Valuing Climate Liabilities: Calculating the Cost of Countries' Historical Damage from Carbon Emissions to Inform Future Climate Finance Commitments

Lee Robinson, Ian Mitchell, Atousa Tahmasebi

Abstract

A central commitment of action on climate is the promise of "developed countries" to jointly mobilize $100 billion of climate finance per year by 2020 (and through to 2025), formalised at the UN climate change conference in 2010 (COP16). Five years later, the Paris Agreement reaffirmed this commitment and promised a new goal after 2025 "from a floor of USD 100 billion per year."

We propose an approach for calculating financial climate liabilities for each country based on their historical CO_2 emissions, using the idea of an externality: a social cost that has not been borne by the agent whose actions produced it. The paper follows earlier work on calculating carbon debts (e.g. Kunnas, 2014) which we update with recent and authoritative research on carbon pricing methods. We also adjust for awareness, calculating the accruing of liabilities only from the time that countries knew that their emissions were harmful. We present several scenarios adjusting this and other assumptions. The main scenario produces a clearly quantified liability for each country and a total carbon liability to the world of $34 trillion, or $4,500 per capita. If this liability was used to set climate finance goals, it would suggest OECD countries would need to contribute $190 billion a year to 2100. The analysis also highlights that other industrialised countries, notably China and Russia, have also built-up substantial liabilities and should therefore also contribute to future climate finance goals.

Center for Global Development
2055 L Street NW
Fifth Floor
Washington DC 20036
202-416-4000
www.cgdev.org

Center for Global Development
www.cgdev.org

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Center for Global Development
2055 L Street NW
Washington, DC 20036

202.416.4000
(f) 202.416.4050

www.cgdev.org

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Executive summary

At the forthcoming Conference of the Parties to the United Nations Framework Convention on Climate Change (COP26), to be held in Glasgow in November, finance is high on the agenda. If the world is to avoid the worst impacts of climate change, financial support for countries facing bigger challenges in mitigating emissions is essential. Yet there is still a shortfall in funding for the $100 billion target "developed" countries pledged to mobilise annually by 2020; and only around half of the almost $80 billion of the climate finance identified is additional to development finance flows provided before the target was set (Mitchell, Ritchie, & Tahmasebi, 2021).

One element of the case for international climate finance commitments is that countries' historic emissions are already damaging the climate. In this paper, we consider the cost of that damage and develop scenarios to value the liability of different countries for those costs.

We review and use the latest thinking on the social cost of carbon, consider how those costs have altered over time, and develop a model that calculates a liability—that is, the total social cost of emissions in total and by country, according to when they were emitted. We also include a cut-off before which emissions do not contribute to a country's liability. This is based on a new systematic analysis of the text in international discussions at the UN General Assembly to assess when societal awareness of climate impacts was such that countries could be deemed responsible for damage created. This analysis suggests there was a step-change in climate awareness in 1979, and in our main scenario we do not include emissions before this date.

Results: Valuing carbon liability

Under our main scenario, we include a cut-off of 1979; use a carbon cost of $51 per tonne in 2020; and reduce that cost by 3 percent per year historically.

On this basis, we estimate the total global carbon liability amounts to approximately $34 trillion, or approximately $4,400 per capita. This is an estimate of the share of total pollution cost of carbon emitted to date for which countries can reasonably be liable.

Carbon liabilities for selected countries and groupings with a carbon cost of $51/tonne

Country	Liability ($bn)	Share of Total Debt	Liability per Capita	Liability/GNI
World	**34,218**	**100%**	**4,459**	**39.0%**
China	7,096	20.7%	5,077	49.8%
United States	6,505	19.0%	19,818	30.0%
Russia	2,081	6.1%	14,412	126.4%
India	1,621	4.7%	1,186	57.1%
Germany	1,058	3.1%	12,729	26.7%
United Kingdom	618	1.8%	9,242	22.2%
South Africa	485	1.4%	8,288	142.1%
Brazil	416	1.2%	1,969	23.2%
Chile	70	0.2%	3,717	26.0%
OECD	15,242	44.5%	11,207	28.2%
EU-28	4,804	14.0%	9,340	26.0%
BRICS	11,698	34.2%	3,681	56.1%

This estimate of total liability for carbon damage to date equates to around 39 percent of one year's global income. In our high-cost scenario (see below), which does not reduce the liability for historic emissions and uses a higher carbon price, this figure is 72.4 percent.

The carbon liability of 37 OECD members in the model is around $15 trillion.[1] Starting in 2022, and over the 78 years to 2100, this equates to approximately $190 billion per year.[2]

This is a reference point for the commitment of "developed countries" to mobilize (though not provide) $100 billion of climate finance per year from 2020 through 2025, with the Paris Agreement promising a new goal after 2025 "from a floor of USD 100 billion per year, taking into account the needs and priorities of developing countries." Our analysis suggests that even under relatively forgiving assumptions on the liability for the social costs of carbon, the value of that liability is well-above commitments made on climate finance.

Liabilities in this model also accrue to both developed and developing countries, based on historical emissions. The liability of the US is $6.5 trillion and that of China $7 billion, though in per capita terms this is £19.8 thousand and $5 thousand respectively, demonstrating that although China is currently the world's largest carbon emitter, the US has been emitting carbon for much longer and at a much higher per-head level. The UK and Germany, long-time emitters, also have relatively high per capita liabilities at $9.2 thousand and $12.7 thousand respectively, while those of BRICS countries are much lower and average $3.6 thousand. China has the highest liability in absolute terms, though in per capita terms it

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[1] The OECD now has 38 members as Costa Rica joined in May 2021.

[2] Some of this liability relates to damage within the OECD, though those costs are likely to be a small share. If climate costs are borne evenly across the global population, then the share of liability that is domestic would be equivalent to the OECD's share of the global population, roughly 18%.

is comparable to other BRICS countries. Countries such as India, Brazil, and Chile also have liabilities, though much smaller ones than the OECD countries.

The analysis also suggests that other countries, particularly those that have industrialised, have also built up substantial liabilities. Under the assumptions we set out, China's liability is just under half that of the OECD. As countries consider a new climate finance goal beyond 2025, there is a case that OECD countries should be contributing more than $100 billion per year and that China and industrialised countries should also be making substantial contributions to international finance in the coming decades.

We also present two alternative scenarios of liabilities which use different assumptions on the social cost of carbon and how this grows over time (reflecting the rising costs of damage with higher atmospheric carbon stock). The lowest cost scenario uses a much-lower social cost of carbon of $14 per tonne of emitted CO2 and discounts historic costs more steeply (at 5 percent per year). Whilst this is well-under the consensus view of the social cost of carbon, it implies a global liability of just over a fifth of the value under the main scenario at $7.2 trillion, and OECD liability which equates to $39 billion per year to 2100. In the higher cost scenario, we use a social cost of carbon of $76 per tonne, remove the cut-off and set the discount rate at 2.5 percent, which doubles the total liability to $63.4 trillion; and suggests an OECD liability of almost $390 billion per year. These scenarios illustrate that damage cost and liability increase proportionally to the social cost of carbon; and that the cut-off and discount rate favour OECD countries whose emissions were earlier than other countries.

Along with this paper, we publish the model that drives the results to allow different assumptions to be tested, and thus allow greater flexibility in contributing to the discussion on climate finance.

Post 2025 climate finance ambitions

We propose these results as a contribution to informing commitments on climate finance, such as the post 2025 climate finance goal. They suggest that developed countries' additional climate finance contributions well-beyond $100 billion per year can be justified; but also that a wider group of countries, notably China, should also be contributing substantial sums.

Introduction

This year, almost six years after the Paris Agreement, countries will come together and look ahead at ways to reduce their carbon emissions. While the focus on curbing future emissions is essential if the world is to avoid the worst impacts of climate change, the responsibility of countries for climate damage to date is also relevant to setting their future commitments equitably, including on finance. So, how should we value those historic emissions and how does this compare to promised levels of climate finance?

This paper looks at an alternative way of calculating climate finance contributions based on cumulative historical emissions but adds some adjustments to quantify countries' liability for climate damage. First, we use recent thinking on carbon prices to cost emissions. Second, we allow that cost to fall for historic emissions, and third, we include a liability cut-off point to reflect the notion that countries should be liable only for actions they knew to be harmful, although this assumption is relaxed in one of the scenarios. The assumptions necessary for this are difficult and contested, so we also publish our model alongside the paper to enable users to consider other scenarios. The paper and model may also be of relevance to the United Nations Framework Convention on Climate Change (UNFCCC) work on financing for loss and damage (UNFCCC, 2020).

The paper proceeds as follows: Section 1 discusses the motivation for the study and the rationale for devising our method of calculating carbon liability. Section 2 discusses the simple model, and its requisite assumptions: carbon costs and a cut-off point. Sections 3 and 4 respectively fill in the values for these assumptions. Section 3 is a literature review on carbon pricing, which discusses the different approaches to pricing carbon, and our choice of the Social Cost of Carbon and the reasons for this choice. Section 4 describes the methodology for establishing a cut-off point: a textual analysis algorithm applied to reports of proceedings of UN General Assembly reports. Section 5 presents the results of the model for three scenarios and discusses the implications of these results. The final section concludes.

Whilst our scenarios have been chosen carefully and draw on evidence where possible, we recognise that the assumptions of the scenarios we present will be considered controversial by some. We hope that by publishing the interactive version of the model along with this paper, and thus allowing users to estimate outcomes with their preferred assumptions, we stimulate discussion further by permitting alternative outcomes to be considered.

Rationale

Whether the Paris Agreement's goals are achieved will depend on the amount of financing mobilized to support mitigation and adaptation actions that address climate change. Climate finance is, therefore, crucial to the world's climate future. The trade-off between climate goals and the rights of countries to develop their economies, using energy and risking ongoing emissions, is a tension exacerbated by the differentiated responsibilities between countries of different income levels. But what if climate finance obligations were based not on goodwill and the balancing of myriad political interests against ever more pressing domestic resource demand, but on a fair distribution of obligations based on the extent to which each country has contributed to the problem?

Modern mainstream economic theory has long been fluent in the idea of externalities, or the costs of one's actions impacting upon others. The idea of engineering policy so that such costs can be internalised—that is, so that the agents responsible bear the costs of their actions rather than society at large—is not new. Pollution is often presented as an example in this concept but rarely elaborated at the global level. We do so here to estimate the costs of the externality of carbon emissions through history and calculate the global carbon liability accrued through historical emissions. This paper builds on the work of Kunnas et al. (2014), updating the concept with recent thinking on carbon pricing.

Cumulative emissions

It is the cumulative total of historic greenhouse gas emissions that cause climate-related problems for economies and ecosystems, and which have consumed much of the "emissions budget" which, had it been adhered to historically, might have allowed newer actors' economies to grow with fewer restrictions today. So, who is responsible for that stock? Our World in Data (Ritchie & Roser, 2020b) uses Carbon Dioxide Information Analysis Centre (CDIAC, 2021) and Global Carbon Project (ICOS, 2019) estimates to calculate carbon emissions stretching back to 1751, when carbon emissions were tiny relative to today's volumes. It was only in the 20th century when emissions began to increase steeply, and it took until around 1991 for them to reach half of today's total accumulated emissions.

In valuing a country's total liability for climate damage, we would ideally have data on all greenhouse gas emissions, not just carbon dioxide (CO_2). Some are much more harmful relative to CO_2. For instance, per unit of mass, methane contributes 84-86 times more to global warming than does CO_2 over 20 years (Mcsweeney, 2020). But there's little data for gases other than carbon before 1990, and even now carbon accounts for around three-quarters of annual greenhouse gas emissions (Ritchie & Roser, 2020a). Accordingly, we think the focus on carbon provides a sound starting point for estimating liability that can be updated if data on other emissions becomes available.

Understandably, it is the more populous countries that have emitted the most, but a country's emissions profile over time and its share of accumulated global emissions also depends on whether and how recently it industrialized.

In assigning liabilities for historic emissions, the timing of the emissions matters. The damage from climate change depends on the cumulative stock of greenhouse gas in the atmosphere and earlier emissions contribute equally to that stock. However, the social cost of emissions has risen over time, reflecting the rising costs associated with more recent emissions. The US government's Interagency Working Group (IWG) report on the social cost of carbon argues that the greater the existing atmospheric carbon stock, the more damaging, at the margin, is emitting an additional tonne of carbon because physical and economic systems become more stressed in response to greater climatic change (IWG, 2021), an argument we elaborate in the later sections on carbon pricing and the Integrated Assessment Models. In our main scenarios, then, we judge that, in the past, the damage a country inflicted by emitting a tonne of carbon should be calculated as lower than that of emitting a tonne today. It follows that the social cost of emissions will likely rise in the future if the world continues on a path that increases the chances of more damaging or catastrophic outcomes.

In assigning liability, we also give a role to societal awareness of the damage of anthropogenic climate change, and limit historical liability based on this. The increase in this awareness in recent years is reflected not only in the adoption of international agreements like the creation of the Intergovernmental Panel on Climate Change (IPCC) in 1988 and the Paris Agreement in 2015, but also in the frequency with which international fora discuss climate related issues.

In our model, we limit liability based on when awareness of the extent to which greenhouse gas emissions were damaging was shown by leaders and policymakers; we assume societies should not be liable for costs arising before that point. Once society knew its emissions were damaging, but that damage was not costed, then it was knowingly underpaying for a resource (energy). The climate liability is a re-accounting of the portion of the price knowingly not paid. From a legal perspective, awareness is not always necessary for establishing legal liability, and where actions have caused damage, there should be full liability for the responsible party, regardless of their intent. We think assigning liability only after widespread awareness of costs is the more reasonable approach and take this in our main scenarios. But we remove the cut-off for liability in our high-cost scenario and in the scenarios contained in the annex.

A factor that might be considered to reduce carbon liability, but which we have chosen to not include in our model, is a country's efforts in developing renewable technologies. Although such efforts do not remove the country's historic physical emissions, they could be considered to offset liability for these emissions for a couple of reasons:

- By creating technology for green energy, they increase the energy opportunities for for all countries in the future, so offset the global carbon budget depletion for which the country is partly liable.
- They represent an opportunity cost—an investment of resources for which there are competing claims to develop technologies that serve a global public good and demonstrate efforts to promote the country's carbon transition.

However, data on these investments do not have as broad coverage as the emission data we use (we would welcome references to such data sources). There also remain questions on how far such investments are philanthropic versus self-interested, including what proportion of the investment's value could be used to offset carbon liabilities and how much royalties from deploying to patent holding countries would offset any philanthropic value. And given that the size of these investments is currently very small relative to carbon liability levels (even total energy and renewable R&D costs less than 4 percent of the value of annual carbon liabilities, see Table 1[3])—even in Germany with its strong policy commitment to

[3] This uses estimates of carbon liabilities which will be obtained through the course of the following analysis.

renewables—we decided to exclude them. We would be interested in incorporating such research into future development to the model, subject to policy interest.

Table 1. Annual spending on energy and renewable energy R&D, $ and % of carbon liability (main scenario)

	$bn	Share of Liability	
		Total Liability	2019 Liability
United States			
Total	7.76	0.12%	2.97%
Renewables	0.77	0.01%	0.29%
Germany			
Total	1.31	0.12%	3.77%
Renewables	0.27	0.03%	0.79%
European Union			
Total	1.78	0.04%	1.09%
Renewables	0.40	0.01%	0.25%

Source: Authors' Calculations using OECD Stat data (2021).

"Liability" and loss and damage

In this paper, we value countries' "liability" according to the evidence and assumptions set out below. However, one of the biggest political tensions in climate negotiations to date has been around loss and damage—and the related issue of compensation, which the term "liability" often refers to.

Whilst our estimates of liability and the related model may inform debate on loss and damage, our estimates do not identify on which countries costs will fall. Indeed, a portion of each country's liability likely relates to climate damage within that country. Further, we take no account of any existing or historic efforts by countries (on development cooperation, climate finance, or R&D) that might contribute towards any loss.

The model

For our purposes, we want to understand the cost of the damage likely to be caused by emissions to date, and which countries are responsible for that damage. We construct a model that calculates the liabilities of every country, taking as inputs the historic emissions of all countries and two assumptions:

- **Carbon cost**: A carbon cost for every year from the first emitted tonne that we have data for (1751), achieved by setting a benchmark year price and reducing (increasing) this price before (after) that point using a discount rate.
- **Cut-off**: A cut-off point, after which time we are confident that emitters knew the harm of their actions but before which liability is less certain.

The following sections will outline the research undertaken to derive the assumptions and the values we arrive at. We adjust the assumptions to derive three scenarios:

- High Social Cost Scenario
- Main Scenario
- Low Social Cost Scenario

We attribute the liability to the country "producer"[4] of the carbon rather than the end country consumers who import it (or import the products whose production generated emissions). This aligns with the approach taken by the UN and the Paris Agreement, and with the principle that the producer is the agent in control and responsible—but it does ignore that some of these emissions are generated in response to demand which tends to be in higher-income countries. We acknowledge the importance of recognising imported emissions, and the usefulness of datasets like the OECD's one on imported emissions (OECD, 2019) in allowing countries' total emissions footprint to be ranked in indices such as the Commitment to Development Index (CGD, 2020). A more detailed analysis might adjust the weights on liabilities by accounting not just for production, but for the demand which drives it. We welcome suggestions on how to incorporate these metrics into a model such as this, but for this iteration, the simplification of assigning liability to producer countries is adopted.

