The True Value of the Social Cost of Carbon

Yuen Kwan Vanessa Ma

Peter Milling

Mical Nobel

Chelsea Tompkins

Abstract

The Social Cost of Carbon (SCC) is a globally-studied metric evaluating the economic damages from carbon dioxide emissions. This paper will review the viability and utility of the SCC as a policy tool for limiting greenhouse gas emissions and mitigating climate change. We do not believe the SCC, in its current form, is fully reliable as the primary tool of global carbon policy. The paper begins with a brief overview of the SCC, its construction using Integrated Assessment Models (IAMs), and the scenarios applied to the IAMs to derive the SCC measure. This will be followed by a thorough review of the three IAMs used by the United States government to calculate the SCC – FUND, PAGE, and DICE. Through a critical evaluation of the processes, variables, and assumptions employed in each – and a similarly thorough analysis of the scenarios used as inputs for the IAMs – we determine key areas of concern and recommended next steps for future researchers.

Key Definitions

Term	Abbr.	Definition
Model		A theoretical construct that simulates interactions by quantifying relationships between input variables to transform input data to desired outputs. (Climate): Simulate changes in climate through estimating quantitative relationships between important drivers such as sea level, ice cover, emissions to arrive at outputs such as temperature change. (Economic): Simulate economic decisions through estimating quantitative relationships between factors such as population, technology, natural resources, to arrive at outputs such as GDP, income inequality.
Integrated Assessment Model	IAM	A model comprised of several discipline-specific models. See Section 1.2 for more detail.
Climate Model	CM	See "Model" definition
Radiative Forcing		Also called climate forcing. The calculated difference between sunlight absorbed by the Earth and energy radiated back into outer space; i.e. the reason why global warming from emissions occurs. Calculation of a gas' contribution to global warming is to convert between emissions and radiative forcing, which is done using a function specific to each emitted gas, accounting for each gas' capability to retain energy from reflected sunlight.
CO2 Pulse Implementation		Refers to the process for capturing CO2 from the atmosphere

Table of Contents

1. Introduction

1.1 What is the SCC and why is it important?

The impacts of climate change are already felt by people around the world. These impacts can be quite devastating: extreme weather events like flooding and deadly storms, the spread of disease, sea level rise, increased food insecurity, and other disasters; these impacts can also be quite costly, affecting individuals, businesses, and governments. The **social cost of carbon** (SCC) is a measure of the economic harm due to these climate change-related damages. More precisely, the SCC is the present discounted value of net harm to current and future generations, worldwide, due to the emission of an additional metric ton of carbon dioxide (CO_2).

The current estimate of the SCC adopted by the federal government of the United States is approximately $40 per metric ton of CO_2[a]. While this figure was informed by research by multiple experts in the field, through the adoption of an average across multiple models' calculations, it still does not include the full spectrum of scientific and economic impacts identified by relevant research communities and continues to be the source of widespread debate. Many experts consider an SCC of $40 to be an underestimate, far lower than the true costs of carbon pollution[b]; meanwhile, some stakeholders argue that this value is too high. Among the latter set of critics is the current U.S. administration, which has made notable attempts to lower the SCC to a value between $1-$7[c]. The SCC is intended to be a comprehensive estimate, and captures factors including (but not limited to): changes in human health, property damages from increased flood risk, net agricultural productivity, and changes in energy costs, such as reduced costs for heating and increased costs for air conditioning. Each model[1] used to calculate the SCC employs its own unique set of factors, underlying assumptions, and methodologies; the inherent complexity of such a demanding calculation and the nuanced differences across the models partly explain the lack of consensus surrounding the actual final value of the SCC.

Many consider determining the correct SCC to be a critical step in developing effective environmental policy (or any forward-thinking policy, for that matter[2]), as it is difficult to

[1] See Key Definitions.

[2] This notion of the SCC being applicable to cost-benefit analyses that extend to policies that are not immediately emissions-related is another point of contention. Such political disagreements are discussed further in section 5.4.

proceed with creating longstanding policy based on a number that is not broadly agreed upon by the relevant stakeholders, especially policymakers. The topic receives a lot of attention given the serious implications of climate change – environmental, social, and financial implications. As governments grapple with how to best serve their constituents and, potentially, future generations of their constituents, the determination and use of an SCC has the potential to influence regulatory and public investment decisions with financial impacts on the scale of billions of dollars and societal implications that are impossible to predict. Indeed, all policy decisions that effectively contribute to the mitigation or causes of climate change inherently assume an SCC.

This paper does not aim to point towards the correct value that the SCC, or even the correct way that the SCC should be calculated; we merely hope to structure the critical conversation around the topic. By surveying the methods by which the SCC is currently calculated and collating the opinions surrounding its applicability as a policy tool, we arrive at several key questions to help shape the scattered discourse regarding the SCC.

1.2 Calculating the SCC: Integrated Assessment Models

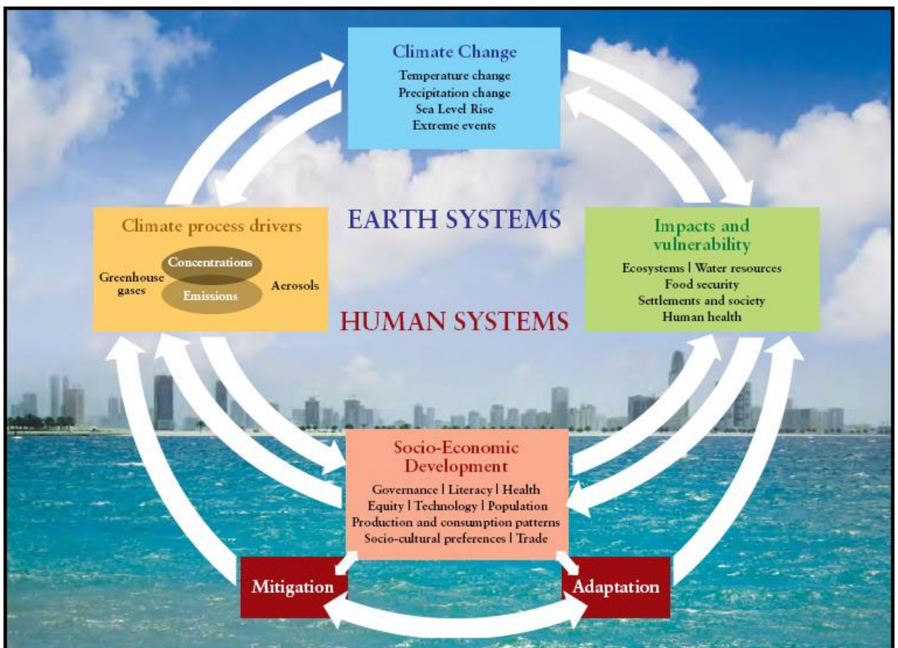


Figure 1[j] **||** The interaction of the different fields that go into modeling. The three primary research communities that are involved in and impacted by the development of new scenarios are Integrated Assessment Model (IAM) groups, Impacts, Adaptation and Vulnerabilities (IAV) groups, and Climate Model (CM) groups.

Integrated Assessment Models (IAMs) are the basis upon which SCC values are derived. **An IAM leverages knowledge from two or more disciplines and combines them into a single framework.** In the case of estimating the economic impacts of climate change, IAMs help explain the implications of changes in geophysical, economic, and political systems.

In spite of immense challenges and limitations inherent in using IAMs to integrate these different disciplines into diagnoses and policy prescriptions, IAMs are still used widely by research groups and policymakers around the world to simulate changes in variable assumptions, gauge uncertainties, evaluate the effects of proposed policies, and project future emissions, among other factors.

1.2.1 Types of IAMs

Climate change IAMs can take a variety of forms, thereby enabling scientists and economists to address a variety of questions. Broadly speaking, they fall into two distinct categories – "simple" and "complex"[d]. Each category presents advantages and disadvantages, indicating the criticality of choosing the appropriate option based on intended applications.

Complex IAMs are constructed by linking multiple different models, and may include thousands of variables, which are individually projected, and aggregated via different methods. These variables are highly specific; for example, international shipping costs as an input to economic performance. The variables may be derived from the manipulation of other variables that are also independently included in the model – following on the prior example, international shipping and multiple other variables are transformed and used to calculate economic performance, which is then used within the complex IAM as a variable itself. There can be multiple layers of such aggregation and manipulation, as well as different methods – weighted averaging, raising to different powers, taking maximums or minimums, etc. In short, the average reader is not easily able to infer the reason that output variables respond in a certain way to the original input variables, due to the many phases of transformation that have taken place from start to finish.

These complex IAMs are the foundation upon which scenarios (see sections 1.3) and some simple IAMs are constructed, and valuable insights – such as economic production projections and costs of policy implementation – can be derived from their use. However, in exchange for this level of specificity and complexity, complex IAMs may take years to update due to additional work needed on re-calculations of errors and rewiring equations. Moreover, as previously alluded to, the sheer number of variables and relationships makes the model inaccessible to the average citizen, who likely does not have the modeling or subject area expertise. There is also a question of whether assumptions about input variables used in complex IAMs lead to particularly compounded effects and greater variability in outcomes (i.e. larger error terms), threatening the accuracy and applicability of complex IAM outputs[3].

Simple IAMs are often used for cost-benefit analyses and primarily focus on levels of warming and economic growth assumptions. Focusing on a smaller subset of variables means that simple IAMs often lack the same degree of granular detail that complex IAMs explicitly incorporate into their structures, e.g. highly specific regional or industrial metrics. Despite this presumed shortcoming, simple IAMs are more easily adaptable than complex IAMs and can be updated quickly as new information comes to light – a critical advantage when considering which models may be best-suited to inform policy decisions in today's world of rapidly evolving climate change insights and technology. Thus, simple IAMs have historically been more readily employed to calculate the SCC. There are three simple models – DICE, FUND, and PAGE – that have been the most broadly accepted by academic researchers and policymakers to calculate the SCC; we will explore these three models in depth in section 3.

1.2.2 Calibration versus estimation

The development of IAM assumptions do not rely on traditional statistical *estimation*, but rather *calibration*. As described by William Nordhaus, a leading economist studying the SCC, calibration involves "determination of system parameters and behavior using external evidence"[e]. While estimation is often preferable due to its singularity and, therefore, its presumed precision, calibration is critical when models are extremely complex and lack relevant data. Calibration therefore becomes the most logical approach for SCC modeling.

Unlike traditional scientific models that rely on experimental evidence from carefully crafted designs to verify underlying assumptions, global climate change and human responses to these changes cannot be measured through a controlled experiment. This is because the SCC attempts to capture the effects of variables that cannot be isolated, but instead interact across nearly all aspects of our environmental and economic ecosystems. Little information exists on how many species will go extinct as a result of emissions when scientists are unsure of how many species exist in the first place; then the related effects of projected extinction must be considered years

[3] See section 3.4.

into the future. Furthermore, the SCC tracks climate change tens to hundreds of years into the future – a time frame that cannot be reliably predicted for any of the variables included in IAMs.

Take the damage function that is embedded is virtually all SCC IAMs, which aims to calculate the aggregate damage caused by emissions. One small slice of this function would be the impact of hurricanes on the SCC. First, a probability distribution must be used to model the intensity of hurricanes over many decades. Then, the damage function must evaluate the economic impact of these increasingly intense storms across various geopolitical regions. Undoubtedly, a "Category 5" storm will have larger economic impacts in New Orleans, as demonstrated by Hurricane Katrina in 2005, than it would in a low-lying undeveloped region of Southeast Asia.

As can be seen in this example, this small slice of the damage pie incorporates multiple degrees of ignorance, thereby undermining the probabilistic structure required in traditional statistical estimation[d]. The compounded effects of projected changes in storm intensities, their economic impacts, and changes in these values over a lengthy time horizon, make calibration a critical tool in developing IAM assumptions.

Another alternative approach to estimation is a reliance on model revisions over the past several decades to inform future assumptions. While this approach is not as widely used as calibration, its basis in verifiable data provides an illustrative method by which future progression can be viewed and projected. In Nordhaus's recent studies, most major revisions have been rooted in changes to economic projections, while environmental revisions have proven to be smaller[f]. This may allude to the fact that economic projections require closer monitoring as IAMs continue to evolve, since economic progress can be more readily detected, evaluated, and updated over shorter time spans than that of scientific projections. Many scientific factors, which we will discuss in greater detail later, are still vague and are not typically revised over short time horizons so as to be captured with each model revision.

1.3 Scenarios: How we evaluate, compare, and generally use IAMs

As previously discussed, the factors to consider when discussing the future of climate change (as well as the models available to analyze, and researchers at work on tackling questions related to, these factors) are vast. Scenarios allow researchers to explore and discuss these questions using a common framework, even across the different disciplines of researchers studying climate change, e.g. economists, technology experts, climate researchers, atmospheric chemists and geologists.

1.3.1 Development of modern scenarios

The Intergovernmental Panel on Climate Change (IPCC) – the branch of the United Nations whose mission is to assess the science related to the investigation, prediction and analysis of climate change through orchestrating global collaborative efforts across academic disciplines and stakeholders in policy - released the first set of climate change scenarios, IS92, in 1992. These were followed by the Special Report on Emissions Scenarios (SRES)[g] (Special Report on Emissions Scenarios, Insert Citation), released by the IPCC in 2000. SRES described four different possible future trajectories of population, economic growth and greenhouse gas emissions. They were used widely over the following decade, not only for the two IPCC reports released during that period (the Third and Fourth Assessment Reports, TAR and AR4), but also by many research teams around the world.

Almost from the moment of their release, however, the SRES were fast becoming dated and did not represent some large changes to society and the global economy that have occurred between the late 1990s and today. Researchers expressed a need for the SRES to be updated and expanded in scope[h]. **In 2006, the IPCC responded to these calls for improvements and initiated the process that would eventually lead to the most recent[4] set of scenarios, the Representative Concentration Pathways (RCPs) and the Shared Socioeconomic Pathways (SSPs), which are explained in greater detail over the following sections.** At a high level, the RCPs describe different levels of greenhouse gases and other radiative forcings[5] that might occur in the future; the SSPs "describe plausible alternative trends in the evolution of society and natural systems over the 21st century."[i]

In considering how to develop a new generation of scenarios to be used for the preparation of its Fifth Assessment Report (AR5), the IPCC decided to adopt a new approach: instead of coordinating and approving new scenarios itself, the process of scenario development and selection would be coordinated by the research community with the IPCC playing a more

[4] As of the completion of this paper, June 2019.
[5] See Key Definitions.

catalytic role. At an IPCC-organized meeting held in Noordwijkerhout, Netherlands in 2007[j], researchers across different disciplines worked together to develop how this community-driven process to craft the new scenarios would work. It was decided that the new process would be a "parallel process" comprised of three main phases: 1) an initial phase, developing a set of pathways for emissions, concentrations and radiative forcing (i.e. RCPs); 2) a parallel phase, involving the development of both climate model projections (based on the RCPs) and new socioeconomic storylines (i.e. SSPs), and 3) an integration phase, combining the information from the first phases into holistic mitigation, impacts and vulnerability assessments. Ultimately, the community submitted more than 1000 new mitigation scenarios for the Working Group III (WGIII) assessment[k], yet these did not include the envisioned new socioeconomic storylines[l], for reasons explained in the following paragraph.

This new process was meant to shorten the time required for producing a consistent set of climate, impact, adaptation as well as mitigation scenarios, compared to the prior sequential process[6]; the RCPs and SSPs were both intended to be completed in time to be used as an integrating element by the three IPCC Working Groups (WG) as part of their work for the AR5[m]. Some of the phases of the parallel process were indeed completed in time for the AR5, such as the RCPs (completed in 2010 and published[n] in 2011) and the climate projections based on the RCPs (used in the multi-model project CMIP5[o] and assessed in the IPCC WGI AR5[p]). However, the more complex SSPs took much longer and were not published until 2015[q], two years after the AR5 came out. As a result, the vast majority of impact and vulnerability studies in the literature available for the assessment in the AR5 were still based on the SRES. The SSPs are only just beginning to be applied in modeling, and are expected to be used during the next round of climate change modeling known as the Coupled Model Intercomparison Project version 6, or CMIP6, in preparation for the IPCC's sixth assessment report (AR6)[7], though some applications of the scenarios have already been made in current research.

It is noteworthy that the terms "pathways" are used in the names of these new scenarios to indicate "plausible trajectories of different aspects of the future"[r]. As stated in the *IPCC Scenario*

---

[6] This "parallel process" was quite different from earlier iterations of scenario development, where the process would move sequentially from socioeconomic scenarios to emission scenarios to radiative forcing scenarios to climate projections and - finally - to impact, adaptation and vulnerability studies, a new "parallel process".

[7] See Section 4.

Process for AR5[s]: “The goal of working with scenarios is not to predict the future but to better understand uncertainties and alternative futures, in order to consider how robust different decisions or options may be under a wide range of possible futures.” This illustrates the main advantage over the prior limited set of specific scenarios defined by the IPCC: the research community at large can submit *many* different scenarios to be incorporated into the IPCC assessment; these all would be guided by the set of representative pathways decided upon by an expert consortium present at the 2007 Noordwijkerhout meeting, and similar meetings thereafter.

2. Modern Scenarios

2.1 **SSPs**

SSPs look at five different ways in which the world might evolve in the absence of climate policy and how different levels of climate change mitigation could be achieved when the mitigation targets of RCPs are combined with the SSPs. The SSPs also define different baseline worlds (each based on a different set of emissions/warming outcomes, which are based on underlying factors, e.g. population, tech, economic growth) that might occur in the absence of any concerted international effort to address climate change, beyond those already adopted by countries. These exclude any commitments to enact new policies, e.g. those within the Paris Agreement up to 2025 and 2030.

