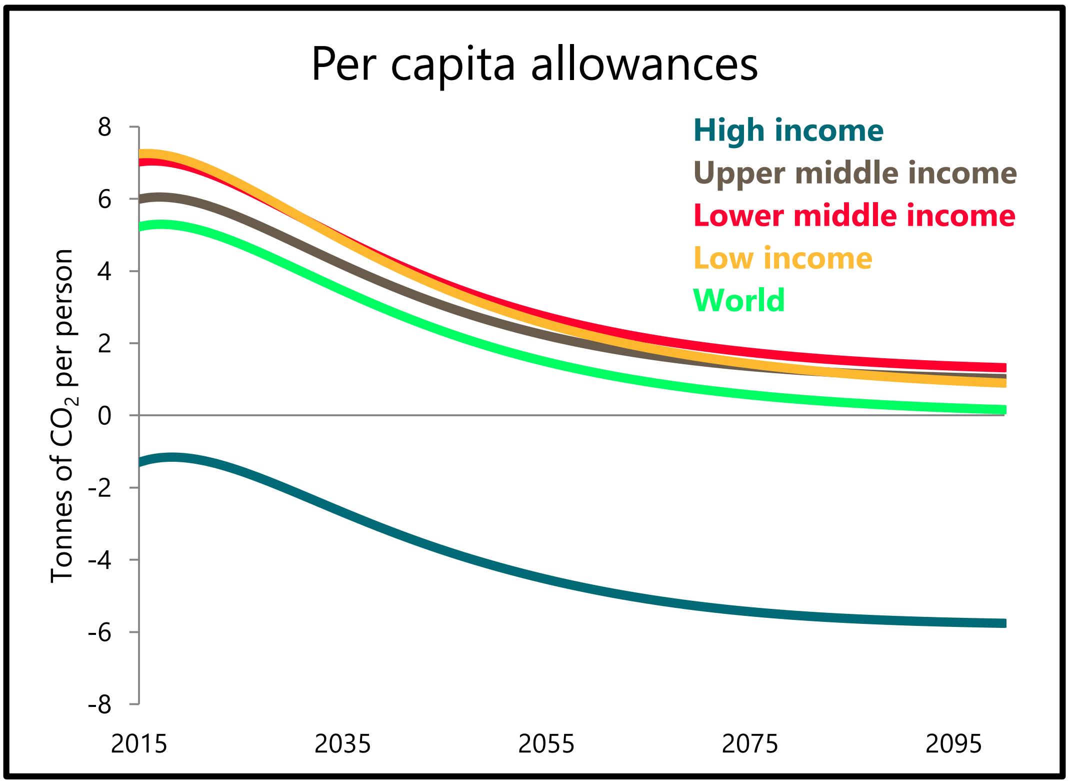
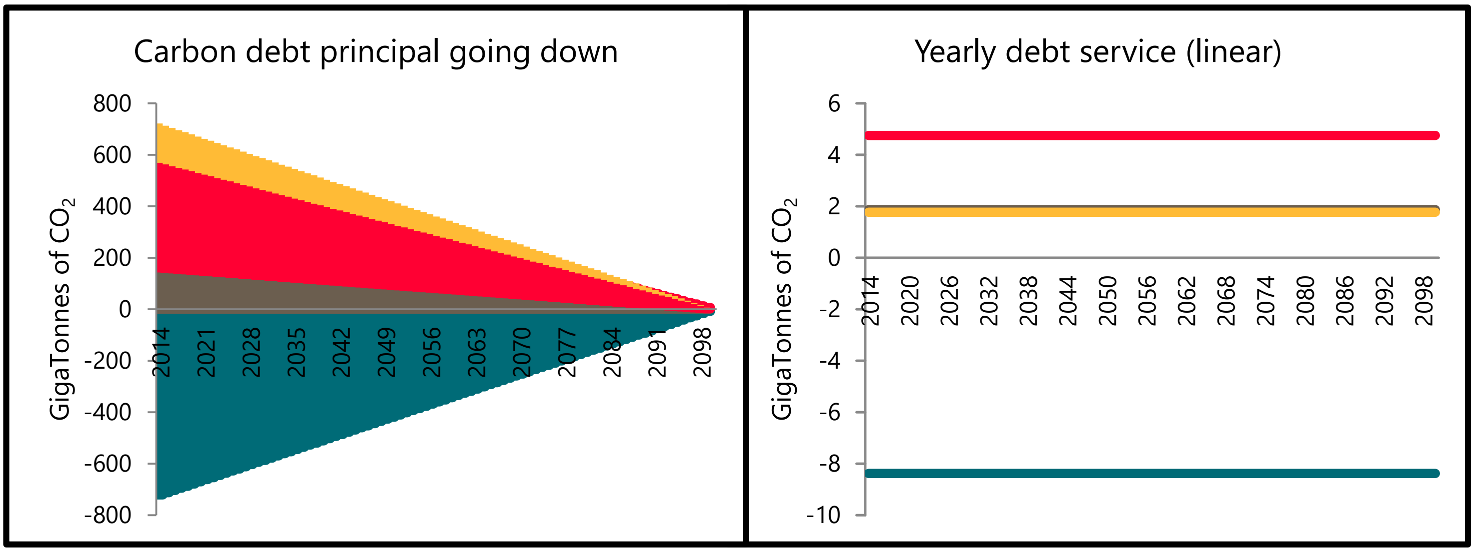


Figure 26. Per capita allowances under the "equal stocks" rule (2°C median warming, early mitigation)



Figures 27 and 28. The carbon debt reaches zero at the end of the century. The payback schedule of the debt is linear.

Historical responsibilities

The historical responsibilities scenario proceeds in a different way than the scenarios described above. Instead of allocation emissions quotas in proportion to an arbitrary user-set parameter, it takes as a starting point each country's Business As Usual projection. That BAU trajectory is then modified so that a country's share of the coalition's mitigation effort is proportional to its share of past emissions within the coalition.

The coalition's abatement target, or required level of mitigation, in any given year is defined by the difference between the coalition's BAU and the annual carbon budget in that year:

$$\bar{a}_{COW,t} = \sum_i \hat{q}_t - E(t) \tag{23}$$

with

$\hat{q}_{i,t}$ Business As Usual emissions
$E(t)$ the annual carbon budget

Under the historical responsibilities allocation, rule, each country's quota is what remains after their BAU projections have been adjusted so that their share of the coalition's abatement target is proportional to their past emissions within the coalition:

$$\bar{q}_{i,t} = \hat{q}_{i,t} - \bar{a}_{COW,t} \cdot \frac{h_i}{H_i} \tag{24}$$

where h_i is a country's past emissions (SkyShares desktop also offers the possibility of choosing whether to start counting past emissions from 1800 to 1990):

$$h_i = \sum_{t=RespDate}^{t=t_{Hist}} q_i \tag{25}$$

and where H_i is the coalition's stock of past emissions $H_i = \sum_i h_i$.

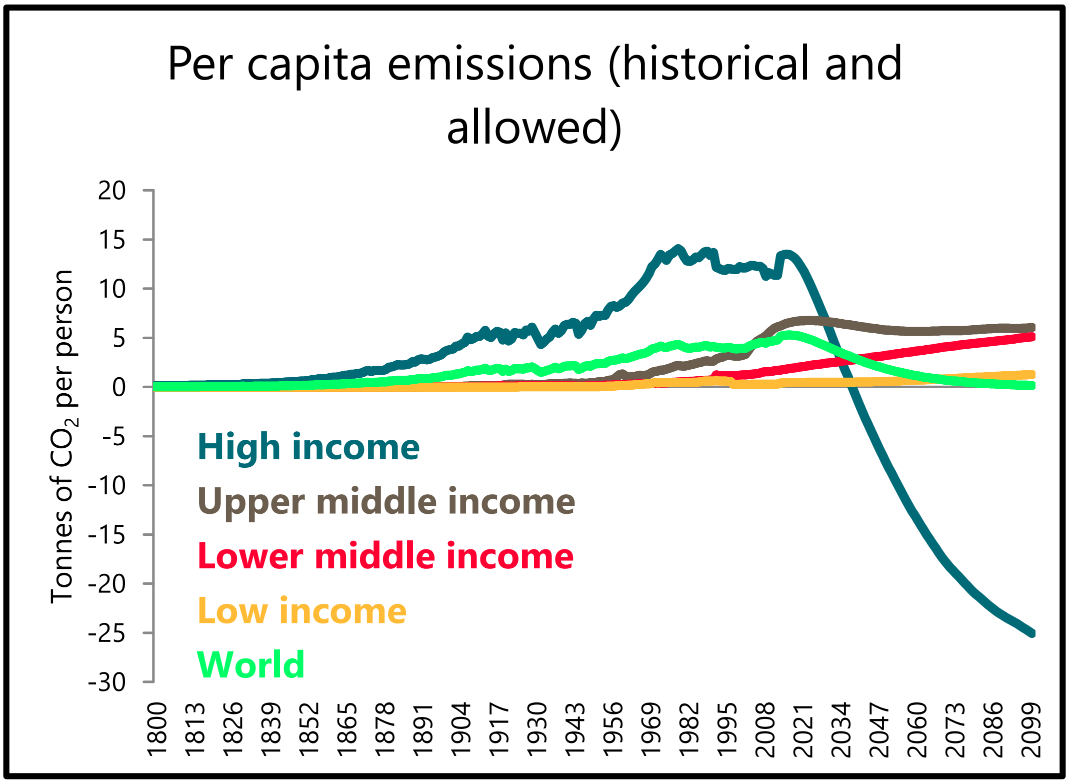


Figure 29. Per capita emissions, as they happened in the past, and as they would be under the Historical Responsibilities scenario (2°C median warming, early mitigation)

Figure 29 contrasts past emissions per person, as they happened, to future allowances under the Historical Responsibilities scenario which are adjusted so that historically high emitters are responsible for the same proportion of the coalition's mitigation as they were for its past emissions. Under this allocation rule, high income countries would have negative allowances, which means that they must decarbonise by up to that amount at home, or if the trading option is enabled, they can buy some of those allowances on the market. However, this allocation rule is much more severe in its treatment of past high emitters than the equal stocks rule, which is based on a "carbon debt" approach. Requiring high income countries to take on a mitigation effort proportional to the emissions they were responsible for contributing in the past would result in them having 3 times less allowances than if the carbon budget were allocated on an equal stocks basis, as shown in Table 10 below.

	Per capita (2030 convergence)			Per dollar (2030 convergence)			Equal stocks			Historical responsibilities		
	2030	*2050*	*2070*	*2030*	*2050*	*2070*	*2030*	*2050*	*2070*	*2030*	*2050*	*2070*
High income	4.1	1.9	0.7	15.0	5.9	2.3	-2.1	-4.2	-5.3	6.3	-7.6	-17.6
Upper middle income	4.1	1.9	0.7	3.7	2.3	1.0	4.8	2.6	1.5	6.6	5.8	5.7
Lower middle income	4.1	1.9	0.7	1.1	0.7	0.3	5.6	3.1	1.9	2.4	3.2	4.1
Low income	4.1	1.9	0.7	0.8	0.5	0.2	5.6	3.0	1.6	0.5	0.6	0.8
World	4.11	1.86	0.73	4.11	1.86	0.73	4.11	1.86	0.73	4.11	1.86	0.73

Table 10. Allowances per person under different allocation rules (2°C median warming, early mitigation

Trading scenarios

Modelling trading with marginal abatement cost curves

SkyShares uses the marginal abatement cost curves generated by either GCAM, EPPA, or McKinsey to model a market for emissions trading.

Marginal abatement cost curves can be thought of as the supply of abatement that each country (or region, depending on the unit of analysis) provides for a certain price. We have generated country-level MAC curves for each of the 194 SkyShares countries, for price points from $5 to $500 (in $10 increments), and for the years 2010 to 2100 (in 5 year increments), as described in the section Marginal abatement cost curves starting on page 18.

Now that we have our country-level MACCs, we proceed to model three different scenarios. This section goes on to describe the methodology behind the three scenarios: (1) no trade, where countries must meet their abatement target by decarbonising at home exclusively; (2) full trade, where the cost-effective mix of domestic abatement and emissions trading is calculated for each country; and (3) regulation, where the user can mandate what share of the abatement target is to be met by emissions reductions at home.

In all of our three scenarios, environmental integrity remains axiomatic. By construction, the coalition will always stay within its carbon budget. Of course, a user can set a very high temperature target if they wish, but by design SkyShares will always solve for the required carbon budged to meet the temperature target.