Carbon costs and prices

There are several ways to think about the cost or price we should place on carbon. For economists, perhaps the most important is the concept of "externality"—the cost of the pollution that spills over onto someone else (outside of the market or transaction). This section reviews the different approaches and related estimates and identifies suitable liability estimates for our model.

An estimated 44 countries currently have a form of carbon pricing in place (World Bank, 2020), covering about half of their emissions and amounting to 21.5 percent of annual global GHG emissions (World Bank, 2021b). According to the IMF, the average price of emissions globally is just $2 per tonne. But prices realised in carbon markets are not the best guide to setting the value of emissions because they fail to fully capture the cost to society of carbon emissions; in economic terminology, they do not reflect the full externality (IMF, 2019). Market prices reflect political and economic trade-offs to some degree and usually fail to cover all emissions.

Theory can provide more robust estimates of carbon prices and can do so in different ways depending on the purpose of the carbon price. We identified four approaches to pricing carbon in the literature. First, the "social cost of carbon" (SCC), also called the

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[4] Producers are firms, households, and individuals, but the analysis amalgamates at country level.

marginal damage cost of emissions, which captures the costs to society of the damage that atmospheric carbon causes. Second, the marginal abatement cost (MAC), or the cost to the economy of reducing carbon emissions. Third, the shadow price of carbon (SPC), which equates the SCC and the MAC in an analogous approach to equating supply and demand curves in microeconomic theory (Clarkson & Deyes, 2001). And fourth, a target-based approach, or the carbon price required to meet a given climate stabilisation goal.

Social cost of carbon

The social cost of carbon (SCC) is a monetary estimate of the total economic damages resulting from emitting one additional tonne of carbon into the atmosphere, usually calculated as the damage done for the entire time the carbon remains and translated into a present value. William Nordhaus is a pioneer of this concept and has received the Nobel prize for his work on it with the DICE (Dynamic Integrated model of Climate and the Economy) model (Nordhaus, 2018). There are currently over 200 estimates of the SCC within the literature (Table 9 in the annex shows the results of a survey by Tol, 2008). The IPCC notes that SCC estimates vary from "a few dollars [to] several hundreds of dollars per tonne of carbon" (Allen et al., 2014). Estimates vary based on the choice of key variables such as discount rates used (which will be elaborated further below), equity weighting, which is the approach to weighting climate impacts, and relative reduction in wealth in different regions (Watkiss et al., 2005), the time horizon of the study, and projected trajectory of GHG emissions. There is a great degree of uncertainty and disagreement within the literature around the parameters for these modules. Indeed, the sheer number of assumptions needed to calculate SCCs using integrated assessment models (IAMs) have led to them being criticized in recent years as esoteric and based on opaque and arbitrary assumptions (e.g. Pindyck, 2015). Nevertheless, the underlying concept is important, and they have been widely calculated and used for some time.

For our SCC estimate we use the results of the Interagency Working Group's (IWG) analysis carried out in 2021 (IWG, 2021). The IWG was established in the US under the Obama administration in 2009[5] to use the "best available science' to establish harmonised estimates of SCC[6] which could be used consistently across government agencies, such as the Environmental Protection Agency (EPA), in their regulatory analysis and to value the climate impacts of various policies.

To estimate the social cost of carbon, IAMs are widely used, which integrate climate and economic models, and the IWG follows this approach. There are three relevant model components, often referred to as modules (Carleton & Greenstone, 2021), in estimating the SCC:

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[5] The agency was discontinued under the Trump administration but re-established by President Biden on January 20, 2021.

[6] It estimated social costs of other greenhouse gases as well, but we restrict our focus to carbon for the reasons outlined previously.

1. A climate sensitivity module, which measures the increase in long-term temperature caused by the increasing of CO_2 concentration.
2. The climate damage module, which captures the relationship between temperature increase and monetary economic damages (Bretschger & Pattakou, 2019).
3. A discounting module, which calculates the present value of future damages.

The three most well-known IAMs—DICE (Nordhaus, 2018), FUND (R. Tol & Anthoff, 2014) and PAGE (Hope, Anderson, & Wenman, 1993)—also arrive at significantly different estimates of SCCs. Each of the IAMs take a different approach to model the relationship emissions and resulting economic damages. In PAGE, for example, economic damages are calculated as a fraction of GDP, depending on the temperature in that period relative to the pre-industrial average temperature in each region. In FUND, damages in each period depend on the rate of temperature change from the prior period. In DICE, temperature increases have an impact on both consumption and investment (Greenstone, Kopits, & Wolverton, 2011).

While DICE, FUND, and PAGE have been used individually to estimate the SCC, IWG's analysis is novel in its experimental design, running multiple models tens of thousands of times. Each estimate is based on an iteration of running the three IAMs to estimate the cost of carbon. However, any estimate of the SCC must be taken as provisional due to the uncertainties and incompleteness associated with the models. For instance, IAMs have often been criticised for incomplete assessment of potential catastrophic damages and extreme weather events. Additionally, the damage functions do not fully consider different sectoral impacts. For instance, while the effect on the agricultural sector is included, the effects on human health are not fully captured. Additionally, the effects of climate damages are heterogenous across different geographies, and this variety is not included in some of the models. IAMs do not typically account for the pace of technical change and adaptation that could change emission pathways and the associated damage (Ackerman, DeCanio, Howarth, & Sheeran, 2009). Despite these limitations, IWG points out that given the lack of data linking the physical impacts to economic damages, it could not identify a better way to convert climate change into economic damages.

In translating damage to the climate into economic figures, the stream of future damage to economic and social outcomes, such as agriculture, health, market performance, and investment, are stated in terms of reduced consumption or consumption equivalents and is discounted to the present value in the year that the emission of the carbon occurred.

Discount rates used in social costs

Of all the parameters used in estimating the SCC using these models, the choice of discount rate on carbon costs is perhaps the most controversial.[7] Given the long time horizon of

[7] Note that there is a distinction between discounting future costs and using the discount rate as a proxy to set historical costs. This is discussed on the carbon pricing summary section.

damage from greenhouse gases, SCC estimates are highly sensitive to the discount rate. For illustration, suppose $1,000 worth of economic damage 50 years from now is discounted backwards. At 2.5 percent, it is worth $291 today and at 5 percent it is worth $87. If the timescale is 100 years, the figures are $85 and $8 respectively. The higher the discount rate, the less weight people put on the future and so less investment is needed now to mitigate against future costs (Box 1).

Box 1. Discount rates and intergenerational equity

The discount rate remains one of the most "critical problems in all of economics" (Weitzman, 2001). The discount rate is the rate at which society as a whole is willing to trade off present for future benefits. A high discount rate assigns less weight to the future and therefore implies less investment is needed now to mitigate climate damages in the future. A lower discount rate puts more weight on future generations' welfare and implies more aggressive climate policy now, rather than delaying action. Although discounting is commonly used to assess the cost and benefits of investment projects and public policies, there is still much controversy about the choice of discount rate (Gollier et al, 2014).

There are two broad approaches within the literature to determine the discount rate, which Arrow et al label "descriptive" and "prescriptive" (Arrow et al., 1995). The descriptive approach bases its estimates on observation—the realised outcomes of society and markets (typically risk-free rates). The descriptive approach relies on the assumption that credit markets are efficient, so that the interest rate observed in markets reflects both the rate of return of capital and the householders' preferences for trading off present welfare against future welfare (IPCC, 2007). The prescriptive approach is more of a top-down view. It takes a social planner perspective and reflects the importance a policy maker attaches to the utility and consumption of current and future generations. It derives the discount rate from the judgement and expertise of policymakers (or their technocratic advisers).

In practice, different governments use different discounting approaches for cost-benefit analysis of climate policy. For instance, the US and the Netherlands take the descriptive approach, extracting the discount rate from market rates of returns on risk-free government gilts, whereas countries such as the UK and France take the prescriptive approach, using theoretical measures of social welfare, and the Social Rate of Time Preference (STP).

Some of the differences between the UK and the US discount rate can be viewed through the Ramsey formula (Aldy, Atkinson, & Kotchen, 2021), which equates the opportunity cost of capital (left hand side) with the social rate of time preference (right hand side)

$$r = \rho + \eta \cdot g$$

ρ, is a time preference parameter, η, the elasticity of the marginal utility of consumption and g is the real growth rate of consumption.

Conceptually, the U.S. approach derives r from observing actual interest rates and returns on investments. The UK's approach, however, involves constructing the discount rate based on an empirical review of the parameter estimates for ρ, η and g, rather than deducing it from observed market behaviour. The Green Book (HM Treasury, 2020) recommends a discount rate of 3.5% annually for the first 30 years of a policy/programme, and a declining discount rate thereafter.

There are arguments for and against each of the perspectives on discount rates. Some argue that if public investment displaces private investment, the market rate is most appropriate. Alternatively, STP is more applicable if projects are funded through general taxation (consumption) (Freeman & Groom, 2016). Another argument states that market rates may not reflect social values due to externalities, whereas the STP takes social welfare function and so better reflects which projects increase societal welfare (Moore, Boardman, & Vining, 2013). But modelling the social welfare function often relies on various assumptions and could be seen by some as arbitrary.

In order to be consistent with IWG, we use the discount rates used in the US, which draws on both descriptive and prescriptive approaches, though primarily the former.

The IWG chose three discount rates to span a range of plausible SCCs: 2.5, 3, and 5 percent per year. Its benchmark rate is 3 percent, which is in line with the US Office of Management and Budget's estimate of the consumption rate of interest. The 5 percent rate reflects a higher discounting of future damages, which are viewed as less urgent to address today, and the 2.5 percent reflects a lower discounting, and implies a more urgent need to do so.

Year of emission and the damage function

As well as the discount rate, the other key input to the IWGs estimates of SCC is the year of emission. The IWG notes that emissions in later years are more harmful as global physical and economic systems get more stressed in response to increasing climate damage, so the incremental damage of a tonne of CO_2 in 2030 is more than a tonne in 2020 (IWG, 2021). We noted this point in the rationale section but it is illustrative to explore here as it forms a critical assumption of our model. It describes a damage function—the damages to economic and social systems resulting from carbon emissions—that is exponentially increasing. This idea has some support in the literature (Burke et al., 2019; Hsiang, 2014; IWG, 2021; Kőműves, 2021). Note that this does not imply an exponential relationship between carbon emissions and *global mean temperature*, which the recent IPCC report found to be near linear. An exponentially increasing damage function is consistent with the IPCC's finding if economic damages rise non-linearly in temperature.

If the damage function is exponential, then if net emissions continue to rise, the costs of emissions must increase over time to capture the higher damage a marginal emitted tonne does. Were the damage function to be modelled as linear, this would imply a constant carbon cost. We adopt the former assumption, in line with the IWG's report, but present some alternative scenarios based on the latter assumption in the annex.

IWG SCC estimates

The IWG is due to publish a comprehensive update of its estimates in January 2022, but in February 2021, it published a preliminary estimate of SCCs based on iterations of the three main IAM models for a tonne of carbon emitted in various years and discount rates (IWG, 2021). The results are shown in Table 2. The prices in this table represent the global social cost of one tonne of CO_2 emitted in a given year for its entire lifetime and for a given discount rate. For example, with a discount rate of 3 percent, and over the course of the entire time it exists in the atmosphere, a tonne emitted in 2020 would cost society $51. This cost is calculated in terms of reduced consumption due to the effect this CO_2 has on economic systems

Table 2. Social cost of CO_2, 2020–2050 (in 2020 dollars per tonne of CO_2)

Emissions Year	Discount Rate and Statistics			
	5% Average	3% Average	2.5% Average	3% 95th Percentile
2020	14	51	77	139
2030	19	62	90	170
2040	25	73	103	201
2050	32	85	117	204

Source: Adapted from IWG Report (2021).

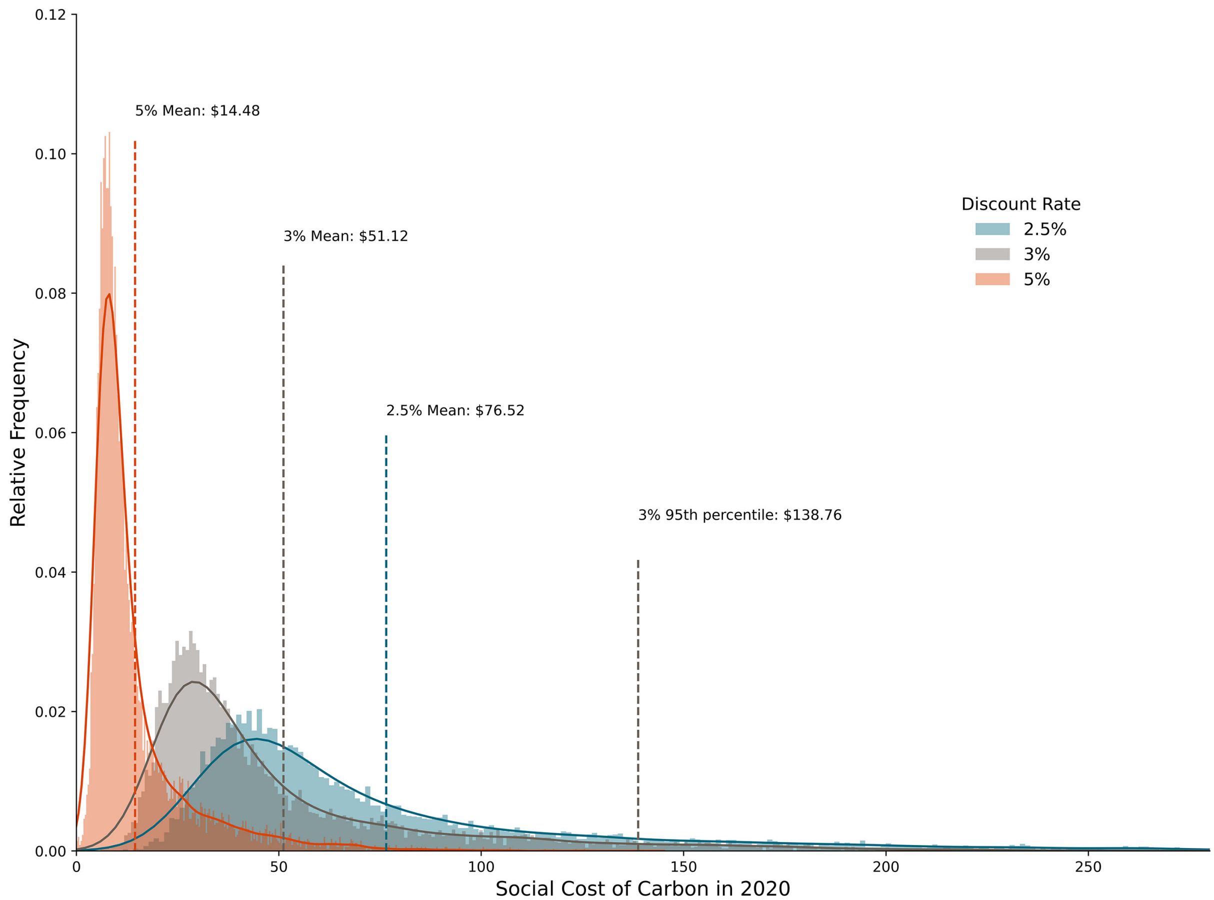
These results are summaries of hundreds of thousands of IAM runs. The IWG ran 10,000 iterations of the DICE model for a 2020 tonne at 2.5 percent, 10,000 for FUND, and 10,000 for PAGE, and took the average of these 30,000 to get the (rounded) $77 figure shown for 2020 at 2.5 percent in this table. The same process was used for every emission year and discount rate to produce the results in the above table.

The distribution of these results is heavily right skewed (Figure 1). Thus the 95th percentile figure reported in the table is much higher than the other figures in the same row. This figure uses the central 3 percent discount rate and captures the possibility of less likely but catastrophic climate outcomes.

A few other things are notable from this chart. First, higher discount rates not only lead to lower estimates of SCCs, but they also lead to more statistically efficient estimates, with lower variance. Second, the 3 percent and 2.5 percent distributions have distinct right skews. Usually in statistical analysis, one might prefer the median to dampen the impact of outliers in such a situation, yet here the mean is still justified; a preference for the median is to dampen the influence of outliers on estimate, but the outliers in this scenario are much worse climate outcomes—perhaps catastrophes. The risk tolerance for these outliers should be very low and we should not strive to mute their influence on SCC estimates. It is this logic that leads the IWG to also report the 95th percentile for the central (3 percent) discount rate.

As a final note on the IWG report, it notes that the global nature of the problem must be acknowledged, and that its purview was no longer confined solely to benefits and costs for those within US borders. This explicitly declares the problem to be one of global externalities—the production of "global bads." Calculating global carbon liabilities is fully in line with this logic, and also that of the basic economic concept of internalising the costs of externalities to correctly align incentives.