Five existing “shared socioeconomic pathways” were developed following the need to understand the possible baseline trajectories of global development following current trends, absent new climate policies beyond those already in place today, and climate change mitigation policies. First qualitatively developed by the IAV and IAM communities, they were quantitatively adapted by 6 IAMs, the results of which were averaged to provide the dataset that now exists on the IPCC platform, upon which the vast majority of carbon tax models are based.

Given the widespread use of this dataset, it is thus important to understand the variables and the assumptions that inform their economic projections to the 2200 horizon. Unlike survey-based datasets, the numerical values for economic production and consumption are modelled, and entail some degree of variation. Plugging such values further into models outputting a carbon tax may thus compound the variation and contributes to the current wide range of carbon tax values arrived at in the current literature, the implications of which are discussed in detail in section 3.4. Key questions to ask therefore include: Does endogeneity exist in this modeling method, and if so, how much? Can endogeneity be mitigated? What assumptions were made in arriving at IPCC dataset values, to how do they skew the final values, and are such assumptions valid?

This section does not aim to provide the truth behind these questions, merely to shed light on, structure, and perhaps in some cases initiate conversations surrounding the usefulness of the existing dataset in policy design and defense.

Narratives of the five SSPs can be found as follows, without alteration:

> *SSP1 - Sustainability - Low challenges to mitigation and adaptation*
>
> The world shifts gradually, but pervasively, toward a more sustainable path, emphasizing more inclusive development that respects perceived environmental boundaries. Management of the global commons slowly improves, educational and health investments accelerate the demographic transition, and the emphasis on economic growth shifts toward a broader emphasis on human well-being. Driven by an increasing commitment to achieving development goals, inequality is reduced both across and within countries. Consumption is oriented toward low material growth and lower resource and energy intensity.
>
> *SSP2 - Middle of the Road - Medium challenges to mitigation and adaptation*
>
> The world follows a path in which social, economic, and technological trends do not shift markedly from historical patterns. Development and income growth proceeds unevenly, with some countries making relatively good progress while others fall short of expectations. Global and national institutions work toward but make slow progress in achieving sustainable development goals. Environmental systems experience degradation, although there are some improvements and overall the intensity of resource and energy use declines. Global population growth is moderate and levels off in the second half of the century. Income inequality persists or improves only slowly and challenges to reducing vulnerability to societal and environmental changes remain.
>
> *SSP3 - Rocky Road - High challenges to mitigation and adaptation*
>
> A resurgent nationalism, concerns about competitiveness and security, and regional conflicts push countries to increasingly focus on domestic or, at most, regional issues. Policies shift over time to become increasingly oriented toward national and regional

security issues. Countries focus on achieving energy and food security goals within their own regions at the expense of broader-based development. Investments in education and technological development decline. Economic development is slow, consumption is material-intensive, and inequalities persist or worsen over time. Population growth is low in industrialized and high in developing countries. A low international priority for addressing environmental concerns leads to strong environmental degradation in some regions.

SSP4 - Inequality - Low challenges to mitigation, high challenges to adaptation

Highly unequal investments in human capital, combined with increasing disparities in economic opportunity and political power, lead to increasing inequalities and stratification both across and within countries. Over time, a gap widens between an internationally-connected society that contributes to knowledge- and capital-intensive sectors of the global economy, and a fragmented collection of lower-income, poorly educated societies that work in a labor intensive, low-tech economy. Social cohesion degrades and conflict and unrest become increasingly common. Technology development is high in the high-tech economy and sectors. The globally connected energy sector diversifies, with investments in both carbon-intensive fuels like coal and unconventional oil, but also low-carbon energy sources. Environmental policies focus on local issues around middle and high income areas.

SSP5 - Fossil-fueled development - High challenges to mitigation, low challenges to adaptation

This world places increasing faith in competitive markets, innovation and participatory societies to produce rapid technological progress and development of human capital as the path to sustainable development. Global markets are increasingly integrated. There are also strong investments in health, education, and institutions to enhance human and social capital. At the same time, the push for economic and social development is coupled with the exploitation of abundant fossil fuel resources and the adoption of resource and energy intensive lifestyles around the world. All these factors lead to rapid growth of the global economy, while global population peaks and declines in the 21st century. Local environmental problems like air pollution are successfully managed. There is faith in the ability to effectively manage social and ecological systems, including by geo-engineering if necessary.

In quantifying the above scenarios, four large pools of variables were considered to model consumption and production: 1) Population, 2) Economic development, 3) Land use, and 4) Energy Use.

A multi-dimensional demographic model developed by IIASA and NCAR was used to project national populations with specificity to every country, based on alternative assumptions on future fertility, mortality, migration, educational transitions.

Economic development consists of two main projections: urbanization and GDP. Urbanization rates are varied across the SSPs, where SSP1, 4, 5 project 92%, while SSP2 projects 80%, and SSP3 projects 60% by the end of the century. This range of estimates encompasses the UN median projection, and is wider than the previously used SRES. Notably, SSP1 and 5, despite the same projected urbanization rate, stem from different causal links: under SSP1, cities fuel growth because of high production efficiencies; in SSP5, cities become attractive for settlement due to technological and other change. It is unclear what impact this directionality has on modeling as a whole.

GDP projections were developed by the Organization of Economic Cooperation and Development (OECD), IIASA, and the Potsdam Institute for Climate Impact Research (PIK). Three models for each SSP were arrived at as a result, and the average was taken as the value presented in the dataset, this aggregation method being a common theme among efforts to project economic-climate model drivers[8]. Drivers considered include: technological progress, efficiency improvements in energy use, income convergence dynamics[9] (modeling inequality) and human capital accumulation. The ranges of GDP projections attained are comparable with earlier literature. Notably, growth is projected to slow down over time, with average growth rates in the second half of the century roughly half of those of the first half. Given that GDP growth of the world has had major fluctuations since 1970[t], this projection may be dubious. It is also unclear whether the drivers and data taken into account to arrive at the GDP projections in the

[8] See Section 3.4
[9] Modeling inequality

IPCC data were repeated in the IAMs used to arrive at carbon taxes utilizing IPCC output, which could create endogeneity that is not yet accounted for[10].

Of the four umbrellas, energy use takes into account the widest array of variables, since the resulting values were taken from the six IAMs that informed the SSPs. As such, output variables include primary energy mix (between fossil fuels, bio fuels and other renewables), technology used in the electrical grid, as well as emissions of greenhouse gases, though most notably carbon dioxide.

Other variables driving energy demand determination overlap with population parameters such as socioeconomic drivers of population development, economic growth, technological change and lifestyles.

Lastly, land use changes in response to agricultural and industrial demands are taken into account in the SSPs. The nature and direction of these changes vary across the narratives and are quantifications based on the characteristics described in the narratives. Resulting assumptions from these variations extend to regulation, demand (for different land uses), productivity, environmental impacts, and also encompass trade and globalization of agricultural and forestry markets (or lack thereof). Eventual land use projects are informed by the 6 IAMs, which all contain land-use modules, but differ in representation and parametrization of biogeochemical, biophysical and socioeconomic processes. Aside from assumptions guided by the narratives, the IAMs also make use of GDP and urbanization projections detailed under the economic development umbrella. Land-use related projections include the following variables, but are not limited to: demand, production, trade, agricultural land allocations, crop yields, greenhouse gas emissions from agriculture, and food price dynamics.

2.2 **RCPs**

The four representative concentration pathways are: RCP8.5; RCP6; RCP4.5; RCP2.6, which is also known as RCP3-PD. The numbers refer to radiative forcing[11], which is to the difference between insolation absorbed by the Earth and energy radiated back to space, measured in watts per meter squared. Peak and Decline (PD) which summarizes the arc of that pathway, as is

---

[10] See Section 3.
[11] See Key Definitions.

described in greater detail later in this section. The report from the 2007 IPCC Expert Meeting on Scenarios[u] states:

> "RCPs are referred to as **pathways** in order to emphasize that their primary purpose is to provide time-dependent projections of atmospheric greenhouse gas (GHG) concentrations. In addition, the term pathway is meant to emphasize that it is not only a specific long-term concentration or radiative forcing outcome, such as a stabilization level, that is of interest, but also the trajectory that is taken over time to reach that outcome. They are representative in that they are one of several different scenarios that have similar radiative forcing and emissions characteristics."

Each RCP is like its own dataset, and all relevant information has been made available for downloading by the public, using a central repository[v] (Table 1). This repository allows the user to preview and download data on emissions, concentrations, radiative forcing and land use—both at the level of aggregated regions and at times in high-resolution gridded form[12]. For each category of emissions, an RCP contains a set of starting values and the estimated emissions up to 2100, as well as "extension" data up to 2300, which is out of scope for this review. Each RCP contains the same categories of data, but the values vary significantly, reflecting different emission trajectories over time as determined by the underlying socioeconomic assumptions that are unique to each RCP. These socioeconomic projections were drawn and synthesized from existing research literature, each RCP based on a specific synthesis. Despite some RCP data being created based on socioeconomic assumptions, it is critical to understand that the

	Resolution (sectors)	Resolution (geographical)
Emissions of greenhouse gases		
CO_2	Energy/industry, land	Global and for 5 regions
CH_4	12 sectors	0.5°×0.5° grid
N_2O, HFCs, PFCs, CFCs, SF_6	Sum	Global and for 5 regions
Emissions aerosols and chemically active gases		
SO_2, Black Carbon (BC), Organic Carbon (OC), CO, NO_x, VOCs, NH_3	12 sectors	0.5°×0.5° grid
Speciation of VOC emissions		0.5°×0.5° grid
Concentration of greenhouse gases		
(CO_2, CH_4, N_2O, HFCs, PFCs, CFCs, SF_6)	–	Global
Concentrations of aerosols and chemically active gases		
(O_3, Aerosols, N deposition, S deposition)	–	0.5°×0.5° grid
Land-use/land-cover data		
	Cropland, pasture, primary vegetation, secondary vegetation, forests	0.5°×0.5° grid with subgrid fractions, (annual maps and transition matrices including wood harvesting)

Table 1[v] || Overview of RCP Information

[12] High-resolution data is generated for a world divided into 'cells' measuring half a degree of latitude and longitude (518,400 cells in total).

socioeconomic data is not included in the RCP database[13]. This was the main difference from SRES: previously, SRES specified the socioeconomic circumstances for each scenario, which essentially fixed the options for socioeconomic change, leading to a large amount of limited, only slightly varied SRES scenarios - 40 in total, a nominally large dataset that fails to capture most sociopolitical outcomes. - Models were then programmed to generate emissions and subsequent climate scenarios. RCPs, with their fixed emissions trajectories, enable socioeconomic options to become much more flexible and, in turn, allow considerably more realism by incorporating political and economic flexibility at regional scales. Researchers can test various socioeconomic measures against the fixed rates of warming built into the RCPs to see which combinations of mitigation or adaptation produce the most timely return on investment and the most cost-effective response.

Each RCP was generated by a different IAM group; the four IAM groups were responsible for the four published scenarios that were selected as "predecessors" of the RCPs (Table 2).

Overview of representative concentration pathways (RCPs)

	Description[a]	Publication—IA Model
RCP8.5	Rising radiative forcing pathway leading to 8.5 W/m^2 (~1370 ppm CO_2 eq) by 2100.	(Riahi et al. 2007)—MESSAGE
RCP6	Stabilization without overshoot pathway to 6 W/m^2 (~850 ppm CO_2 eq) at stabilization after 2100	(Fujino et al. 2006; Hijioka et al. 2008)—AIM
RCP4.5	Stabilization without overshoot pathway to 4.5 W/m^2 (~650 ppm CO_2 eq) at stabilization after 2100	(Clarke et al. 2007; Smith and Wigley 2006; Wise et al. 2009)—GCAM
RCP2.6	Peak in radiative forcing at ~3 W/m^2 (~490 ppm CO_2 eq) before 2100 and then decline (the selected pathway declines to 2.6 W/m^2 by 2100).	(Van Vuuren et al., 2007a; van Vuuren et al. 2006)—IMAGE

[a] Approximate radiative forcing levels were defined as ±5% of the stated level in W/m^2 relative to pre-industrial levels. Radiative forcing values include the net effect of all anthropogenic GHGs and other forcing agents

Table 2[w] || Predecessor scenarios to RCPs

The four design criteria required of the RCPs - which helped inform the selection of the four predecessor IAMs – were the following[w]:

1. The RCPs should be based on scenarios published in the existing literature, developed independently by different modeling groups and, as a set, be 'representative' of the total literature, in terms of emissions and concentrations; At the same time, each of the RCPs should provide a plausible and internally consistent description of the future;

[13] This is a key difference from the old SRES scenarios from 2000: each RCP emission trajectory/final concentration is not explicitly linked to specific socioeconomic storylines.

2. The RCPs should provide information on all components of radiative forcing that are needed as input for climate modeling and atmospheric chemistry modeling (emissions of greenhouse gases, air pollutants and land use). Moreover, they should make such information available in a geographically explicit way;
3. The RCPs should have harmonized base year assumptions for emissions and land use and allow for a smooth transition between analyses of historical and future periods;
4. The RCPs should cover the time period up to 2100, but information also needs to be made available for the centuries thereafter.

The outputs of the RCPs are illustrated in Figure 2, while details on the four pathways and their differences are listed below.

RCP 8.5 - Rising Radiative Forcing to 8.5 W/m² by 2100

RCP 8.5 was developed using the MESSAGE model and the IIASA Integrated Assessment Framework by the International Institute for Applied Systems Analysis (IIASA), based in Austria. This RCP is characterized by increasing greenhouse gas emissions over time, representative of scenarios in the literature that lead to high greenhouse gas concentration levels[x]. While the median temperatures in RCP8.5 are comparable to SRES A1FI, they rise slower than they do in SRES A1FI during the period

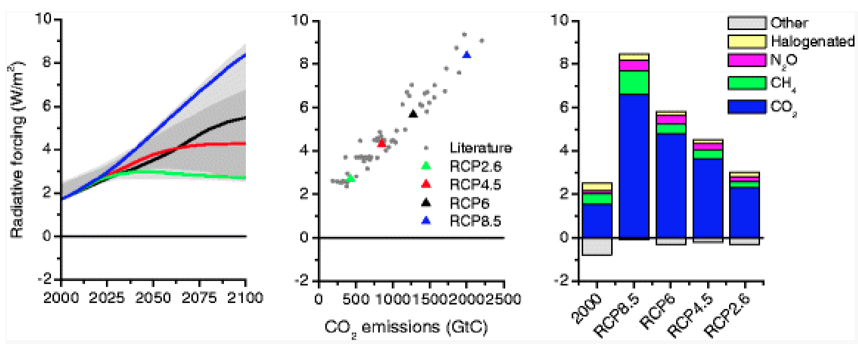


Figure 2[n] || RCP Outputs. Trends in radiative forcing (left), cumulative 21st century CO_2 emissions vs 2100 radiative forcing (middle), and 2100 forcing level per category (right). Light/dark grey areas (left) indicate the 98th/90th percentiles of the literature. Dots (middle) represent a large number of studies. Forcing is relative to pre-industrial values and does not include land use (albedo), dust, or nitrate aerosol forcing.

between 2035 and 2080, and faster during other periods of the twenty-first century. Some critics say that this RCP is too extreme, and unrealistic[14].

RCP6 - Stabilization without Overshoot Pathway at 6 W/m^2

RCP6 was developed by the AIM modeling team at the National Institute for Environmental Studies (NIES) in Japan. It is a stabilization scenario in which total radiative forcing is stabilized shortly after 2100, without overshoot, by the application of a range of technologies and strategies for reducing greenhouse gas emissions[y]. RCP6 is most similar to the SRES B2; the main differences are that median temperatures in RCP6 rise faster than in SRES B2 during the three decades between 2060 and 2090, and slower during other periods of the twenty-first century.

RCP4.5 - Stabilization without Overshoot Pathway at 4.5 W/m^2

RCP 4.5 was developed by the GCAM modeling team at the Pacific Northwest National Laboratory's Joint Global Change Research Institute (JGCRI) in the United States. It is a stabilization scenario in which total radiative forcing is stabilized shortly after 2100, without overshooting the long-run radiative forcing target level[z]. This RCP has a median temperature increase by 2100 comparable to that of the SRES B1, except that median temperatures in RCP4.5 rise faster than in SRES B1 until mid-century and slower afterwards.

RCP2.6 - Peak and Decline from 3 to 2.6 W/m^2 by 2100

RCP2.6 was developed by the IMAGE modeling team of the PBL Netherlands Environmental Assessment Agency. The emission pathway is representative of scenarios in the literature that lead to very low greenhouse gas concentration levels. It is a "peak-and-decline" scenario; its radiative forcing level first reaches a value of around 3.1 W/m^2 by mid-century, and returns to 2.6 W/m^2 by 2100. In order to reach such radiative forcing levels, greenhouse gas emissions (and indirectly emissions of air pollutants) are reduced substantially, over time[n]. This scenario does not really have any comparable SRES. The ratio between temperature increase and net radiative forcing in 2100 is 0:88 C/(W/m^2), whereas all other scenarios show a ratio of about 0:62 C/(W/m^2), meaning that RCP2.6 (a.k.a. RCP3-PD) is closer to equilibrium in 2100 than are the other scenarios.

[14] See Section 2.2.

2.2.1 Current integrated use, and looking ahead

Since the scenarios were developed, various initiatives have arisen to apply the databases towards more industry and region-specific projections of climate change impacts[aa]. One such initiative is the Coupled Model Intercomparison Project (CMIP6), which is a collaborative effort globally in climatology to improve knowledge of climate change through the study and comparison of different relevant models.