SkyShares can only be said to be cost-effective when it is run on the full trade scenario. In Barder, Evans and Lépissier (2015), we propose a policy solution to avoid dangerous climate change which offers a triple win: it is environmentally sound, it is socially just, and it is economically efficient. The scenario we have run on SkyShares to generate this 'perfect triple' is one where the entire world participates, mitigation starts immediately, allowances converge to equal per capita entitlements in 2030, and importantly where full trade is allowed. SkyShares allows users to toggle between different trading scenarios, but it is only if the full trade scenario is enabled that the cost-minimising behaviour of SkyShares will kick in.

There is a "no-banking, no-borrowing" rule, which precludes countries from hoarding emissions surplus in the hope of selling them at higher prices in future years.

Description of the main variables at play

Abatement targets

Each country's abatement target $\bar{a}_{i,t}$ is the difference between their projected BAU emissions, and their allowances.

$$\bar{a}_{i,t} = \hat{q}_{i,t} - \bar{q}_{i,t} \tag{26}$$

A country can either have a surplus ($\bar{a}_{i,t} < 0$) or a deficit ($\bar{a}_{i,t} > 0$) of allowances, depending on their individual BAU and on the allocation rule chosen. This means a country either has a negative or a positive abatement target.

The coalition's abatement target $\bar{a}_{cow,t}$ should be equal to the coalition's projected BAU minus the carbon budget for that year $E(t)$, as noted by equation (23), which we copy below again:

$$\bar{a}_{cow,t} = \sum_i \hat{q}_t - E(t)$$

Transfers

Transfers refer to the amount of permits (set to 1 permit as 1 tonne of CO_2, though of course in practice this can easily be changed by the implementing institution) which are sold or purchased on the emissions trading market.

Transfers are simply the difference between a country's abatement target $\bar{a}_{i,t}$ and the (optimal) level of domestic decarbonisation $a^*_{i,t}$. We denote domestic abatement with a star when it gives the cost-minimising mix of emissions reduction and of trading (i.e. when the Full Trade scenario is chosen). In the No Trade and Regulation scenarios, the amount of decarbonisation at home will simply be $a_{i,t}$.

$$tf_{i,t} = \bar{a}_{i,t} - a^*_{i,t} \tag{27}$$

If a country's transfers are positive ($tf_{i,t} > 0$), this means that they are buying allowances. If a country's transfers are negative ($tf_{i,t} < 0$), this means that they are selling that quantity of allowances. Transfers thus refer to a quantity of CO_2 emissions.

Emissions

SkyShares models the emissions that each country will have under the various trading scenarios. Each country's emissions are what they were entitled to emit, in addition to whatever they trade. So emissions are the sum of allowances plus transfers.

$$q_{i,t} = \bar{q}_{i,t} + tf_{i,t} \tag{28}$$

By construction, the sum of the allowances of countries in the coalition should be equal to the coalition's carbon budget for that year.

$$\sum_i q_t = \bar{q}_{COW,t} \tag{29}$$

A country's future emissions are also its BAU emissions minus whatever it reduces at home plus transfers:

$$\begin{aligned} q_{i,t} &= \hat{q}_{i,t} - \left(a_{i,t} + tf_{i,t}\right) \\ q_{i,t} &= \hat{q}_{i,t} - (a_{i,t} + \bar{a}_{i,t} - a_{i,t}) \\ q_{i,t} &= \hat{q}_{i,t} - \bar{a}_{i,t} \end{aligned} \tag{30}$$

Aggregating equation (30) to the coalition level, we can see that the coalition's emissions are indeed equal to the annual carbon budget for that year.

$$\begin{aligned} \sum_i q_t &= \sum_i \hat{q}_t - \bar{a}_{COW,t} \\ \sum_i q_t &= \sum_i \hat{q}_t - \left(\sum_i \hat{q}_t - E(t)\right) \\ \sum_i q_t &= \mathrm{E(t)} \end{aligned} \tag{31}$$

Domestic abatement and equilibrium price

Let us now define the two endogenous variables in SkyShares:

$a^*_{i,t}$ the level of domestic abatement for country i at time t

p^*_t the price of CO_2 emissions on the market at time t

Note that the law of one price applies so each country faces the same world price.

Financial flows

Financial flows are simply the volume of transfers multiplied by the market price of allowances:

$$f_{i,t} = \theta_t p^*_t \cdot \left(\bar{a}_{i,t} - a^*_{i,t}\right) \tag{32}$$

SkyShares offers the possibility to discount the monetary value of financial flows by multiplying them with θ_t:

$$\theta_t = {}^{1}\!/_{(1+d)^{(t-t_1)}} \tag{33}$$

where d is the chosen discount rate and t_1 is the starting period for the discounting.

Solution algorithm

SkyShares does not have functional forms for the different marginal abatement cost curves. All of the solutions in SkyShares are arrived at numerically. The two main numerical methods at play are interpolation and numerical integration. SkyShares functions entirely numerically for tractability reasons, since (1) it would require too much computational power to solve simultaneously for each country in the coalition, (2) the MACCs can be toggled between different data-sets which themselves rely on different underlying methodologies and have different implicit functional forms, and (3) SkyShares is built as a web tool in JavaScript, and as a desktop version in Excel and Visual Basic.

We use a linear interpolation function to find the equilibrium price p_t^* and the optimal level of domestic abatement $a_{i,t}^*$. The desktop version offers the ability to use a spline interpolation (Bézier interpolation).

To calculate the area under a curve, we use a Simpson function (numerical integration).

In the next 3 sections, we turn our attention to how these variables play out in the different scenarios. The figures in these sections graphically represent a trading scheme with 2 countries.

No Trade

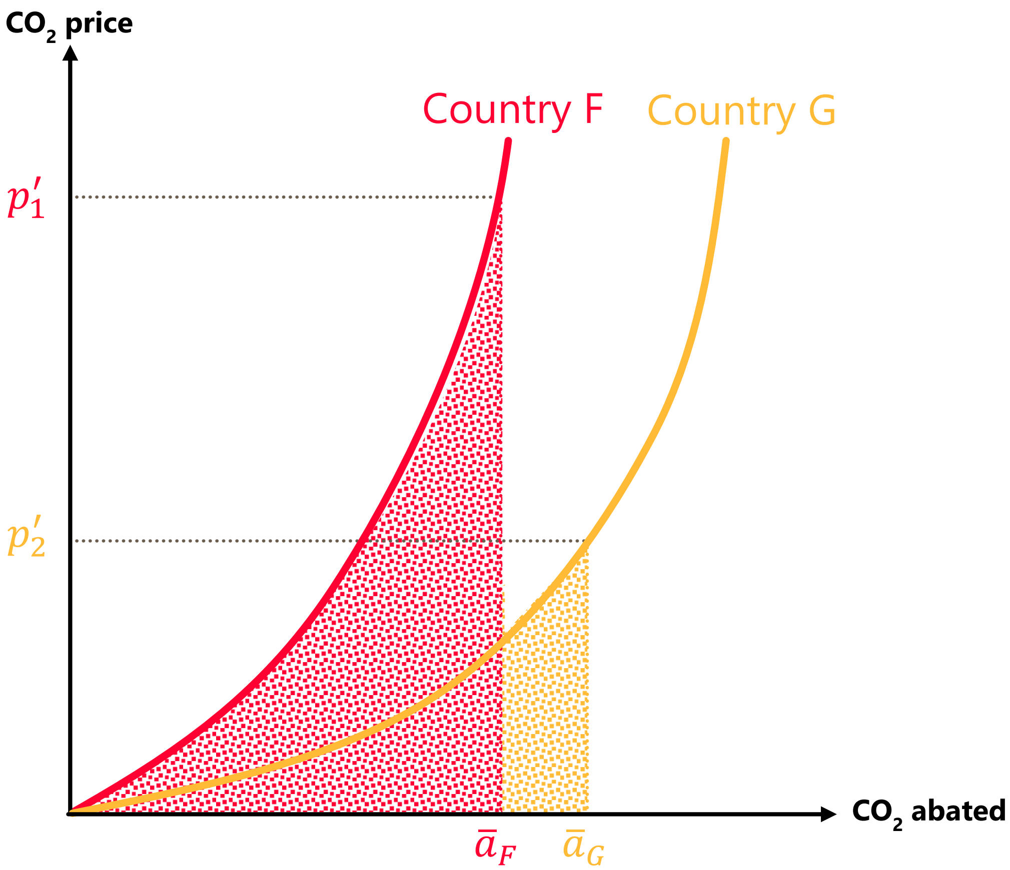


Figure 30. Costs without trading (at time t)

Figure 30 above depicts the marginal abatement cost curves of two countries: country F in fuchsia and country G in gold. We can imagine that country F is France, and country G is Germany. At first glance we note that France faces higher incremental costs of reducing emissions at home, whereas Germany can abate more emissions at the same price (it has a flatter marginal abatement cost curve). The MACCs in the graphs above and below represent a particular point in time, so for simplicity we can abstract the subscript t without loss of generality. The underlying method is the same for every year considered in the SkyShares model.

Each country has a specific abatement target $\bar{a}$ which we simply plot on the horizontal axis. If trading were forbidden, then the countries would be forced to meet their abatement target by reducing their emissions at home (since by construction SkyShares does not allow the coalition to break past its carbon budget).

The total costs for each country are simply the costs of decarbonisation up to their abatement target, which can be calculated by taking the area under the respective MAC curve. We use an adaptive Simpson function to numerically integrate the area under the curve.

The result of the No Trade scenario is that each country emits its allowances in a particular year (since they meet their abatement target entirely at home). Countries with negative abatement targets (i.e. countries which have a surplus of allowances) emit all of their available allowances. This scenario completely ignores any "green growth" domestic strategies countries may have, such as Ethiopia for instance[32], which may in practice prefer to sell their surplus allowances in the market in order to recycle the revenues into developing further sources of renewable energies (like hydropower).

Variables under the No Trade scenario		
Transfers	$tf_{i,t} = \bar{a}_{i,t} - a_{i,t} = 0$	Trading is not allowed so there are no transfers.
Domestic abatement	$a_{i,t} = \bar{a}_{i,t}$	Domestic abatement is each country's abatement target.
Market price of allowances	$p_t = 0$	There is no trading so allowances have no price.
Flows	$f_{i,t} = \theta_t p_t \cdot (\bar{a}_{i,t} - a_{i,t})$ $= \theta_t \times 0 \times 0$	Flows are equal to zero.
Decarbonisation costs	$DC_{i,t} = \int_0^{a_{i,t}} f(q,p)_{i,t}$	Area under each country's MAC curve, up to the level of abatement required.
Total costs	$TC_{i,t} = DC_{i,t} + f_{i,t}$ $TC_{i,t} = DC_{i,t} + 0$	Total costs are the costs of emissions reduction at home.
Emissions	$q_{i,t} = \bar{q}_{i,t} + tf_{i,t}$ $q_{i,t} = \bar{q}_{i,t} + 0$	Countries emit their allowances.

Table 11. Main variables under No Trade scenario

[32] Ethiopia has announced that it wants to be a middle income country by 2025 with no net growth of emissions. See http://www.worldbank.org/en/news/speech/2015/07/14/ethiopia-rising-carbon-neutral-middle-income-manufacturing-hub.

Full Trade

Under a Full Trade scenario, each country an optimal level of domestic abatement a_i^* in order to minimise their total costs. SkyShares automatically finds the optimal mix between emissions reduction and buying allowances on the market for each country, and so that the coalition always stays within below its carbon budget in any given year.

The problem here for each country is:

$$\begin{gathered} \min \quad TC_{i,t} + f_{i,t} \\ s.t. \sum_i q_t = \bar{q}_{cow,t} \\ \sum_i f_t = 0 \end{gathered} \tag{34}$$

We can rewrite the constraints above in terms of the equilibrium price p_t^* or of the optimal level of abatement $a_{i,t}^*$.

$$\bar{q}_{cow,t} = \sum_i q_t = \sum_i \bar{q}_t + tf_t = \sum_i \bar{q}_t + \bar{a}_t - a_t^* \tag{35}$$

$$\sum_i f_t = \sum_i p_t^* \cdot tf_t = 0 \tag{36}$$

We thus need to find p_t^* and $a_{i,t}^*$ to satisfy the conditions above. SkyShares proceeds numerically by interpolation.

The coalition equilibrium price of allowances at any given year p_t^* is the price which clears the coalition's abatement target $\bar{a}_{cow,t}$.