Figure 1. Frequency distribution of SC-CO_2 Estimates for 2020

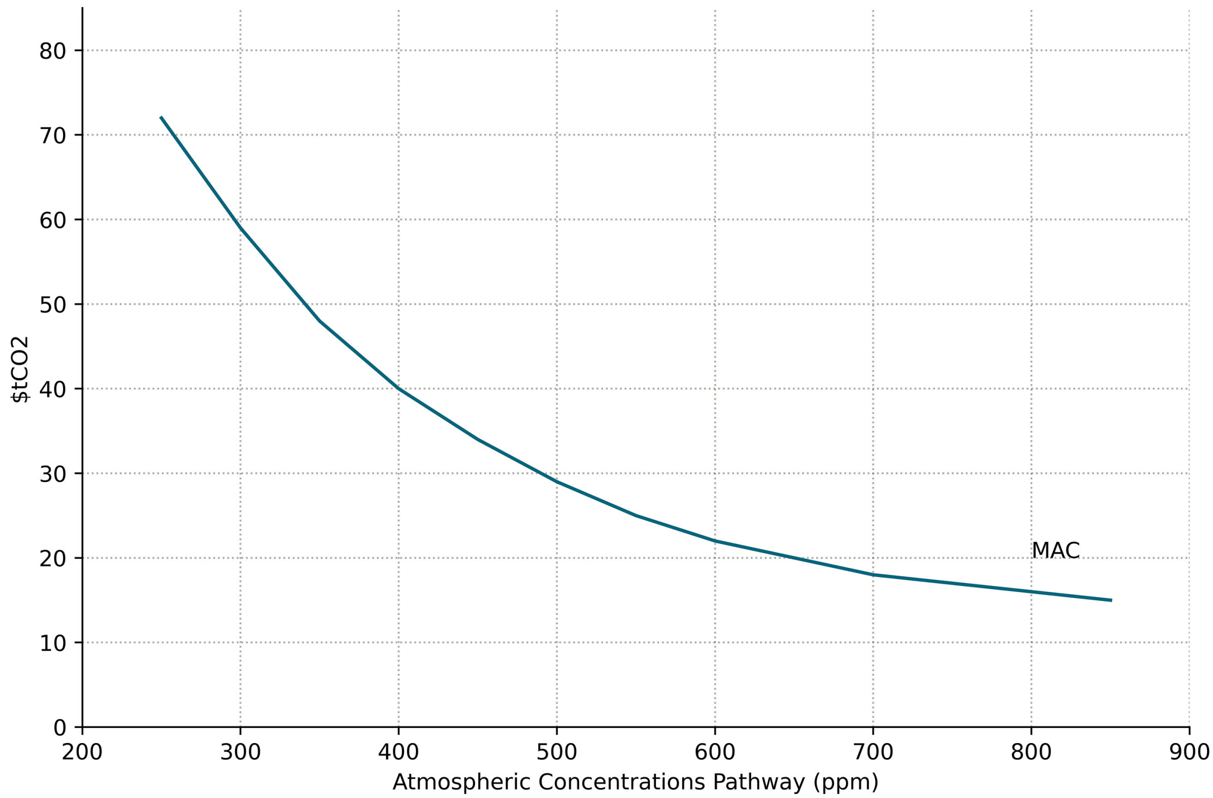


Source: Authors, using data from IWG Report (2021).
Note: This represents the first row in Table 2—the carbon prices for 2020 emissions given different discount rates.

Marginal abatement cost

The marginal abatement cost (or MAC) represents the cost to the economy of reducing emissions: the costs to homes and businesses of switching to lower emitting energy sources or reducing emissions overall. An MAC curve plots a target concentration pathway against a carbon price and is downward sloping (Figure 2) because the lower emissions are, the more costly it is to reduce them further and vice versa: activities that are less costly to transition to will be undertaken first, while those that are prohibitively costly to wean off carbon will hold out until last.

Figure 2. Marginal abatement curve (MAC)



Source: Authors' Calculations.

Various organisations use MAC curves. For example, the World Bank has developed several country-specific MAC curves, including for Brazil (World Bank, 2014), and Armenia and Georgia (World Bank, 2017). In the case of Armenia and Georgia, for instance, MAC curves were used to assess the cost competitiveness of various energy efficiency measures, and to identify the most efficient measure in saving energy and reducing greenhouse gas emissions.

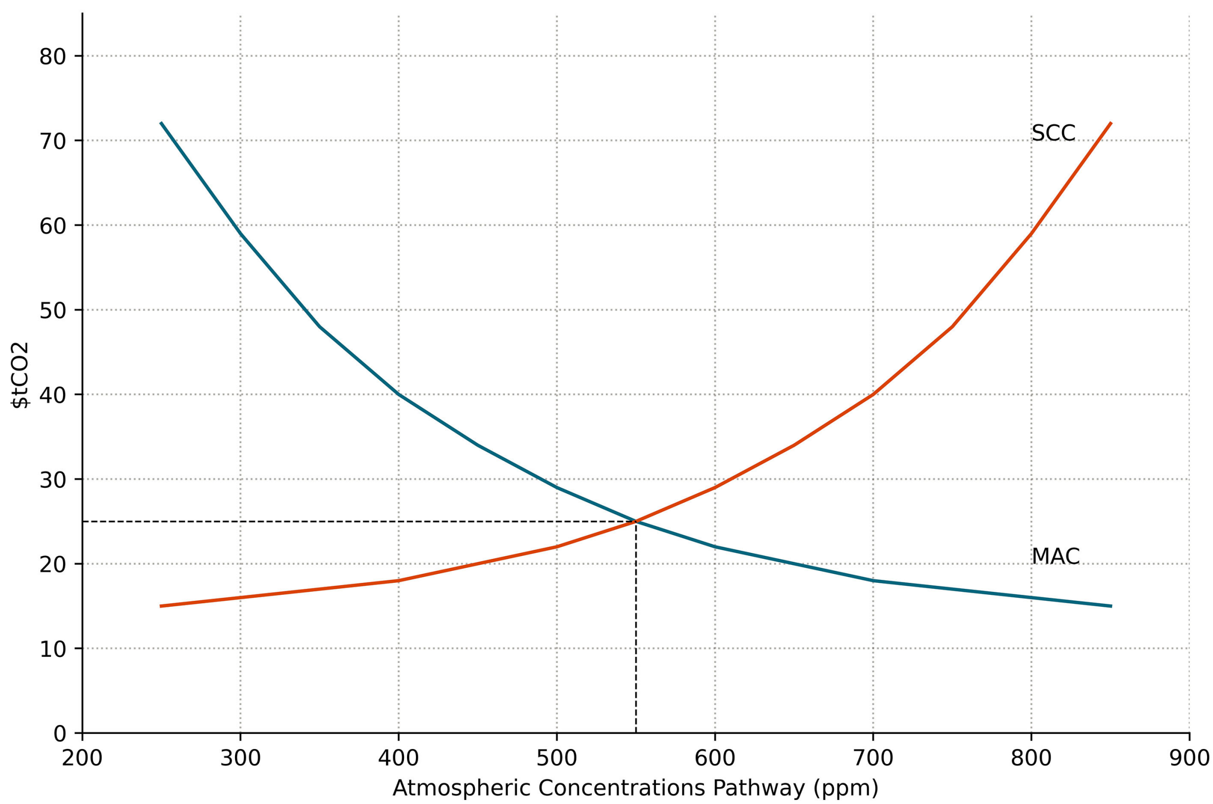
The most well-known MAC curve was developed by McKinsey and Company, updated in 2010 (McKinsey & Company, 2010). It has been used in various reports commissioned by governments and international organisations on how to respond to climate change, including on reducing emissions from deforestation and forest degradation in developing countries (REDD). In 2007, McKinsey's analysis focuses on abatement measures are estimated at 40 euros per tonne or less in 2030 (Enkvist, Nauclér, & Rosander, 2007).

Shadow price of carbon

A shadow price is a value assigned to a good or service that has not been priced by markets or has been mispriced due to market failures. Shadow prices can be used in cost-benefit analysis and impact assessments and can therefore guide decision-makers to socially optimum decisions. The EBRD and other multilateral development banks such as the World Bank and

IFC have recently adopted a shadow price (EBRD, 2019) following the recommendations of the Report by the High Level commission (World Bank, 2019). The UK Department for Environment, Food and Rural Affairs also used a shadow price approach due to the uncertainty about the SCC and MAC associated with any particular stabilisation goal (Price, Thornton, & Nelson, 2007). According to Stern, the risks of the worst impacts of climate change can be substantially reduced if greenhouse gas levels in the atmosphere can be stabilised between 450 and 550ppm CO_2 equivalent (Stern, 2006). By intersecting the SCC and MAC curve for the stabilisation goal of 550ppm CO2e, based on the higher part of Stern's suggested stabilisation range, Price adopted a price of £25/tCO2e in 2007 (Figure 3). The intuition is that in any project, the costs associated with avoiding emitting an additional tonne of CO_2 should be incurred up to that level to be consistent with the global optimum level of carbon.

Figure 3. Shadow price of carbon



Source: Authors, based on Price et al (2007).

Target-based approach

A target-based approach to pricing carbon aims to set the price of carbon that is consistent with some climate goal, such as net zero emissions by 2050. This approach can follow from economic or scientific analysis and/or from political negotiation which balances scientific and economic considerations with equity concerns.

With governments collectively agreeing to limit global temperature increases as part of the Paris Agreement, there are several target-based examples relating to that goal, including the Near Term to Net Zero (Kaufman, Barron, Krawczyk, Marsters, & McJeon, 2020) and the Report of the High-Level Commission on Carbon Prices (World Bank, 2019). The latter estimated that to meet the goals of the Paris Agreement temperature targets of "well below 2°C˝ (UN, 2015), global carbon prices of $40–80 and $50-100 per tonne of CO_2 would need to be in place by 2020 and 2030 respectively.

In 2009, the UK moved from an SCC to a target-based approach to pricing carbon, with the goal of an 80 percent reduction in GHG emissions by 2050. In May 2019, the UK's Committee on Climate Change recommended that the UK adopt a "net-zero" target for all greenhouse gas emissions by 2050 (Committee on Climate Change, 2019). A price that is consistent with net-zero would start at £50 (with a range of £40–100) in 2020, reaching £75 (£60–140) in 2030 and £160 (£125–300) per tonne of CO_2 in 2050. The LSE Grantham institute have also explored the prices needed to achieve net zero within the UK and conclude similar estimates of prices to meet the UK's net zero target: around £40/tCO2 in 2020 which would rise to around £100–125/tCO2 by 2050 (Burke et al., 2019). For the US, based on the GCAM-USA model, carbon prices would reach $32, $52 and $93 per tonne (in 2018 dollars) by 2025 for net-zero targets in 2060, 2050, and 2040, respectively (GCAM-USA, 2021). AN IMF blog estimates that most large emitters must set a price of $50 to $100 per ton or more by 2030 to meet their pledges for carbon emission reduction (Parry, 2016). The IPCC estimates much larger figures: estimates for a below-1.5°C pathway range from

- 2030: $135–6,050
- 2050: $245–14,300
- 2070: $420–19,300
- 2100: $690–30,100

Note, these are expressed in real (2010) US Dollars per tonne of CO2.
(IPCC, 2018).

Carbon pricing summary and the choice of carbon price in the model

The different carbon prices are useful for different policy goals. SCC is useful for measuring the damage done by carbon to society, whereas MAC is useful when measuring the social cost of investing for mitigation. Equating them, the SPC is useful for setting a price that balances these opposing societal needs for energy and climate health. The target-based approach is concerned with the incentive mechanism of a carbon price in meeting climate goals.

For our model, the most appropriate approach is the SCC. This is because we are calculating the likely costs of historic carbon emissions and we conceptualise this liability as being a form of compensation for historic damage. Therefore, the price that is constructed to reflect the costs to society of carbon emissions is most conceptually appropriate. We thus refer to the carbon "cost" in the model rather than the carbon "price."

There is a huge range of options for the SCC price, but we choose three central scenarios in accordance with the IWG, as their report is up to date, uses a range of models to estimate costs, and incorporates the full global damage of emissions into account. The IWG report is also produced by an authoritative team with notable expertise. The prices in 2020 and discount rates we use in the model are therefore:

- $76 per tonne of CO_2 in the **high social cost** scenario, "discounted" at 2.5 percent/year
- $51 per tonne in the **main** scenario, "discounted' at 3 percent/year
- $14 per tonne in the **low social cost** scenario, "discounted" at 5 percent/year

The prices are taken from the IWG report (IWG, 2021) and are shown in Table 2. The SCC approach does have the caveats noted above but as discussed above it seems most appropriate to our purpose of estimating liabilities and provides a range consistent with most other studies.

As a final point, the distinction between discounting into the future and setting historical costs should be noted (and is the reason we put quotation marks around discounting in the above bullet points). As discussed in Box 1, the discount rate reflects the idea that costs in the future are preferrable to costs today and could suggest a trade-off between incurring the costs of addressing climate change today versus in the future (with a lower discount rate implying greater urgency of addressing the problem sooner). But setting social costs of carbon for historic emissions is conceptually different. The emissions have already occurred, so there is no trade-off between past and present to be considered. The cost of historical carbon does not capture this intergenerational decision, and instead represents the lifetime damage a tonne of carbon emitted at the time would cause, given the existing stock of atmospheric carbon. We use the scenario discount rates as a proxy for setting this price in the absence of other information, but it is not strictly a discounting exercise. This subtle distinction should be borne in mind when interpreting results.

Liability cut-off

One of the challenges of assigning a financial liability for historical emissions past misdeeds is the notion of awareness. If we present liability as being analogous to a bill for goods bought when they were under-priced, then a sense of fairness might require that we only recoup costs for those that were *knowingly* bought below the fair price.

For how long has society been aware of the harm of carbon emissions? To assign financial liability at the sovereign level, we may take national leaders and policymakers to represent "society" and ask for how long they have been aware of how damaging carbon emissions are? Other agents within society may have known before this (Bell, 2021), but we are interested in when broader society, as the bearer of the liability, became aware. Can we pinpoint a cut-off for their carbon liability?

Methodology

The goal is to establish a point in time when awareness of climate issues among national leaders was sufficiently high so that it cannot plausibly be said that they were ignorant of these problems. At risk of stretching the judicial analogy, the approach is akin to allowing the defence of plausible deniability, to then show how much carbon liability would exist even in the context of this leniency. In the blog that preceded this paper (Mitchell, Robinson, & Tahmasebi, 2021), we used the date of the establishment of the IPCC in 1989 as the cut-off point. The establishment of the IPCC was clear proof that the international community knew of these issues sufficiently to devote resources to addressing them. But the IPCC's establishment followed this awareness, rather than preceding it.

We answer the question of culpability by analysing the proceedings of the UN General Assembly (UNGA) back to the first publication of these records in 1946. Since we are posing this question about all countries, national document archives are insufficient, and of the multilateral bodies, the UN has a long backdated proceeding in the public domain. There are 169 such documents (UN, 2020), the larger of which surpass 1,000 pages, so rather than manually analysing these documents, we wrote a Python algorithm to analyse them and report the relative frequency of climate-related terminology over time.

The algorithm essentially counts the occurrences of particular words in a given document, and the wordcount of climate-related words divided by total wordcount indicates levels of awareness and importance around these issues. We compiled the following list of search words:

> *Global warming, Environment, Climate, Carbon, Carbon Price, Man Made, Anthropogenic, Weather, Destabilisation, Extreme Events, Sea Level, Greenhouse, Ozone, Carbon Dioxide, CO2, Emissions Trading System, Emissions Trading scheme, Renewable, Solar Power, Sequestration, Emission, Climate Finance, Carbon Tax, Border Tax*

We used regular expressions so that variations of the terms would also be captured, e.g., carbon price, carbon pricing, and carbon prices would all be captured, as would alternative spellings, such as destabilisation/destabilization. We made the search case neutral.

A naïve wordcount would be misleading because several of these terms can be used in ways unrelated to climate issues. We told the algorithm to not increase the wordcount if the word occurred in particular phrases. Our list of ignore terms is:

> *Business Climate, Political Climate, Investment Climate, Transparent Climate, Security Climate, Business Environment, Political Environment, Transparent Environment, Investment Environment, policy Environment, enabling environment, Learning Environment, Drug free environment, Climate control, Climate service, Dangerous environment, Working environment, Climate free from, International Climate, Favourable climate, Climate for disarmament, a CLIMATE conducive to*

We dropped "destabilisation" as its alternate uses were too numerous ("political destabilisation," for example, was frequent). We also ignore sentences that are repeated in the same document (of which there are several in these write-ups of multilateral proceedings).

For the relative usage of climate words to be captured, they must be expressed as a proportion of total wordcount. However, to increase precision, we constructed the denominator not as total wordcount, but as wordcount minus filler words, such as prepositions, conjunctions, and articles, that have grammatical rather than lexical meaning. Some issues may be more sensitive or complex than others and thus demand more complex grammatical constructions, which would increase the size of the denominator even though the relative frequency of the *issue* being discussed would be the same as if the issue was amenable to more succinct syntax. We wish only to capture how large climate issues loomed relative to others so we can ignore filler words and scale climate words to other "meaning" words.