Aside from the CMIP6, other model comparison studies such as Inter-Sectoral Impacts Model Comparison Project (ISMIP) and the Agricultural Model Intercomparison and Improvement Project (AgMIP) have similarly begun studies incorporating the analysis of these new scenarios. The ISMIP analyzes over 95 biophysical impacts models, investigating impacts with specificity to water and agricultural sectors. Notably, GDP projections from some subsets of SSPs were utilized in the analyzes as a common starting point for model comparison in Phase 1 of the project, and Phase 2 is anticipated to utilize more socioeconomic data, such as inequality scenarios and metrics in the SSP database.

The AgMIP[bb]focuses more on variables and outcomes particularly in the agricultural sector through the creation of representative agricultural pathways, and, by extension, regional agricultural assessments. Important interaction variables include impacts to soil, water resources, pests and disease, livestock and grassland, feeding into crop models that inform larger agricultural economics models. These regional investigations inform projects under this initiative focused on aggregation to reach global effects, developmental pathways and resulting agricultural-economic scenarios.

Outside of the model comparison studies, development of other models that take the databases into account are already under way. Some models are region-specific: A southeastern-US project is focused on developing nested versions of SSPs; a Brazil-based project is developing narratives for environmental and social development triangulating against the SSPs; the Arctic Council's assessment for the region is developing sub-regional scenario development.

Since most of these initiatives have only begun incorporating the scenarios since their full publication in 2015, limited conclusions have been drawn from such projects. While development is under way for the applications of the current scenarios, there is also more discussion regarding the refinement of SSPs to incorporate more nuanced sociopolitical variables, such as metrics for armed conflict, weights for different types of political systems, and data points for health conditions.

2.2.2 Critiques of scenarios and questions of validity

130 people gathered into a room at the 2007 Expert Meeting on Scenarios to construct this latest generation of baseline pathways.

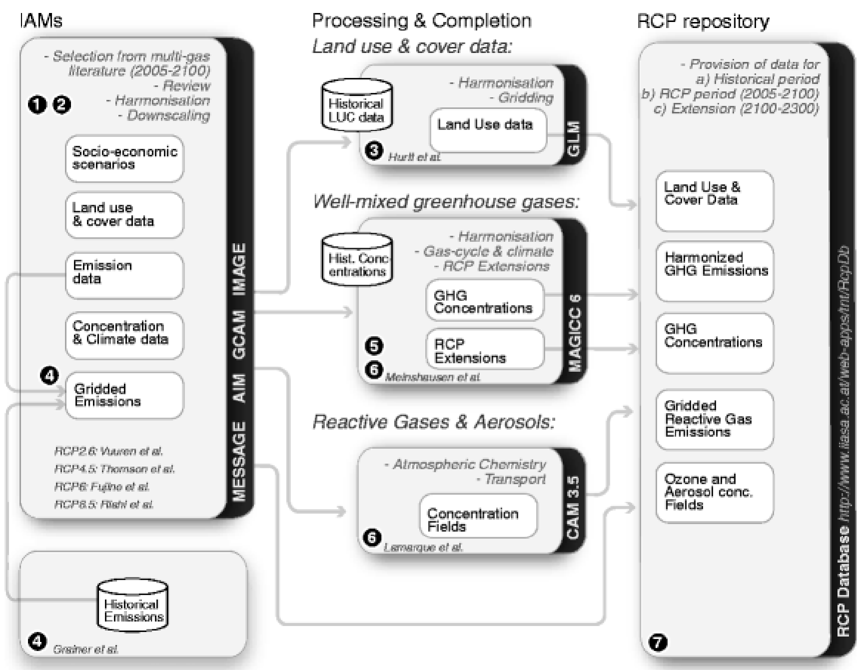
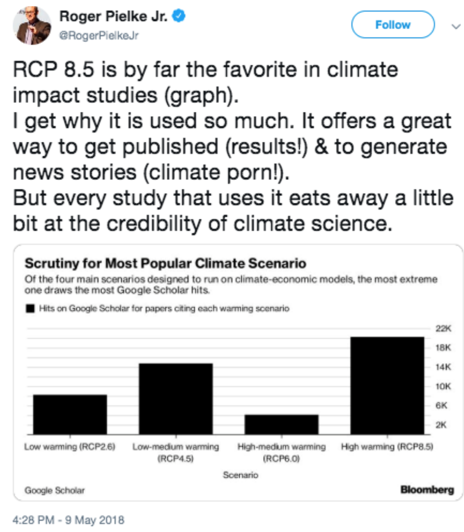


Figure 3[n] || Schematic illustrating the development process of representative climate pathways (RCPs). Generally, there are seven steps in the development of a pathway. 1) Four qualitative scenarios were selected from the literature; 2) The selected scenarios were calibrated with common base year emissions, land-use data, and reviewed by research groups for use in integrated assessment modeling; 3) Land-use data of RCPs was ensured to be consistent and downscaled; 4) Emissions data was calibrated and downscaled; 5) Emissions data is converted to concentration data using carbon-cycle model where gases are well-mixed, and atmospheric chemistry model where gases are reactive; 6) Extension data for 2100-2300 horizons developed; 6) Data - both projections and underlying calibration, base year data is made available to the public in both geographically aggregated and disaggregated form.

There are inherent tradeoffs in complex model construction, and just because the four models were selected as being representative of the existing literature does not mean that the existing literature is the best source to work from. See section 3.4 for examples of controversial inputs within IAMs: many assumptions need to be made to construct IAMs, and if scenarios are created based on IAM outputs, that indicates a risk of problematic compounded effects within the scenarios themselves.

Furthermore, even though many researchers attempt to validate the models against historical data, it’s still a limited, and possibly biased process: modeling results might influence decision-makers so that assumptions become self-fulfilling or self-defeating. “The most appropriate representations of human preferences are changing and contested… Decision makers may even respond reflexively to modeling analysis, changing the relationships enshrined within the models."[cc]

Putting aside the question of economic assumptions and technology adaptation, there is also the matter of how likely such a combination is to happen, and which scenarios are worthwhile to incorporate into research studies and serve as the basis of policy-informing analyses. For example, there is a fair amount of skepticism surrounding the RCP8.5; it has been called unlikely as it may well overestimate the supply of fossil fuel[dd]. Some go as far as to say its inclusion is just to encourage sensationalist journalism[ee].



3. Three Primary Simple IAMs Used to Calculate SCC

3.1 Key Functions

3.1.1 FUND

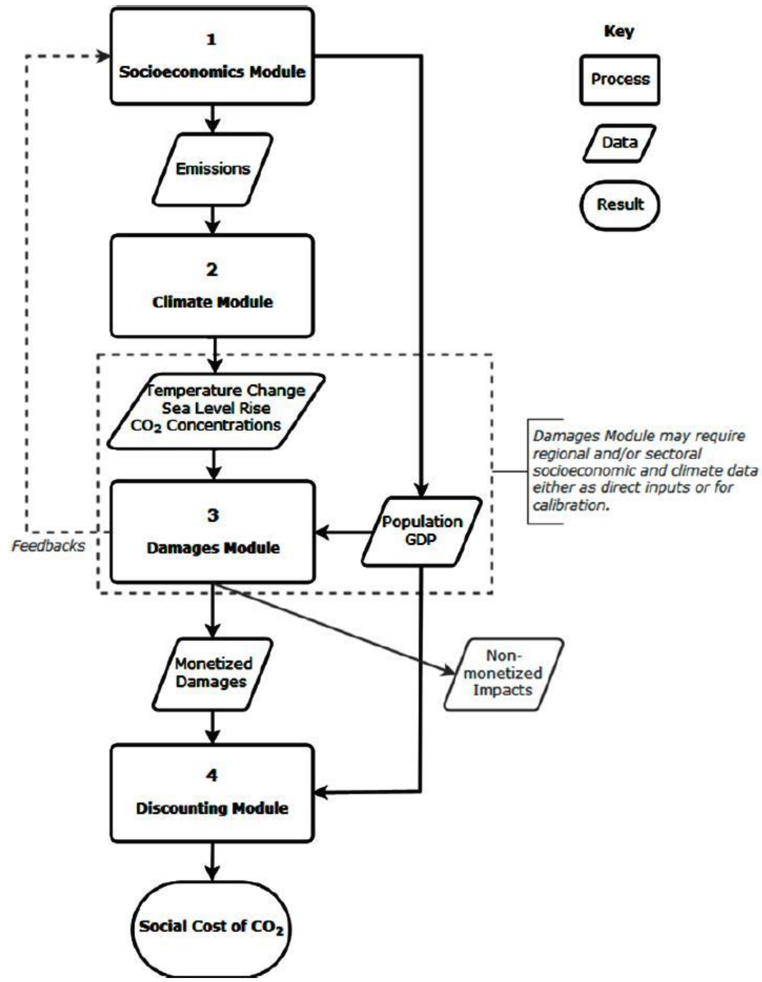


Figure 4[hh] || Schematic for general simple IAM development.

The FUND model was initially created by Professor Richard Tol at the University of Sussex, an established climate change economics expert, to evaluate the impact of capital transfers from rich countries to poor countries to fight climate change.[ff] More recently, the model has expanded beyond its original purpose, and is often used to calculate the SCC. The model tends to produce smaller SCC values compared to other models, varying from $0.30 per metric ton to $28 per metric ton, depending on the assumed discount rate; this difference is indicative of Tol's unique approach - unlike the DICE and PAGE models, the FUND model also incorporates *benefits* from emissions.

The model[15] divides the world into 16 regions, which are independent of each other for almost all parameters. Some values - e.g. total carbon emissions - are global, but the model generally takes a regional approach. Like with most Integrated Assessment Models, FUND begins with a climate model, and then translates that into an economic model. Emissions, which are a function of economic carbon intensity, economic growth and population growth, are considered to be global. Economic and population growth are from old IPCC scenarios. Radiative forcing is then calculated from emissions levels. After that, economic costs are calculated by applying the physical climate changes to damage functions

[15] The FUND model version discussed in this paper is 3.9, the most recent edition with sufficient documentation.

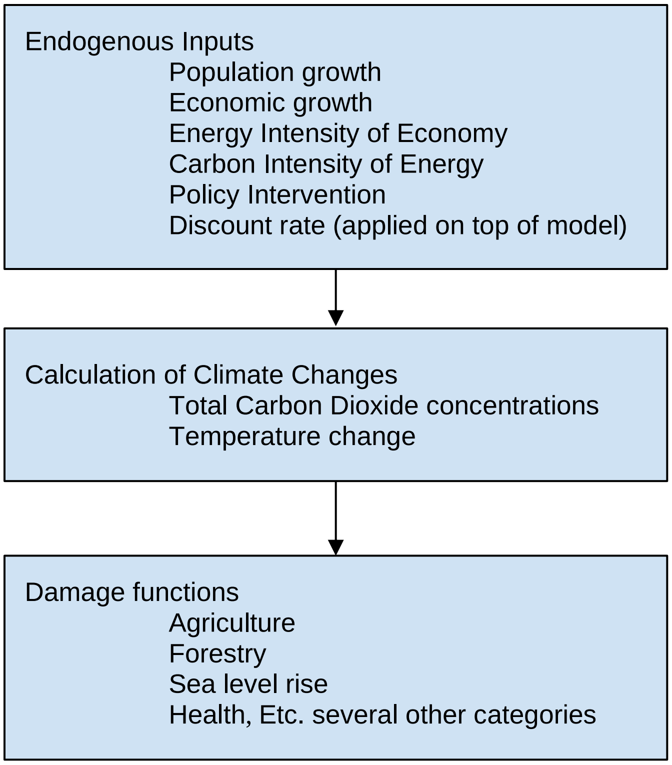


Figure 5 || Overview of FUND Model.

across a range of categories, like agriculture, forestry and sea level rise. The model does not have feedback loops. Significant portions of the model's input data date back to the 1990s.

The model starts off by assuming endogenous variables that determine the amount of Carbon emissions according to the following equation:

$$M_{t,r} = \frac{M_{t,r}E_{t,r}Y_{t,r}}{E_{t,r}Y_{t,r}P_{t,r}}$$

$$= \psi_{t,r}\varphi_{t,r}Y_{t,r} \ (1)$$

Here, M is emissions, E is energy, Y is GDP and P is population; t is the index for time and r is for region. Carbon intensity of energy use and energy intensity of production are as follows:

$$\psi_{t,r} = g^{\Psi}_{t-1,r}\psi_{t-1,r} - \alpha_{t-1,r}\tau_{t-1,r} \ (2)$$

$$\varphi_{t,r} = g^{\varphi}_{t-1,r}\varphi_{t-1,r} - \alpha_{t-1,r}\tau_{t-1,r} \ (3)$$

where τ is policy intervention or carbon tax and α is a parameter related to the temporality of emissions reductions - more on this in a moment. The growth rates g are energy efficiency improvements that have different values for various scenarios.

Policy interventions are modeled as follows:

$$M_{t,r} = (\psi_{t,r} - \chi^{\psi}_{t,r})(\varphi_{t,r} - \chi^{\varphi}_{t,r}) \ (4)$$

$$\chi^{\psi}_{t,r} = \kappa_{\Psi}\chi^{\psi}_{t,r} + (1 - \alpha_{t-1,r})\tau^{\Psi}_{t-1,r} \ (5)$$

$$\chi^{\varphi}_{t,r} = \kappa_{\varphi}\chi^{\varphi}_{t,r} + (1 - \alpha_{t-1,r})\tau^{\varphi}_{t-1,r} \ (6)$$

α is between 0 and 1 and states which part of emissions reduction is permanent, with lower values meaning more permanent. κ represents the rate at which emission reductions fade over time.

$$\alpha_{t,r} = 1 - \frac{\tau_{t,r}/100}{1+\tau_{t,r}/100} \quad (7)$$

Cost of emissions reductions are also calculated from the following equations:

$$\frac{C_{t,r}}{Y_{t,r}} = \frac{\beta_{t,r}\tau_{t,r}^2}{H_{t,r}H_t^g} \quad (8)$$

$$\beta_{t,r} = 0.784 - 0.084\sqrt{\frac{M_{t,r}}{Y_{t,r}} - min_s \frac{M_{t,s}}{Y_{t,s}}} \quad (9)$$

C is the cost of emissions reduction, H is the stock of knowledge, while B is a parameter that is designed to make emissions reduction more costly for regions with lower emissions. The stock of knowledge H is dependent on the carbon policy value $\tau_{t,r}$and accumulates over time. Cutting emissions quickly is also modeled to be more expensive than cutting over time. Total stock of knowledge has a global component as well as local component. In this respect, policy interventions in one region would benefit other regions as well.

Other greenhouse gases that contribute to radiative forcing (e.g. methane, nitrous oxide, and sulfur hexaflouride) follow single scenarios outlined in IS92a[gg]. Radiative forcing is calculated form a empirical model considering the aforementioned greenhouse gases.

Temperature rise is calculated as follows:

$$T_t = \left(1 - \frac{1}{\varphi}\right)T_{t-1} + \frac{1}{\varphi}\frac{CS}{5.35ln2}RF_t (10)$$

In this equation, φ is the e-folding time. The climate sensitivity term (CS) can be adjusted based on assumptions but is kept around 3 degrees celsius.

Other noteworthy facets of the key variables and functions include that regional temperatures are based on the global temperature, with changes multiplied by a fixed factor to account for differences by region; sea level is considered to increase proportionally to temperature.

The damages are the more interesting parts of the model. Agriculture is possibly the most important cost element in the model, but its calculation remains highly uncertain. In the model, agriculture is comprised of three different elements: first, an increase in agricultural production due to higher carbon emissions; second, a reduction due to a need to adapt; and third, possibly positive or negative, a measure of whether a region is moving closer to or further from the optimal conditions for agriculture. Several parameters are defined by Tol's "expert guesses", particularly when it comes to the costs of adaptation. The National Academy of Sciences cited agriculture as an area where FUND could be improved in modeling[hh].

The model also incorporates carbon fertilization, the concept that plants will grow more quickly with higher carbon dioxide concentrations and boost agriculture. Carbon fertilization can have a significant impact on the cost of carbon, especially because the benefits of carbon fertilization happen earlier than most of the damages. Carbon fertilization is one of the reasons that FUND gets lower SCC results than other models. Carbon fertilization is also dependent on carbon dioxide levels, which are easier to predict than temperature, suggesting that carbon fertilization may be an element with greater certainty in the model.

Forestry is also modeled in FUND, with a bit of speculation and expert guesses. Water resources is yet another impact, modeled through calibration of various parameters.

Energy consumption is also considered to change with global temperature. Space heating costs will decrease, while space cooling costs will increase. Assuming that the temperature predictions are accurate, these costs could be fairly reasonably calculated, as these technologies are likely to remain similar for an extended period of time. The National Academy of Sciences specified energy demand as an area for improvement regarding the damage function and in light of recent literature.

Sea level rise takes the climate impact calculated earlier and adds an economic value to it. FUND calculates the losses for dryland and wetland separately. Protection is a theoretical possibility for dryland as a means to reduce costs. However, the model does use dryland land values as a constant over large areas, which may be inappropriate as land values vary extremely based on the location. FUND further explores protecting all, just the wetlands, or no protection, as further scenarios. Coastal protection was an area noted by the National Academy of Sciences as a possible area for improvement with more recent research.

Ecosystems is a rather bizarre cost, modeling a species going extinct as a specific cost, with cost increasing as the total number of species falls. This cost is highly speculative.

Finally come the costs that are related to human mortality. These include health risks, like Diarrhoea, vector borne diseases, and cardiovascular and respiratory mortality. Also considered are disaster-related events, like storms or extreme weather. Mortality is related to the value of a statistical-life. Mortality and human health were also recommended as areas needing improvement by the National Academy of Sciences.