We have generated country-level MAC curves, as described in the sections starting on page 21. We then create a coalition-level MACC curve by summing the MACCs of each country that the user has selected to be in the coalition.

$$F_{cow}(q,p) = \sum_i f(q,p) \tag{37}$$

We can think of $F_{cow}(q,p)$ as the supply curve of abatement for the coalition. In each year, the coalition will have a required abatement target $\bar{a}_{cow,t}$ to meet in order to live within its carbon budget. For each year, SkyShares looks up the quantity $\bar{a}_{cow}$ in the coalition MAC curve (or supply curve) $F_{cow}(q,p)$ and interpolates the matching price p. This is therefore the equilibrium price p_t^* which is the shadow price of carbon allowances so that the coalition meets its abatement target. This is also the price which clears the market and matches supply and demand.

Figure 31 below illustrates how this works in a 2-country coalition, at any given year. We have plotted the equilibrium price p^*. From there we can read off the graph how much domestic abatement each country will supply at the coalition price (recall that each country's MACC represents a supply curve of emissions reduction).

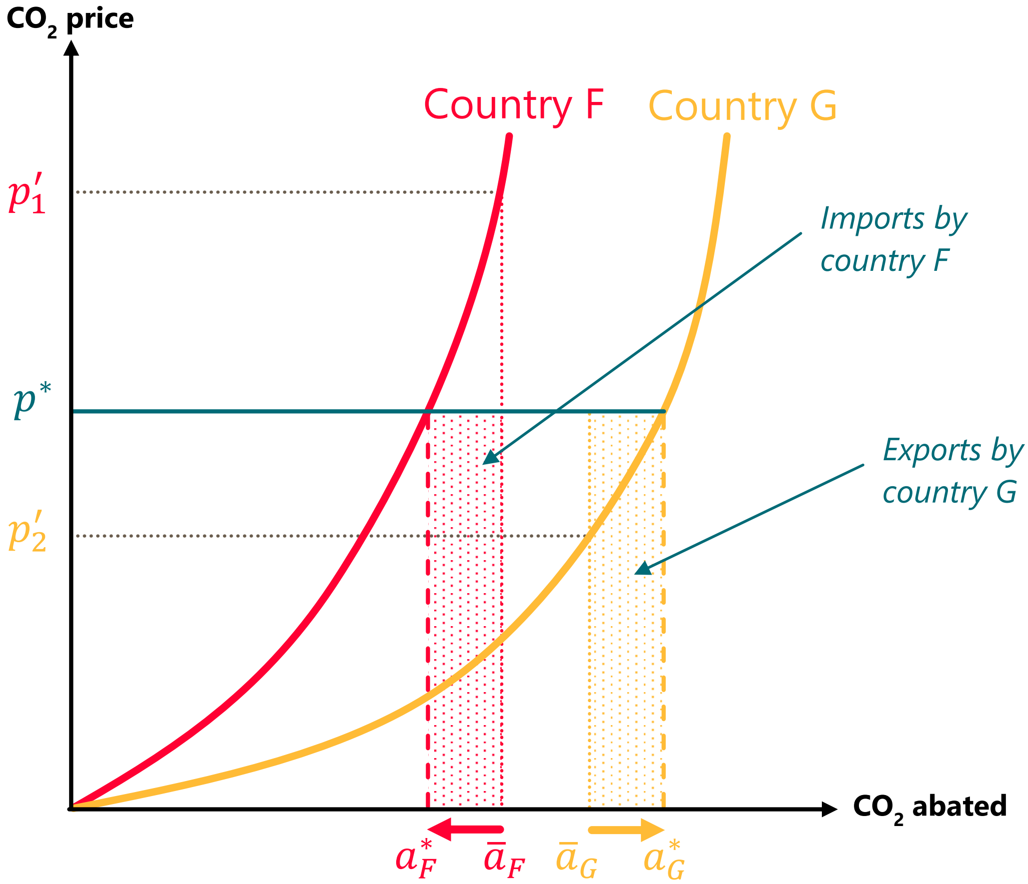


Figure 31. Financial flows (adapted from Ellerman and Decaux, 1998)

Each country has an abatement target $\bar{a}$ that they must meet, by fiat. If trading were not allowed, countries would decarbonise by that amount, at a price p'.

We can see that for country F, it would be more expensive to decarbonise at home since $p_1' \times \bar{a}_F > p^* \times \bar{a}_F$. Instead, at the world price p^*, the optimal level of abatement for country F to supply is a_F^*.

SkyShares again proceeds by interpolation, and this time looks up the interpolated price p^* in each country's MAC curve $f_i(q, p)$ and finds the matching q. This interpolated q is thus each country's optimal level of abatement $a_{i,t}^*$.

Therefore, country F decarbonises less than what its abatement target would prescribe. Country F emits more than its abatement target and buys the extra $\bar{a}_F - a_F^*$ emissions at the world price p^*. In turn, country G decarbonises by $a_G^* - \bar{a}_G$ units more and sells those to country F. Country G reduces its emissions by more than what its abatement target would prescribe. The coalition collectively stays within its cap.

The world price p^* is such that supply matches demand $a_G^* - \bar{a}_G = \bar{a}_F - a_F^*$.

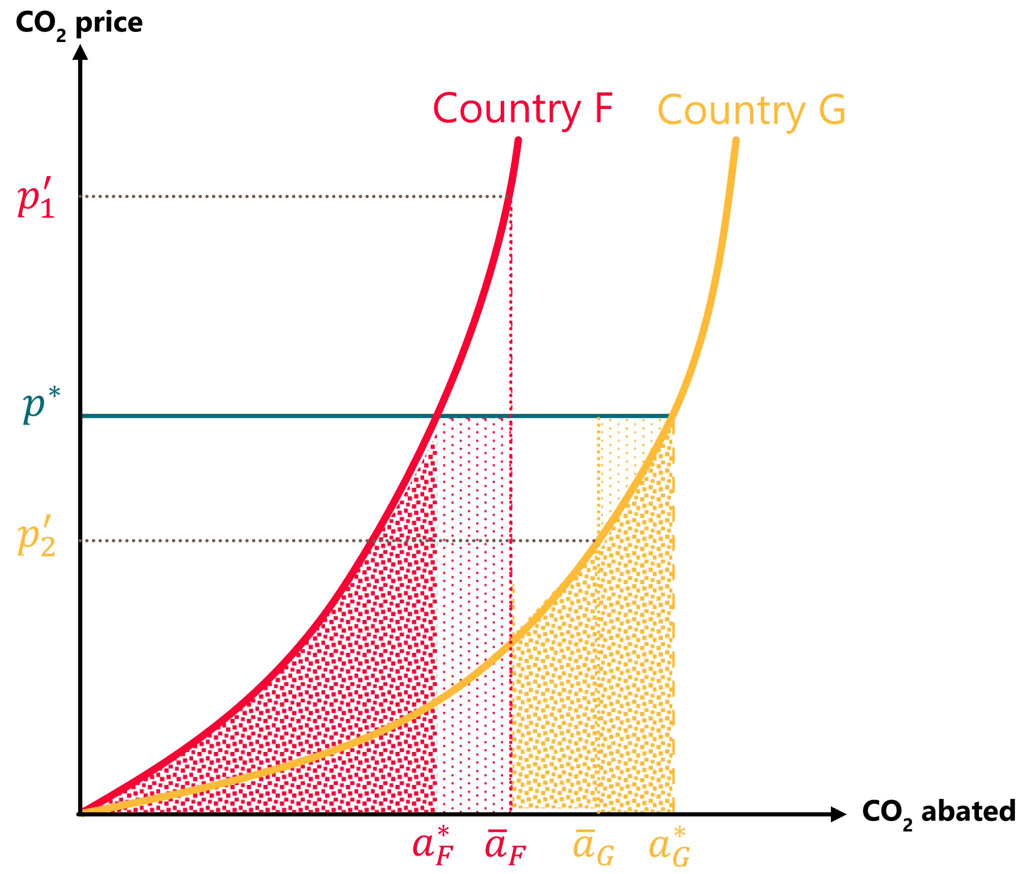


Figure 32. Adding up the costs under trading

The total costs are the sum of abatement costs and the financial flows.

The abatement costs are the area under each country's MAC curve, up to the optimal abatement level a_i^* (the shaded area).

For country F we add the payment for imports $p^* \cdot (\bar{a}_F - a_F^*)$ to the decarbonisation costs so its total costs are the shaded plus dotted pink areas.

For country G, the flows $p^* \cdot (\bar{a}_G - a_G^*) < 0$. Therefore, its total costs are the gold shaded area (its cost of decarbonisation, up to the extra amount they sell to country F), minus the dotted area (the amount they receive for the sale of their allowances).

Various approaches to calculating the costs of climate mitigation exist (Paltsev and Capros, 2013), and summing the area under the MAC curve to financial flows from trading only provides a coarse-grained brush. These may ignore existing distortions in the economy and are not able to offer insights on changes in macroeconomic consumption. Therefore, they should only be considered as rudimentary measures to give an idea of the overall cost of a 'SkyShares policy proposition'.

Variables under the Full Trade scenario		
Transfers	$tf_{i,t} = \bar{a}_{i,t} - a^*_{i,t}$ $tf_{i,t} > 0$ for importers $tf_{i,t} < 0$ for exporters	Supply matches demand so $\sum_i tf_t = 0$
Market price of allowances	p^*_t	For each t, interpolate $\bar{a}_{cow}$ in coalition MAC curve $F_{cow}(q,p)$ and find p^*
Domestic abatement	$a^*_{i,t}$	For each t, interpolate p^* in each country's MAC curve $f_i(q,p)$ and find a^*_i
Flows	$f_{i,t} = \theta_t p^*_t \cdot (\bar{a}_{i,t} - a^*_{i,t})$ $f_{i,t} > 0$ for importers $f_{i,t} < 0$ for exporters	Importers pay money (positive outflows), exporters receive money (negative outflows). The market clears so $\sum_i f_t = 0$
Decarbonisation costs	$DC_{i,t} = \int_0^{a^*_{i,t}} f(q,p)_{i,t}$	Area under each country's MAC curve, up to the optimal of abatement.
Total costs	$TC_{i,t} = DC_{i,t} + f_{i,t}$ $TC_{i,t} = \int_0^{a^*_{i,t}} f(q,p)_{i,t} + \theta_t p^*_t \cdot (\bar{a}_{i,t} - a^*_{i,t})$	Total costs are the costs of emissions reduction at home, plus the cost of transfers.
Emissions	$q_{i,t} = \bar{q}_{i,t} + tf_{i,t}$	Countries emit their allowances plus (minus) what they have bought (sold) on the market.

Table 12. Main variables under the Full Trade scenario

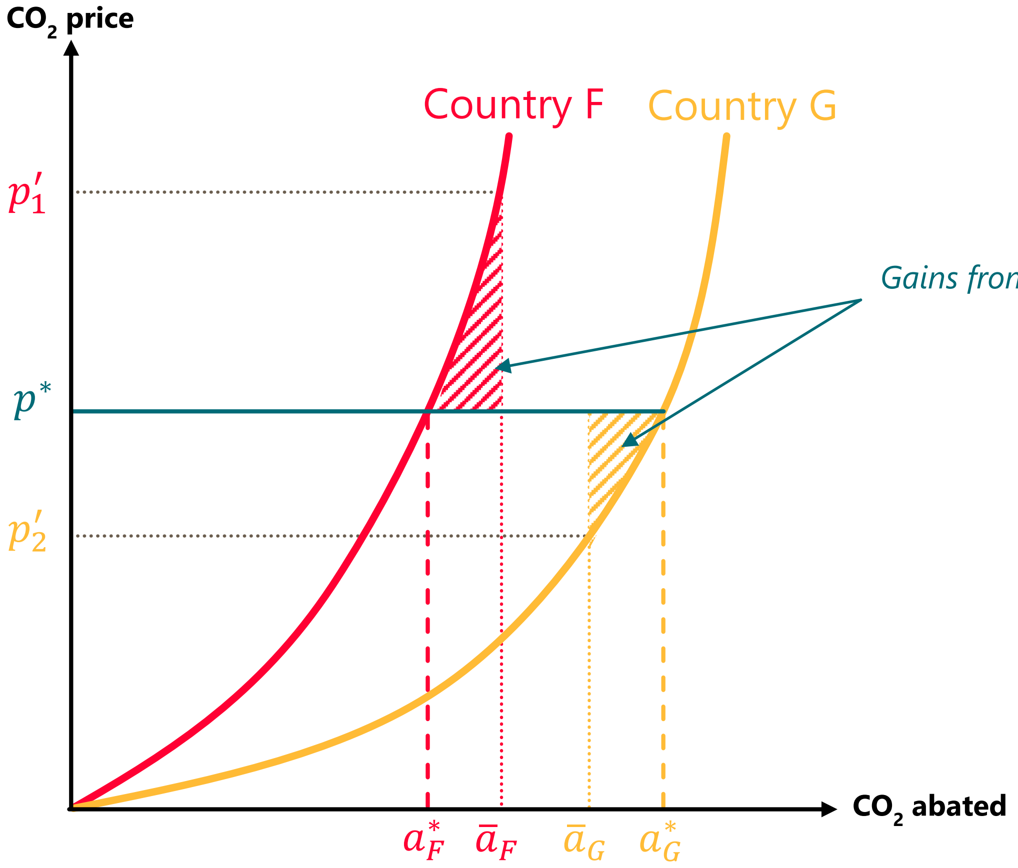


Figure 33. Gains from trading (adapted from Ellerman and Decaux, 1998)

The gains from trading are shown in the hatched areas.