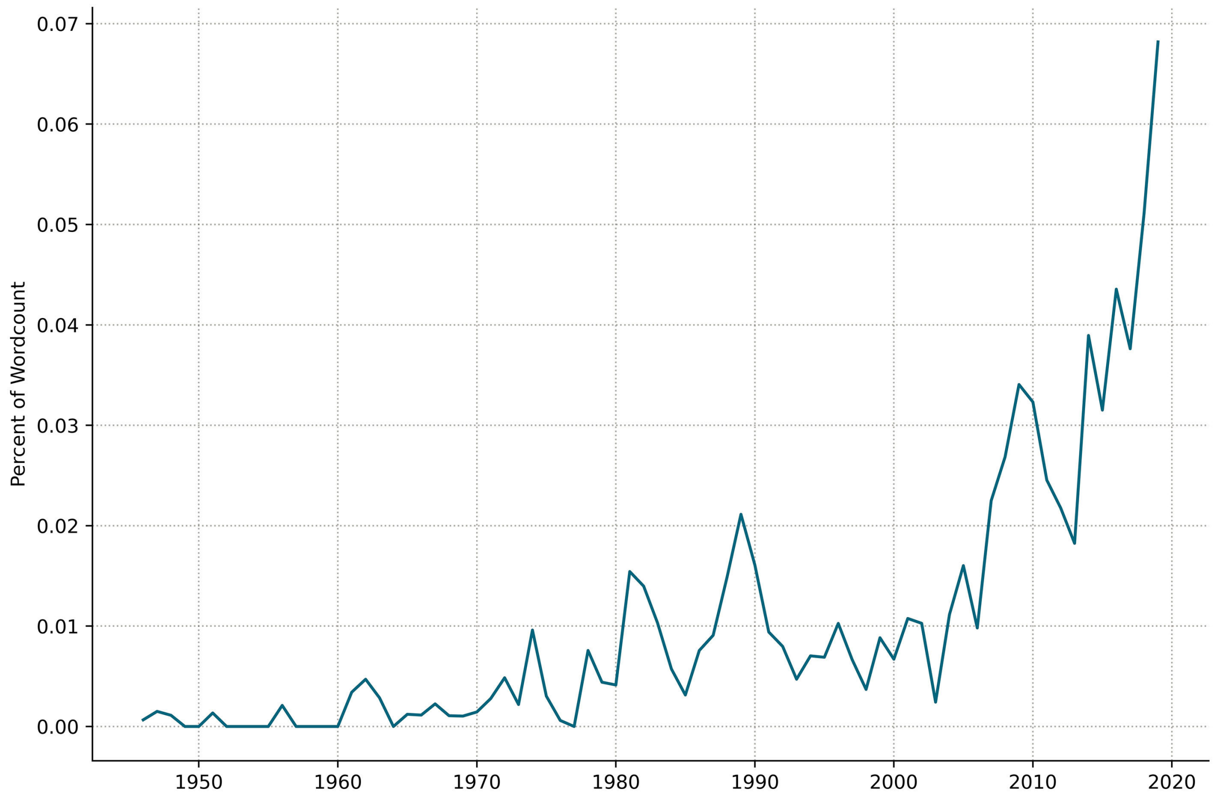
We take the relative wordcount by year to construct a timeline of the use of language terms. We also streamline this by only counting the three most used of our list of climate terms in a given year. This figure changes over time (see Figure 10 in the annex) and thus allows us to capture the use of trend climate language in a given period, rather than imposing current fashions in terminology backwards.

To summarise, our headline figure to track awareness of climate issues at UNGA is obtained by taking a wordcount of the three most commonly used climate terms in a given year as a percentage of all words used in that year (minus filler/non meaning words).

Results and cut-off decision

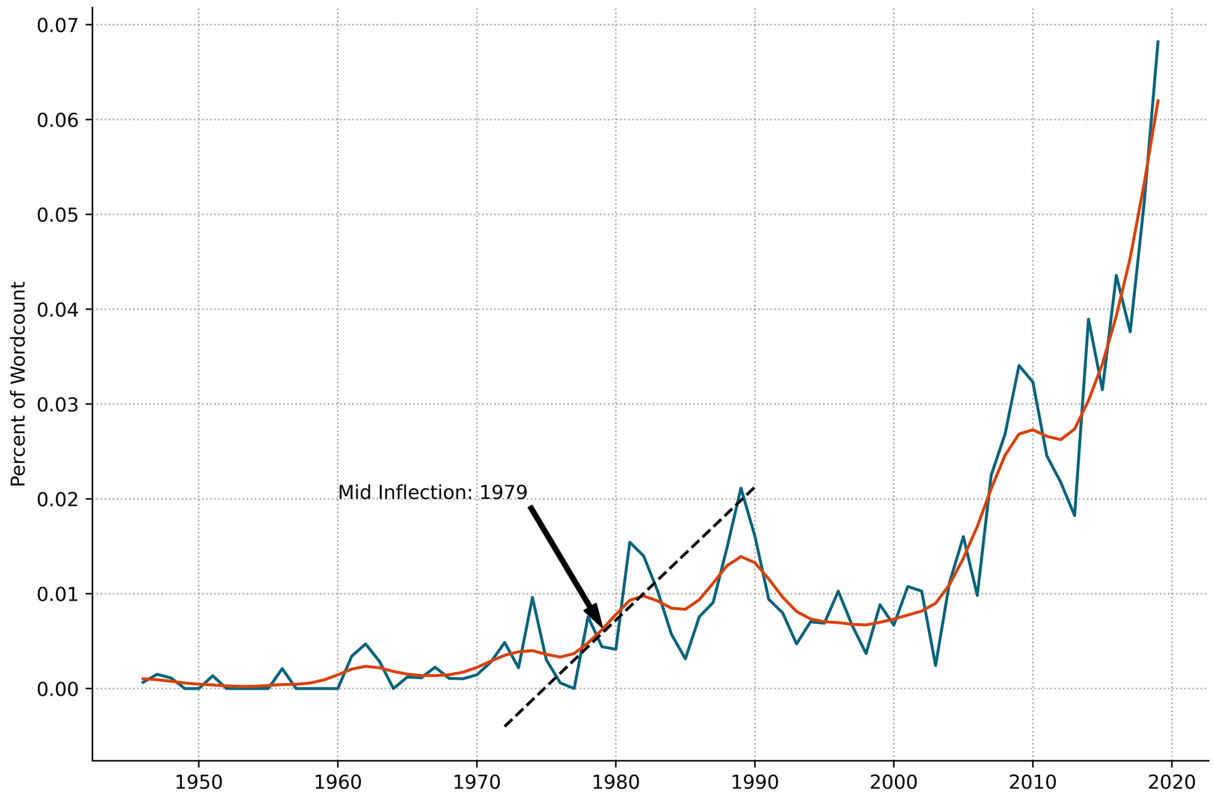
The results are shown in Figure 4. There are a few spikes, representing increased climate language use at the UN, where the cut-off point could be placed: 1961, 1974, and frequent upticks from 1981 onwards.

Figure 4. Count of three most common climate terms as % of total wordcount



What we want to capture, however, is not a burst of sudden concern followed by the issue falling off the radar, but a sustained rise in language use that is reflective of a growing consciousness of the issue. Rather than look for a spike, therefore, we look for an inflection point, where the trend growth in the use of these terms turns upwards and continues to increase. Figure 5 shows that this is somewhere between 1977 and 1980. After a spike in 1989 (coinciding with the establishment of the IPCC) there is a falloff in the trend, but as by this point the IPCC had already been established, our point must precede that date. Taking the middle point of the earlier inflection, we take the year 1979 as our cut-off point.

Figure 5. Inflection in trend curve



Conclusion on cut off for use in liability estimates

We conclude that we should include a cut-off point at 1979 in the liability estimates; that is, we set the price of carbon to zero before this year, reflecting a lack of societal awareness of the negative impact of carbon emissions. Whilst it could be argued that countries, or individuals, are responsible and liable for the impact of their actions on others regardless of intention, we take the—perhaps conservative—view that emissions from before countries were aware of their damage should not contribute to their liabilities.

This shift in awareness among leaders followed the first "World Climate Conference" in February 1979 and organised by the World Meteorological Organisation (WMO) which brought together scientists from a range of disciplines.[8]

Whilst awareness of emissions and their polluting impact clearly emerged in various quarters earlier in the 20th century, in our main scenario we have chosen 1979 as the cut-off, denoting the point when international policymakers could not claim ignorance of this issue. This ignores around 35 percent of global emissions. Again, we recognise that this produces

[8] For more details see https://public.wmo.int/en/bulletin/history-climate-activities.

a conservative estimate[9] (see the high social cost scenario in Table 5 for an alternative), and also reduces both the absolute responsibility of early industrialisers like the UK, Germany, and the US and their relative share of the current global liability.

Results

Main scenario

The previous sections outline how we arrive at the key parameters for the model: a carbon cost of $51 per tonne emitted in 2020, historic prices proxied by reducing current prices at a rate of 3 percent per year, the discount rate, and a liability cut-off in 1979. We now present the results produced by the model using these parameters for nine countries:

- US, China—the largest global economies and the largest cumulative carbon emitters
- UK, Germany—the largest European economies and both early industrialisers
- Four other BRICS economies[10]—as representatives of the large economies of the future
- Chile—as a middle-income country with relatively good environment credentials (e.g., the Commitment to Development Index (CDI) environment component)

We also present the results for OECD, EU, and BRICS groupings for reference. Results for all countries for which data exist are shown in Table 8 in the Annex. Before showing the calculated carbon liabilities in Table 4, we show the emissions profile of these countries and groupings in Table 3:

[9] See the high social cost scenario in Table 4 for an alternative.

[10] Brazil, Russia, India, China, and South Africa (Wilson & Purushothaman, 2006).

Table 3. CO_2 emissions for selected countries and groupings, 1751–2019

Country	Total (Mt)	Share of Total	Per Capita (tonnes)	Share of 2019 Emissions
World	**1,652,920**	**100.00%**	**215**	**100%**
China	219,986	13.31%	157	27.9%
United States	410,238	24.82%	1,250	14.5%
Russia	113,884	6.89%	789	4.6%
India	51,937	3.14%	38	7.2%
Germany	91,979	5.56%	1,106	1.9%
United Kingdom	77,836	4.71%	1,165	1.0%
South Africa	20,722	1.25%	354	1.3%
Brazil	15,125	0.92%	72	1.3%
Chile	2,822	0.17%	149	0.2%
OECD	940,590	56.90%	692	33.9%
EU-28	364,860	22.07%	709	9.0%
BRICS	421,655	25.51%	133	42.3%

Between the US and China, the two largest emitters, the US takes the largest share of historical emissions, but China's single year emissions in 2019 were a much larger share of the global total than were the US's. The BRICS economies' historical share of emissions has outpaced the EU's (largely due to China). The UK and Germany, despite having centuries of industrialisation behind them, have small shares of the cumulative global total of emissions.

The emissions per capita figure simply divides total cumulative emissions by today's population. It is oft noted that China is the world's largest emitter today, perhaps less commonly observed that its per capita share of carbon emissions (not shown here) is much lower than the second largest emitter, the US. Its per capita historical emissions are comparably even smaller. The UK and Germany's per capita historical emissions are similar to those of the US, which is not surprising as these were the first countries to industrialise.

When we apply the carbon pricing model discussed above to these emissions, using the main scenario of a carbon cost of $51 in 2020, discounted at 3 percent annually and with a cut-off in 1979, we obtain the carbon liability figures in Table 4.[11]

[11] Figure 7 shows the historical accumulation of this liability, and how it would look were no cut-off implemented in 1979.

Table 4. Carbon liabilities (main scenario) for selected countries and groupings

Country	Liability ($bn)	Share of Total Debt	Liability per Capita	Liability/GNI
World	**34,218**	**100%**	**4,459**	**39.0%**
China	7,096	20.7%	5,077	49.8%
United States	6,505	19.0%	19,818	30.0%
Russia	2,081	6.1%	14,412	126.4%
India	1,621	4.7%	1,186	57.1%
Germany	1,058	3.1%	12,729	26.7%
United Kingdom	618	1.8%	9,242	22.2%
South Africa	485	1.4%	8,288	142.1%
Brazil	416	1.2%	1,969	23.2%
Chile	70	0.2%	3,717	26.0%
OECD	15,242	44.5%	11,207	28.2%
EU-28	4,804	14.0%	9,340	26.0%
BRICS	11,698	34.2%	3,681	56.1%

The total global carbon liability is $34 trillion. This sounds enormous, but this is a liability built up over generations—even centuries—of emissions. Relative to the total global financial debt of around $289 trillion (World Bank, 2021a), it is an increment under 12 percent. For the total global economic growth fuelled by the energy consumption over this time, which has been effectively leveraged by not accounting for social cost, it is arguably surprising that the figure is this small.

The OECD carbon liability of around $15 trillion is roughly a third of its $49 trillion private pension assets (OECD, 2017). The per head costs of climate damage to date (some $19,000 in the US) are also significant, but manageable—conceptually this is the per head payment to clear the entire debt of emissions since 1979, which might appear a good investment compared to the growth in living standards, driven by economic growth on the back of vast energy consumption, has achieved in that period.

Returning to the concept of the carbon cost, this is the value of pollution that wasn't paid for by the initial activity (and in our scenario, that occurred after countries fully understood the damage of their carbon burning actions). Countries could seek to repay for this damage over time. So, spread over the 80 years to 2100, the OECD's liability would equate to $190 billion per year, and part of that would be owed to itself. This provides an interesting reference point for the commitment for "developed countries" to mobilize (though not provide) $100 billion of climate finance per year through 2025 (UN, 2010), with the Paris Agreement endorsing that, and promising a new goal after 2025 "from a floor of USD 100 billion per year, taking into account the needs and priorities of developing countries." (UN, 2021).

Figure 7 suggests one way of thinking about the accumulation of liability. It shows carbon liability as a proportion of GNI since 1900 and demonstrates how pollution intensive have been countries' income growth pathways, or interpreted differently, it shows the degree to which countries have achieved a good "return" on the carbon costs they hypothetically incurred[12]—how much income growth they have bought on the back of these pollution costs.[13] Both vertical axes, left (income per capita) and right (liability per capita/income per capita), of these charts have the same scale for all countries to allow comparison. Note that these charts assume no liability cut-off, as the point is to compare growth against hypothetical historical liability through history. These charts suggest that the US and China's growth pathways are comparable in how pollution intensive they have been. South Africa's and Russia's have been very pollution intensive, accumulating large carbon liabilities per person during income growth. The US, Germany, and the UK have, in later years, decoupled pollution from growth to some degree, experiencing high income per capita growth without large increases in carbon liability.

Another implication is that whilst OECD countries contributed over 40 percent of the liability under these assumptions, China also contributed over 20 percent. So, China—along with India and Russia, who each contributed close to 5 percent—should also be contributing to any successor climate finance commitments.

Although China's share of historical emissions is lower than the US's, the bulk of its emissions occurred more recently, when existing atmospheric carbon levels meant that the marginal damage—and thus carbon cost—of an additional tonne of emitted carbon was higher. Where a country's share of the total liability exceeds its share of total historical emissions, this is because its emissions have occurred more recently and vice versa. This can also be seen by comparing these two figures for the OECD and BRICS groupings

This is a development challenge of employing this model for calculating carbon liability: it inevitably favours early emitters at the expense of late industrialisers like China. However, later emissions being more damaging than earlier ones is a technical argument which stands even if it has unequitable consequences and must be acknowledged in any historical pricing of carbon. Rather than forcing a false equivalence into the pricing methodology, the political argument must be adapted in response to this technical argument, not the other way round. Alternative methods for making concessions in carbon liabilities on countries should be considered, rather than incorporating these in the way liabilities are calculated.