Related to sea level rise is a modeled increase in tropical storms; wind speeds are known to increase with temperature, potentially increasing storm damage. Mortality, along with property damage, contribute to the damage function.

The calculation of all of these damages take place within the model itself, but the final tabulation, including the use of the discount rate, is done external to the model. The damages do not feedback to the beginning of the model, which only incorporates endogenous variables.

3.1.2 DICE

The Dynamic Integrated model of Climate and the Economy, or DICE, is a global SCC IAM that was popularized by Nobel Prize winner William Nordhaus[ii]. Based on 2016 model revisions and the 5th Assessment Report of the IPCC, DICE estimates SCC at $31 per metric ton of CO_2 in 2010 USD. The DICE model is rooted in economic growth theory, and uses the standard neoclassical optimal growth model known as the Ramsey equation. It is embraced in the Stern Review as “the organizing concept for thinking about intertemporal choices fro policies for global warming”[jj]. This fundamental equation assumes that people invest in capital goods that reduce today’s consumption in exchange for greater future consumption. One adaptation, which will be discussed in greater detail in the following paragraphs, is the inclusion of climate investments into Ramsey, which are treated similarly to capital investments.

The DICE model optimizes two variables – well-being and consumption – through a series of behavioral equations. The output of these equations provides values for variables used in the SCC estimate, where the $SCC(t) \equiv -[\partial W/\partial E(t)] / [\partial W/\partial C(t)]$[kk]. In essence, the SCC is defined in this model as the marginal impact of emissions on welfare, relative to the marginal welfare value of a unit of aggregate consumption in a given period t.

The model begins with the *Social Welfare Function* W(t) which captures the cumulative utility of consumption over time, while accounting for social discount rates. Utility estimates U(t) consider per capita consumption c(t) and total population L(t), along with a generational inequality aversion (α), or the willingness of today's generation to curb consumption for the benefit of future generations. A low α, for example, indicates that consumption across different generations could be thought of as substitutes. It is worth noting that consumption relates not only to traditional market goods, but also to non-market goods such as health or environmental well-being. The discount factor R(t) includes the pure rate of social time preference (ρ), or a welfare weight on utility across generations[ll].

$$W = \sum U[c(t), L(t)]R(t) \quad (1)$$

$$1a.\ U[c(t),L(t)] = L(t)[c(t)^{1-\alpha} / (1-\alpha)]$$

$$1b.\ R(t) = (1+\rho)^{-t}$$

The *Net Output Function* Q(t) then measures gross output less damages and mitigation costs. Key variables in the function include Y(t), or the gross output as measured by the Cobb-Douglas function of capital, labor and technology. Global output is based on purchasing power parity (PPP) assumptions employed by the International Monetary Fund (IMF), whereby output growth is a weighted growth rate of real GDP for countries based on their relative share in world nominal GDP[mm]. Gross output is then multiplied by the abatement-cost function and damage function, which will be outlined next. The intuition behind the Abatement-Cost Function is that costs associated with emissions reductions are dependent upon the reduction rate μ(t) and output.

$$Q(t) = \Omega(t)[1 - \Lambda(t)]Y(t) = C(t) + I(t) \quad (2)$$

$$2a.\ \Lambda(t) = \theta_1(t)\mu(t)^{\theta}$$

$$2b.\ \Omega(t) = D(t)/[1+D(t)]$$

$$2c.\ Y(t) = A(t)\,K(t)^{r}\,L(t)^{1-r}$$

The *Damage Function* D(t) is one of the most disputed functions in all climate change IAMs. The DICE damage function is based on the assumption that damage can be approximated by a quadratic function of globally averaged temperature change (TAT), but fails to consider tipping points or thresholds should temperatures reach extremes not yet modeled. While monetary damages are approximated beginning with survey data from Tol (2009)[nn], an additional 25% adjustment is included to account for factors omitted from Tol's study[oo]. Examples of omitted criteria include impacts to biodiversity, political reactions, sea-level rise, catastrophic events, and an array of additional factors inherently difficult to model. It's worth noting that 25% is largely a judgmental approximately, whose value might very well be much different in actuality.

$$D(t) = \psi_1 T_{AT}(t) + \psi_2 [T_{AT}(t)]^2 \quad (3)$$

Total CO_2 Emissions E(t) are then modeled through an approximation of industrial carbon intensity σ(t) and the emissions reduction rate, and their impact on gross output. There is an additional consideration for exogeneous land use emissions.

$$E(t) = \sigma(t)[1 - \mu(t)]Y(t) + E_{Land}(t) \quad (4)$$

The final two equations are used to link economic outcomes with geophysical forces. The *Carbon Cycle Function* accounts for carbon in the atmosphere (MAT), upper oceans and biosphere (MUP), and lower oceans (MLO). Carbon flows in both directions between adjacent reservoirs, accounted for by flow parameters ϕ_{ij} between each. Emissions will ultimately flow into the atmosphere, while deep oceans serve as a sink for carbon in the long run. It's widely accepted that this simplification of the carbon cycle involves tradeoffs between accuracy and transparency.

$$M_j(t) = \varphi_{0j} E(t) + \sum \varphi_{ij} M_i(t - 1) \quad (5)$$

Based on carbon accumulations in the atmosphere, the *relationship between greenhouse gas (GHG) accumulations and increased radiative forcing* can be modeled to determine the change in total radiative forcings caused by humans F(t). The output of this function is then incorporated into a *two-level global climate model* that estimates the mean surface and lower oceans temperatures.

$$F(t) = \eta\{\log_2[M_{AT}(t)/M_{AT}(1750)]\} + F_{EX}(t) \quad (6)$$

6a. $T_{AT}(t) = T_{AT}(t - 1) + \xi_1\{F(t) - \xi_2 T_{AT}(t - 1) - \xi_3[T_{AT}(t - 1) - T_{LO}(t - 1)]\}$

6b. $T_{LO}(t) = T_{LO}(t - 1) + \xi_4[T_{AT}(t - 1) - T_{LO}(t - 1)]$

The *Ramsey equation* provides "the equilibrium rate of return in an optimal growth model with constant growth in population and per capita consumptions without risk or taxes" (W. D. Nordhaus 2017a). In other words, it is used for the purposes of discounting. This variable, which Nordhaus describes as "the wild card in calculations of the SCC," is another point of contention that has large implications for resulting SCC values[pp].

$$r = \rho + \alpha g \quad (7)$$

In this equation, the real interest rate depends on the pure rate of social time preference (ρ), the growth in per capita output, consumption, and damages (g), and consumption elasticity (α). In the DICE model, the use of the Ramsey equation begins with the selection of an r value that matches the real goods interest rate, which Nordhaus determines to be 4.5%. The growth rate, g, is also assumed to be exogenous with values declining from 2.2% to 1.9% through 2100 based on data from the United Nations and the Carbon Dioxide Information Analysis Center[qq]. In this model, damages are presumed to begin immediately, with the damage-output ratio declining at a decay rate of ɗ per year.

From here, the model is calibrated to determine ρ and α values. Rho can be thought of as as a generational discount rate, whereby the welfare or utility of future generations is discounted relative to today's generation. Alpha can be thought of as our willingness to delay consumption today so we can consume more in later periods. These variables are the source of ethical debate since some believe they serve to prioritize current generations over future generations. Since these values can be rather subjective across various IAMs, they are often the source of discounting discrepancies that result in conflicting SCC values.

3.1.3 PAGE

3.1.3.1 Development and utilization

The PAGE2002 and PAGE09[rr] models were developed at the Cambridge Judge Business School, and the PAGE2002 model was notably selected as one of the three IAMs informing the SCC that is now in use by the federal government of the United States, in the Stern Review[ss], and the Asian Development Bank's review of climate change in Southeast Asia[tt].

3.1.3.2 The model

The entire model consists of 53 equations[16], which are parcelled out into four steps:

1. Computing the global temperature rise (Equations 1- 21)
2. Computing the value of global warming impacts (Equations 22 - 39)
3. Computing costs of implementing adaptive and preventative policies (Equations 40 -53)

[16] See Appendix II

4. Representing uncertainty

Importantly, the model takes the approach of calculating effects - both impacts and costs - in one focus region, which they determined to be the European Union, and then scales other regions accordingly using different sets of regional multipliers for different estimates.

3.1.3.2.1 Computing the global temperature rise

$$GRT_i = \frac{\sum_r \quad RT_{i,r} * AREA_r}{\sum_r \quad AREA_r} \text{ (II.21)}$$

The global temperature rise is estimated by averaging the regional temperature rises per year (II.21). This is done by aggregating the estimated greenhouse gas emissions in each region simply informed by regressions of past data. The gases considered in the PAGE2002 model include carbon dioxide, methane, nitrous oxide, and a fourth parameter for linear, trace gases. An individual radiative forcing function is derived for every single gas (II.13-18), and in particular the half-life of carbon dioxide gas is also separately modelled to account for absorption of carbon dioxide emissions by oceans and forest.

$$FT_i = \sum_g \quad F_{g,i} + EXF_i \text{(II.16)}$$

The aggregate radiative forcing from all of these gases (II.16) are scaled by climate sensitivity parameters to attain an equilibrium temperature, representing the expected temperature that the region will warm to by the end of the model horizon (Equation 19).

$$ET_{i,r} = \frac{SENS}{ln(2)} * \frac{FT_i + FS_{i,r}}{FSLOPE_1} \text{(II.19)}$$

In each analytical period, the Earth attains a “realized temperature”, which is a function of dividing up the difference between the equilibrium and present day temperature amongst the modelled years (Equation 20).

$$RT_{i,r} = RT_{i-1,r} + \ (1 - exp\ (\frac{Y_i - Y_{i-1}}{OCEAN}) * (ET_{i,r} - RT_{i-1,r}) \text{ (II.20)}$$

Eventually, the estimates in temperature rises are weighted by area of the regions, and aggregated to attain a global temperature rise estimate (II.21).

3.1.3.2.2 Computing the value of global warming impacts

Once the global temperature rise is modelled, the value of global warming impacts is determined by valuing the effect of the temperature rise in different sectors. Importantly, the model only assumes two damage sectors: economic (*d = 0*) and noneconomic (*d = 1*).

Two key assumptions are made here: impacts for temperature rise only occur if the rise is in excess of some range of tolerable change (TR), or if the cumulative change exceeds the tolerable plateau (TP). Both of these parameters are stochastic, and are essentially unknowns that have not yet been able to be projected by climate scientists.

$$WI_{i,d,r} = (\frac{I_{i,d,r}}{2.5})^{POW} * W_{d,r} * (1 - \frac{IMP_{i,d,r}}{100}) * GDP_{i,r} \text{ (II.31)}$$

$$WIDIS_{i,r} = IDIS_i * (\frac{PDIS}{100}) * WDIS_r * GDP_{i,r} \text{(II.32)}$$

In modeling impacts, or damage, two types of impacts are considered: first, effects on GDP by aggregating effects from the different sectors (II.31), and second, effects from discontinuity (II.32). Discontinuity refers to large, catastrophic events with high costs, such as the complete melting of ice sheets, flooding of key coastal productive hubs, etc. Both of these effects are weighted for every single region and aggregated. Importantly, the weighting for individual impacts is done by an exponent *POW*, which is subject to the choice of the modeller.

$$WIT_{i,r} = \sum_d \quad WI_{i,d,r} + WIDIS_{i,r} \text{ (II.33)}$$

$$AD_{i,r} = WIT_{i,r} * (Yhi_i - Ylo_i) \text{ (II.38)}$$

Yearly impact for each region is arrived at by summing the weighted effects in the two aspects in the abovementioned paragraph (Equation 33), and then aggregated across all years in the analysis period (38). This assumes that the amount of damage in each year in the analysis period is the same, which may be a dubious claim.

$$DD = \sum_{i,r} \quad (AD_{i,r}) * \Pi_{k=1}{}^{i}(1 + dr_{k,r} * \frac{ric}{100})^{-(Y_k - Y_{k-1})} \text{ (II.39)}$$

From here, to arrive at global effects, two discount rates are incorporated into the model to discount the simple aggregate damage (II.39):

- *dr* - Discount rate for costs. A value that is used to discount the costs of policy implementation.

- *ric* - Impact discount rate multiplier. A value that is used to discount the costs related to climate change impacts. This is where the Ramsey equation, and subsequently the pure rate of time preference, if used to calculate the discount rate, gets factored in.

3.1.3.2.3 Computing the costs of implementing adaptive and preventative policies

Before continuing on review of this step in the model, it is important to note that this part of the model is not used in the calculation of marginal impacts. As a result, it is also unclear if this aspect of the model was utilized to arrive at the SCC, and if it were, what parameters were used.

Adaptation refers to the evolutionary ability of the human race and behaviours that increase the Earth's and our race's ability to tolerate climate change. Thus, the tolerable level of temperature change will be increased with adaptation, and some climate change impacts can be mitigated.

$$AC_{i,d,r} = CS_{d,r} * SLOPE_{i,d,r} + CP_{d,r} * PLAT_{i,d,r} + CI_{d,r} * IMP_{i,d,r} \text{(II.43)}$$

Cost of Slope Adaptation (CS), Cost of Plateau Adaptation (CP), and Cost of Impact Adaptation (CI) are uncertain adaptive cost parameters, corresponding to the two aspects - slope and plateau - that make up the tolerance level, and the change in impact. The costs are estimated with respect to a focus region estimate, and scaled by a regional multiplier.

$$AAC_{i,d,r} = AC_{i,d,r} * (Yhi_i - Ylo_i) \text{ (II.44)}$$

$$DAC = \sum_{i,d,r} AAC_{i,d,r} * \Pi_{k=1}{}^{i} (1 + \frac{dr_{k,r}}{100})^{-(Y_k - Y_{k-1})} \text{ (II.45)}$$

The effect from these three terms are then aggregated assuming the costs are the same each year (II.44), and discounted with the discount rate for costs (II.45).

The other type of policy is that of **preventative policies**, which are aimed at reducing the emissions of different greenhouse gases into the atmosphere. Successful attempts at doing this are referred to as cutbacks (CB).

$$if\ CB_{i,g,r,} < MAX_{g,r,0}: PC_{i,g,r} = (\frac{CL_{g,r} * MAX_{g,r}}{100} + CL_{g,r} * \frac{CB_{i,g,r} - MAX_{g,r}}{100}) * E_{i=0,g,r}$$

$$Otherwise: PC_{i,g,r} = (\frac{CL_{g,r} * MAX_{g,r}}{100} + (CL_{g,r} + CH_{g,r}) * \frac{CB_{i,g,r} - MAX_{g,r}}{100}) * E_{i=0,g,r} \text{ (II.51)}$$

Similar to adaptive policies, the costs are modelled by a handful of uncertain terms, CL and CH. The prior refers to costs from cheap preventative measures that require little research and development, such as cuts to consumption, better waste processing, just to name a few. The latter refers to costs from more expensive preventative measures that will require research and development, and are likely currently unattainable, such as carbon sequestration or even negative emissions methods. This term is only triggered if the cutbacks exceed the maximum (MAX) amount of emissions that can be cut back using cheap preventative policies. As such, explicit policies are not modelled - these parameters are completely hypothetical and subject to the choice of a random number generator.

$$APC_{i,d,r} = PC_{i,d,r} * (Yhi_i - Ylo_i) \text{ (II.52)}$$

$$DPC = \sum_{i,d,r} \quad APC_{i,d,r} * \Pi_{k=1}{}^{i}(1 + \frac{dr_{k,r}}{100})^{-(Y_k - Y_{k-1})} \text{(II.53)}$$

The effect from these two terms are then aggregated assuming cost of each year in the analysis period is the same (Equation 52) and discounted with the discount rate for costs (II.53).

3.1.3.2.4 Accounting for uncertainty

Recognizing that most of these estimates are rooted in unknowns, scattered across the model are "uncertain", or stochastic parameters that change in every run of the model, and thus increase variability of the results that are produced from this model. To do this, Latin Hypercube Sampling, a random sampling method, is used to select a different set of values for ~ 80 "uncertain" input parameters.

3.1.3.3 Key hurdles to model accuracy

In modeling the marginal impact of emissions, the original PAGE2002 model identified six major unknowns affecting modeling accuracy:

1. *Climate sensitivity*

As with many climate models of the time, it is unknown how the climate will response to aggregate temperature increase and other associated phenomena, such as deforestation, erosion, sea level rise, to name just a few. Higher sensitivity of the climate towards changes in the environment would possibly lead to more drastic consequences and impacts, and is a great source of variability in the model results.

2. *Non-economic impact parameter*

While impact is separated into economic and non-economic sectors, is it even possible to indicate what type of damage is non-economic? The unobservable nature of non-economic, and therefore less easily quantifiable effects led to its immense influence in the model, and thus became a hurdle to model accuracy.

3. *Impact function exponent*

Since the modeller is able to choose whatever exponent he wishes for the impact function to take upon, the impacts of emissions can vary wildly depending on this single variable.

4. *Half-life of global warming*

The justification for the variability induced by this parameter is similar to that of (1) - Climate sensitivity. The parameter currently assumes homogenous life cycle of global warming and the gases that are trapped in the atmosphere, but this could be subject to change as the make-up of the atmosphere changes.

5. *Indirect sulphate parameter*

Due to the nature of sulphate aerosols, it is difficult to estimate the unobserved effect (thus, indirect) of sulphate emissions. In response to this, the PAGE09 model allows for PSE and EXF to vary by policy, but this solution is not completely foolproof, since the parameter remains one of the most influential factors of the model.