For country F, the area under the curve up to $\bar{a}$ on the horizontal axis and p_1' (what it would have had to pay under No Trade) is greater than the area under the curve up to a^* and p^* (its decarbonisation costs) plus the area representing its imports $p^* \cdot (\bar{a} - a^*)$. This means that total costs are less under the Full Trade scenario.

For country G, the benefits of participating in the trading scheme are the additional revenues it gets from selling its allowances (taking into account its extra decarbonisation costs).

SkyShares finds the world price p^* and each country's optimal level of abatement a_i^* in order to maximise the gains from trade (or to minimise total costs).

Regulation

Under the Regulation scenario, SkyShares allows the user to act as a policy-maker and mandate what percentage of the abatement target must be met by decarbonising at home. This scenario might be of use to policy-makers who, in the context of their national political priorities and legislative requirements, are interested in seeing what it would cost to reduce emissions to meet a certain target.

The user can set the regulated share R, which is the share of each country's abatement target that must be reduced through mitigation actions at home. Setting $R = 1$ is equivalent to choosing a No Trade scenario, since countries are not able to buy any allowances on the market. Setting $R = 0$, by contrast, does not imply the equivalent Full Trade scenario. Under the Full Trade scenario, SkyShares automatically calculates the optimal mix of emissions reduction at home and buying allowances on the market. Choosing a Regulation scenario where the regulated share is 0 means that countries must buy all of the contributions towards meeting their abatement target at home. Only countries in surplus (with $\bar{a}_{i,t} < 0$) will be able to sell allowances.

However, if $R < 1$ for the countries with positive abatement targets, in order for the coalition to stay within its cap, the countries with a surplus of allowances must undertake additional decarbonisation to match the additional amount of abatement needed.

We first calculate what the abatement supplied would be if the deficit countries undertook decarbonisation by the share R of their abatement target:

$$A_{regul} = \sum_{i,\bar{a}>0} \bar{a}_i \cdot R \tag{38}$$

If $R = 1$, then $A_{regul} = \bar{a}_{COW,t}$ since all of the deficit countries will reduce their emissions by the entirety of their abatement target. But for the coalition to meet its abatement target collectively under a Regulation scenario where the regulated share is less than 1, we need to calculate the remainder of abatement needed which is not met by mandated decarbonisation.

This is simply the difference between the coalition's abatement target and the abatement supplied under Regulation (at time t, which we omit for simplicity):

$$T = \bar{a}_{COW} - A_{regul} \tag{39}$$

T represents the total transfers that would occur under a regulation scenario, and if positive represents additional emissions reduction that the countries selling allowances would need to make in order to meet the demand. This additional abatement required T is then shared by the countries which have a surplus of allowances ($\bar{a}_{i,t} < 0$).

If there aren't any countries with negative abatement targets in the coalition, then every country emits at its cap $\bar{q}_{i,t}$ so that the coalition can live within its carbon budget. In the case where no country in the coalition has a surplus of allowances and $R < 1$, SkyShares will no longer obey the Regulation rule whereby countries meet their abatement target by a user-chosen share of decarbonisation and automatically will change the value of R to 1.

Variables under the Regulation scenario		
Transfers	$tf_{i,t} = \bar{a}_{i,t} - a_{i,t}$ $tf_{i,t} > 0$ for importers $tf_{i,t} < 0$ for exporters	Supply matches demand so $\sum_i tf_t = 0$
Market price of allowances	p_t	For each t, interpolate $\sum_i \bar{a}_i \cdot R$ in coalition MAC curve $F_{COW}(q,p)$ and find p
Domestic abatement	if $\bar{a}_{i,t} > 0$ $\quad a_{i,t} = \bar{a}_{i,t} \cdot R$ if $\bar{a}_{i,t} < 0$ $\quad a_{i,t} = \frac{T}{\sum i, \bar{a} < 0}$	Domestic abatement is set by the user who decides the regulated share R. Countries with a surplus of allowances undertake additional emissions reduction so that the coalition stays within its cap.
Flows	$f_{i,t} = \theta_t p_t \cdot (\bar{a}_{i,t} - a_{i,t})$ $f_{i,t} > 0$ for importers $f_{i,t} < 0$ for exporters	Importers pay money (positive outflows), exporters receive money (negative outflows). The market clears so $\sum_i f_t = 0$
Decarbonisation costs	if $\bar{a}_{i,t} > 0$: $DC_{i,t} = \int_0^{\bar{a}_{i,t} \cdot R} f(q,p)_{i,t}$ if $\bar{a}_{i,t} < 0$ $DC_{i,t} = \int_0^{\frac{T}{\sum i, \bar{a} < 0}} f(q,p)_{i,t}$	For deficit countries: area under each country's MAC curve, up to the level of abatement mandated by the user. For surplus countries: area under each country's MAC curve, up to the additional level of decarbonisation needed.
Total costs	$TC_{i,t} = DC_{i,t} + f_{i,t}$	Total costs are the costs of emissions reduction at home, plus the cost of transfers.
Emissions	$q_{i,t} = \bar{q}_{i,t} + tf_{i,t}$	Countries emit their allowances plus (minus) what they have bought (sold) on the market.

Table 13. Main variables under the Regulation scenario

References

Data-sets and software

Carbon emissions

Boden, T., Marland G. and Andres, B., "National CO_2 Emissions from Fossil-Fuel Burning, Cement Manufacture, and Gas Flaring: 1751-2010", Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory: Oak Ridge, Tennessee; Research Institute for Environment, Energy and Economics, Appalachian State University: Boone, North Carolina, 31 July 2013, doi: 10.3334/CDIAC/00001_V2013. Available at http://cdiac.ornl.gov/ftp/ndp030/nation.1751_2010.ems.

Le Quéré, C., R. Moriarty, R. M. Andrew, G. P. Peters, P. Ciais, P. Friedlingstein, S. D. Jones, S. Sitch, P. Tans, A. Arneth, T. A. Boden, L. Bopp, Y. Bozec, J. G. Canadell, F. Chevallier, C. E. Cosca, I. Harris, M. Hoppema, R. A. Houghton, J. I. House, A. K. Jain, T. Johannessen, E. Kato, R. F. Keeling, V. Kitidis, K. Klein Goldewijk, C. Koven, C. S. Landa, P. Landschützer, A. Lenton, I. D. Lima, G. H. Marland, J. T. Mathis, N. Metzl, Y. Nojiri, A. Olsen, T. Ono, W. Peters, B. Pfeil, B. Poulter, M. R. Raupach, P. Regnier, C. Rödenbeck, S. Saito, J. E. Sailsbury, U. Schuster, J. Schwinger, R. Séférian, J. Segschneider, T. Steinhoff, B. D. Stocker, A. J. Sutton, T. Takahashi, B. Tilbrook, G. R. van der Werf, N. Viovy, Y.-P. Wang, R. Wanninkhof, A. Wiltshire, and N. Zeng. "Global Carbon Budget 2014 version 1.0", Earth System Science Data Discussions, 2014, doi: 10.5194/essdd-7-521-2014. Available at http://cdiac.ornl.gov/ftp/Global_Carbon_Project/Global_Carbon_Budget_2014_v1.0.xlsx.

Population

United Nations, Department of Economic and Social Affairs, Population Division (2011), "Total population (both sexes combined) by major area, region and country, annually for 1950-2100 (thousands). Medium-fertility variant, 2010-2100. World Population Prospects: The 2010 Revision", POP/DB/WPP/Rev.2010/02/F01, April 2011. Available at http://esa.un.org/wpp/Excel-Data/population.htm.

Lindgren, Mattias, "Total population, with projections" (estimates range from 1086-2100), version 3, the Gapminder Foundation, 07 September 2012. Available at http://spreadsheets.google.com/pub?key=tL0jLxFBF9TbXIN_39b1qcQ&output=xls.

Gross Domestic Product

CEPII, "BASELINE database, MaGE model data and projections 1980-2050", version 2.1 (September 2012). Reference document: "The Great Shift: Macroeconomic projections for the world economy at the 2050 horizon", CEPII Working Paper 2012-03, by Jean Fouré, Agnès Bénassy-Quéré and Lionel Fontagné, February 2012. Available at http://www.cepii.fr/anglaisgraph/bdd/baseline.htm.

Currency deflator

International Monetary Fund, "United States Gross Domestic Product, deflator (index)", World Economic Outlook Database, April 2014. Available at http://www.imf.org/external/pubs/ft/weo/2014/01/weodata/weorept.aspx?sy=1989&ey=2011&scsm=1&ssd=1&sort=country&ds=.&br=1&pr1.x=59&pr1.y=8&c=111&s=NGDP_R%2CNGDP_D&grp=0&a

GCAM 4.0

Joint Global Change Research Institute, "Global Change Assessment Model", Pacific Northwest National Library and University of Maryland.

Kim, S. H., Edmonds, J., Lurz, J., Smith, S. J. & Wise, M. (2006). The ObjECTS Framework for Integrated Assessment: Hybrid Modeling of Transportation, *Energy Journal, Special Issue No. 2*, 63-91.

http://wiki.umd.edu/gcam/

EPPA 4.1

Massachusetts Institute of Technology, "Emissions Prediction and Policy Analysis (EPPA) model". Cambridge, MA.

Paltsev, S., Reilly, J. M., Jacoby, H. D., Eckaus, R., McFarland, J., Sarofim, M., Asadoorian, M. & Babiker, M. (2005). The MIT Emissions Prediction and Policy Analysis (EPPA) Model: Version 4, MIT Joint Program on the Science and Policy of Global Change, Report No. 125, 1-72. Cambridge, MA.

Disclaimer: Some results in this paper were derived from a modified version of the MIT Emissions Prediction and Policy Analysis (EPPA) model. Modifications of the model and interpretation of the results are the responsibility of the authors.

http://globalchange.mit.edu/research/IGSM/eppadl

McKinsey

McKinsey & Company, "Version 3 of the Global Greenhouse Gas Abatement Cost Curve", unpublished. Gratefully received on 29 July 2014.

Disclaimer: We gratefully acknowledge McKinsey & Company for allowing us access to the newest version of their cost curves. The results of modelling using the McKinsey cost curves do not reflect the position of McKinsey & Company, and any errors arising from their usage remain our responsibility alone.

Literature

Allen, M. R., Frame, D., Frieler, K., Hare, W., Huntingford, C., Jones, C., Knutti, R., Lowe, J., Meinshausen, M., Meinshausen, N. & Raper, S. (2009). The exit strategy, *Nature Reports Climate Change*, *3*, 56-58. doi:10.1038/climate.2009.38.

Allen, M. R., Frame, D., Huntingford, C., Jones, C., Lowe, J., Meinshausen, M. & Meinshausen, N. (2009). Warming cause by cumulative carbon emissions towards the trillionth tonne, *Nature, 458*, 1163-1166. doi:10.1038/nature08019.

Andres, R. J., Boden, T. A. & Higdon, D. (2014). A new evaluation of the uncertainty associated with CDIAC estimates of fossil fuel carbon dioxide emission, *Tellus B, 66*, 1-15. doi:10.3402/tellusb.v66.23616

Bowerman, N. H. A., Frame, D. J., Huntingford, C., Lowe, J. A. & Allen, M. R. (2011). Cumulative carbon emissions, emissions floors and short-term rates of warming: implications for policy, *Philosophical Transactions of the Royal Society, 369*, 45-66. doi:10.1098/rsta.2010.0288.