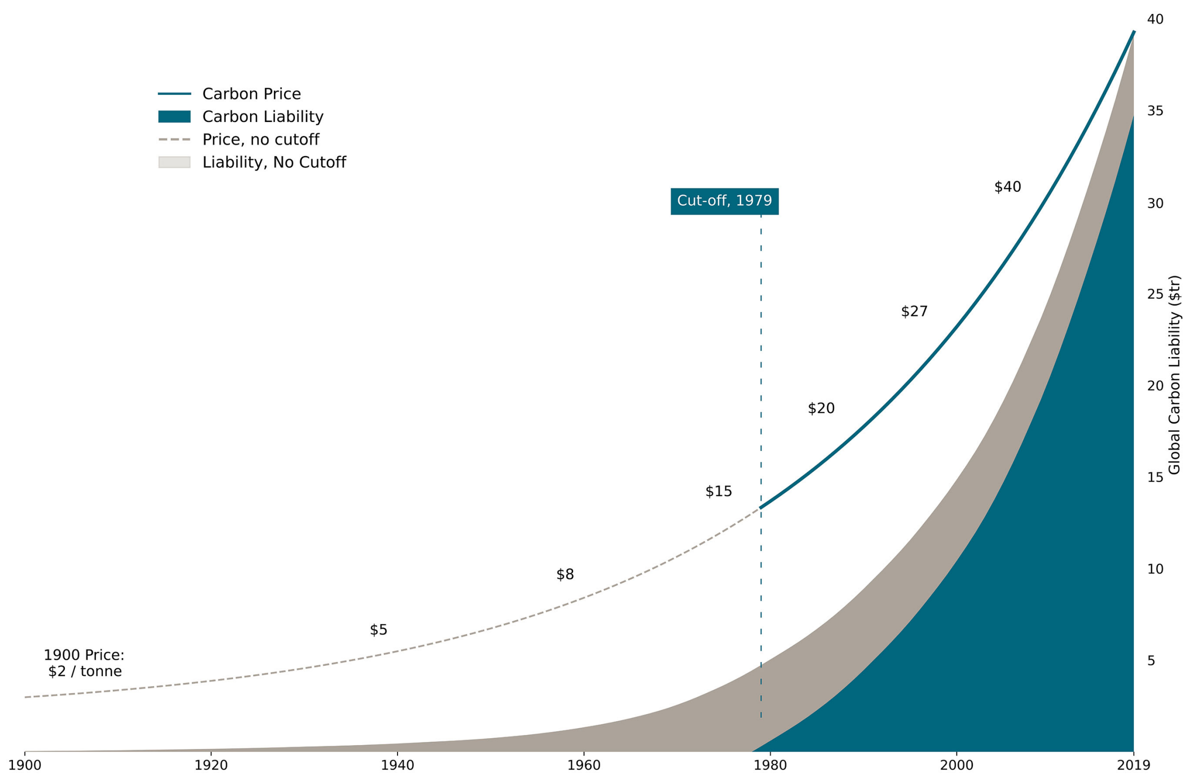
Figure 8 suggest one such option. Whereas the figures and charts so far have focused on the technical results of the model, this chart visualises the political aspects and the arguments on equity and capacity. The horizontal axis shows countries' shares of the total global liability. If this is relatively small, then it may be politically easier to negotiate concessions as percentage reductions in these countries' liabilities (if these liabilities were used as the basis of climate finance commitments, it would have only limited impact the global total given their relatively small share). The vertical axis shows carbon liability per head divided by income per head. The principle of common but differentiated responsibilities recognises capacity to pay as critical in raising climate finance and this is one way of considering that. Any sovereign liability ultimately gets translated into tax liabilities of citizens. If a country

[12] They would have incurred such costs had markets fully incorporated the cost of carbon at the time of emission.
[13] Of course, there are a myriad of other causal factors in economic growth. This thought exercise seeks to assess whether, in the broader context of these, incurred carbon liabilities were good investments.

gets a high figure on the vertical axis here, it means that the carbon liability is a heavier burden on citizens, or at least on taxpaying citizens (which in a developing country is the fraction of workers engaged in the formal sector and thus, being a fraction, are shouldering a disproportionate burden of any formal liabilities). A carbon liability would impact people in these countries more and be politically difficult to negotiate. Finally, income is an important factor in negotiating concessions. The wealthier people are—represented by the size of the bubbles in Figure 8—the more able citizens are to tolerate an increased tax burden without it impacting on their ability to provide themselves with essentials. Set against this, however, would be the carbon intensity of the country's energy mix. A country whose energy profile is very dirty, such as South Africa, would find it politically difficult to demand concessions on its liability for historical emissions while it continues to burn dirty fuels. This stylistic framework is just one way of thinking about how the distribution of the liabilities could be negotiated and suggests that demonstrated commitment to a clean energy transition, wealth, burden on citizens, and share of the global burden might all be factors to consider.

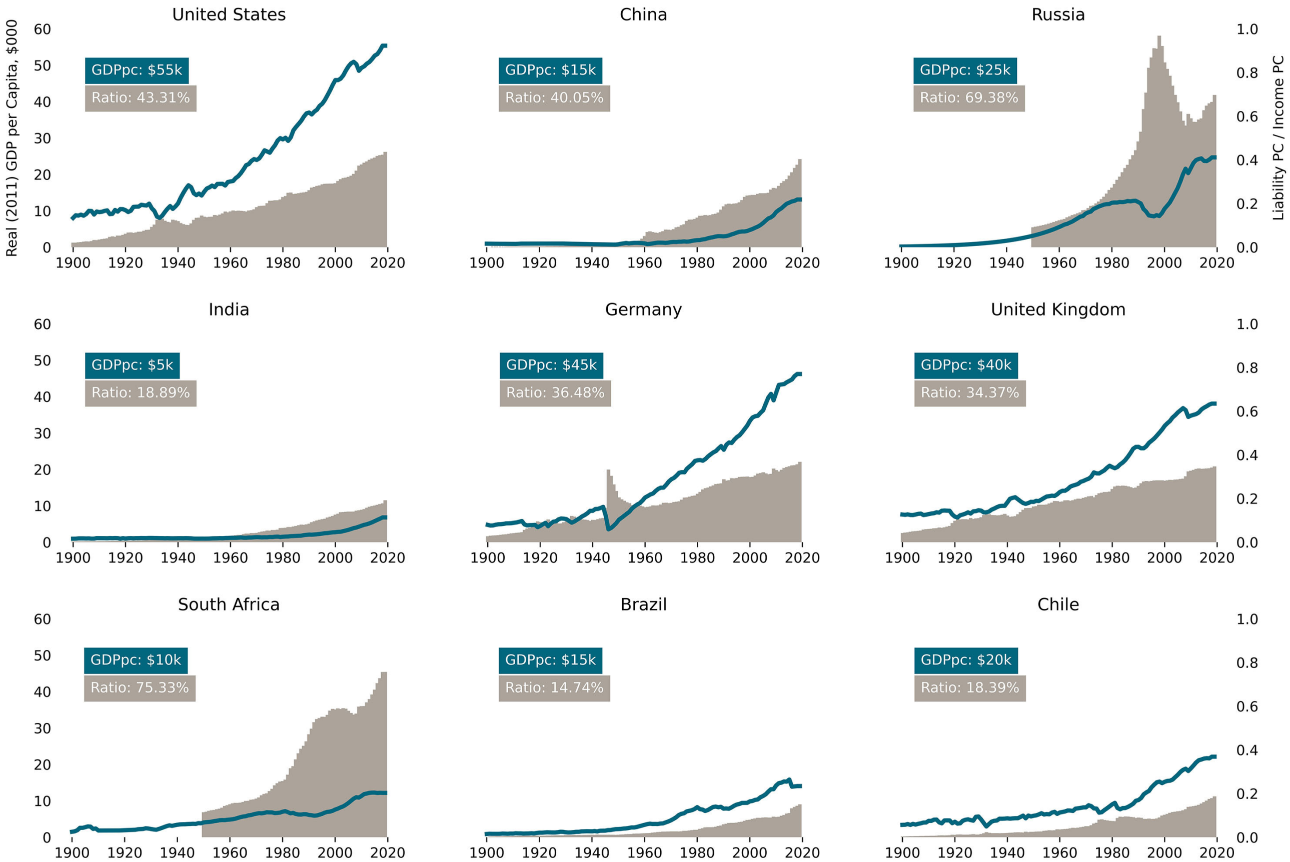
One question might be: if all countries owe a liability, both to themselves and others, why can we not net off and set the benchmark to be zero for the poorest countries. But this would be to misunderstand the nature of the liability. It is not to the public purses of individual countries, but a historical liability to the planet for damage already done and valued. The liability would go some way towards fixing some damage and preparing societies and economies to adapt the remainder, so that the cost to societies is not too great.

Figure 6. Carbon cost and global liability, with and without cut-off



Source: Authors' Calculations.

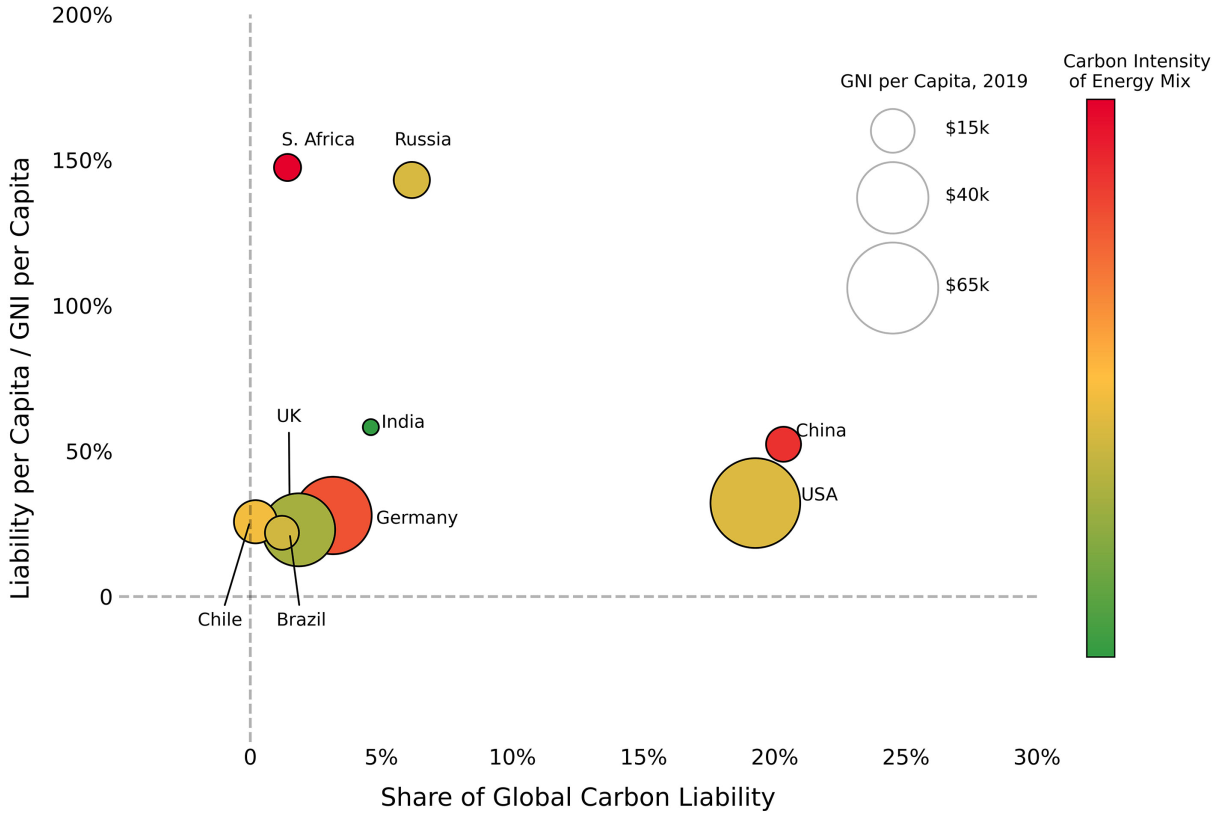
Figure 7. Carbon liability vs. income—cumulative pollution cost as a share of GNI (grey) vs GNI per capita (teal), main scenario, selected countries



Source: Authors' Calculations.

Note: These calculations assume no cut-off in 1979 to permit comparisons against secular income growth.

Figure 8. Share of global liability vs. burden on citizens' incomes



Source: Authors' Calculations.

Alternative scenarios

The results above relate to the main scenario of a carbon cost of $51 in 2020. Historic prices are proxied by reducing current prices at a rate of 3 percent per year, the discount rate, and with a 1979 liability cut-off. Adjusting these assumptions has substantial impacts on the results. We present two other scenarios here, and further scenarios in Annex A.[14]

- **Low social cost scenario**: The impact on the planet of carbon emissions is relatively minor compared to the main scenario, and liabilities are thus accumulated at a lower level.
- **High social cost scenario**: The impact on the planet is much higher than in the main scenario and this is reflected in a higher carbon cost.

The low social cost scenario assumes carbon emissions to be relatively less harmful than the main scenario, and with a lower liability attached to historical emissions. It sets the 2020 carbon cost at $14 per tonne of CO_2, as shown in the first row of Table 2. Prices in earlier

[14] Note that we also publish the model, so that the interested reader can experiment with their own scenarios.

periods are calculated by reducing this price by 5 percent per year. The high social cost scenario assumes carbon emissions are more serious than in the main scenario. The price per tonne in 2020 is $76, and this is reduced by 2.5 percent per year relative to 2020 in previous years. This scenario also removes the liability cut off, meaning that all historic emissions incur liabilities, not just those since 1979.

Before discussing the results, it is illustrative to outline the implications of these scenario choices. In the low social cost scenario, the price of carbon is reduced more steeply as we travel back in time. This favours early emitters such as the UK, Germany, and the US. So even as the share of total emissions does not change, the distribution of the total carbon liability shifts more towards later industrialisers, such as China. In contrast, in the high social cost scenario, the price is not reduced as much per year through history, so early industrialisers pay a higher relative price for their emissions and the distribution of the liability shifts more towards these countries. In this scenario, the absence of a cut-off point also adversely affects early industrialisers, as they are now liable for all of their historic emissions.

The results of these scenarios are shown in Table 5. Under the lowest case scenario, global liability is just over a fifth of the value under the main scenario at $7.2 trillion. This is roughly $943 per person, although the distribution would obviously not be uniform. US liability per capita, at just over $4,000, is about 6 percent of GNI per capita (which is roughly $65k in the US). Chinese liability per head is close to $1,000 and India's is just $267.

In the highest case scenario, global debt is 185 percent of that under the main scenario at over $54 trillion. This is almost three quarters of global annual income and represents a debt of over $8,000 per person. The US liability per person would be over 60 percent of US GNI per capita. For China, the ratio would be 80 percent and for Russia it would be 260 percent.

These huge figures would clearly be politically almost impossible to even suggest in most policy circles, yet some climate experts would suggest they are still too low. The IWG includes a 95th percentile carbon cost of $139. This means that of all of the simulations of damages of carbon emissions costed by IWG using IAMs, around 5 percent of them suggest this price or higher is needed to capture the impact of carbon emissions on the planet. To capture the risk of climate catastrophe, a price this high may be justified. Such extremes may at the very least serve the purpose of framing the main scenario estimates and showing them to be moderate in context.

As a final point on the scenario analysis, we present two alternative scenarios in the annex where the carbon cost is constant. This is somewhat different to the modelling here as it is simply multiplying cumulative carbon emissions by a scalar, the constant carbon cost.

Table 5. Carbon liabilities under the three scenarios

High Social Cost Scenario

Country	Liability ($bn)	Share of Total Debt	Liability per Capita	Liability/GNI
World	**63,466**	**100%**	**8,271**	**72.4%**
China	11,565	18.2%	8,274	81.2%
United States	13,279	20.9%	40,456	61.2%
Russia	4,153	6.5%	28,765	252.3%
India	2,656	4.2%	1,944	93.6%
Germany	2,435	3.8%	29,286	61.4%
United Kingdom	1,551	2.4%	23,202	55.8%
South Africa	868	1.4%	14,816	254.0%
Brazil	711	1.1%	3,369	39.7%
Chile	124	0.2%	6,555	45.8%
OECD	30,648	48.3%	22,536	56.7%
EU-28	10,359	16.3%	20,141	56.2%
BRICS	19,952	31.4%	6,278	95.6%

Main Scenario

Country	Liability ($bn)	Share of Total Debt	Liability per Capita	Liability/GNI
World	**34,218**	**100%**	**4,459**	**39.0%**
China	7,096	20.7%	5,077	49.8%
United States	6,505	19.0%	19,818	30.0%
Russia	2,081	6.1%	14,412	126.4%
India	1,621	4.7%	1,186	57.1%
Germany	1,058	3.1%	12,729	26.7%
United Kingdom	618	1.8%	9,242	22.2%
South Africa	485	1.4%	8,288	142.1%
Brazil	416	1.2%	1,969	23.2%
Chile	70	0.2%	3,717	26.0%
OECD	15,242	44.5%	11,207	28.2%
EU-28	4,804	14.0%	9,340	26.0%
BRICS	11,698	34.2%	3,681	56.1%

Low Social Cost Scenario

Country	Liability ($bn)	Share of Total Debt	Liability per Capita	Liability/GNI
World	**7,235**	**100%**	**943**	**8.3%**
China	1,595	22.1%	1,141	11.2%
United States	1,329	18.4%	4,049	6.1%
Russia	413	5.7%	2,861	25.1%
India	365	5.1%	267	12.9%
Germany	210	2.9%	2,523	5.3%
United Kingdom	122	1.7%	1,826	4.4%
South Africa	102	1.4%	1,737	29.8%
Brazil	90	1.2%	425	5.0%
Chile	15	0.2%	810	5.7%
OECD	3,114	43.0%	2,290	5.8%
EU-28	957	13.2%	1,861	5.2%
BRICS	2,565	35.5%	807	12.3%

Conclusion

This paper has presented an alternative framework for assessing climate finance obligations from all countries based on the liability for the unpaid costs of historical emissions.

One element of the climate negotiations relates to financing from "developed" to "developing" countries. Our estimates are broader in the sense that they relate to the damage caused globally, not just to developing countries. Still, we think that valuing the climate damage done to date is relevant, and this is a first cut of those calculations. Our main scenario suggests that OECD countries' liability is well above the current $100 billion goal for "mobilizing" climate finance, and several middle-income countries, notably China and Russia, also have liabilities that are large enough to imply they should make a contribution to a post-2025 climate finance target.