6. *Tolerable temperature rise before discontinuity*

Since discontinuity is such a catastrophic event, the costs associated are immensely high, and even the slightest variation in the temperature rise prior to triggering discontinuity could increase variability of the model results by a large fraction.

3.1.3.4 Key updates from PAGE2002 to PAGE09

Aside from those mentioned above, As an update to the PAGE2002 Model, the PAGE09 model takes into account all six gases in the Kyoto protocol, implying that the resultant externalities calculated are no longer limited to only carbon dioxide, but also nitrous oxide, as well as an aggregate “gas” representing low concentration gaseous pollutants such as HFCs, PFCs and SF_6. Carbon dioxide (CO_2) and methane (CH_4) remain separately modelled.

In recent years, an important development in climate modeling has been to take account the possibility of transient climate response. In simple terms, an "uncertainty" or buffer term is included to model the possibility of a more responsive climate to adverse scenarios than is currently predicted - also termed climate sensitivity. In PAGE2002, climate sensitivity is an uncertain parameter, which PAGE09 aims to define from two inputs -

- the transient climate response (TCR): temperature rise at the end of 70 years of carbon dioxide concentration rising at 1% per year, thus corresponding to a doubling of carbon dioxide concentration
- Half-life of global warming / Feedback Response Time (FRT) of the Earth to a change in radiative forcing

Ocean factors

The PAGE2002 model also does not take into account sea level rise and the damages associated with. In the PAGE09 model, the sea level rise is linked to temperature rise:

$$es(i) = SLTEMP * rt_{g(i)} + SLA$$

$YP(i) = Y(i) - Y(i-1)$ where $YP(1) = Y(1) - 0$and $i = 2,...,10$

$$EXPFS\ (i) = exp\ (\frac{-YP(i)}{SLTAU})$$

YP(i) = Y(i) - Y(i-1) where

- S - sea level
- es - equilibrium sea level
- SLTEMP, SLA, SLTAU - sensitivity parameters of sea level to temperature, asymptotic sea level rise (no temperature change), characteristic time for sea level to respond to temperature rise respectively. These uncertain parameters require the input of $S(0)$, which brings the number of uncertain parameters to 4 in total, in addition to the ~80 that already currently exist in the model.

Compared to the PAGE2002, PAGE09 delineates the following as the renewed, 7 most influential factors in the model :[17]

[17] https://pdfs.semanticscholar.org/6add/77639773f551e8fc55a0799fde72f55df7fa.pdf

1. TCR - Transient Climate Response
2. PTP - Pure Time Rate of Preference
3. EMUC - Equity weightings
4. FRT - Feedback Response Time, also the half-life of global warming
5. IND - indirect forcing increase, also an uncertain, stochastic parameter, for a doubling of the natural sulphur flux
6. POW_2 - power of impact exponent function for nitrous oxides (g = 2)
7. W_2 - weights

Surveying these parameters, they have not changed much from the PAGE2002 influential parameters.

3.2 **Key Results**

3.2.1 FUND

The FUND model's results, when applied by the author Richard Tol, will be summarized here[uu]. FUND offers lower social cost of carbon calculations compared to other models. The social cost of carbon values from the FUND model are summarized in figure 6.

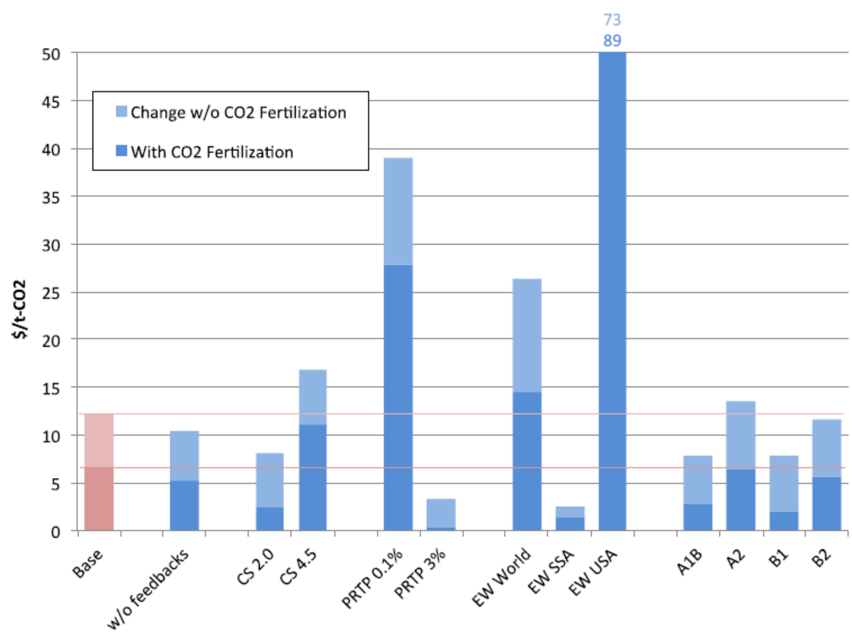


Figure 6[uu] || Social Cost of Carbon with Segmented CO_2 Fertilization Contribution

The "base case" estimate is \$6.6 per metric ton of carbon dioxide. The carbon fertilization calculated by the model makes a very large impact - without carbon fertilization, the base case would come out to \$12/t CO_2.

The greatest impact, however, comes from the discount rate, as shown in bars “PRTP 0.1%” and “PRTP 3%.” With a 0.1% discount rate, the social cost of carbon is around \$28/t-CO_2, while with a 3% discount rate the SCC is \$0.3/t CO_2.

Then there is the question of equity weighting, which considered variations in regional GDP and the impact of climate change on poorer readings. The social cost of carbon is \$14/t-CO_2 with these weightings on the world average, with U.S. weighting around \$89/t-CO_2 and sub-Saharan African weighting around \$1.4-t/CO_2, as shown by the “EW” bars.

Equity weighting is a method trying to emphasize climate damages in poorer regions since populations in those regions, having lower overall consumption, are thought to lose more utility due to climate damages. This is why the equity weighting using the world average is higher than the base case. Equity weighting is standardized to a certain region to make comparisons across regions possible. The world average, U.S. weighting and sub-Saharan African weighting are all global metrics but standardized to different parts of the globe. Because the U.S. has much higher consumption, using it as the equity weighting standard leads to a much higher SSC, as its expressed relative to US levels of consumption.

The scenario used also has an impact. The SCC is highest in the high emissions/high growth scenario A2 at \$6.5/t-CO_2, while lowest in the low growth low emissions scenario B1 at \$2.0/t-CO_2.

Finally, certain regions are impacted by climate change differently than others. Some regions, like Russia, will likely benefit in total as their climate becomes more suitable to agriculture and forestry. All regions benefit from carbon fertilization, but for most regions these benefits are offset by damages in other categories, making climate change a cost for the world as a whole.

3.2.2 DICE

The DICE model relies on several key assumptions that ultimately influence its final results. These assumptions include global per capita output growth of 2.2% per year from 1980-2015, 2.1% per year through 2050, and 1.9% through 2100. These numbers are based on population data from the United Nations and CO_2 emissions data from the Carbon Dioxide Information Analysis Center[vv]. Furthermore, the model assumes that damages amount to 2.1% of global income in the event of 3 degrees of warming. Given recent trends in increased decarbonization, the DICE-2016R model uses the IMF output concept of decarbonization to assume a rate of -1.5%[18]. It is still unclear as to whether the sharp downward tilt in recent years can be attributed to climate policies.

The Ramsey equation is also critical in arriving at a final SCC value. In the DICE-2016R model, it is assumed that the discount rate is 4.5%, based on observed economic returns on capital. Here, a “descriptive approach” to discounting was used, whereby lower discount rates for the United States are averaged with higher values for less developed nations[ww]. Additionally, the pure rate of social time preference is assumed to be 1.5% per year, and consumption elasticity to be 1.45. These variables are often debated across various models.

Baseline results for the DICE-2016R model assume there have been no changes to climate policy since 2010 levels. The resulting SCC value is $31.20 in 2010 USD. However, DICE has also been modeled along different parameters to illustrate how SCC values change under different assumptions. The first alternative approach assumes optimal policy controls, meaning the path of emissions reductions and investments is optimized. Optimal policies are defined as those that maximize economic welfare, with “full participation by all nations starting in 2020”[xx]. Perhaps surprisingly, the two values are not very different. This is because optimized emissions have only a slight impact on marginal damages in early periods.

The next set of alternatives caps temperature increases at 2.5 degrees Celsius above 1900 levels. Prior versions of the model sought to cap temperature increases at 2 degrees, which have since been deemed unrealistic given carbon emissions rates in recent years. Since baseline SCC estimates are predicted to yield an approximately 4 degree increase in global mean temperatures from 1900, SCC values drastically increase under these temperature capped provisions.

Next, the Stern Review assumes a social time preference close to zero, deeming it immoral to discount the well-being of future generations. By reducing ρ to 0.001, the SCC reaches a value that is nearly 6.5 times greater than the baseline rho value of 0.015. Lastly, DICE-2016R has been modeled under different discount rates. Similar to adjustments in ρ, small adjustments in r

---

[18] The decade through 2010 showed relatively slow decarbonization, with the global CO2/GDP ratio changing at −0.8% per year. However, the most recent data indicate a sharp downward tilt, with the global CO2/GDP ratio changing at −2.1% per year over the 2000–2015 period (preliminary data) (Nordhaus, 2017)

can have great implications for final SCC values. Results of these various approaches can be found in Table 3[19].

Social Cost of Carbon (2010 U.S. Dollars / Ton of CO_2)

Scenario	2015	2020	2025	2030	2050
Base parameters					
Baseline	30.0	35.7	42.3	49.5	98.3
Optimal controls	29.5	35.3	41.8	49.2	99.6
2.5 degree maximum					
Maximum	184.1	229.0	284.0	351.0	1,008.4
Max. for 50 years	147.2	183.2	227.2	280.4	615.6
Stern Review discounting					
Uncalibrated	256.5	299.6	340.7	381.7	615.5
Alternative discount rates					
2.5%	111.1	133.4	148.7	162.3	242.6
3%	71.6	85.3	94.4	104.0	161.7
4%	34.0	39.6	44.5	49.8	82.1
5%	18.9	21.7	24.8	28.1	48.4

Table 3[ss] || SCC Values under various DICE assumptions.

The DICE-2013R model was the basis for much climate discussion prior to the 2016 revision. As shown in the following chart, 2013 SCC values changed quite dramatically as new information became available (W. D. Nordhaus 2017a). By updating a handful of variables – most notably components of the damage function, carbon cycle, and estimated economic activity – SCC estimates increased 68% in just 3 years. This chart is included to illustrate how quickly and drastically SCC values can fluctuate based on revised information and assumptions.

It is worth noting that there are several critiques, most notably from the National Academy of Sciences, associated with the underlying assumptions of DICE model[hh]. First, the climate component of the model excludes feedback between climate and the carbon cycle. Without frequent model updates, the compounding effects of this feedback will go unchecked, affecting the accuracy of its output. Additionally, the DICE model omits parametric uncertainty with respect to select variables. One such example relates to CO_2 pulse implementation[20]. By

Version	Model	SCC (2015), 2010 $	Change, %
1	Dice-2016	31.23	
2	1 + old damages	35.63	14
3	2 + old population	33.36	−6
4	3 + old temp sensitivity	30.58	−8
5	4 + old economics	21.25	−31
6	5 + old carbon cycle	16.01	−25
7	DICE-2013R	17.03	6

The table shows the impact of introducing model changes starting with the 2016 model and ending with the 2013 model in a step fashion. The last column shows the change moving from a later specification to an earlier one. A negative number in the last column is a decrease from 2016 to 2013. For example, introducing "old economics" in version 5 lowers the SCC by 25% relative to DICE-2016. The two major changes are economic assumptions and the carbon cycle (see *Accounting for the SCC Changes Since DICE-2013R* for a discussion).

Table 4[hh] || Accounting for changes in SCC from DICE-2013R.

[19] Results were generated by Nordhaus in 2017. An interactive model capturing additional variables is available at http://webdice.rdcep.org/standard#graph:essential.

[20] See Key Definitions.

omitting a range of possible values for these inherently unpredictable variables, the accuracy of DICE is again limited.

3.2.3 PAGE

The PAGE model outputs the impacts of carbon dioxide emissions as a proportion of GDP, which can then be back-translated to attain a dollar value loss per metric ton of carbon dioxide emitted.

The default PAGE2002 model outputs the value of the SCC as $19 average per metric ton of CO_2, with a 5-95% range of $4-51 (Table XX), calculated for the scenario of implementing policies to reduce carbon emissions by 10%, which is A2 in the SRES scenarios that predated the SSPs.

	5%	mean	95%
		US$(2000)	
Total impact for 10% drop in carbon ($\times 10^9$)	3.6	15.5	40.8
Marginal impact per tonne carbon ($\times 1$)	4	19	51

Source: PAGE2002 model runs

Table 5[rr] || Default PAGE2002 Model Results.

Most notably, the PAGE2002 model was utilized in the Stern Review, a report that was comissioned by the Chancellor of the Exchequer in the United Kingdom in July 2005. The report had three broad goals - first, to understand the economics of the transition from a high- to low-carbon global economy, with sensitivity to timescale of the transition; second, to elucidate

Table 6.1 Losses in current per-capita consumption from six scenarios of climate change and economic impacts*.

Scenario		Balanced growth equivalents: % loss in current consumption due to climate change		
Climate	Economic	Mean	5th percentile	95th percentile
Baseline climate	Market impacts	2.1	0.3	5.9
	Market impacts + risk of catastrophe	5.0	0.6	12.3
	Market impacts + risk of catastrophe + non-market impacts	10.9	2.2	27.4
High climate	Market impacts	2.5	0.3	7.5
	Market impacts + risk of catastrophe	6.9	0.9	16.5
	Market impacts + risk of catastrophe + non-market impacts	14.4	2.7	32.6

*Utility discount rate = 0.1% per annum; elasticity of marginal utility of consumption = 1.0.

Table 6[ss] || Losses in global current per-capita consumption from 6 scenarios of climate change and economic impacts.

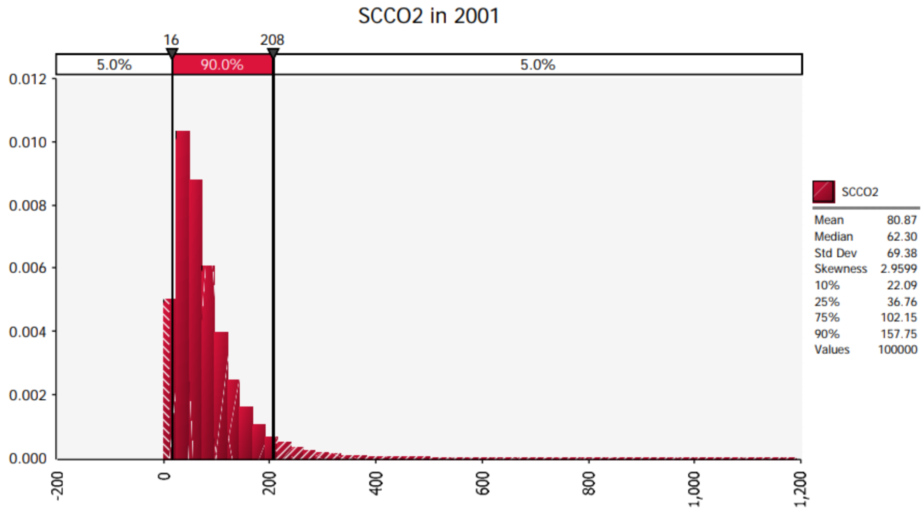


Table 8[rr] || Stern Model Results

the different approaches available for adaptation to climate change; third, to deepen analysis with specificity to the United Kingdom. Numerically, the report realized an SCC of $85 mean, much higher than the default model. The 5-95% range was $16-208, taking the A1B SRES scenario, which is the business-as-usual scenario in the narratives delineated by the IPCC prior to the development of the SSPs. It is important to note that the distribution of results is not normal, but in fact skewed heavily to the left, suggesting that while the SCC is definitely non-zero, it may not be that close to the astronomical $208 number. Though, the long tail suggests that there is the possibility of realizing a high SCC if catastrophic events occur.

A1B scenario	*2010*	
	Mean SCCO2	Drop from default
	$	%
Default model	**106**	
No non-economic impacts	62	*42*
No economic impacts	80	*25*
No sea level impacts	100	*6*
No discontinuities	79	*25*

Table 9[rr] || Stern Model Results. The underlying effects are broken down to indicate the contribution of economic, non-economic, sea level and discontinuity impacts towards the derived SCC.

Following the PAGE09 overhaul, the new calculated SCC from the default inputs is of mean $106/metric ton of CO_2, and a sensitivity range from $12 - $290/metric ton. The authors note that this is higher than the mean value of $102/metric ton reported in 2011, but is consistent with model assumption that the SCC will likely increase over time due to marginal damages with increase of stock of greenhouse gases in the atmosphere.