Collins, M., R. Knutti, J. Arblaster, J.-L. Dufresne, T. Fichefet, P. Friedlingstein, X. Gao, W.J. Gutowski, T. Johns, G. Krinner, M. Shongwe, C. Tebaldi, A.J. Weaver and M. Wehner (2013). Chapter 12: Long-term Climate Change: Projections, Commitments and Irreversibility. In Stocker, T. F., D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P. M. Midgley (Eds.), *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Ellerman, A. D. & Decaux, A. (1998). Analysis of post-Kyoto CO_2 emissions trading using marginal abatement cost curves, *Joint Program Report Series*, 1-32. Cambridge, MA.

Friedlingstein, P., Andrew, R. M., Rogelj, J., Peters, G. P., Canadell, J. G., Knutti, R., Luderer, G., Raupach, M. R., Schaeffer, M., van Vuuren, D. P. & Le Quéré, C. (2014). Persistent growth of CO_2 emissions and implications for reaching climate targets, *Nature Geoscience, 7*, 709-715. doi:10.1038/ngeo2248.

Gillett, N. P., Arora, V. K., Matthews, D. & Allen, M. A. (2013). Constraining the ratio of global warming to cumulative CO_2 emissions using CMIP5 simulations, *Journal of Climate, 26*, 6844-6858. doi:10.1175/jcli-d-12-00476.1.

Intergovernmental Panel on Climate Change. (2013). Summary for Policymakers. In Stocker, T. F., D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P. M. Midgley (Eds.), *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Intergovernmental Panel on Climate Change. (2014). Summary for Policymakers. In Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (Eds.), *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Kesicki, F. (2011). Marginal abatement cost curves for policy-making – expert-based vs. model-derived curves, *UCL Energy Institute*, 1-19.

Kesicki, F. & Ekins, P. (2012). Marginal abatement cost curves: a call for caution, Climate Policy, 12, 219-236. doi:10.1080/14693062.2011.582347.

Kim, S. H., Edmonds, J., Lurz, J., Smith, S. J. & Wise, M. (2006). The ObjECTS Framework for Integrated Assessment: Hybrid Modeling of Transportation, Energy Journal, Special Issue No. 2, 63-91.

Klepper, G. & Peterson, S. (2006). Marginal abatement cost curves in general equilibrium: The influence of world energy prices, Resource and Energy Economics, 28, 1-23. doi:10.1016/j.reseneeco.2005.04.001.

Matthews, H. D., Gillett, N. P., Stott, P. A. & Zickfeld, K. (2009). The proportionality of global warming to cumulative carbon emissions, *Nature, 459*, 829-833. doi:10.1038/nature08047.

Matthews, H. D., Solomon, S. & Pierrehumbert, R. (2012). Cumulative carbon as a policy framework for achieving climate stabilization, *Philosophical Transactions of the Royal Society, 370*, 4365-4379. doi:10.1098/rsta.2012.0064.

McKinsey & Company. (2009). Pathways to a low-carbon economy. Version 2 of the Global Greenhouse Gas Abatement Cost Curve, 1-192.

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*, 1158-1163. doi:10.1038/nature08017.

Meinshausen, M., Raper, S. C. B. & Wigley, T. M. L. (2011). Emulating coupled atmosphere-ocean and carbon cycle models with a simpler model, MAGICC6 – Part 1: Model description and calibration, *Atmospheric Chemistry and Physics, 11*, 1417-1456. doi:10.5194/acp-11-1417-2011.

Morris, J., Paltsev, S. & Reilly, J. M. (2008). Marginal abatement costs and marginal welfare costs for greenhouse gas emissions reductions: Results from the EPPA model, *MIT Joint Program on the Science and Policy of Global Change*, *Report No. 164*, 1-45. Cambridge, MA.

Morris, J., Paltsev, S. & Reilly, J. M. (2012). Marginal abatement costs and marginal welfare costs for greenhouse gas emissions reductions: Results from the EPPA model, *Environmental Modeling and Assessment, 17(4)*, 325-336. doi:10.1007/s10666-011-9298-7.

Paltsev, S., Reilly, J. M., Jacoby, H. D., Eckaus, R., McFarland, J., Sarofim, M., Asadoorian, M. & Babiker, M. (2005). The MIT Emissions Prediction and Policy Analysis (EPPA) Model: Version 4, *MIT Joint Program on the Science and Policy of Global Change*, *Report No. 125*, 1-72. Cambridge, MA.

Paltsev, S. & Capros, P. (2013). Cost concepts for climate change mitigation, *Climate Change Economics, 4(1)*, 1-26, doi:10.1142/S2010007813400034.

Paltsev, S., Reilly, J. & Sokolov, A. (2013). What GHG concentration targets are reachable this century?, *MIT Joint Program on the Science and Policy of Global Change*, *Report No. 247*, 1-9. Cambridge, MA.

Raupach, M. R., Canadell, J. G., Ciais, P., Friedlingstein, P., Rayner, P. J. & Trudinger, C. M. (2011a). The relationship between peak warming and cumulative CO_2 emissions, and its use to quantify vulnerabilities in the carbon-climate-human system, *Tellus B, 63*, 145-164. doi:10.1111/j.1600-0889.2010.00521.x.

Raupach, M. R., Harman, I. N. & Canadell, J. G. (2011b). Global climate goals for temperature, concentrations, emissions and cumulative emissions, *The Centre for Australian Weather and Climate Research, Technical Report No. 042*, 1-62.

Raupach, M. R., Davis, S. J., Peters, G. P., Andrew, R. M., Canadell, J. G., Ciais, P., Friedlingstein, P., Jotzo, F., van Vuuren, D. P. & Le Quéré, C. (2014). Sharing a quota on cumulative carbon emissions, *Nature Climate Change, 4*, 873-879. doi:10.1038/nclimate2384.

Skoufias, E. (Ed.) (2012). *The poverty and welfare impacts of climate change: quantifying the effects, identifying the adaptation strategies*. Washington, DC: World Bank.

Smith, S. M., Lowe, J. A., Bowerman, N. H. A., Gohar, L. K., Huntingford, C. & Allen, M. R. (2012). Equivalence of greenhouse-gas emissions for peak temperature limits, *Nature Climate Change, 2*, 535-538. doi:10.1038/nclimate1496.

Stocker, T. F. (2012). The closing door of climate targets, *Science Express*, 1-4. doi:10.1126/science.1232468.

Stocker, T. F., D. Qin, G.-K. Plattner, L. V. Alexander, S. K. Allen, N. L. Bindoff, F.-M. Bréon, J. A. Church, U. Cubasch, S. Emori, P. Forster, P. Friedlingstein, N. Gillett, J. M. Gregory, D. L. Hartmann, E. Jansen, B. Kirtman, R. Knutti, K. Krishna Kumar, P. Lemke, J. Marotzke, V. Masson-Delmotte, G. A. Meehl, I. I. Mokhov, S. Piao, V. Ramaswamy, D. Randall, M. Rhein, M. Rojas, C. Sabine, D. Shindell, L. D. Talley, D. G. Vaughan and S.-P. Xie. (2013). Technical Summary. In Stocker, T. F., D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P. M. Midgley (Eds.), *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Thomson, A. M., Calvin, K. V., Smith, S. J., Kyle, G. P., Volke, A., Patel, P., Delgado-Arias, S., Bond-Lamberty, B., Wise, M. A., Clarke, L. E. & Edmonds, J. A. (2011), RCP4.5: A pathway for stabilization of radiative forcing by 2100, *Climatic Change, 109(1)*, 77-94. doi:10.1007/s10584-011-0151-4.

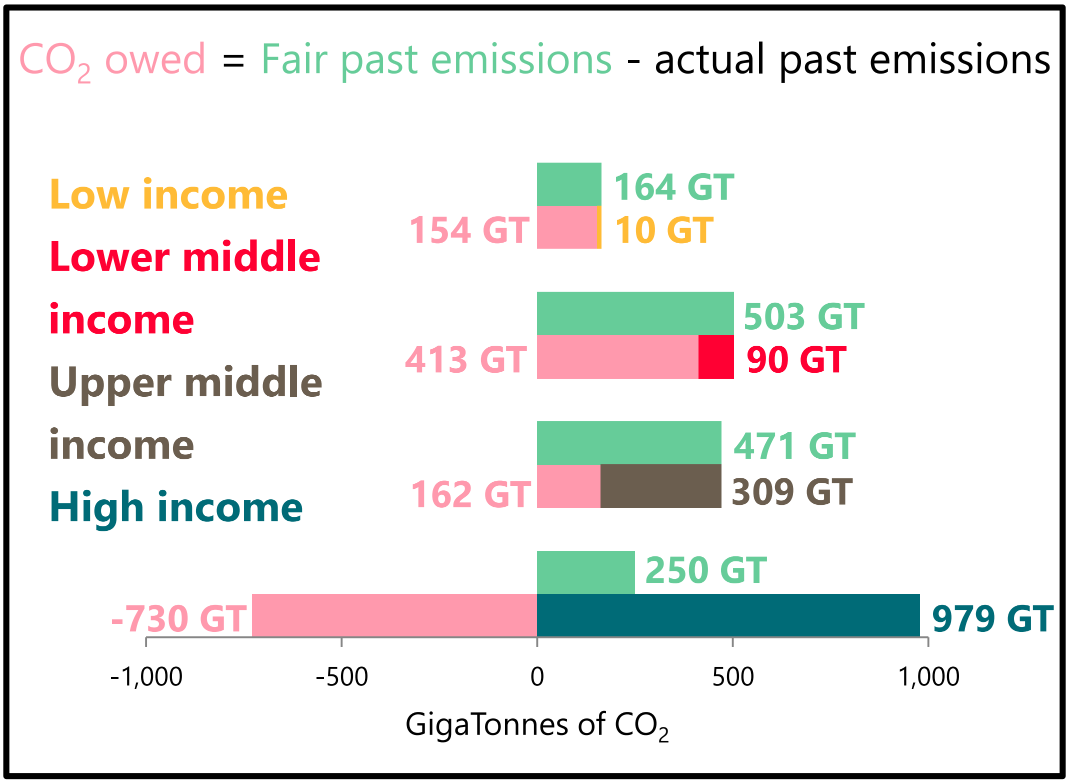
van Vuuren, D.P., de Vries, B., Eickhout, B. & Kram. T. (2004). Responses to technology and taxes in a simulated world, *Energy Economics*, *26(4)*, 579-601. doi:10.1016/j.eneco.2004.04.027.

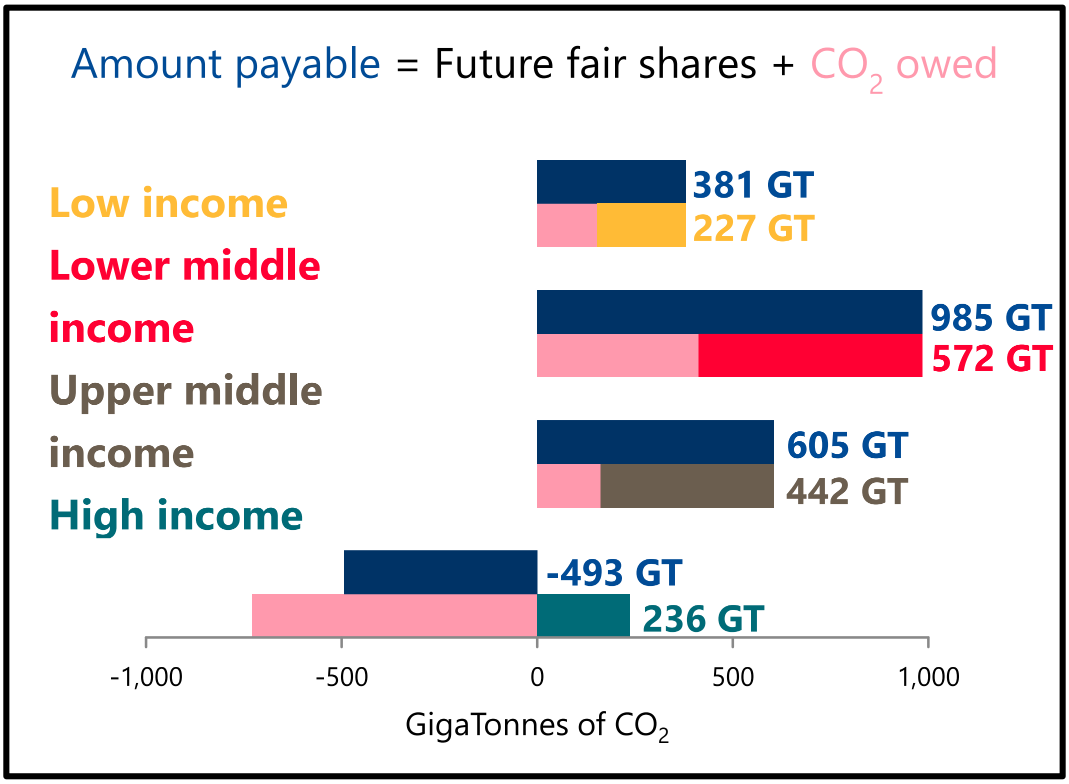
World Bank. (2014), *Turn Down the Heat: Confronting the New Climate Normal*, Washington, DC: World Bank.