These results may seem a long way from the reality of climate negotiations. Still, they provide a contribution to the discussions, and one that quantifies in concrete terms how climate finance commitments may be calculated and how they may be framed to overcome some historical difficulties associated with the term "liability." Of course, the model provides technical results whereas in reality, political aspects must also be addressed, as well as further research. This paper also suggests some ways of thinking about concessions that take into account capacity.

On the technical level, if China, the US, or the UK don't think this is a fair assessment of liability, is that because they disagree that countries should be responsible for the damage they have done? And if they accept that, is it that they disagree about the cost of carbon and how it changes over time, about the discount rate, or about *when* countries should take responsibility?

We welcome feedback both on the methodology and the scenarios we've chosen. The model we use to calculate these results is available for download here (https://www.cgdev.org/sites/default/files/robinson-et-al-climate-liability-model.zip), so that users can experiment with their own scenarios.

Technical annex

Annex A. Constant carbon cost scenario

The three scenarios presented in the main text all have in common a carbon cost that increases over time (that is, reduces for historic emissions). We feel this is the most plausible approach from an economics standpoint, in which a price is constructed based on its expected cost at the margin; the economic damage of a more recently emitted tonne is greater than an earlier emitted tonne reflecting that as atmospheric carbon accumulates, economics systems are already under greater stress from the effects of this.

However, we acknowledge that such a marginal approach may not be the most appropriate from a climate science perspective where any emissions contribute similarly to the stock. To address this, we present two alternative scenarios here that have a constant carbon cost. The assumption would be that the damage function is linear, or that each tonne of carbon emitted does as much damage as all other tonnes, whenever they occurred. The carbon cost is not discounted therefore and is the same throughout history. This is effectively equivalent to multiplying a country's cumulative carbon emissions by a scalar, the carbon cost, so is not modelling a scenario in the sense of the other three presented in the main text, in which damage is implicitly a variable, not an exogenous given.

We present two constant price scenarios, both using the carbon cost of the main scenario ($51), both having 0 percent discount rate, but with one having a 1979 liability cut-off and one having no such cut-off. The results are shown below (Table 6).

Table 6. Liabilities with a constant carbon price, selected countries

No Cut-off

Country	Liability ($bn)	Share of Total Debt	Liability per Capita	Liability/GNI
World	**84,299**	**100%**	**10,986**	**96.1%**
China	11,219	13.3%	8,027	78.8%
United States	20,922	24.8%	63,741	96.5%
Russia	5,808	6.9%	40,230	352.8%
India	2,649	3.1%	1,938	93.3%
Germany	4,691	5.6%	56,427	118.3%
United Kingdom	3,970	4.7%	59,395	142.9%
South Africa	1,057	1.3%	18,048	309.4%
Brazil	771	0.9%	3,655	43.1%
Chile	144	0.2%	7,594	53.1%
OECD	47,970	56.9%	35,273	88.8%
EU-28	18,608	22.1%	36,178	100.9%
BRICS	21,504	25.5%	6,766	103.1%

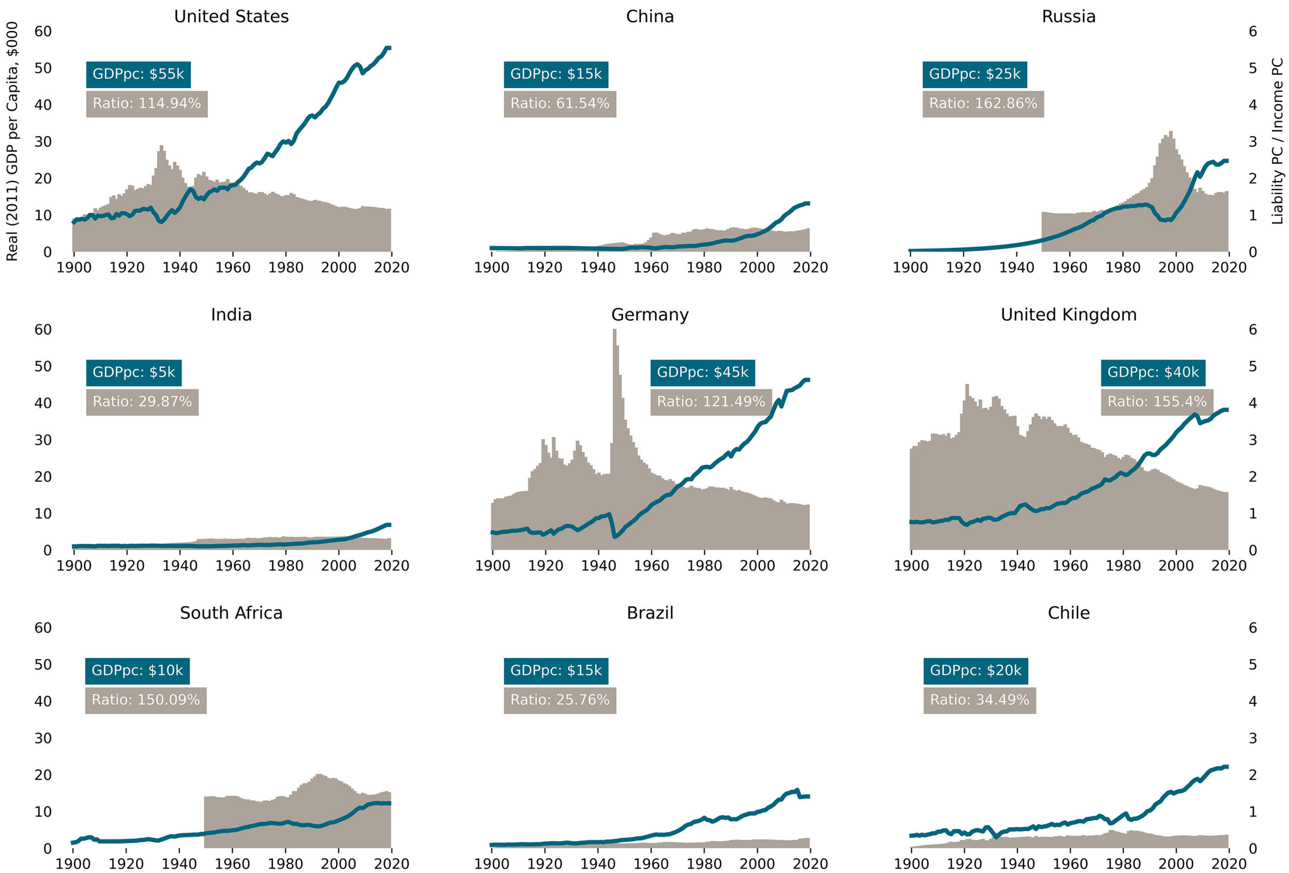
Cut-off in 1979

Country	Liability ($bn)	Share of Total Debt	Liability per Capita	Liability/GNI
World	**55,697**	**100%**	**7,258**	**63.5%**
China	10,249	18.4%	7,332	71.9%
United States	11,178	20.1%	34,055	51.5%
Russia	3,798	6.8%	26,308	230.7%
India	2,332	4.2%	1,707	82.2%
Germany	1,924	3.5%	23,147	48.5%
United Kingdom	1,122	2.0%	16,782	40.4%
South Africa	799	1.4%	13,650	234.0%
Brazil	650	1.2%	3,080	36.3%
Chile	108	0.2%	5,681	39.7%
OECD	26,223	47.1%	19,282	48.5%
EU-28	8,635	15.5%	16,788	46.8%
BRICS	17,829	32.0%	5,610	85.5%

Predictably, a constant carbon cost has a much greater impact on early emitters. Whereas with a declining carbon cost, emissions in the distant past are largely insignificant, with a constant price, they become a lot more expensive. Comparing the results with a 1979 cut-off demonstrate this. With a constant carbon cost and a cut-off, the UK's carbon liability of $1.1 trillion is 1.8x higher than in the main scenario ($648 billion). But if that cut-off is dropped and the carbon cost is constant, the liability of $3,9 trillion is 6.4x higher than in the main scenario amount.

On the following page, we produce Figure 9, which replicates Figure 7 for the above scenarios. Recall, this chart is intended to show the carbon pollution cost and income growth, or whether countries have achieved a good 'return' on the carbon liabilities they would have incurred had the market priced these. This version of the chart does this analysis for a constant carbon cost. Note that while all axes have the same scale, as previously, the second vertical axis, liability per capita/income per capita, now has the scale 0-5 instead of 0-1 as before, because the liabilities accumulated are orders of magnitude larger if carbon costs are constant. Russia and South Africa still have the most pollution intensive growth pathways, but now the UK, Germany, and the US are comparable to them. China's pathway has been a little over half as pollution intensive as has been the US's, though it is still considerably more so than that of the fellow middle-income countries, Brazil, India, and Chile. Germany and the UK accumulated tremendous carbon liabilities per head up to the 1960s, after which, income growth outstripped carbon liability growth, suggesting a decoupling of growth from pollution. Analysing the potential causes of this is beyond present scope, but some possibilities might include the faster growth of services relative to industry, and an increased incidence of importing emission intensive products rather than producing them domestically.

Figure 9. Carbon liability vs. income—Cumulative pollution cost as a share of GNI (grey) vs. GNI per Capita (teal). Constant carbon cost, selected countries

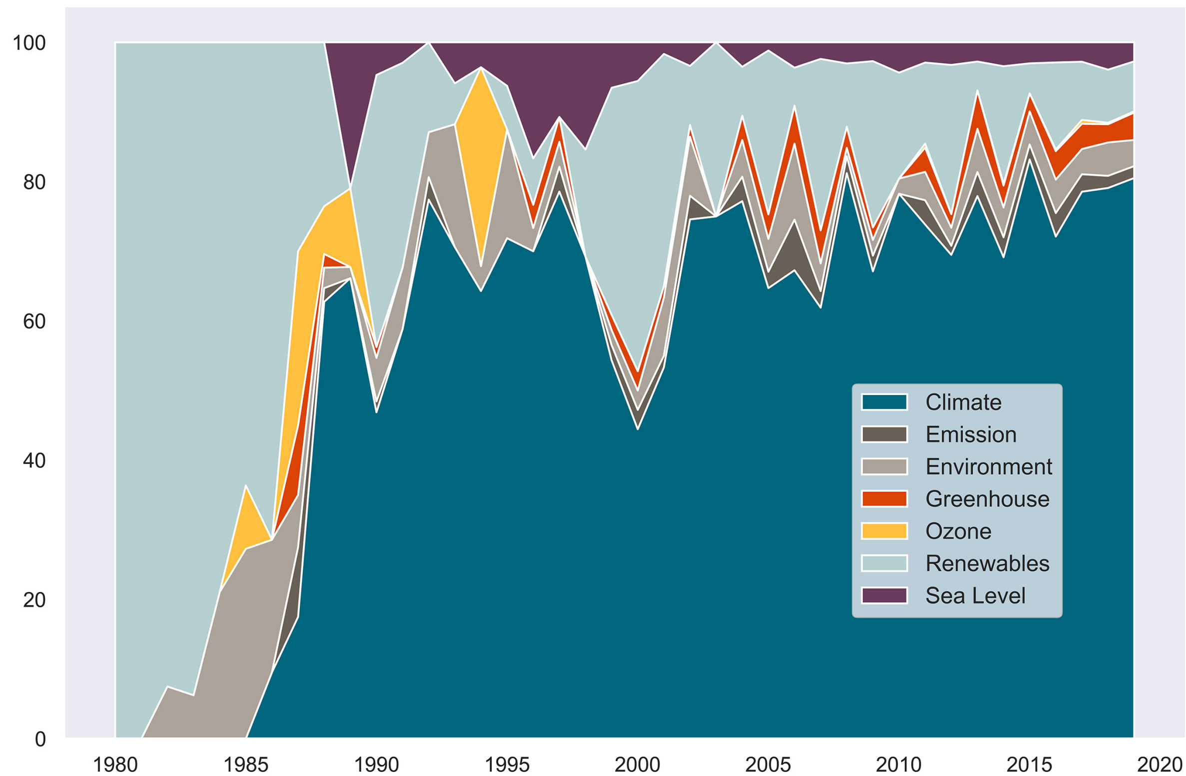


Source: Authors' Calculations.

Annex B. Textual analysis detail

The changing concern of the UN on climate issues is shown in Figure 10. The ozone layer, a matter of small concern today, for example, spiked up a few times in the 1980s and early 1990s.

Figure 10. Changing trends in climate terminology at UNGA



Source: Authors' Calculations.

The full breakdown of the three most common climate terms in each year of the analysis is shown in Table 7.

Table 7. Three most common climate terms used in UNGA proceedings, 1946:2019

Year	1st Most Common	2nd	3rd
2019	Climate (471)	Renewables (42)	Weather (37)
2018	Climate (363)	Renewables (35)	Weather (23)
2017	Climate (282)	Renewables (30)	Weather (17)
2016	Climate (300)	Renewables (52)	Environment (20)
2015	Climate (193)	Weather (12)	Environment (11)
2014	Climate (242)	Renewables (59)	Environment (15)
2013	Climate (113)	Environment (9)	Greenhouse (8)
2012	Climate (107)	Renewables (33)	Weather (8)
2011	Climate (127)	Renewables (20)	Environment (7)
2010	Climate (36)	Renewables (7)	Sea Level (2)
2009	Climate (149)	Renewables (53)	Sea Level (6)
2008	Climate (134)	Renewables (15)	Weather (8)
2007	Climate (78)	Renewables (31)	Greenhouse (6)
2006	Climate (37)	Weather (8)	Environment (6)
2005	Climate (55)	Renewables (20)	Weather (8)
2004	Climate (44)	Weather (11)	Renewables (4)
2003	Climate (3)	Renewables (1)	
2002	Climate (44)	Renewables (5)	Environment (5)
2001	Climate (32)	Renewables (20)	Environment (5)
2000	Climate (16)	Renewables (15)	Sea Level (2)
1999	Climate (25)	Renewables (15)	Sea Level (3)
1998	Climate (9)	Renewables (2)	Sea Level (2)
1997	Climate (22)	Sea Level (3)	Environment (1)
1996	Climate (21)	Sea Level (5)	Renewables (2)
1995	Climate (23)	Environment (5)	Renewables (2)
1994	Climate (18)	Ozone (8)	Environment (1)
1993	Climate (12)	Environment (3)	Renewables (1)
1992	Climate (24)	Renewables (4)	Environment (2)
1991	Climate (20)	Renewables (10)	Environment (3)
1990	Climate (30)	Renewables (25)	Environment (4)
1989	Climate (41)	Sea Level (13)	Ozone (7)
1988	Climate (64)	Renewables (24)	Ozone (7)
1987	Renewables (12)	Ozone (10)	Climate (7)
1986	Renewables (15)	Environment (4)	Climate (2)
1985	Renewables (7)	Environment (3)	Ozone (1)
1984	Renewables (15)	Environment (4)	
1983	Renewables (30)	Environment (2)	Weather (1)
1982	Renewables (37)	Environment (3)	
1981	Renewables (40)		
1980	Renewables (11)		
1979	Renewables (11)		

Year	1st Most Common	2nd	3rd
1978	Renewables (15)		
1977			
1976	Weather (1)		
1975	Climate (2)	Environment (2)	Weather (1)
1974	Climate (10)	Weather (4)	Environment (1)
1973	Weather (2)	Environment (1)	
1972	Environment (5)		
1971	Environment (4)		
1970	Environment (1)	Weather (1)	
1969	Environment (1)		
1968	Environment (1)		
1967	Environment (1)	Weather (1)	
1966	Environment (1)		
1965	Environment (1)		
1964			
1963	Weather (2)		
1962	Environment (2)	Weather (1)	
1961	Climate (1)	Weather (1)	
1960			
1959			
1958			
1957			
1956	Climate (1)		
1955			
1954			
1953			
1952			
1951	Climate (1)		
1950			
1949			
1948	Emission (1)		
1947	Climate (1)		
1946	Renewables (1)		

Annex C. Full country results

Table 8. Full country results, emissions & carbon liability (in main scenario)