As is previously analyzed, it is important to note the distribution of results for the SCC calculated from the default PAGE09 model. The skewness is even more pronounced than that of

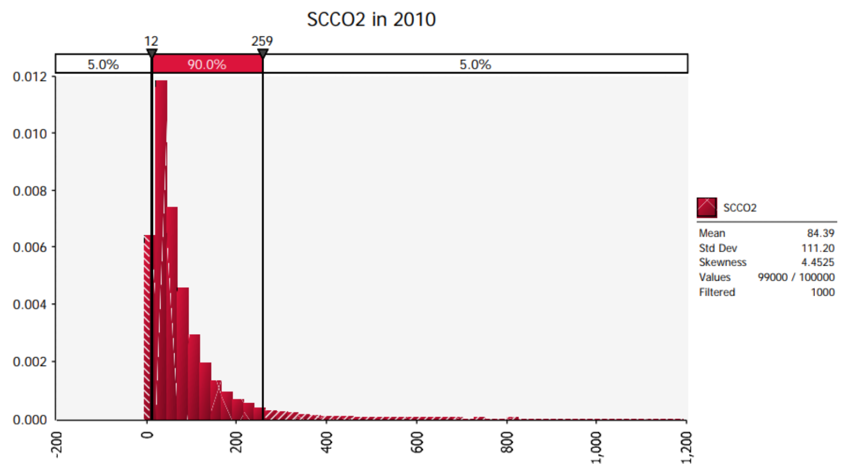


Table 10[rr] || Default PAGE09 Model Results Distribution. Notably, the top 1% of values were excluded in this visualization, as the shape of the distribution could not be observed otherwise due to the length of the tail.

the Stern model, though the mean is much higher, at $106. Some values of the SCC reach above $100,000. Removing the top 1% of SCC values, however, the skewness is more tenable, and the shape of the distribution more resembles that of the PAGE2002 results, and the mean hovers at $85, which is roughly the recommended value in the Stern Review.

3.3 **Differences across Modeling Techniques**

DICE, FUND, and PAGE share a similar framework that integrates economic output and emissions via key climate metrics such as temperature change. As described earlier, this is the essence of an IAM. Aside from their structural similarities, however, much of the underlying assumptions vary quite drastically, explaining the large variation in SCC results[yy].

The FUND model is primarily focused on climate change impacts across 16 regions, assuming many economic variables as exogenous. A fundamental differentiator of the FUND model, therefore, is the assumption that climate change does not necessarily have a negative impact on economic growth. In fact, carbon fertilization theories posit that carbon emissions might actually enable economic growth in certain industries. This is not a belief held by either DICE or PAGE. The bulk of the FUND model is devoted to monetizing climate change impacts across a number of sectors, including agriculture, forestry, health, etc. Each sector is evaluated independently from years 1950 through 3000. In order to arrive at an economic value for each region, FUND begins with emissions data, which then is used to calculate temperature estimates and ultimately a damage value, which is associated with a monetary value. The PAGE model is used to project changes in temperature, as well as the economic costs of damages and mitigation efforts. The

DICE model is aimed at calculating emissions, net output, and welfare in order to arrive at an SCC value. Unlike FUND and PAGE, this model focuses on economic impacts of utility, rather than a sole focus on output.

Both the FUND and PAGE models evaluate climate change with respective to changes in CO_2 emissions, as well as other greenhouse gases, across specific geographic regions. DICE is primarily focused on CO_2 effects on an aggregated, global scale. These emissions are then tied damage functions that account for the environmental and human impacts of climate change. In FUND and PAGE, these damage functions are quite specific. PAGE, for example, incorporates tipping points associated with potential catastrophic events. While DICE gathers much of its damage data from Tol's work with the FUND model, it incorporates a series of revisions and adjustments to arrive at what Nordhaus believes to be a more accurate damage projection. This practice of approximating adjustments for areas of uncertainty is used in various aspects of the model, which is a departure from the FUND and PAGE approach. These models, instead, aim to approximate individual uncertainties with a relative degree of meticulousness. Whether specific or broad-stroke estimates are preferable is open for debate.

Despite the stark differences between these models, the SCC estimates of FUND, DICE, and PAGE are combined with equal consideration in determining an SCC value for the United States. The values of each model have been averaged to arrive at a final value for use in United States policy.

3.4 **Concerns Regarding Validity of Inputs in SCC Calculations**

While each of these models has proven instrumental in guiding carbon policy discussions, the ambiguity surrounding climate change and its economic and political repercussions raises many uncertainties. Most variables in these models have been calibrated based on parameters that are believed to be feasible over the projected time horizon, yet none can be confirmed with absolute conviction. The most pressing issues facing current IAM models are outlined below. This is not a comprehensive list, but includes concerns that we believe deserve the most attention if SCC values are to become more reliable over time.

3.4.1 Economic factors

A few controversially modelled economic variables include GDP growth, productivity (or human capital) growth, inequality projections, and adaptation sensitivities.

The first two variables are currently greatly reliant on historical data reported by region, and seem, at first glance, to be fairly reliable projections. However, given that global warming is an unprecedented phenomenon in the data that currently exists on GDP and productivity, it can be argued that GDP growth and productivity levels cannot be reliably extrapolated from historical data that has never endured this challenge. The world has never observed a developing country growing in the midst of constraints imposed by global warming and rising temperatures, and economists have made arguments for lowering GDP growth rates in developing nations. The PAGE and FUND models do not have feedback loops on how climate damages could impact economic growth. Furthermore, predicting economic growth is always difficult. If the DICE economic growth function is applied to historical US economic performance from 1870 until 2010, DICE predicts that US GDP would only be half of what it actually was in 2010[zz].

The latter two variables are less observed, and their measurements are subject to idiosyncrasies. Many measurements of inequality exist, and the effects of inequality are difficult to isolate given the many confounding factors of wealth, opportunity, community, geography, to name a few. Similarly, adaptation, by definition, is a phenomenon that cannot be predicted - a "surprise" factor that comes with evolution. As such, economic models that rely, somewhat, on both of these parameters may be right to recognize that they have significant effects on calculated impacts, but the impact associated with them cannot truly be estimated accurately with given data and approaches.

3.4.2 Scientific factors

Current SCC models account for a variety of scientific factors, including but not limited to sea-level rise, warming, species extinction, agriculture, etc. The difficulty in predicting the gravity and impact of these threats is that there has been no documentation of similar phenomena occurring as rapidly or as broadly as witnessed in recent years. Additionally, there exists no plausible means of conducting a controlled experiment to measure climate effects as different variables are adjusted - not to mention there are countless scientific factors that must be accounted for in order to get a comprehensive picture of our future state. Therefore, it's virtually impossible to predict with precision the potential cumulative scientific impacts of climate change.

Some scientific variables that have been analyzed more closely, such as sea-level rise and human health, may have more footing than other areas of scientific research. Once such example is Michael Greenstone's research that is discussed in more detail in section 4. However, the effects of changing agricultural patterns and species extinction, for example, are more ambiguous. We believe SCC estimates will gradually become more refined as these ambiguous factors are traced and evaluated more closely in coming decades. However, without a more thorough understanding of many scientific factors today, the SCC is still estimated using incomplete and imprecise scientific inputs.

3.4.3 Intergenerational Discount rate

The intergenerational discount rate is perhaps the most controversial variable when calculating the social cost of carbon in IAMs. Understood as an interest rate or time-value of money, the discount rate is frequently used to estimate the present value of future cash flows from an enterprise so as to assess the promise of a decision or investment. It may also be adjusted for the risk-level of a project, with more risky projects having higher discount rates. The intergenerational discount rate refers specifically to the lowered weighting of damage in the future compared to damage today resulting from emissions.

The exact value of the intergenerational discount rate is a matter of great controversy in the literature. Most calculations use around 3%, but the range can be from 0%, no discounting, to up to 7%, often justified as similar to discounting best practices for a risky asset.

The Stern review utilizes a 0% intergenerational discount rate, which was highly controversial among the academic community, since it suggests that the utility of future generations should be equally weighed with our own, nonsensical in an economic model where actors are self-serving. Proponents of a low discount rate may also point to the capital asset pricing model, which relates the rate to systemic market risk and is based on the decreasing marginal utility of money. In this view, investing in climate change mitigation could be seen as avoiding potentially large loses, corresponding with a lower discount rate, in contrast to risky investments with a large upside that would have a high discount rate.

Advocates of a lower discount rate argue that future generations would have far superior technology and wealth to adapt to climate change; they suggest that it would be immoral to ask people a century ago to sacrifice their well-being to make us better off today, when we are presently so much better off than they were.

Ultimately, no concrete value or range of values can effectively estimate the discount rate with certainty, although it is always assumed to be non-negative. While there could be a "true" value for the discount rate, it would be based on the economic risks of climate change in conjunction with humanity's associated utility function. The IAMs themselves are trying to approximate the economic risks, but estimates vary widely. Multiple justifications for different intergenerational discounting practices exist, they remain normative inputs into what the community would like to observe as a positive economic modeling effort. The difficult conclusion is that there is truly no "accurate" intergenerational discount rate value.

3.4.4 Potential for catastrophic damages

Thankfully, occurrences of abrupt, catastrophic and irreversible climate change over the course of modern human history is unheard of. However, it is irresponsible to assume that this pattern will continue unchecked over future generations, especially given the rapid acceleration of recent climate trends. The difficulty in incorporating these scenarios into the above IAMs is the ambiguity associated with these unprecedented events. While it is desirable to explicitly define climate tipping points and their economic impacts in order to enhance the accuracy of SCC estimates, it's simply impossible to gauge the size, timing or probability of their occurrence. As explained by Richard Moss, then a Director of the Office of the U.S. Global Change Research Program in Washington, DC, "It is important to note that by providing only a truncated estimate of the full range of outcomes (e.g., not specifying outliers that include "surprises", and thus making the range of outcomes described smaller), one is not conveying to potential users a representation of the full range of uncertainty associated with the estimate"[aaa].

The debate then follows that economists and climate scientists must choose an appropriate method by which to adjust for the possibility in their models, knowing that these adjustments can have large effects on the SCC. As evaluated by Weitzman, "the combination of fat tails and strong risk aversion may lead to large losses in expected welfare. As a result, the SCC may be unbounded or extremely large" (W. Nordhaus 2014). While an extremely large value for SCC can be viewed as undesirable from an economic perspective, the alternative – widespread environmental and population devastation – may exceed these upfront costs. This is an existential debate that will undoubtedly persist for many years, but is a threat that should not be discounted when evaluating the reliability of SCC estimates.

3.4.5 Compounding effects and modeling feedback loop

In this section we have outlined four variables whose values remain uncertain. This is due to the inherent ambiguity of input values as well as ethical debate surrounding various input assumptions. Now consider tens, if not thousands, of variables. As the ambiguity, or range of values for each additional variable compound, SCC estimates can vary quite broadly and becoming increasingly misleading.

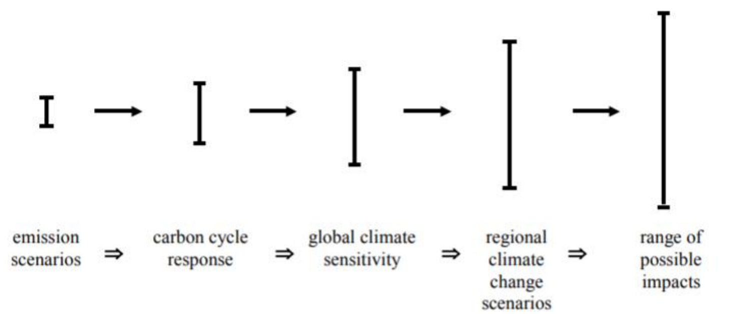


Figure 1. Range of major uncertainties typical in impact assessments showing the "uncertainty explosion" as these ranges are multiplied to encompass a comprehensive range of future consequences, including physical, economic social and political impacts and policy responses (modified after Jones, 2000, and the "cascading pyramid of uncertainties" in Schneider, 1983).

Figure 7[ccc] || Schematic for the "Uncertainty Explosion".

This concept is similar to that of overfitting a regression. Some might think that adding more variables will enhance regression accuracy since it includes more raw data. However, when too many independent variables are included in a model, the regression may become tailored to noise and illustrate relationships between variables that do not actually exist.

In a similar sense, as more and more highly variable, imprecisely modelled factors are added to an IAM, the possible range for the SCC broadens and the possibility for misleading policymakers increases. This phenomenon has been described by several researches as a "cascade of uncertainty", or the "uncertainty explosion," illustrated in Figure 7 and described by Moss[bbb] as those following,

> "If a causal chain includes several different processes, then the aggregate distribution might have very different characteristics than the various distributions that comprise the

links of the chain of causality[ccc]. Thus, poorly managed projected ranges in impact assessment may inadvertently propagate uncertainty".

The issue then becomes choosing which variables to include to prevent the SCC from becoming too general or imprecise so as to become an effective measure for instituting policy.

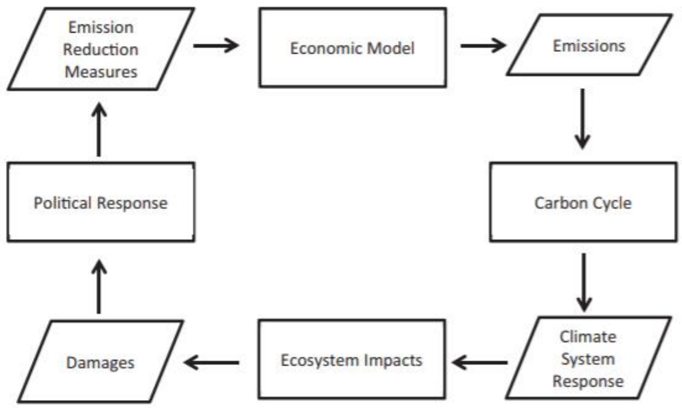


Figure I Schematic of a generic integrated assessment model.

Figure 8[ccc] || Feedback Loop and Compounding

To make this compounding effect more complex, variable inputs used at each stage of IAMs incorporate results determined at different stages, by different researchers, using different assumptions. This creates a feedback loop that's incredibly difficult to disentangle (Fig. 8[ccc]). Take, for example, the DICE damage function. This function is based on research conducted by Tol, whose fundamental beliefs about climate change and its economic impacts vary quite drastically from those of Nordhaus. Furthermore, Tol's research for the FUND model is based on information that has not been updated since the 1990s. Despite this, policymakers use DICE estimates to guide policy decisions. These policy decisions – the U.S. SCC of $40, for example – will inevitably affect future economic and climate projections, and will be incorporated into subsequent model revisions. The inaccuracies of each DICE iteration are thus compounded over time.

4. The future of SCC modeling

Given the many unknowns associated with modeling the future of climate change as delineated in the previous sections, some researchers have begun exploring other methods of attaining a value for a carbon tax and for quantifying harms caused by emissions.

4.1 **On health**

One unconventional method is to quantify the harms of climate change, not via environmental and economic damage, but by health damages, such as mortality, life expectancy, and increased rates of disease.

The benefits to this form of modeling lie in an increased degree of certainty. Such a model requires two aspects:

1. Detailed health data, which can be obtained from regular census in different regions
2. Carefully designed natural experiments, such as the Huai River Line[ddd], that allow for two identical populations save for differences in pollution and emissions exposures to be compared with respect to metrics of health, opportunity, and wealth.

While some estimations and errors will necessarily be incurred to extrapolate the harms from a regional natural experiment to a national, or even a global scale, regional quantitative results such as differences in wealth, life expectancy are at the very least based on verifiable data, compared to projections of climate adaptation and harm. This approach may therefore pave the way for a less disputed SCC, given that the methodology has fewer user-defined variables compared to IAMs used today, and are thus less subject to whims of normative judgment.

On the other hand, this method has its limitations - the potential to substantially underestimate the true SCC value due to limitations in experimentation – controlled experiments with respect to health and climate cannot be conducted for all the variables that are modelled in IAMs.

4.2 **On Cost**

A method that has been proposed by members of geophysical sciences community such as Elizabeth Moyer, that has not been extensively documented in literature, is based on cost of technology investment to switch from fossil fuel electricity generation to renewables. Such a method assumes that stakeholders see emissions abatement as a high and imminent policy priority. So far, all the climate models implicitly aim to convince skeptics of the harms of climate change, since the overwhelming proportion of the equations are dedicated towards projecting environmental and economic harms. The benefit to this approach is that the imperative for mitigating measures is clear and dire. The drawback that results from this careful link between projected damages and the resulting carbon tax amount, however, is that policymakers now shift the original "tax or not" debate to "how much," and the absence of actual mitigating policy continues.

With a cost-based model, two key aspects are required:

1. Willingness to pay for fossil fuels, which can essentially be modelled by historic prices
2. Cost of electricity generation via fossil fuels, including their maintenance, raw material acquisition, waste disposal
3. Cost of electricity generation via renewables, including their installation, maintenance, raw material acquisition (if applicable), waste disposal (if applicable), and necessary new infrastructure to connect renewables facilities to the grid

All of the above information is publicly accessible and fairly accurate. The output of such a model would inform the amount of governmental and economic investment needed to switch an economy to become 100% renewable within a set time horizon. A proposed back-of-the-envelope calculation is to set aside 1% of U.S. national GDP yearly towards switching costs. Coincidentally, an SCC of ~$40/metric ton of CO_2 emissions makes up to roughly 1% of national GDP.

Item	**Calculation**	**Value**
Assumptions: U.S. National Emissions per capita U.S. National GDP per capita		 16 metric tons $60,000
CO_2 intensity of the U.S. economy	GDP per capita / Emissions p.c.	$3750
1% Carbon Tax (per ton CO_2)	CO_2 intensity * 1%	**$37.5**

Table 11 || Back-of-the-envelope Calculations for "On Cost" Model.

5. Shortcomings for current policy application

IAMs seek to determine an SCC value so it can be applied to climate policy and ultimately discourage carbon emitting behaviors. From a high-level, the SCC can be used to guide policy makers in issuing an optimal carbon tax or cap-and-trade emissions policy. Secondly, it can help to facilitate rulemaking, specifically around GHG emissions. However, the SCC as a policy will only be effective if it can overcome the contending forces of industry, politics, and public perception. It is of no surprise that many corporate entities – oil companies, for example – will oppose a carbon tax. So too will the public if they are expected to bear the bulk of fossil fuel price increases without suitable alternatives or an unambiguous justification for the necessity of their participation. To address these concerns, however, there are many issues that still need to be resolved.