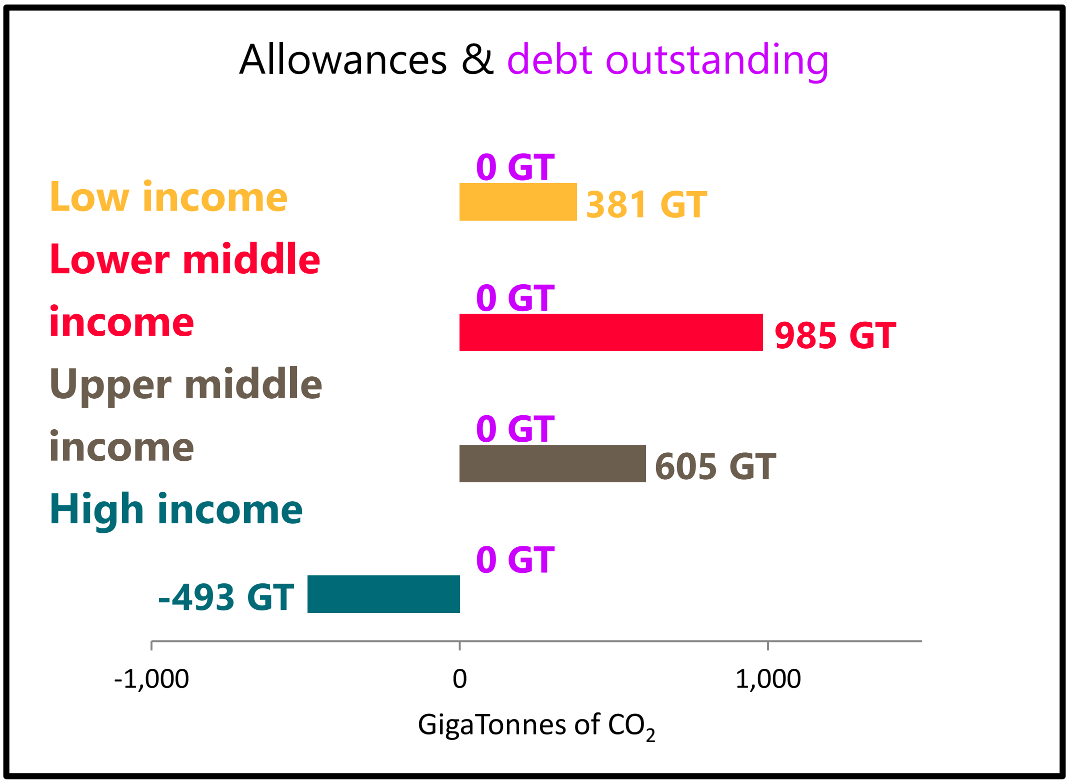
Zickfeld, K., Eby, M., Matthews, H. D. & Weaver, A. J. (2009). Setting cumulative emissions targets to reduce the risk of dangerous climate change, *PNAS, 106(38)*, 16129-16134. doi:10.1073/pnas.0805800106.

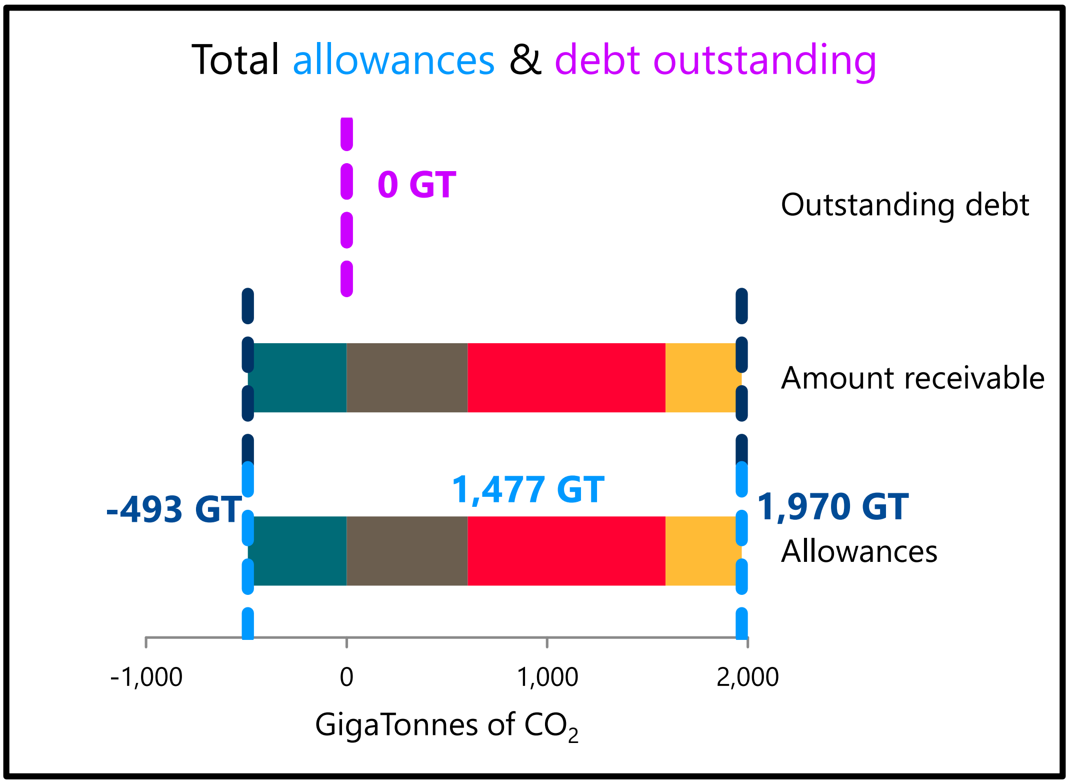
Annex: Graphs

Equal stocks rule





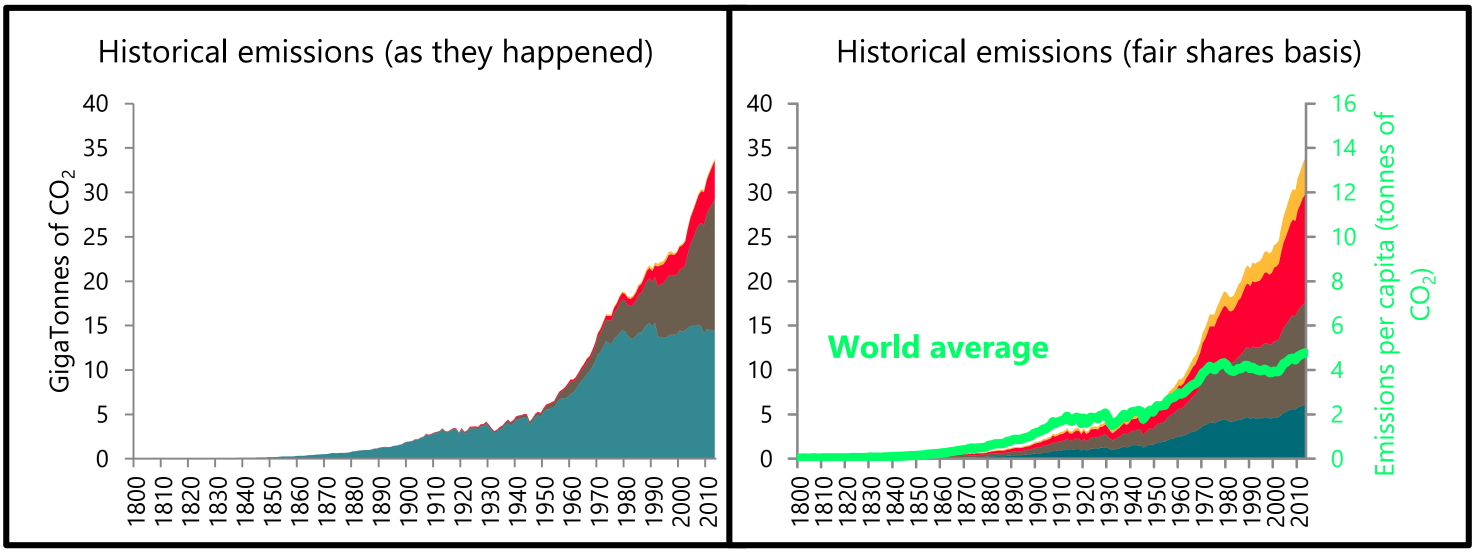




Figures 34, 35, 36 and 37. CO_2 owed and paid back under the equal stocks rule

The four figures above illustrate how the "equal stocks" rule works under a reference scenario (2°C median warming with early mitigation), and if the carbon debt is counted from 1800. We can indeed verify that at the end of the century, the entire carbon debt is paid back.

Historical emissions on a per capita basis



Figures 38 and 39. Comparing historical emissions as they happened to fair historical per capita shares

The figure on the left shows how much different income groups emitted since the beginning of the Industrial Revolution. The data comes from CDIAC, as detailed in the section on page 14.

The figure on the right shows how much each country would have emitted, if yearly past emissions had been emitted on a per capita basis at that time. To construct "historical fair shares", we have used the Lindgren data-set of the Gapminder foundation, detailed on page 15.

This "historical emissions on a per capita basis" is available in the Desktop version of SkyShares.

Annex: Datasets

Proxies for GNI/capita for countries which are missing data in CEPII's BASELINE database

Countries with missing GDP data in CEPII's BASELINE database	Country with closest GNI / capita	Proxy
Afghanistan	no data	*Egypt*[33]
Antigua and Barbuda	Venezuela	*Chile*
Aruba	no data	*Netherlands*
Azerbaijan	Dominican Republic	*Albania*[34]
Bermuda	no data	*United Kingdom*
Bosnia and Herzegovina	Macedonia	*Algeria*
Cayman Islands	no data	*United Kingdom*
Comoros	Haiti	*Haiti*
Democratic Republic of the Congo	Liberia	*Burundi*
Croatia	Hungary	*Hungary*
Cuba	no data	*Peru*[35]
Cyprus	no data	*Iceland*[36]
Dominica	Montenegro	*Venezuela*
Ecuador	Turkmenistan	*Panama*[37]
El Salvador	Armenia	*Belize*[38]
Equatorial Guinea	Croatia	*Hungary*
Eritrea	Ethiopia	*Ethiopia*
Faeroe Islands	no data	*Denmark*
French Polynesia	no data	*France*
Greenland	no data	*Denmark*
Grenada	Dominica	*Venezuela*
Iraq	Egypt	*Egypt*
Jamaica	China	*Suriname*
Kiribati	Bhutan	*Bhutan*
Democratic Republic of Korea	no data	*Yemen*
Liberia	Democratic Republic of the Congo	*Burundi*
Libya	no data	*Tunisia*[39]
Macao	no data	*Singapore*
Macedonia	Namibia	*Algeria*
Marshall Islands	Belize	*Papua New Guinea*
Montenegro	South Africa	*South Africa*

[33] Closest proxy would be Iraq, which has been proxied by Egypt.
[34] Closest proxy in terms of geography and GNI/GDP per capita is Albania.
[35] Closest GNI/capita is Peru according to the CIA World Factbook, so the proxy is Peru.
[36] Iceland is closest in terms of GNI per capita.
[37] According to the CIA factbook, Ecuador's main export partners in 2011 were US (37.8%), Panama (9.9%), Peru (6.2%), Venezuela (5.2%), Chile (4.9%), Russia (4.6%), so the proxy is Panama.
[38] Closest proxy in terms of geography and GNI/GDP per capita is Belize.
[39] Closest proxy is terms of geography and GNI per capita is Tunisia.