Country	Cumulative Emissions				Liability			
	Total (Mt)	Share of Total	Per Capita (tonnes)	Share of 2019 Emissions	Liability ($bn)	Share of Total Debt	Liability per Capita	Liability/ GNI
World	**1,652,920**	**100%**	**215**	**100%**	**34,218**	**100%**	**4,459**	**39.0%**
Afghanistan	181	0.01%	5	0.03%	5	0.02%	144	27.9%
Albania	282	0.02%	99	0.02%	6	0.02%	1,943	36.8%
Algeria	4,445	0.27%	103	0.47%	129	0.38%	3,003	77.5%
Angola	711	0.04%	22	0.10%	24	0.07%	756	29.6%
Antigua and Barbuda	21	0.00%	217	0.00%	0	0.00%	4,413	27.1%
Argentina	8,289	0.50%	184	0.49%	185	0.54%	4,123	43.3%
Armenia	687	0.04%	232	0.02%	9	0.03%	2,966	63.1%
Aruba	75	0.00%	709	0.00%	2	0.00%	15,516	57.2%
Australia	18,182	1.10%	717	1.13%	421	1.23%	16,613	31.2%
Austria	5,446	0.33%	613	0.19%	79	0.23%	8,945	17.8%
Azerbaijan	2,595	0.16%	259	0.11%	46	0.13%	4,591	100.1%
Bahamas	164	0.01%	421	0.01%	2	0.01%	6,406	19.0%
Bahrain	892	0.05%	543	0.09%	26	0.08%	15,811	71.5%
Bangladesh	1,479	0.09%	9	0.28%	51	0.15%	311	16.0%
Barbados	54	0.00%	187	0.00%	1	0.00%	4,876	27.8%
Belarus	5,229	0.32%	552	0.17%	86	0.25%	9,055	140.0%
Belgium	12,460	0.75%	1,085	0.27%	136	0.40%	11,835	25.2%
Belize	18	0.00%	47	0.00%	1	0.00%	1,322	30.0%
Benin	112	0.01%	9	0.02%	4	0.01%	342	28.3%
Bermuda	28	0.00%	445	0.00%	1	0.00%	10,359	8.7%
Bhutan	17	0.00%	23	0.00%	1	0.00%	866	28.7%
Bolivia	505	0.03%	44	0.06%	15	0.04%	1,331	38.2%
Bosnia & Herz.	935	0.06%	283	0.07%	21	0.06%	6,292	103.1%
Botswana	143	0.01%	62	0.02%	5	0.01%	2,080	28.3%
Brazil	15,125	0.92%	72	1.28%	416	1.21%	1,969	23.2%
Brunei	348	0.02%	803	0.02%	8	0.02%	17,539	54.9%
Bulgaria	3,791	0.23%	543	0.12%	67	0.20%	9,600	99.3%
Burkina Faso	60	0.00%	3	0.01%	2	0.01%	103	13.7%
Burundi	12	0.00%	1	0.00%	0	0.00%	31	11.7%
Cambodia	144	0.01%	9	0.04%	5	0.02%	326	21.1%
Cameroon	204	0.01%	8	0.02%	6	0.02%	231	15.6%
Canada	33,114	2.00%	881	1.58%	638	1.87%	16,983	37.1%
Cape Verde	13	0.00%	23	0.00%	0	0.00%	751	21.3%
Central African Rep.	12	0.00%	3	0.00%	0	0.00%	62	12.4%
Chad	25	0.00%	2	0.00%	1	0.00%	49	6.9%
Chile	2,822	0.17%	149	0.23%	70	0.21%	3,717	26.0%
China	219,986	13.31%	157	27.92%	7,096	20.74%	5,077	49.8%

Country	Cumulative Emissions				Liability			
	Total (Mt)	Share of Total	Per Capita (tonnes)	Share of 2019 Emissions	Liability ($bn)	Share of Total Debt	Liability per Capita	Liability/ GNI
World	**1,652,920**	**100%**	**215**	**100%**	**34,218**	**100%**	**4,459**	**39.0%**
Colombia	3,341	0.20%	66	0.28%	82	0.24%	1,638	26.3%
Comoros	5	0.00%	6	0.00%	0	0.00%	176	12.8%
Congo	75	0.00%	14	0.01%	2	0.01%	407	23.0%
Costa Rica	247	0.01%	49	0.02%	7	0.02%	1,423	12.3%
Croatia	1,085	0.07%	267	0.05%	24	0.07%	5,818	39.5%
Cuba	1,613	0.10%	142	0.07%	33	0.10%	2,923	36.8%
Cyprus	287	0.02%	239	0.02%	8	0.02%	6,561	32.8%
Czechia	11,885	0.72%	1,114	0.28%	155	0.45%	14,554	66.0%
Congo, DRC	189	0.01%	2	0.01%	3	0.01%	33	5.8%
Denmark	4,057	0.25%	697	0.09%	60	0.18%	10,329	16.7%
Djibouti	19	0.00%	19	0.00%	0	0.00%	491	14.8%
Dominica	5	0.00%	65	0.00%	0	0.00%	2,002	25.1%
Dominican Republic	727	0.04%	68	0.08%	22	0.06%	2,005	25.4%
Ecuador	1,174	0.07%	68	0.11%	35	0.10%	1,987	33.1%
Egypt	6,143	0.37%	61	0.68%	187	0.55%	1,860	63.9%
El Salvador	225	0.01%	35	0.02%	6	0.02%	970	24.4%
Equatorial Guinea	131	0.01%	97	0.02%	5	0.01%	3,653	59.5%
Eritrea	17	0.00%	5	0.00%	1	0.00%	183	28.7%
Estonia	1,511	0.09%	1,139	0.04%	25	0.07%	18,612	80.3%
Eswatini	40	0.00%	35	0.00%	1	0.00%	985	28.1%
Ethiopia	244	0.01%	2	0.04%	8	0.02%	72	8.5%
Faeroe Islands	30	0.00%	615	0.00%	1	0.00%	15,397	24.9%
Fiji	53	0.00%	59	0.01%	1	0.00%	1,566	27.6%
Finland	3,151	0.19%	571	0.11%	66	0.19%	11,920	24.3%
France	38,258	2.31%	571	0.89%	466	1.36%	6,945	16.8%
French Polynesia	28	0.00%	100	0.00%	1	0.00%	2,768	22.4%
Gabon	254	0.02%	117	0.01%	6	0.02%	2,701	37.8%
Gambia	14	0.00%	6	0.00%	0	0.00%	176	23.0%
Georgia	1,041	0.06%	280	0.03%	13	0.04%	3,561	77.7%
Germany	91,979	5.56%	1,106	1.93%	1,058	3.09%	12,729	26.7%
Ghana	351	0.02%	12	0.04%	10	0.03%	345	16.0%
Greece	4,023	0.24%	375	0.18%	103	0.30%	9,591	50.5%
Greenland	29	0.00%	514	0.00%	1	0.00%	10,454	28.8%
Grenada	8	0.00%	70	0.00%	0	0.00%	2,125	21.8%
Guatemala	424	0.03%	26	0.06%	13	0.04%	759	16.7%
Guinea	81	0.00%	6	0.01%	2	0.01%	173	18.1%
Guinea-Bissau	10	0.00%	5	0.00%	0	0.00%	137	18.3%
Guyana	98	0.01%	125	0.01%	2	0.01%	2,705	41.3%
Haiti	76	0.00%	7	0.01%	2	0.01%	201	15.8%

Country	Cumulative Emissions				Liability			
	Total (Mt)	Share of Total	Per Capita (tonnes)	Share of 2019 Emissions	Liability ($bn)	Share of Total Debt	Liability per Capita	Liability/ GNI
World	**1,652,920**	**100%**	**215**	**100%**	**34,218**	**100%**	**4,459**	**39.0%**
Honduras	250	0.02%	26	0.03%	8	0.02%	792	33.3%
Hong Kong	1,589	0.10%	212	0.11%	45	0.13%	5,934	11.6%
Hungary	4,970	0.30%	509	0.13%	72	0.21%	7,338	45.1%
Iceland	149	0.01%	412	0.01%	4	0.01%	9,756	14.3%
India	51,937	3.14%	38	7.18%	1,621	4.74%	1,186	57.1%
Indonesia	13,498	0.82%	50	1.69%	412	1.21%	1,524	38.0%
Iran	18,280	1.11%	220	2.14%	532	1.55%	6,413	116.5%
Iraq	4,444	0.27%	113	0.61%	131	0.38%	3,337	56.3%
Ireland	2,189	0.13%	443	0.10%	46	0.13%	9,299	14.9%
Israel	2,339	0.14%	258	0.18%	65	0.19%	7,168	16.5%
Italy	24,380	1.47%	404	0.93%	496	1.45%	8,227	24.5%
Jamaica	445	0.03%	151	0.02%	10	0.03%	3,444	63.3%
Japan	64,585	3.91%	512	3.04%	1,411	4.12%	11,178	26.8%
Jordan	675	0.04%	67	0.07%	21	0.06%	2,101	47.7%
Kazakhstan	13,308	0.81%	719	0.86%	277	0.81%	14,966	174.3%
Kenya	449	0.03%	9	0.05%	12	0.04%	232	13.0%
Kiribati	2	0.00%	17	0.00%	0	0.00%	463	14.3%
Kuwait	2,850	0.17%	677	0.30%	81	0.24%	19,355	51.1%
Kyrgyzstan	854	0.05%	132	0.03%	12	0.04%	1,902	156.7%
Laos	154	0.01%	21	0.09%	6	0.02%	905	36.6%
Latvia	759	0.05%	397	0.02%	12	0.03%	6,226	35.4%
Lebanon	710	0.04%	104	0.08%	20	0.06%	2,986	40.1%
Lesotho	60	0.00%	28	0.01%	2	0.01%	982	74.4%
Liberia	52	0.00%	11	0.00%	1	0.00%	194	35.3%
Libya	2,025	0.12%	299	0.13%	54	0.16%	8,003	102.3%
Liechtenstein	6	0.00%	157	0.00%	0	0.00%	5,097	2.8%
Lithuania	1,390	0.08%	499	0.04%	21	0.06%	7,671	40.5%
Luxembourg	746	0.05%	1,204	0.03%	12	0.04%	19,593	26.7%
Macao	58	0.00%	90	0.01%	2	0.01%	2,699	3.4%
Madagascar	93	0.01%	3	0.01%	3	0.01%	93	18.5%
Malawi	49	0.00%	3	0.00%	1	0.00%	62	15.5%
Malaysia	5,735	0.35%	179	0.69%	188	0.55%	5,879	52.9%
Maldives	23	0.00%	43	0.00%	1	0.00%	1,624	17.0%
Mali	53	0.00%	3	0.01%	2	0.01%	92	10.8%
Malta	103	0.01%	205	0.00%	3	0.01%	5,264	19.1%
Marshall Islands	3	0.00%	56	0.00%	0	0.00%	2,002	41.7%
Mauritania	73	0.00%	16	0.01%	2	0.01%	497	30.0%
Mauritius	112	0.01%	89	0.01%	4	0.01%	2,789	22.4%
Mexico	19,758	1.20%	155	1.20%	493	1.44%	3,866	40.0%
Moldova	1,027	0.06%	387	0.02%	12	0.04%	4,646	98.1%

Country	Cumulative Emissions				Liability			
	Total (Mt)	Share of Total	Per Capita (tonnes)	Share of 2019 Emissions	Liability ($bn)	Share of Total Debt	Liability per Capita	Liability/ GNI
World	**1,652,920**	**100%**	**215**	**100%**	**34,218**	**100%**	**4,459**	**39.0%**
Mongolia	693	0.04%	215	0.18%	23	0.07%	7,083	183.9%
Montenegro	101	0.01%	162	0.01%	2	0.01%	3,684	41.2%
Morocco	1,714	0.10%	47	0.20%	52	0.15%	1,416	44.0%
Mozambique	174	0.01%	6	0.02%	4	0.01%	129	26.1%
Myanmar	558	0.03%	10	0.07%	15	0.04%	272	20.0%
Namibia	72	0.00%	29	0.01%	3	0.01%	1,070	22.2%
Nepal	143	0.01%	5	0.04%	5	0.02%	183	16.9%
Netherlands	11,627	0.70%	671	0.42%	200	0.58%	11,529	21.9%
New Caledonia	150	0.01%	523	0.02%	4	0.01%	13,490	144.7%
New Zealand	1,849	0.11%	376	0.10%	38	0.11%	7,721	18.9%
Nicaragua	172	0.01%	26	0.02%	5	0.01%	704	38.2%
Niger	45	0.00%	2	0.01%	1	0.00%	59	10.2%
Nigeria	3,825	0.23%	19	0.38%	106	0.31%	529	24.5%
North Macedonia	629	0.04%	302	0.02%	12	0.04%	5,807	101.1%
Norway	2,599	0.16%	486	0.12%	50	0.14%	9,270	11.8%
Oman	1,208	0.07%	243	0.20%	43	0.12%	8,557	60.7%
Pakistan	4,945	0.30%	23	0.68%	155	0.45%	715	56.8%
Palestine	57	0.00%	12	0.01%	2	0.01%	449	11.0%
Panama	301	0.02%	71	0.03%	9	0.03%	2,022	13.8%
Papua New Guinea	164	0.01%	19	0.02%	5	0.01%	567	20.9%
Paraguay	170	0.01%	24	0.02%	5	0.02%	746	14.3%
Peru	1,892	0.11%	58	0.15%	44	0.13%	1,343	20.2%
Philippines	3,250	0.20%	30	0.40%	93	0.27%	857	22.4%
Poland	27,561	1.67%	726	0.89%	418	1.22%	11,020	73.1%
Portugal	2,572	0.16%	250	0.13%	62	0.18%	6,005	26.4%
Qatar	2,039	0.12%	720	0.30%	69	0.20%	24,226	40.0%
Romania	8,498	0.51%	439	0.21%	137	0.40%	7,056	55.4%
Russia	113,884	6.89%	789	4.61%	2,081	6.08%	14,412	126.4%
Rwanda	28	0.00%	2	0.00%	1	0.00%	63	7.9%
Saint Kitts and Nevis	6	0.00%	116	0.00%	0	0.00%	3,931	20.7%
Saint Lucia	12	0.00%	65	0.00%	0	0.00%	1,892	17.3%
St Vincent	7	0.00%	62	0.00%	0	0.00%	1,944	26.3%
Samoa	7	0.00%	36	0.00%	0	0.00%	1,030	24.9%
Sao Tome & Principe	3	0.00%	15	0.00%	0	0.00%	442	22.8%
Saudi Arabia	14,904	0.90%	435	1.60%	465	1.36%	13,565	58.1%
Senegal	228	0.01%	14	0.03%	7	0.02%	416	29.4%
Serbia	2,740	0.17%	395	0.15%	58	0.17%	8,330	118.8%
Seychelles	16	0.00%	163	0.00%	1	0.00%	5,263	31.2%
Sierra Leone	36	0.00%	5	0.00%	1	0.00%	98	18.9%
Singapore	2,125	0.13%	373	0.11%	56	0.16%	9,739	16.4%

Country	Cumulative Emissions				Liability			
	Total (Mt)	Share of Total	Per Capita (tonnes)	Share of 2019 Emissions	Liability ($bn)	Share of Total Debt	Liability per Capita	Liability/ GNI
World	**1,652,920**	**100%**	**215**	**100%**	**34,218**	**100%**	**4,459**	**39.0%**
Sint Maarten (Dutch)	66	0.00%	1,632	0.00%	1	0.00%	18,474	64.9%
Slovakia	3,867	0.23%	709	0.09%	52	0.15%	9,476	50.1%
Slovenia	838	0.05%	402	0.04%	18	0.05%	8,793	34.4%
Solomon Islands	10	0.00%	15	0.00%	0	0.00%	449	19.1%
South Africa	20,722	1.25%	354	1.31%	485	1.42%	8,288	142.1%
South Korea	17,074	1.03%	330	1.68%	532	1.56%	10,297	32.1%
South Sudan	38	0.00%	3	0.00%	1	0.00%	101	10.6%
Spain	14,643	0.89%	311	0.69%	328	0.96%	6,971	23.5%
Sri Lanka	483	0.03%	22	0.07%	14	0.04%	660	17.6%
Sudan	429	0.03%	10	0.06%	13	0.04%	304	45.1%
Suriname	113	0.01%	195	0.01%	3	0.01%	4,385	77.7%
Sweden	4,949	0.30%	481	0.12%	63	0.18%	6,149	11.6%
Switzerland	2,991	0.18%	349	0.10%	50	0.15%	5,849	7.0%
Syria	1,819	0.11%	107	0.07%	50	0.14%	2,901	124.7%
Tajikistan	415	0.03%	45	0.02%	6	0.02%	657	64.9%
Tanzania	231	0.01%	4	0.03%	7	0.02%	118	11.2%
Thailand	7,152	0.43%	103	0.79%	234	0.68%	3,362	44.7%
Timor	6	0.00%	4	0.00%	0	0.00%	186	8.9%
Togo	69	0.00%	9	0.01%	2	0.01%	268	39.4%
Tonga	4	0.00%	41	0.00%	0	0.00%	1,201	23.3%
Trinidad and Tobago	1,529	0.09%	1,096	0.10%	38	0.11%	27,499	159.2%
Tunisia	876	0.05%	75	0.09%	26	0.07%	2,190	68.3%
Turkey	10,453	0.63%	125	1.11%	315	0.92%	3,772	42.0%
Turkmenistan	2,691	0.16%	453	0.24%	62	0.18%	10,410	158.4%
Turks & Caicos	4	0.00%	98	0.00%	0	0.00%	3,719	13.1%
Tuvalu	0	0.00%	24	0.00%	0	0.00%	822	14.7%
Uganda	100	0.01%	2	0.02%	3	0.01%	67	8.7%
Ukraine	29,549	1.79%	666	0.61%	451	1.32%	10,155	284.3%
United Arab Emirates	4,669	0.28%	478	0.52%	152	0.45%	15,590	36.0%
United Kingdom	77,836	4.71%	1,165	1.01%	618	1.81%	9,242	22.2%
United States	410,238	24.82%	1,250	14.50%	6,505	19.01%	19,818	30.0%
Uruguay	365	0.02%	105	0.02%	7	0.02%	2,021	13.3%
Uzbekistan	6,609	0.40%	197	0.30%	135	0.39%	4,013	229.2%
Vanuatu	5	0.00%	15	0.00%	0	0.00%	385	12.2%
Venezuela	7,741	0.47%	271	0.32%	176	0.51%	6,177	36.9%
Vietnam	3,636	0.22%	38	0.68%	117	0.34%	1,212	47.4%
Yemen	615	0.04%	21	0.03%	17	0.05%	586	75.7%
Zambia	235	0.01%	13	0.02%	4	0.01%	217	16.9%
Zimbabwe	769	0.05%	53	0.03%	14	0.04%	946	69.8%