A popular framework that's often used to think through policy making is a simple cost-benefit analysis, whereby the cost of externalities in the absence of regulation is compared to the net benefit of enforced regulation. In order to effectively measure costs and benefits, however, regulators must account for adjustments to the SCC, which have not yet been fully integrated into policy frameworks. Issues that require consideration for further adjustment and integration into SCC values are outlined in the following subsections.

5.1 **Regional separation and policy interventions**

Climate change is recognized as a collective action problem. The benefits of emitting carbon are concentrated, while the benefits of combating climate change are diffuse. Furthermore, international efforts such as the Paris Agreement to combat climate change are non-binding. Therefore, unilateral actions to combat climate change may not effectively reduce global emissions if such actions made the benefits of emitting carbon greater for the rest of the world. This could happen if, for example, a country's unilateral actions to get off oil lowered prices, making it more appealing for other countries to use oil. The prospects for international cooperation are unclear, and educated opinion varies on the subject.

The models would ideally posit some consideration of this issue. Unfortunately, none of the models do, rather treating policy intervention as a static number, region by region, or in the case of DICE, only on a global scale. In the model, a policy intervention in one region has no impact on any other region, singularly causing a decrease in carbon emissions in that one region and decreasing global emissions by the same amount.

5.2 **Taxation discounts**

There are three primary issues relating to the institution and pricing of an SCC tax. The first pertains to whether taxation should account for damages on a national or global scale. Since the environment is a global public good, as mentioned above, the costs and benefits resulting from SCC policies would theoretically impact all global citizens. However, many governments, including that of the United States, tend to limit their consideration to domestic interests. As stated by the EPA in a 2009 report, “EPA’s consideration of international effects for purposes of determining endangerment is limited to how those international effects impact the health and welfare of the U.S. population” (W. Nordhaus 2014). However, if the SCC is to be implemented as it was intended, national governments must depart from this previously accepted norm. Without weighing domestic and foreign impacts equally, curbing carbon emissions cannot be effectively coordinated. This hurdle to global harmonization, particularly in the first world, has the potential to greatly increase the SCC in practice.

The second issue, that of leakage, arises from the inability to apply carbon taxes uniformly to sectors that have the potential to serve as substitutes. The example offered by Nordhaus his 2013 report relates this issue to automobiles versus air travel. Assuming regulators could impose a carbon tax on the first but not the second sector, and these sectors have equal CO_2 intensities, then optimal tax on automobiles would be equivalent to the marginal damages if these sectors exhibited no substitution. In the case of perfect substitution, on the other hand, optimal tax would be zero. In cases where any level of substitution exists, the full value of the SCC is not applied. Nordhaus refers to this as a “leakage discount”[eee].

Nordhaus also refers to a “distortion discount,” which accounts for existing tax distortions that cause carbon taxes to fall below the ideal SCC or Pigouvian tax. This occurs because an increase in the price of carbon intensive goods will increase the tax wedge between those and non-taxed goods in the economy. In a study conducted by Barrage in 2013, using assumptions from the DICE model and a simple tax system, he determined “a range of discounts up to one-third, with the size of the discount depending upon the structure of existing tax distortions as well as the way the revenues are used or recycled”[fff]. Nordhaus argues that despite these findings, a carbon tax is more effective than emissions limitations. Since the latter mechanism produces similar distortions but yields no revenues for investment by the regulating body, its benefits in emissions abatement fall short.

5.3 **Translation from science to policy**

The IPCC’s 5th assessment attempts to outline with various degrees of confidence the cause, scale, and impacts of climate change. This tactic, however, is controversial as many scientific findings are tailored for interpretation for policymakers. Despite common understanding in the scientific community that climate change cannot be captured by a single number or confidence interval, policymakers must in some way distill large amounts of complex data for interpretation by the average citizen. As Schneider and Moss wrote[ggg]:

> "It is certainly true that 'science' itself strives for objective empirical information to test theory and models. But at the same time 'science for policy' must be recognized as a different enterprise than 'science' itself, since science for policy involves being responsive to policymakers' needs for expert judgment at a particular time, given the information currently available, even if those judgments involve a considerable degree of subjectivity."

An example of misleading language used in the report is the use of "almost certain," "probable," "likely," "possible," "unlikely," "improbable," and "doubtful" to describe the outcomes of climate change. These are coupled with "very high," "high," "medium," "low," and "very low" confidence ratings[hhh]. In academic language, Bayesian approach is often meant when probabilities are attached to outcomes with "an inherent component of subjectivity or to an assessment of the state of the science from which confidence considerations are offered," which is characteristic of many scenarios outlined in the IPCC. However, these terms are used differently across teams and therefore across sections of the report, and are not specifically calibrated or defined by those claim them. Statements of "medium confidence" are particularly misleading. While these might allude to vague casual effects, they often garner little support or denial since they are generally characterized by confidence indifference. The culminating result of these documentation shortcomings is subjective interpretation by policymakers, who often draw their own conclusions based on an inaccurate understanding of the underlying data.

Through this process, a familiar game of "telephone" translates complex scientific modeling into an oversimplified statement that's then debated and regulated by those who do not fully understand its derivation. Therefore, it's critical that communication between researchers contributing to the IPCC report and those interpreting the report for policy prescription is enhanced. Richard Moss offers a series of suggestions for how to better document findings to alleviate the ambiguities and translation challenges embedded in the IPCC report[iii]. As of late, however, not much attention has been paid to these inconsistencies and their potential to misinform or distort public policy perceptions.

5.4 **Partisan politics**

A familiar conflict in United States politics is that of partisanship. Not only is global harmonization critical for SCC implementation, but so too is long-term, consistent agreement on a national scale to ensure continued commitment to international accords. However, political discourse and agendas can sway public opinion and ultimately dictate whether commitment to national SCC policy persists.

A recent example of political agendas affecting climate policy occurred in the November 2018 with the release of the National Climate Assessment. This report, which is required to be released every four years, comprehensively details the effects of climate change on the United States. This edition painted a dire picture, and thus was not well received by the Trump administration, whose regulatory agenda actively promotes the use and extraction of fossil fuels. Findings indicate that continued GHG emissions could “knock as much as 10% off of U.S. GDP by the end of the century,” as well as the occurrence of “more frequent and more devastating weather crises”[jjj].

In response to the assessment, many believe that the administration attempted to bury it. First, it was published online in the middle of Black Friday - a day when most Americans are preoccupied. Perhaps more concerning, however, is the subsequent institution of new policies that will change the outcome of the next report. For example, the geological survey - a critical component of the report - can no longer include projections beyond 2040. The problem is that the worst impacts of global climate change models occur after 2050, thereby painting a falsely optimistic picture. To reinforce this false reality, the next report can no longer use the worst case scenario RCP. This scenario, however, will become increasingly likely if current emissions patterns continue under the Trump administration.

The Trump administration isn’t the only source of political debate around climate policy. The Obama administration was also criticized for its approach to carbon taxation, since their proposed tax structure created a disproportionate burden on low-income households. As described by the Manhattan Institute, “a household in the bottom 10 percent spends more than 35 percent of its income on energy, one in the top 10 percent spends only 3 percent”[kkk]. Taxation rates, however, fell uniformly across all income levels, thereby increasing relative energy costs for low-income households. This is yet another example of debate surrounding the SCC and its application in U.S. policy.

A clear illustration of partisan divide over climate change can be seen in the transition from the Obama to the Trump administration. Obama's $45 estimate of the SCC were derived using a 3% discount rate. Several years later, Trump estimated the SCC to be between $1 and $6, using a 7% discount rate[lll]. This striking incongruity is proof that partisanship has the potential to derail climate change activism, meaning that the effective implementation of the SCC will remain uncertain.

6. Conclusion

The SCC remains highly speculative and significant further research is required before accurate estimates can be made, if they ever can be. Great uncertainties exist in the exogenous inputs of the IAMs as shown by the wide range of scenarios and in the endogenous processes the IAMs use to estimate damages, so that SSC estimates can range from near zero to in the hundreds per metric ton. Nevertheless, some judgments can be made from the current literature; the SSC is almost certainly higher than zero, it is probably higher the corresponding efforts humanity is taking to mitigate climate change, and significant damages are possible.

In short, there is a long way to go to implement a fiscal mitigatory measure for carbon emissions. There are more questions than answers regarding the calculation of a carbon tax itself, and even more debates regarding the efficiencies and efficacies of the tax policy structure. As with many issues in policy-making, there is no "right" answer, merely an optimistic compromise. Thus, in lieu of passing judgment on the recommended value of a carbon tax and the structure that such a policy should take on, we have condensed the many moving parts into a few key questions that, we believe, are critical to resolving the bottleneck which currently policymaking has stagnated at:

1. Firstly, who are the stakeholders to be affected by a potential tax, and how can their reservations towards the policy be alleviated?
2. Secondly, how much should a tax be in order to serve its disincentive function to shift firm resources towards the development and investment into renewable generation, without crippling small and medium enterprises?

3. Thirdly, what should the fiscal revenue be used for - standard Pigouvian taxes will have served their purpose once collected, and can easily be rebated, but is there a gap in the generation of more public goods in the form of intellectual property or renewables technology that can be encouraged by the government?

It is our hope that, by asking these questions and encouraging all sides of this conversation to consider and negotiate the answers, that we can take a step towards collective action against climate change.

Works Cited

[a] "Technical Support Document: -Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis -Under Executive Order 12866" [2013] 2016

[b] "Omitted Damages: What's Missing From the Social Cost of Carbon." Omitted Damages: What's Missing From the Social Cost of Carbon –, costofcarbon.org/resources/entry/omitted-damages-whats-missing-from-the-social-cost-of-carbon.

[c] Regulatory Impact Analysis for the Proposed Emission Guidelines for Greenhouse Gas Emissions from Existing Electric Utility Generating Units; Revisions to Emission Guideline Implementing Regulations; Revisions to New Source Review Program. U.S. Environmental Protection Agency Office of Air Quality Planning and Standards, Aug. 2018, www.epa.gov/sites/production/files/2018-08/documents/utilities_ria_proposed_ace_2018-08.pdf.

[d] Nordhaus, William D. 2017b. "Integrated Assessment Models of Climate Change." NBER Reporter 2017 Number 3. October 2017. https://www.nber.org/reporter/2017number3/nordhaus.html.

[e] Nordhaus, William D. 2017c. "Integrated Assessment Models of Climate Change." NBER Reporter 2017 Number 3. October 2017. https://www.nber.org/reporter/2017number3/nordhaus.html.

[f] Nordhaus, William D. 2017b. "Integrated Assessment Models of Climate Change." NBER Reporter 2017 Number 3. October 2017. https://www.nber.org/reporter/2017number3/nordhaus.html.

[g] Nakicenovic N , Alcamo J, Grubler A , Riahi K , Roehrl RA, Rogner H-H, & Victor N (2000). Special Report on Emissions Scenarios (SRES), A Special Report of Working Group III of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press. ISBN 0-521-80493-0

[h] Moss, Richard H., et al. "The next Generation of Scenarios for Climate Change Research and Assessment." Nature News, Nature Publishing Group, 11 Feb. 2010, www.nature.com/articles/nature08823.

[i] O'Neill, Kriegler et al. 2014: 387-388

[j] Moss, R. H., N. Nakicenovic, and B. C. O'Neill. 2008. Towards New Scenarios for Analysis of Emissions, Climate Change, Impacts, and Response Strategies. Geneva: IPCC.

[k] IPCC, 2014: Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.

[l] Huber, Schellnhuber et al. 2014; Nelson, Valin et al. 2014; Warszawski, Frieler et al. 2014

[m] Moss, R. H., N. Nakicenovic, and B. C. O'Neill. 2008. Towards New Scenarios for Analysis of Emissions, Climate Change, Impacts, and Response Strategies. Geneva: IPCC.

[n] Vuuren, Detlef P. van, Jae Edmonds, Mikiko Kainuma, Keywan Riahi, Allison Thomson, Kathy Hibbard, George C. Hurtt, et al. 2011. "The Representative Concentration Pathways: An Overview." Climatic Change 109 (1-2): 5.

[o] Taylor, Stouffer et al. 2012

[p] IPCC, 2013: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

[q] Citation needed: special issue of climate change (Ebi, Hallegatte et al. 2014)

[r] Richard H. Moss, Jae A. Edmonds, Kathy A. Hibbard, Martin R. Manning, Steven K. Rose, Detlef P. van Vuuren, Timothy R. Carter, Seita Emori, Mikiko Kainuma, Tom Kram, Gerald A. Meehl, John F. B. Mitchell, Nebojsa Nakicenovic, Keywan Riahi, Steven J. Smith, Ronald J. Stouffer, Allison M. Thomson, John P. Weyant1 & Thomas J. Wilbanks, 2010. The next generation of scenarios for climate change research and assessment. Nature 463: 747-756. doi:10.1038/nature08823

[s] Richard H. Moss, Jae A. Edmonds, Kathy A. Hibbard, Martin R. Manning, Steven K. Rose, Detlef P. van Vuuren, Timothy R. Carter, Seita Emori, Mikiko Kainuma, Tom Kram, Gerald A. Meehl, John F. B. Mitchell, Nebojsa Nakicenovic, Keywan Riahi, Steven J. Smith, Ronald J. Stouffer, Allison M. Thomson, John P. Weyant1 & Thomas J. Wilbanks, 2010. The next generation of scenarios for climate change research and assessment. Nature 463: 747-756. doi:10.1038/nature08823

[t] "GDP Growth (Annual %)." Data, data.worldbank.org/indicator/NY.GDP.MKTP.KD.ZG.

[u] Moss, R. H., N. Nakicenovic, and B. C. O'Neill. 2008. Towards New Scenarios for Analysis of Emissions, Climate Change, Impacts, and Response Strategies. Geneva: IPCC.

[v] RCP Database. https://tntcat.iiasa.ac.at/RcpDb/dsd?Action=htmlpage&page=welcome

[w] Moss, R. H., N. Nakicenovic, and B. C. O'Neill. 2008. Towards New Scenarios for Analysis of Emissions, Climate Change, Impacts, and Response Strategies. Geneva: IPCC.

[x] Riahi K, Gruebler A, Nakicenovic N (2007) Scenarios of long-term socio-economic and environmental development under climate stabilization. Technol Forecast Soc Chang 74(7):887–935

[y] Fujino J, Nair R, Kainuma M, Masui T, Matsuoka Y (2006) Multigas mitigation analysis on stabilization scenarios using aim global model. The Energy Journal Special issue #3:343−354

[z] Clarke et al 2007, Smith and Wigley et al 2006, Wise et al 2009

[aa] "IPCC Expert Meeting on Scenarios." IPCC, May 2015, www.ipcc.ch/publication/ipcc-expert-meeting-on-scenarios/.

[bb] "About Us | AgMIP." AgMIP About Us Comments, www.agmip.org/about-us/.

[cc] Wilson C , Kriegler E, van Vuuren DP, Guivarch C, Frame D, Krey V , Osborn TJ, Schwanitz VJ, et al. (2017). Evaluating Process-Based Integrated Assessment Models of Climate Change Mitigation. IIASA Working Paper. IIASA, Laxenburg, Austria: WP-17-007

[dd] Wang, Jianliang; Feng, Lianyong; Tang, Xu; Bentley, Yongmei; Höök, Mikael (February 2017). "The implications of fossil fuel supply constraints on climate change projections: A supply-side analysis". Futures. 86 (2): 58–72. doi:10.1016/j.futures.2016.04.007.
Rutledge, David (2011-01-01). "Estimating long-term world coal production with logit and probit

transforms". International Journal of Coal Geology. 85 (1): 23–33. doi:10.1016/j.coal.2010.10.012. page 32

[ee] Jr., Roger Pielke. “RCP 8.5 Is by Far the Favorite in Climate Impact Studies (Graph).

[ff] Tol, Richard. 2014. “THE CLIMATE FRAMEWORK FOR UNCERTAINTY, NEGOTIATION AND DISTRIBUTION (FUND), TECHNICAL DESCRIPTION, VERSION 3.9” http://www.fund-model.org/Fund-3-9-Scientific-Documentation.pdf.

[gg] Leggett et al., 1992

[hh] National Academies of Sciences, Engineering, and Medicine, Division of Behavioral and Social Sciences and Education, Board on Environmental Change and Society, and Committee on Assessing Approaches to Updating the Social Cost of Carbon. 2017. Valuing Climate Damages: Updating Estimation of the Social Cost of Carbon Dioxide. National Academies Press.

[ii] Nordhaus, William D. Dice Manual. http://www.econ.yale.edu/~nordhaus/homepage/homepage/documents/DICE_Manual_100413r1.pdf

[jj] Nordhaus, William D. 2007. "A Review of the Stern Review on the Economics of Climate Change." Journal of Economic Literature 45, no. 3 (September 2007): 686-702.

[kk] Nordhaus, William. 2014. “Estimates of the Social Cost of Carbon: Concepts and Results from the DICE-2013R Model and Alternative Approaches.” Journal of the Association of Environmental and Resource Economists 1 (1/2): 273–312.

[ll] Nordhaus, William, and Paul Sztorc. 2013. “DICE 2013R: Introduction and User’s Manual.” Retrieved November.

[mm] Nordhaus, William D. 2017a. “Revisiting the Social Cost of Carbon.” Proceedings of the National Academy of Sciences of the United States of America 114 (7): 1518–23.

[nn] Tol, Richard S. J. “The Economic Effects of Climate Change.” Journal of Economic Perspectives, vol. 23, no. 2, 2009, pp. 29–51., doi:10.1257/jep.23.2.29.