Myanmar	no data	*Thailand*[40]
Namibia	Algeria	*Algeria*
New Caledonia	no data	*South Africa*
Palau	Grenada	*Venezuela*
Samoa	Ukraine	*Vanuatu*
São Tomé and Principe	Vietnam	*Vietnam*
Serbia	Peru	*Belarus*[41]
Seychelles	Brazil	*Brazil*
Slovenia	Portugal	*Portugal*
Somalia	no data	*Ethiopia*[42]
Saint Kitts and Nevis	Latvia	*Latvia*
Timor-Leste	no data	*Angola*
Tonga	Cape Verde	*Fiji*
Turkmenistan	Tunisia	*Tunisia*
Turks and Caicos Islands	no data	*United Kingdom*
Uzbekistan	Papua New Guinea	*Kazakhstan*[43]
Zimbabwe	The Gambia	*The Gambia*[44]

[40] According to the CIA factbook, Myanmar's main export partners in 2011 were Thailand (36.7%), China (18.8%), India (14.1%), Japan (6.6%), so the proxy is Thailand.
[41] Best proxy would be Macedonia because it is closest in terms of GDP per capita according to the CIA World Factbook. The proxy is Belarus in terms of population and GNI.
[42] Best proxy would be Eritrea because it is closest in terms of GDP per capita according to the CIA World Factbook, so the proxy is Ethiopia.
[43] According to the CIA factbook, Uzbekistan's main export partners in 2011 were Russia (20.9%), Turkey (17.1%), China (14.7%), Kazakhstan (10.3%), Bangladesh (8.7%), so the proxy is Kazakhstan.
[44] According to the CIA factbook, Zimbabwe's main export partners in 2011 were South Africa (17.3%), China (16.9%), Democratic Republic of the Congo (11.7%), Botswana (10.5%), Italy (6.1%), so the proxy is The Gambia.

Annex: code and data for marginal abatement cost curves

Mapping of countries to MACC data-sets

GCAM region	SkyShares country	Mapping
Africa, Eastern	Burundi, Chad, Comoros, Djibouti, Eritrea, Ethiopia, Kenya, Madagascar, Malawi, Mauritius, Mozambique, Rwanda, Seychelles, Somalia, Tanzania, Uganda	AFRE, 16 countries
Africa, Northern	Algeria, Egypt, Libya, Morocco, Sudan, Tunisia	AFRN, 6 countries
Africa, Southern	Angola, Botswana, Namibia, Swaziland, Zambia, Zimbabwe	AFRS, 6 countries
Africa, Western	Benin, Burkina Faso, Cameroon, Cabo Verde, Central African Republic, Democratic Republic of the Congo, Republic of the Congo, Côte d'Ivoire, Equatorial Guinea, Gabon, The Gambia, Ghana, Guinea, Guinea-Bissau, Liberia, Mali, Mauritania, Niger, Nigeria, São Tomé and Principe, Senegal, Sierra Leone, Togo	AFRW, 23 countries
Australia and New Zealand	Australia, Fiji, French Polynesia, Kiribati, Marshall Islands, New Caledonia, New Zealand, Palau, Samoa, Solomon Islands, Tonga, Vanuatu	ANZg, 12 countries
Argentina	Argentina	ARGg, 1 country
Brazil	Brazil	BRAg, 1 country
Central America and Caribbean	Antigua and Barbuda, Aruba, The Bahamas, Barbados, Belize, Cayman Islands, Costa Rica, Cuba, Dominica, Dominican Republic, El Salvador, Grenada, Guatemala, Haiti, Honduras, Jamaica, Nicaragua, Panama, Saint Kitts and Nevis, Saint Lucia, Saint Vincent and the Grenadines, Trinidad and Tobago, Turks and Caicos	CAC, 23 countries
Canada	Canada	CANg, 1 country
Central Asia	Armenia, Azerbaijan, Georgia, Kazakhstan, Kyrgyz Republic, Mongolia, Tajikistan, Turkey, Turkmenistan, Uzbekistan	CASI, 10 countries
China	China, Hong Kong, Macao	CHNg, 3 countries
Colombia	Colombia	COLg, 1 country
Eastern Europe	Belarus, Bulgaria, Croatia, Cyprus, Czech Republic, Estonia, Hungary, Latvia, Lithuania, Malta, Moldova, Montenegro, Poland, Romania, Serbia, Slovak Republic, Slovenia, Ukraine	EEUR, 18 countries
European Free Trade Association	Iceland, Norway, Switzerland	EFTA, 3 countries
Europe (non-EU)	Albania, Bosnia and Herzegovina, Faeroe Islands, Macedonia	EnEU, 4 countries

EU-12	Belgium, Bermuda, Denmark, France, Germany, Greece, Greenland, Ireland, Italy, Luxembourg, Netherlands, Portugal, Spain, United Kingdom	EU12, 14 countries
EU-15	Austria, Finland, Sweden	EU15, 3 countries
Indonesia	Indonesia	IDZg, 1 country
India	India	INDg, 1 country
Japan	Japan	JPNg, 1 country
South Korea	Republic of Korea	KORg, 1 country
Middle East	Bahrain, Islamic Republic of Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, Syrian Arab Republic, United Arab Emirates, Yemen	MESg, 13 countries
Mexico	Mexico	MEXg, 1 country
Pakistan	Pakistan	PAKg, 1 country
Russia	Russia	RUSg, 1 country
South America, Northern	Ecuador, Guyana, Peru, Suriname, Venezuela	SAN, 5 countries
South America, Southern	Chile, Paraguay, Uruguay	SAS, 3 countries
South Asia	Afghanistan, Bhutan, Bolivia, Maldives, Nepal, Sri Lanka	SASI, 6 countries
Southeast Asia	Bangladesh, Brunei Darussalam, Cambodia, Democratic Republic of Korea, Lao People's Democratic Republic, Malaysia, Myanmar, Papua New Guinea, Philippines, Singapore, Thailand, Timor-Leste, Vietnam	SEASI, 13 countries
USA	United States	USAg, 1 country
South Africa	South Africa	ZAFg, 1 country

Table 14. Mapping of SkyShares countries to GCAM regions

EPPA region	SkyShares country	Mapping
Africa	Angola, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Cabo Verde, Central African Republic, Chad, Comoros, Democratic Republic of the Congo, Republic of the Congo, Côte d'Ivoire, Equatorial Guinea, Eritrea, Ethiopia, Gabon, The Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Liberia, Madagascar, Malawi, Mali, Mauritania, Mauritius, Morocco, Mozambique, Namibia, Niger, Nigeria, Rwanda, São Tomé and Principe, Senegal, Seychelles, Sierra Leone, Somalia, South Africa, Sudan, Swaziland, Tanzania, Togo, Tunisia, Uganda, Zambia, Zimbabwe	AFR, 48 countries
Australia and New Zealand	Australia, New Zealand	ANZ, 2 countries
Higher Income East Asia	Brunei Darussalam, Republic of Korea, Malaysia, Philippines, Singapore, Thailand	ASI, 6 countries
Canada	Canada	CAN, 1 country
China	China, Hong Kong, Macao	CHN, 3 countries
Eastern Europe	Bulgaria, Czech Republic, Hungary, Latvia, Lithuania, Macedonia, Moldova, Montenegro, Poland, Romania, Serbia, Slovak Republic, Slovenia	EET, 13 countries
European Union	Austria, Belgium, Croatia, Cyprus, Denmark, Faeroe Islands, Finland, France, Germany, Greece, Greenland, Ireland, Italy, Luxembourg, Malta, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, United Kingdom	EUR, 22 countries
Former Soviet Union	Armenia, Azerbaijan, Belarus, Estonia, Georgia, Kazakhstan, Kyrgyz Republic, Russia, Tajikistan, Turkmenistan, Ukraine, Uzbekistan	FSU, 12 countries
Indonesia	Indonesia	IDZ, 1 country
India	India	IND, 1 country
Japan	Japan	JPN, 1 country
Central and South America	Argentina, Belize, Bolivia, Brazil, Chile, Colombia, Costa Rica, Cuba, Ecuador, El Salvador, Grenada, Guatemala, Guyana, Honduras, Nicaragua, Panama, Paraguay, Peru, Suriname, Uruguay, Venezuela	LAM, 21 countries
Middle East	Algeria, Bahrain, Djibouti, Egypt, Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Libya, Oman, Qatar, Saudi Arabia, Syria, United Arab Emirates, Yemen	MES, 17 countries
Mexico	Mexico	MEX, 1 country

Rest of World	Afghanistan, Albania, Antigua and Barbuda, Aruba, The Bahamas, Bangladesh, Barbados, Bermuda, Bhutan, Bosnia and Herzegovina, Cambodia, Cayman Islands, Dominica, Dominican Republic, Fiji, French Polynesia, Haiti, Iceland, Jamaica, Kiribati, Democratic Republic of Korea, Lao People's Democratic Republic, Maldives, Marshall Islands, Mongolia, Myanmar, Nepal, New Caledonia, Pakistan, Palau, Papua New Guinea, Samoa, Solomon Islands, Sri Lanka, Saint Kitts and Nevis, Saint Lucia, Saint Vincent and the Grenadines, Timor-Leste, Tonga, Trinidad and Tobago, Turkey, Turks and Caicos, Vanuatu, Vietnam	ROW, 44 countries
United States	United States	USA, 1 country

Table 15. Mapping of SkyShares countries to EPPA regions

McKinsey region	SkyShares country	Mapping
Brazil	Brazil	BRA, 1 country
Canada	Canada	CANm, 1 country
China	China, Hong Kong, Macao, Singapore	CHNm, 4 countries
Germany	Germany	DEU, 1 country
France	France	FRA, 1 country
United Kingdom	United Kingdom	GBR, 1 country
India	India	INDm, 1 country
Italy	Italy	ITA, 1 country
Japan	Japan	JPNm, 1 country
Middle East	Algeria, Bahrain, Djibouti, Egypt, Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Libya, Oman, Qatar, Saudi Arabia, Syria, United Arab Emirates, Yemen	MESm, 17 countries
Mexico	Mexico	MEXm, 1 country
Rest of Africa	Angola, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Cabo Verde, Central African Republic, Chad, Comoros, Democratic Republic of the Congo, Republic of the Congo, Côte d'Ivoire, Equatorial Guinea, Eritrea, Ethiopia, Gabon, The Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Liberia, Madagascar, Malawi, Mali, Mauritania, Mauritius, Morocco, Mozambique, Namibia, Niger, Nigeria, Rwanda, São Tomé and Principe, Senegal, Seychelles, Sierra Leone, Somalia, Sudan, Swaziland, Tanzania, Togo, Tunisia, Uganda, Zambia, Zimbabwe	rAFR, 47 countries
Rest of Developing Asia	Afghanistan, Armenia, Azerbaijan, Bangladesh, Bhutan, Brunei Darussalam, Cambodia, Georgia, Indonesia, Kazakhstan, Kiribati, Democratic Republic of Korea, Kyrgyz Republic, Lao People's Democratic Republic, Malaysia, Maldives, Marshall Islands, Mongolia, Myanmar, Nepal, Pakistan, Palau, Papua New Guinea, Philippines, Samoa, Sri Lanka, Tajikistan, Thailand, Timor-Leste, Tonga, Turkey, Turkmenistan, Uzbekistan, Vietnam	rdASI, 34 countries
Rest of Eastern Europe	Albania, Belarus, Bosnia and Herzegovina, Macedonia, Moldova, Montenegro, Serbia, Ukraine	rEET, 8 countries
Rest of EU-27	Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Faeroe Islands, Finland, Greece, Greenland, Hungary, Ireland, Latvia, Lithuania, Luxembourg, Malta, Netherlands, New Caledonia, Poland, Portugal, Romania, Slovak Republic, Slovenia, Spain, Sweden	rEUR, 27 countries

Rest of Latin America	Antigua and Barbuda, Argentina, Aruba, The Bahamas, Barbados, Belize, Bolivia, Cayman Islands, Chile, Colombia, Costa Rica, Cuba, Dominica, Dominican Republic, Ecuador, El Salvador, Grenada, Guatemala, Guyana, Haiti, Honduras, Jamaica, Nicaragua, Panama, Paraguay, Peru, Saint Kitts and Nevis, Saint Lucia, Saint Vincent and the Grenadines, Suriname, Trinidad and Tobago, Turks and Caicos, Uruguay, Venezuela	rLAM, 34 countries
Rest of OECD Europe	Iceland, Norway, Switzerland	rOECDE, 3 countries
Rest of OECD Pacific	Australia, Fiji, French Polynesia, Republic of Korea, New Zealand, Solomon Islands, Vanuatu	rOECDP, 7 countries
Russia	Russia	RUS, 1 country
Northern America	Bermuda, United States	USAm, 2 countries
South Africa	South Africa	ZAF, 1 country