Annex D. Estimates of SCC

Table 9. Estimates of social cost of carbon from Tol, 2008

Author	Year	Weight	SCC	Peer Rev.	Indep. Estimate	Correct Est. Method	Dynamic Vuln. Model	Realistic Scenario	Cons. Discount Rate	Pure Time Pref. Rate	Equity Weighted
Nordhaus	1982	1	146.7	1	1	0	0	0	NA	1	0
Ayres & Walter	1991	1	119	1	1	0	0	0	3	1	0
Nordhaus	1991	1	26.8	1	1	0	0	0	3	1	0
Haradan	1992	1	7.3	1	1	0	0	0	4	2	0
Cline	1992	1	64.9	0	1	1	0	1	NA	NA	0
Hoymeyer & Gaertner	1992	1	1,667	0	1	0	0	1	0	–2.0	0
Haradan	1993	0.25	1.9	1	0	0	0	0	4	2	0
	1993	0.5	3	1	0	0	0	0	4	2	0
	1993	0.25	8.8	1	0	0	0	0	4	2	0
Nordhaus	1993	1	5	1	0	1	0	1	5	3	0
Peck & Teisberg	1993	1	10	1	0	1	0	1	5	3	0
Reilly & Richards	1993	0.5	14.3	1	0	1	0	0	5	3	0
	1993	0.5	21.2	1	0	1	0	0	5	3	0
Fankhauser	1994	1	20.3	1	1	1	0	1	NA	NA	0
Nordhaus	1994	1	5.3	0	1	1	0	1	5	3	0
Azar	1994	0.25	50	1	0	0	0	0	NA	0	0
	1994	0.5	200	1	0	0	0	0	NA	0	0
	1994	0.25	500	1	0	0	0	0	NA	0	0
Maddison	1995	1	16.5	1	0	1	0	1	5	3	0
Schauer	1995	0.5	8.3	1	1	1	0	1	4.9	2.3	0
	1995	0.5	112.5	1	1	1	0	1	4.9	2.3	0
Plambeck & Hope	1996	0.3	3	1	1	1	0	1	5	3	0
	1996	0.1	8	1	1	1	0	1	5	3	0
	1996	0.1	8	1	1	1	0	1	5	3	0
	1996	0.3	21	1	1	1	0	1	5	3	0
	1996	0.1	46	1	1	1	0	1	4	2	0
	1996	0.1	440	1	1	1	0	1	2	0	0
Azar & Sterner	1996	0.044	85	1	0	1	0	1	2	0	0
	1996	0.089	200	1	0	1	0	1	2	0	0
	1996	0.033	75	1	0	1	0	1	2.1	0.1	0
	1996	0.067	140	1	0	1	0	1	2.1	0.1	0
	1996	0.022	32	1	0	1	0	1	3	1	0
	1996	0.044	33	1	0	1	0	1	3	1	0

Author	Year	Weight	SCC	Peer Rev.	Indep. Estimate	Correct Est. Method	Dynamic Vuln. Model	Realistic Scenario	Cons. Discount Rate	Pure Time Pref. Rate	Equity Weighted
	1996	0.011	13	1	0	1	0	1	5	3	0
	1996	0.022	13	1	0	1	0	1	5	3	0
	1996	0.089	260	1	0	1	0	1	2	0	1
	1996	0.178	590	1	0	1	0	1	2	0	1
	1996	0.067	230	1	0	1	0	1	2.1	0.1	1
	1996	0.133	410	1	0	1	0	1	2.1	0.1	1
	1996	0.044	95	1	0	1	0	1	3	1	1
	1996	0.089	98	1	0	1	0	1	3	1	1
	1996	0.022	39	1	0	1	0	1	5	3	1
	1996	0.044	39	1	0	1	0	1	5	3	1
Downing et al.	1996	0.5	53.5	0	1	0	1	1	0	–2.0	0
	1996	0.5	18.3	0	1	0	1	1	0	–2.0	0
Hohmeyer	1996	1	800	0	0	0	0	1	0	–2.0	0
Hope & Maul	1996	0.1	7	1	1	1	0	0	4	2	0
	1996	1	24	1	1	1	0	0	4	2	0
	1996	0.8	5	1	1	1	0	1	4	2	0
	1996	0.1	29	1	1	1	0	0	4	2	0
Nordhaus & Yang	1996	1	6.2	1	1	1	0	1	5	3	0
Nordhaus & Popp	1997	0.9	11.6	1	0	1	0	1	5	3	0
	1997	0.1	6.3	1	0	1	0	1	5	3	0
Cline	1997	1	88	0	1	1	0	1	NA	NA	0
Eyre et al.	1999	0.5	170	0	0	1	1	1	1	–1.0	1
	1999	0.5	70	0	0	1	1	1	3	1	1
	1999	0.5	160	0	0	1	1	1	1	–1.0	1
	1999	0.5	74	0	0	1	1	1	3	1	1
Tol	1999	0.25	60	1	1	1	1	1	3	1	1
	1999	0.05	62	1	1	1	1	1	3	1	1
	1999	0.05	23	1	1	1	1	1	3	1	0
	1999	0.05	66	1	1	1	1	1	3	1	1
	1999	0.05	65	1	1	1	1	1	3	1	1
	1999	0.05	56	1	1	1	1	1	3	1	1
	1999	0.05	317	1	1	1	1	1	0	–2.0	1
	1999	0.01	243	1	1	1	1	1	0	–2.0	1
	1999	0.01	142	1	1	1	1	1	0	–2.0	0
	1999	0.01	360	1	1	1	1	1	0	–2.0	1
	1999	0.01	348	1	1	1	1	1	0	–2.0	1
	1999	0.01	288	1	1	1	1	1	0	–2.0	1

Author	Year	Weight	SCC	Peer Rev.	Indep. Estimate	Correct Est. Method	Dynamic Vuln. Model	Realistic Scenario	Cons. Discount Rate	Pure Time Pref. Rate	Equity Weighted
	1999	0.05	171	1	1	1	1	1	1	–1.0	1
	1999	0.01	172	1	1	1	1	1	1	–1.0	1
	1999	0.01	73	1	1	1	1	1	1	–1.0	0
	1999	0.01	192	1	1	1	1	1	1	–1.0	1
	1999	0.01	187	1	1	1	1	1	1	–1.0	1
	1999	0.01	156	1	1	1	1	1	1	–1.0	1
	1999	0.1	26	1	1	1	1	1	5	3	1
	1999	0.02	26	1	1	1	1	1	5	3	1
	1999	0.02	9	1	1	1	1	1	5	3	0
	1999	0.02	28	1	1	1	1	1	5	3	1
	1999	0.02	28	1	1	1	1	1	5	3	1
	1999	0.02	25	1	1	1	1	1	5	3	1
	1999	0.05	6	1	1	1	1	1	10	8	1
	1999	0.01	6	1	1	1	1	1	10	8	1
	1999	0.01	2	1	1	1	1	1	10	8	0
	1999	0.01	6	1	1	1	1	1	10	8	1
	1999	0.01	6	1	1	1	1	1	10	8	1
	1999	0.01	6	1	1	1	1	1	10	8	1
Roughgarden & Schneider	1999	1	40.4	1	1	1	0	1	5	3	0
Nordhaus & Boyer	2000	1	5.9	0	1	1	0	1	NA	NA	0
Tol & Downing	2000	0.1	26.1	0	0	1	1	1	3	1	1
	2000	0.1	3.5	0	0	1	1	1	3	1	0
	2000	1	45.8	0	0	1	1	1	3	1	1
	2000	0.8	5.1	0	0	1	1	1	3	1	0
Clarkson & Deyes	2002	1	101.5	0	0	1	0	1	3	1	1
Tol	2002	0.083	19.9	0	1	1	1	1	2	0	0
	2002	0.167	16.1	0	1	1	1	1	2	0	1
	2002	0.167	3.8	0	1	1	1	1	3	1	0
	2002	0.333	6.6	0	1	1	1	1	3	1	1
	2002	0.083	–6.6	0	1	1	1	1	5	3	0
	2002	0.167	–0.5	0	1	1	1	1	5	3	1
Newell & Pizer	2003	0.1	5.7	1	0	1	0	1	4	2	0
	2003	0.2	10.4	1	0	1	0	1	NA	2	0
	2003	0.2	6.5	1	0	1	0	1	NA	2	0
	2003	0.05	21.7	1	0	1	0	1	2	0	0
	2003	0.1	33.8	1	0	1	0	1	NA	0	0

Author	Year	Weight	SCC	Peer Rev.	Indep. Estimate	Correct Est. Method	Dynamic Vuln. Model	Realistic Scenario	Cons. Discount Rate	Pure Time Pref. Rate	Equity Weighted
	2003	0.1	23.3	1	0	1	0	1	NA	0	0
	2003	0.05	1.5	1	0	1	0	1	7	5	0
	2003	0.1	2.9	1	0	1	0	1	NA	5	0
	2003	0.1	1.8	1	0	1	0	1	NA	5	0
Pearce	2003	1	23.5	1	0	1	0	1	3	1	1
Uzawa	2003	1	160.7	0	1	0	0	0	NA	NA	NA
Mendelsohn	2003	1	1.5	0	1	0	0	0	5	3	0
Hope	2003	1	19	0	0	1	0	1	NA	3	0
Link & Tol	2004	0.165	79	1	1	1	1	1	NA	0	0
	2004	0.165	170	1	1	1	1	1	NA	0	1
	2004	0.165	25.2	1	1	1	1	1	NA	1	0
	2004	0.165	94.1	1	1	1	1	1	NA	1	1
	2004	0.165	5.1	1	1	1	1	1	NA	3	0
	2004	0.165	45.1	1	1	1	1	1	NA	3	1
	2004	0.002	75.6	1	1	1	1	1	NA	0	0
Link & Tol	2004	0.002	167.8	1	1	1	1	1	NA	0	1
	2004	0.002	24.4	1	1	1	1	1	NA	1	0
	2004	0.002	93.6	1	1	1	1	1	NA	1	1
	2004	0.002	5	1	1	1	1	1	NA	3	0
	2004	0.002	45	1	1	1	1	1	NA	3	1
Hohmeyer	2004	0.5	32	0	0	1	0	1	NA	1	0
	2004	0.5	590	0	0	1	0	1	NA	0	1
Cline	2004	0.9	128	0	0	1	0	1	NA	NA	0
	2004	0.05	450	0	0	1	0	1	NA	NA	0
	2004	0.05	10	0	0	1	0	1	NA	NA	0
Manne	2004	0.05	300	0	0	1	0	1	NA	NA	0
	2004	0.95	12	0	0	1	0	1	NA	NA	0
Hope	2005	1	21	0	1	1	0	1	NA	3	0
Ceronsky et al.	2005	0.238	58	0	0	1	1	1	NA	0	0
	2005	0.238	11	0	0	1	1	1	NA	1	0
	2005	0.238	–2.3	0	0	1	1	1	NA	3	0
	2005	0.238	18	0	0	1	1	1	NA	NA	0
	2005	0.001	54	0	0	1	1	1	NA	0	0
	2005	0.001	11	0	0	1	1	1	NA	1	0
	2005	0.001	–2.5	0	0	1	1	1	NA	3	0
	2005	0.001	17	0	0	1	1	1	NA	NA	0
	2005	0.001	54	0	0	1	1	1	NA	0	0
	2005	0.001	13	0	0	1	1	1	NA	1	0
	2005	0.001	–0.1	0	0	1	1	1	NA	3	0
	2005	0.001	20	0	0	1	1	1	NA	NA	0

Author	Year	Weight	SCC	Peer Rev.	Indep. Estimate	Correct Est. Method	Dynamic Vuln. Model	Realistic Scenario	Cons. Discount Rate	Pure Time Pref. Rate	Equity Weighted
	2005	0.001	54	0	0	1	1	1	NA	0	0
	2005	0.001	10	0	0	1	1	1	NA	1	0
	2005	0.001	–2.5	0	0	1	1	1	NA	3	0
	2005	0.001	17	0	0	1	1	1	NA	NA	0
	2005	0.001	55	0	0	1	1	1	NA	0	0
	2005	0.001	11	0	0	1	1	1	NA	1	0
	2005	0.001	–2.5	0	0	1	1	1	NA	3	0
	2005	0.001	18	0	0	1	1	1	NA	NA	0
	2005	0.001	58	0	0	1	1	1	NA	0	0
	2005	0.001	12	0	0	1	1	1	NA	1	0
	2005	0.001	–2.3	0	0	1	1	1	NA	3	0
	2005	0.001	18	0	0	1	1	1	NA	NA	0
	2005	0.001	73	0	0	1	1	1	NA	0	0
	2005	0.001	16	0	0	1	1	1	NA	1	0
	2005	0.001	–1.6	0	0	1	1	1	NA	3	0
	2005	0.001	24	0	0	1	1	1	NA	NA	0
	2005	0.001	94	0	0	1	1	1	NA	0	0
	2005	0.001	21	0	0	1	1	1	NA	1	0
	2005	0.001	–0.7	0	0	1	1	1	NA	3	0
	2005	0.001	30	0	0	1	1	1	NA	NA	0
	2005	0.001	330	0	0	1	1	1	NA	0	0
	2005	0.001	89	0	0	1	1	1	NA	1	0
	2005	0.001	17	0	0	1	1	1	NA	3	0
	2005	0.001	100	0	0	1	1	1	NA	NA	0
	2005	0.001	1,500.00	0	0	1	1	1	NA	0	0
	2005	0.001	360	0	0	1	1	1	NA	1	0
	2005	0.001	75	0	0	1	1	1	NA	3	0
	2005	0.001	270	0	0	1	1	1	NA	NA	0
	2005	0.001	2,400.00	0	0	1	1	1	NA	0	0
	2005	0.001	580	0	0	1	1	1	NA	1	0
	2005	0.001	120	0	0	1	1	1	NA	3	0
	2005	0.001	360	0	0	1	1	1	NA	NA	0
Hope	2005	0.167	43	0	0	1	0	1	NA	3	1
	2005	0.167	35	0	0	1	0	1	NA	3	1
	2005	0.167	31	0	0	1	0	1	NA	3	0
	2005	0.167	46	0	0	1	0	1	NA	3	1
	2005	0.167	37	0	0	1	0	1	NA	3	1
	2005	0.167	32	0	0	1	0	1	NA	3	0
Downing et al.	2005	1	50.8	0	0	0	0	0	NA	NA	1

Author	Year	Weight	SCC	Peer Rev.	Indep. Estimate	Correct Est. Method	Dynamic Vuln. Model	Realistic Scenario	Cons. Discount Rate	Pure Time Pref. Rate	Equity Weighted
Guo et al.	2006	0.016	58	1	0	1	1	1	NA	0	0
	2006	0.016	11	1	0	1	1	1	NA	1	0
	2006	0.016	–2.3	1	0	1	1	1	NA	3	0
	2006	0.143	18	1	0	1	1	1	NA	NA	0
Guo et al.	2006	0.008	6.6	1	0	1	1	1	3.5		0
	2006	0.143	88	1	0	1	1	1	NA	NA	0
	2006	0.008	2.1	1	0	1	1	1	4		0
	2006	0.214	88	1	0	1	1	1	NA	NA	0
	2006	0.008	2.1	1	0	1	1	1	4		0
	2006	0.036	185	1	0	1	1	1	NA	0	0
	2006	0.036	29	1	0	1	1	1	NA	1	0
	2006	0.036	–1.3	1	0	1	1	1	NA	3	0
	2006	0.036	85	1	0	1	1	1	NA	0	0
	2006	0.036	15	1	0	1	1	1	NA	1	0
	2006	0.036	–2.1	1	0	1	1	1	NA	3	0
	2006	0.214	35	1	0	1	1	1	NA	NA	0
Wahba & Hope	2006	0.2	19	1	0	1	0	1	NA	3	0
	2006	0.2	14	1	0	1	0	1	NA	3	0
	2006	0.1	47	1	0	1	0	1	NA	2	0
	2006	0.1	145	1	0	1	0	1	NA	1	0
	2006	0.1	30	1	0	1	0	1	NA	2	0
	2006	0.1	91	1	0	1	0	1	NA	1	0
	2006	0.1	29	1	0	1	0	1	NA	3	0
	2006	0.1	21	1	0	1	0	1	NA	3	0
Hope	2006	1	19	1	0	1	0	1	NA	3	0
Stern et al.	2006	1	314	0	0	1	0	1	NA	0	1

Source: Reproduced from Tol (2008).

Note: The references from this table can be found in Tol (2008), as can the various parameters in the header. The purpose here is to illustrate the great variety of estimates of SCCs it is possible to obtain from adjusting a handful of input parameters.

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