Table 16. Mapping of SkyShares countries to McKinsey regions

Sample case file a $10 carbon price run in EPPA 4.1

```
* ..\active\price010.cas
*

$TITLE  EPPA4 --- Fixed carbon price at 010 dollars

$ontext
&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&
EPPA 4.0
Emission Prediction and Policy Analysis (EPPA) Model
.
Massachusetts Institute of Technology
.
http://globalchange.mit.edu/
&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&&


Copyright 2005-2010 Massachusetts Institute of Technology.

This Software Model is released subject to the terms and conditions
specified by the MIT Joint Program on the Science and Policy of Global
Change at http://globalchange.mit.edu/ .

THE SOFTWARE MODEL IS PROVIDED "AS IS" AND MIT MAKES NO
REPRESENTATIONS OR WARRANTIES CONCERNING THE SOFTWARE MODEL, AND
EXPRESSLY DISCLAIMS ALL SUCH WARRANTIES, INCLUDING WITHOUT LIMITATION
ANY EXPRESS OR IMPLIED WARRANTY OF MERCHANTABILITY, FITNESS FOR A
PARTICULAR PURPOSE, AND NON-INFRINGEMENT OF INTELLECTUAL PROPERTY
RIGHTS.  IN NO EVENT SHALL MIT BE LIABLE TO YOU FOR ANY LOST PROFITS
OR OTHER INCIDENTAL OR CONSEQUENTIAL DAMAGES RELATING TO THE SUBJECT
MATTER OF THIS AGREEMENT.
$offtext

$ontext
########################################################
Center for Global Development, July 2014
Alice Lepissier, alepissier@cgdev.org
########################################################
This case file has been written to run the EPPA4-1 model at a fixed carbon price.
The eppaloop2.gms file has been modified to remove the time trend of the variable
pcarblag. The trend was parametrised at *1.04**5. The numeraire is the USA.

We modify the initial price p_ini to achieve the desired fixed carbon price,
which is multiplied by a factor of 27.27272727.
$offtext
```

```
* Number of periods (1997=1, 2000=2, 2005=3, ..., 2100=22)
parameter nper;
nper = 22;

* Period when depletion module starts: (a)ge 2 (b)should be the same as in v-ref.cas
* set to 2, or nper+1 to set price paths exogenously
parameter depper(ff);
depper(ff) = 2;
*depper("gas") = 23;

* Activate backstop technology.

BACKSTOP(T) = YES$(ORD(T) GE 2);
ACTIVE(BT,R) = NO;

*       Assume that after 40 years, we move to putty-putty:

THETA0(G,R) = 0.3;
THETA0("elec",R) = 0.7;
THETA(G,T) = 0.3;
THETA("elec",T) = 0.7;
THETAB(VBT,T) = 0.7;
VBMALSHR = 0;


*       Specify the benchmark conditions:

PARAMETER CLAY_SHR(G,R)   Benchmark fraction of capital stock which is old;

CLAY_SHR(G,R) = THETA0(G,R);

ALIAS (V,VV);
PARAMETER VINT_SHR  SHARE OF BENCHMARK PRODUCTION BY VINTAGE;
VINT_SHR(V,R) = SRVSHR(R)**ORD(V) / SUM(VV,SRVSHR(R)**ORD(VV));

*       Then adopt the putty clay assumption for certain sectors:

SET PCGOODS(G) / AGRI, ELEC, EINT, OTHR, tran /;


VINTG(PCGOODS,R) = yes;
VINTGBS(VBT,R) = yes;

V_DE(R,E,G,V)$VINTG(G,R) = (XDP0(R,E,G)+XMP0(R,E,G)) / XP0(R,G);
V_DF(R,G,V)$VINTG(G,R)   = FFACTD0(R,G)              / XP0(R,G);
V_DK(R,G,V)$VINTG(G,R)   = KAPD0(R,G)                / XP0(R,G);
V_DL(R,G,V)$VINTG(G,R)   = LABD(R,G)                 / XP0(R,G);
V_K(G,V,R)$VINTG(G,R)    = CLAY_SHR(G,R) * KAPD0(R,G) * VINT_SHR(V,R);

VB_K(VBT,V,R)$VINTGBS(VBT,R)   =  0.0001;
VB_KM(VBT,V,R)$VINTGBS(VBT,R) = 0.0001;


*       Adjust the new vintage capital stock:

KAPITAL(R) = KAPITAL(R) - SUM(G$VINTG(G,R), SUM(V,V_K(G,V,R)))



*       Recalibrate the new vintage capital:

D.L(G,R )$VINTG(G,R) = 1 - CLAY_SHR(G,R);
EN.L(G,R)$VINTG(G,R) = 1 - CLAY_SHR(G,R);
DV.L(G,V,R)$VINTG(G,R) = XP0(R,G) * CLAY_SHR(G,R) * VINT_SHR(V,R);

SET     CO2CF(R,T);
SET     SCO2CF(R,T);
SET     TCO2CF(R,T);
SET     TTCO2F(T);
SET

CO2CF(R,T)  = NO;
SCO2CF(R,T)  = NO;
TCO2CF(R,T)  = NO;
TTCO2F(T)  = NO;
SREN(R,T) =NO;

SCO2CF(r,T)$(ORD(T) GE 4)  = no;
TCO2CF(R,T)$(ORD(T) GE 4)  = yes;
```

```
TTCO2F(T)$(ORD(T) GE 4)  = yes;
CTAXF(R) = no;


PCARB.L(R) = 0;
pghg.l(ghg,r) = 0;
SCARB.L(G,R) = 0;
FCARB.L(R) = 0;
sghg.l(ghg,g,r) = 0;
fghg.l(ghg,r) = 0;


* If no GHG constraint (ghgt=0), check ghgk flag (yes=constraint, no=no constraint)
ghgt = 0;

* Initializing the same-gas GHG trading across regions to 0 (off)
wghgk = 0;


cquota(r,t)$(ord(T) ge 4)= co2_ref(t,r)/100;
gquota(ghg,r,t)$(ord(T) ge 4)= ghg_ref(ghg,t,r)/100;


* Flag for when to start a pre-determined carbon price increase (det_pr=23 - never).

parameter det_pr;
det_pr = 4;

* Initial price for price increase

parameter p_ini;
p_ini = 0.264611517706105;

parameter off_sum(t);
off_sum(t) = 0;

offtran = 0;
```

Configuration file to fed to GCAM 4.0

```
<?xml version="1.0" encoding="UTF-8"?>
<Configuration>
	<Files>
		<Value name="xmlInputFileName">../output/calibrated_ref150106.xml</Value>
		<Value name="xmlOutputFileName">../output/output.xml</Value>
		<Value name="xmldb-location">../output/database.dbxml</Value>
		<Value name="xmlDebugFileName">debug.xml</Value>
		<Value name="BatchFileName">batch_tax.xml</Value>
		<Value name="policy-target-file">../input/policy/carbon_tax_10.xml</Value>
		<Value name="climatFileName">gas.emk</Value>
		<Value name="GHGInputFileName">../input/magicc/inputs/input_gases.emk</Value>
		<Value name="outFileName">outFile.csv</Value>
		<Value name="dbFileName">../output/output.mdb</Value>
		<Value name="supplyDemandOutputFileName">SDCurves.csv</Value>
		<Value name="dependencyGraphName">DependencyGraph</Value>
		<Value name="ObjectSGMFileName">ObjectSGMout.csv</Value>
		<Value name="ObjectSGMGenFileName">ObjectSGMGen.csv</Value>
	</Files>
	<ScenarioComponents>
		<Value name = "solver">../input/solution/cal_broyden_config.xml</Value>
	</ScenarioComponents>
	<Strings>
		<Value name="scenarioName">BatchTax</Value>
		<Value name="debug-region">USA</Value>
		<Value name="MAGICC-input-dir">../input/magicc/inputs</Value>
		<Value name="MAGICC-output-dir">../output</Value>
	</Strings>
	<Bools>
		<Value name="CalibrationActive">0</Value>
		<Value name="BatchMode">1</Value>
		<Value name="find-path">0</Value>
		<Value name="createCostCurve">1</Value>
		<Value name="write-xml-db">1</Value>
		<Value name="write-access-db">0</Value>
		<Value name="print-debug-file">1</Value>
		<Value name="write-gas-emk">1</Value>
		<Value name="debugChecking">0</Value>
		<Value name="debugFindSD">0</Value>
		<Value name="simulActive">1</Value>
		<Value name="PrintDependencyGraphs">0</Value>
		<Value name="PrintValuesOnGraphs">1</Value>
```

```
            <Value name="ShowNullPaths">0</Value>
            <Value name="PrintPrices">1</Value>
        </Bools>
        <Ints>
            <Value name="numMarketsToFindSD">10</Value>
            <Value name="numPointsForSD">21</Value>
            <Value name="numPointsForCO2CostCurve">5</Value>
            <Value name="carbon-output-start-year">1705</Value>
            <Value name="climateOutputInterval">5</Value>
            <Value name="parallel-grain-size">15</Value>
            <Value name="stop-period">-1</Value>
        </Ints>
        <Doubles>
        </Doubles>
</Configuration>
```

Sample case file for $10 carbon price run in GCAM 4.0

```
<?xml version="1.0" encoding="UTF-8"?><scenario name="CCSP450">
    <world>
        <region name="USA">
            <ghgpolicy name="CO2">
                <market>global</market>
                <isFixedTax>1</isFixedTax>
                <fixedTax year="2015">6.1</fixedTax>
                <fixedTax year="2020">6.1</fixedTax>
                <fixedTax year="2035">6.1</fixedTax>
                <fixedTax year="2050">6.1</fixedTax>
                <fixedTax year="2065">6.1</fixedTax>
                <fixedTax year="2080">6.1</fixedTax>
                <fixedTax year="2095">6.1</fixedTax>
                <fixedTax year="2100">6.1</fixedTax>
            </ghgpolicy>
        </region>
        <region name="Canada">
            <ghgpolicy name="CO2">
                <market>global</market>
            </ghgpolicy>
        </region>
        <region name="EU-15">
            <ghgpolicy name="CO2">
                <market>global</market>
            </ghgpolicy>
        </region>
        <!--
             Repeat for all GCAM regions (commented out for Methodology paper).
        -->
    </world>
</scenario>
```

Acknowledgements

This model would not have been possible without the generosity of researchers whose guidance and encouragement as we formalised the model we gratefully acknowledge. In particular,

the late Michael R. Raupach, a pioneer in the field of carbon budgets who has left a huge legacy for scientists. The Carbon Budget module of SkyShares relies on the analytical insights of Michael and his co-authors' works.

Jonah Busch at the Center for Global Development and David Roodman, who reviewed an early version of the model.

Sergey Paltsev at the Massachusetts Institute of Technology, for his guidance in using and running the EPPA model. The modifications of the EPPA code remain are our sole responsibility and any errors arising from the usage of EPPA remain our own.

The community of GCAM developers at the Joint Global Change Research Institute, for the resources and advice they provide for those running GCAM.

Joanna D. Haigh at the Grantham Research Institute for her guidance on probabilistic analysis.

Sebastian Schienle and his colleagues at McKinsey & Company, for allowing us access to their Global Greenhouse Gas Cost Curve.

Niel Bowerman, Richard Millar and Adam Levy at the Atmospheric Physics Clarendon Laboratory at University of Oxford.

About the Authors

Alice Lépissier

Alice is a Research Associate at the Center for Global Development. She has built the SkyShares quantitative model and led the development of the website. Her research is on carbon budgets, carbon pricing, climate finance and modelling emissions trading. Alice holds degrees from University College London, Sciences Po Paris/École Polytechnique, and the London School of Economics.

Owen Barder

Owen is Senior Fellow and Director for Europe at the Center for Global Development, and Visiting Professor in Practice at the LSE. He works on improving development cooperation, innovative finance, public finance and complexity. He spent a quarter of a century working for the British government as a civil servant, in the Prime Minister's office, the Treasury and the Department for International Development. He holds degrees from Oxford University and the London School of Economics.

Alex Evans

Alex Evans is Senior Fellow at New York University's Center on International Cooperation, where he works on international development, with a particular focus on the SDGs and finance for development. He has worked as Special Advisor to two UK Secretaries of State for International Development, and has twice been seconded in to the UN Secretary-General's office as an adviser on climate change and sustainability. He has degrees from Imperial College and Edinburgh University.