[oo] Nordhaus, William, and Paul Sztorc. 2013. “DICE 2013R: Introduction and User’s Manual.” Retrieved November.

[pp] Nordhaus, William. 2014. “Estimates of the Social Cost of Carbon: Concepts and Results from the DICE-2013R Model and Alternative Approaches.” Journal of the Association of Environmental and Resource Economists 1 (1/2): 273–312.

[qq] Nordhaus, William D. 2017a. “Revisiting the Social Cost of Carbon.” Proceedings of the National Academy of Sciences of the United States of America 114 (7): 1518–23.

[rr] Hope C, forthcoming, “The PAGE09 integrated assessment model: A technical description”,

submitted to Climatic Change.

[ss] "The Stern Review on the Economic Effects of Climate Change." Population and Development Review, vol. 32, no. 4, 2006, pp. 793–798., doi:10.1111/j.1728-4457.2006.00153.x.

[tt] "ADB Annual Report 2009." Asia Development Bank, 2009. https://www.adb.org/documents/adb-annual-report-2009.

[uu] Waldhoff, Stephanie, David Anthoff, Steven Rose and Richard S.J. Tol. 2014. "The Marginal Damage Costs of Different Greenhouse Gases: An Application of FUND." Economics: The Open-Access, Open-Assessment E-Journal. Vol. 8 2014-31.

[vv] Nordhaus, William D. 2017a. "Revisiting the Social Cost of Carbon." Proceedings of the National Academy of Sciences of the United States of America 114 (7): 1518–23.

[ww] Nordhaus, William D. 2017a. "Revisiting the Social Cost of Carbon." Proceedings of the National Academy of Sciences of the United States of America 114 (7): 1518–23.

[xx] Nordhaus, William D. 2017a. "Revisiting the Social Cost of Carbon." Proceedings of the National Academy of Sciences of the United States of America 114 (7): 1518–23.

[yy] National Academies of Sciences, Engineering, and Medicine, Division of Behavioral and Social Sciences and Education, Board on Environmental Change and Society, and Committee on Assessing Approaches to Updating the Social Cost of Carbon. 2017. Valuing Climate Damages: Updating Estimation of the Social Cost of Carbon Dioxide. National Academies Press.

[zz] Millner, Antony and McDermott, Thomas K. J. (2016) Model confirmation in climate economics. Proceedings of the National Academy of Sciences of the United States of America, 113 (31). pp. 8675-8680. ISSN 1091-6490

[aaa] Schneider, Stephen H., and R. Moss. 1999. "Uncertainties in the IPCC TAR: Recommendations to Lead Authors for More Consistent Assessment and Reporting." Unpublished Document. http://climate-action.engin.umich.edu/CLIMATE_530_Uncertainty_Stationarity_Readings/Moss_Schneider_Consistent_Reporting_Uncertainty_IPCC_2000.pdf.

[bbb] Schneider, Stephen H., and R. Moss. 1999. "Uncertainties in the IPCC TAR: Recommendations to Lead Authors for More Consistent Assessment and Reporting." Unpublished Document. http://climate-action.engin.umich.edu/CLIMATE_530_Uncertainty_Stationarity_Readings/Moss_Schneider_Consistent_Reporting_Uncertainty_IPCC_2000.pdf.

[ccc] Jones, Roger. (2000). Managing Uncertainty in Climate Change Projections – Issues for Impact Assessment. Climatic Change. 45. 403-419. 10.1023/A:1005551626280.

[ddd] Almond, Douglas, Yuyu Chen, Michael Greenstone, and Hongbin Li. 2009. "Winter Heating or Clean Air? Unintended Impacts of China's Huai River Policy." American Economic Review, 99 (2): 184-90.

[eee] Nordhaus, William. 2014. "Estimates of the Social Cost of Carbon: Concepts and Results from the DICE-2013R Model and Alternative Approaches." Journal of the Association of Environmental and Resource Economists 1 (1/2): 273–312.

[fff] Nordhaus, William. 2014. "Estimates of the Social Cost of Carbon: Concepts and Results from the DICE-2013R Model and Alternative Approaches." Journal of the Association of Environmental and Resource Economists 1 (1/2): 273–312.

[ggg] Schneider, Stephen H., and R. Moss. 1999. "Uncertainties in the IPCC TAR: Recommendations to Lead Authors for More Consistent Assessment and Reporting." Unpublished Document. http://climate-action.engin.umich.edu/CLIMATE_530_Uncertainty_Stationarity_Readings/Moss_Schneider_Consistent_Reporting_Uncertainty_IPCC_2000.pdf.

[hhh] "AR5 Synthesis Report: Climate Change 2014 — IPCC." n.d. Accessed June 8, 2019. https://www.ipcc.ch/report/ar5/syr/.

[iii] "Uncertainties in the IPCC TAR: Recommendation to Lead Authors for More Consistent Assessment and Reporting"

[jjj] Bordoff, Jason. 2017. "Trump vs. Obama on the Social Cost of Carbon–and Why It Matters." WSJ. wsj.com. November 15, 2017. https://blogs.wsj.com/experts/2017/11/15/trump-vs-obama-on-the-social-cost-of-carbon-and-why-it-matters/.

[kkk] "Issues 2016: Who Pays the Bill for the Obama Climate Agenda? | Manhattan Institute." 2016. Manhattan Institute. April 20, 2016. https://www.manhattan-institute.org/html/issues-2016-who-pays-bill-obama-climate-agenda-8802.html.

[lll] Bordoff, Jason. 2017. "Trump vs. Obama on the Social Cost of Carbon–and Why It Matters." WSJ. wsj.com. November 15, 2017. https://blogs.wsj.com/experts/2017/11/15/trump-vs-obama-on-the-social-cost-of-carbon-and-why-it-matters/.

[nnn] "Integrated Assessment Models of Climate Change." n.d. Accessed June 8, 2019.

[ooo] "webDice". The University of Chicago. http://webdice.rdcep.org/standard#graph:essential

Appendix I: Calculation of the United States Social Cost of Carbon

The Interagency Working Group on the Social Cost of Carbon (IWG), established by the United States government in 2009, arrived at this estimate by running each of the FUND, DICE, and PAGE models[21] 10,000 times (each time with a different 'climate sensitivity'[22] value, picked at random) under five different socioeconomic scenarios[23], resulting in a total of 150,000 estimates that were then averaged to compute a final figure. Equal weighting was then given to each model and scenario (Metcalf and Stock 2017). This process was actually repeated to find different annual figures under three different discount rates (2.5%, 3%, and 5%).

Social Cost of CO_2, 2015-2050 [a] (in 2007 dollars per metric ton CO_2)
Source: Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866 (May 2013, Revised August 2016)

	Discount Rate and Statistic			
Year	5% Average	**3% Average**	2.5% Average	High Impact (3% 95th percentile)
2015	$11	**$36**	$56	$105
2020	$12	**$42**	$62	$123
2025	$14	**$46**	$68	$138
2030	$16	**$50**	$73	$152
2035	$18	**$55**	$78	$168
2040	$21	**$60**	$84	$183
2045	$23	**$64**	$89	$197
2050	$26	**$69**	$95	$212

[a] The SC-CO_2 values are dollar-year and emissions-year specific.

[21] See Section 3.
[22] This is a key factor that is discussed in greater depth later in the paper.
[23] See Section 2.

Appendix II: PAGE Equations

Table II.1

1	**Equation 1: Excess concentration** of each greenhouse gas caused by human activity $$EXC_{g,t=0} = C_{g,t=0} - PIC_{g,t=0}$$ • G - stands for *gas*, the model takes into account 4 greenhouse gases, numbered as follows: (1) Carbon Dioxide (CO_2); (2) Methane (CH_4); (3) Nitrous oxide (N_2O); (4) Linear gas, which is a representative parameter for trace greenhouse gases • C - concentration at the base year (i = 0) • PIC - pre-industrial concentration, estimated from XXX
2	Level of **emissions remaining** in the atmosphere in the base year $$RE_{g,t=0} = EXC_{g,t=0} * DEN_g$$ • DEN - density of gas *g* (Mtonne / ppbv)
3	**Natural emissions stimulated by temperature rise** - using natural emissions of the modelled gases, stimulated by increasing global mean temperature. This generates an area-weighted average of regional temperature increases $$NtE_{g,i} = STIM_g * \frac{\sum_r (RT_{i=1,r} * AREA_r)}{\sum_r AREA_r}$$ • STIM - uncertain biospheric feedback parameter (Mtonne / degC), stochastic parameter • RT - Realized temperature of each region *r* • AREA - Area of each region *r*
4	**Regional greenhouse gas emissions from human activity at period *i*.** Specified as the percentage of base year emissions in each region. $$E_{g,i,r} = \frac{ER_{g,i,r} * E_{g,i=0,r}}{100}$$ • ER - emissions compared to the base year (%)

5	**Global greenhouse gas emissions of gas *g* from human activity at period *i*,** which is simply the aggregate of all regions'. $$E_{g,i} = \sum_{r} E_{g,i,r}$$
6	**Total emissions to the atmosphere for gas *g* at period *i*.** $$TEA_{g,i} = (E_{g,i} + NtE_{g,i}) * \frac{AIR_g}{100}$$ • AIR - proportion of emissions that make it into the atmosphere, taking into account initial decays of gases into the atmosphere prior to settling into steady state or exponential decline.
7	**Total emissions to the atmosphere of gas *g* since the previous analysis year at period *i*.** $$TEAY_{g,i} = \frac{(TEA_{g,i} + TEA_{g,i-1})(Y_i - Y_{i-1})}{2}$$ • Y - analysis year
8	**Cumulative Emissions of CO_2 (gas *g = 1*) into the atmosphere at period *i*.** $$CEA_{g=1,i=0} = CE_{g=1,i=0} * \frac{AIR_{g=1}}{100}$$ • CE - cumulative emissions, calculated as the total of anthropogenic emissions up to the base year, and is thus informed by data
9	**Cumulative emissions to the atmosphere for CO_2 (gas *g = 1*) at period *i*.** Calculated as the sum of cumulative emissions in the last analysis year, and total emissions to the atmosphere calculated from the base year to the last analysis year. $$CEA_{g=1,i} = CEA_{g=1,i=1} + TEAY_{g=1,i}$$
10	**Emissions remaining in the atmosphere at period *i* for non-CO_2 gases (*g = 2-4*).** This equation differs from Equation 2, in that it calculates for all years, not simply the base year (i = 0).

	$RE_{g,i} = RE_{g,i-1} * exp\,(\frac{-(Y_i - Y_{i-1})}{RES_g}) + \frac{TEAY_{g,i} * RES_g * (1 - exp\,(\frac{-(Y_i - Y_{i=1})}{RES_g}))}{Y_i - Y_{i-1}}$ ● RES - Half life of atmospheric residence
11	**Emissions remaining in the atmosphere at period *i* for CO_2 (*g = 1*).** CO_2 must be modelled differently due to the interactions between the environment and atmospheric CO2, which causes equilibrium partitioning between atmosphere and oceans. The half-life of CO2 is also much larger than the time step between model years, so the timing of emissions must also be specially modelled. The following equation does this by assuming that all emissions since the previous model year occur in a year midway between the previous analytical year and year *i*. $RE_{g=1,i} = STAY_1 * CEA_{g=1,i-1} * (1 - exp\,(\frac{-(Y_i - Y_{i-1})}{RES_{g=1}})) + RE_{g=1,i-1} * exp\,(\frac{-(Y_i - Y_{i-1})}{RES_{g=1}}) + TEAY_{g=1,i} * exp\,(\frac{-(Y_i - Y_{i-1})}{2RES_{g=1}})$ ● STAY -Proportion of emissions that stay in the atmosphere
12	**Concentration of each gas in the atmosphere,** modelled as the sum of pre-industrial and excess concentration (PIC) in the base year, scaled by the remaining emissions (RE) in the atmoshere compared to the base year. $C_{g,i} = PIC_g + EXC_{g,0} * \frac{RE_{g,i}}{RE_{g,0}}$
13	**Extra radiative forcing due to the concentration of CO_2 in the atmosphere.** The shape of this curve is a logarithmic function of concentration, and not linear. This is because the concentration of CO2 in the atmosphere currently is high enough that it is past the linear stage. $F_{1,i} = F_{1,0} + FSLOPE_1 * ln(\frac{C_{1,i}}{C_{1,0}})$ ● FSLOPE_g - slope of radiative forcing equation for gas g.

14	**Extra radiative forcing from methane (g = 2).** This is proportional to the square root of the concentration, net of the overlap with nitrous oxide (g = 3) $$F_{2,i} = F_{2,0} + FSLOPE_2 * (\sqrt{C_{2,i}} - \sqrt{C_{2,0}}) + OVER_{2,i} - OVER_{2,0}$$
15	**Extra radiative forcing from (g = 3).** This is currently low enough to be linear in concentration. $$F_{3,i} = F_{3,0} + FSLOPE_3 * (C_{3,i} - C_{3,0})$$
16	**Total extra radiative forcing from human emissions.** This sums up equations 13-15, plus an additional term for trace gases. $$FT_i = \sum_g F_{g,i} + EXF_i$$ ● EXF - excess forcing from other gases that are not modelled explicitly
17	**Radiative forcing from sulphate aerosols (SFX), or sulphur flux for region *r* at period *i*.** $$SFX_{i,r} = SE_{0,r} * \frac{PSE_{i,r} * 0.01}{AREA_r}$$ ● PSE - sulphate emissions in period *i* as percentage of base year emissions
18	**Extra radiative forcing from sulphur aerosols (FS).** Takes into account the direct effect of linear backscattering and an indirect effect from cloud interactions. $$FS_{i,r} = D * 1E6 * SFX_{i,r} + \frac{IND}{ln(2)} * ln(\frac{NF_r + SFX_{i,r}}{NF_r})$$ ● D - uncertain, stochastic parameter representing increase in direct radiative forcing per unit sulphur flux ● IND - indirect forcing increase, also an uncertain, stochastic parameter, for a doubling of the natural sulphur flux.
19	**Equilibrium temperature (ET) in year *i* for region *r*,** as a linear function of net extra radiative forcing in the region

	$$ET_{i,r} = \frac{SENS}{ln(2)} * \frac{FT_i + FS_{i,r}}{FSLOPE_1}$$ ● SENS - climate sensitivity for a doubling of CO_2. This is not calculated in PAGE2002, but PAGE09 includes an updated calculation for this (see upcoming section)
20	**Realized temperature (RT) in year *i* in region *r*.** The Earth is assumed to warm towards an equilibrium temperature at a rate proportional to difference between the equilibrium temperature and the realized temperature in the previous model year. $$RT_{i,r} = RT_{i-1,r} + (1 - exp\,(\frac{Y_i - Y_{i-1}}{OCEAN}) * (ET_{i,r} - RT_{i-1,r})$$ ● OCEAN - variable that assumes the Earth is a homogenous body, which is false, and that the effects of warming affect the region similarly irrespective of time. In reality, a more complex warming pattern is expected to be realized over time..
21	**Global mean temperature (GRT) in period *i*.**Calculated as an area-weighted average of regional temperatures in the year. $$GRT_i = \frac{\sum_r \quad RT_{i,r} * AREA_r}{\sum_r \quad AREA_r}$$

Table II.2

22	**Tolerable Change (TR) for sector *d* and region *r*.** $$TR_{d,r} = TR_{d,r=0} * TM_r$$ ● TM- regional multiplier. This is an unknown parameter.
23	**Tolerable Plateau (TP) for sector *d* and region *r*.** $$\boldsymbol{TP_{d,r} = TP_{d,r=0} * TM_r}$$
24	**Adaptation (ATP) for period *i*, sector *d*, and region *r*. *(1)*** $$\boldsymbol{ATP_{i,d,r} = TP_{d,r} + PLAT_{i,d,r}}$$ ● PLAT - non-negative factor characteristic to an adaptive policy
25	**Adaptation (ATP) for period *i*, sector *d*, and region *r*. *(2)***

	$$ATP_{i,d,r} = TP_{d,r} + SLOPE_{i,d,r}$$ ● SLOPE - non-negative factor characteristic to an adaptive policy
26	**Regional impact of global warming (I)** corresponding to **Adjusted Tolerable Level (ATL)** $$I_{i,d,r} = max\{0, RT_{i,r} - ATL_{i,d,r}\}$$ **Assumptions** $$ATL_{i-0,d,r} = 0$$ $$ATL_{i,d,r} = min\{ATP_{i,d,t}, ATL_{i-1,d,r} + ATR_{d,r} * (Y_i - Y_{i-1})\}$$
27	**Impact from discontinuity (IDIS)** $$IDIS_i = max\{0, GRT_i - TDIS\}$$ ● TDIS - tolerable temperature rise before risk of discontinuity
28	**Regional GDP (GDP)**, assuming no additional climate effects $$GDP_{i,r} = GDP_{i-1,r} * (1 + \frac{GRW_{i,r}}{100})^{Y_i - Y_{i-1}}$$ ● GRW - growth rate of GDP
29	**Regional weights** for percentage of GDP lost for benchmark warming of 2.5 degrees Celsius. $$W_{d,r} = W_{d,r=0} * \frac{WF_r}{100}$$ ● W_d,0 - value for focus region ● WF - regional multiplier
30	**Regional discontinuity** $$WDIS_r = min\{1, \frac{WDIS_0 * WF_r}{100}\}$$ Used to check that the regional weight does not exceed 100% of GDP
31	**Weighted Impact for region *r* for sector *d* in period *i*.** $$WI_{i,d,r} = (\frac{I_{i,d,r}}{2.5})^{POW} * W_{d,r} * (1 - \frac{IMP_{i,d,r}}{100}) * GDP_{i,r}$$ ● POW - impact function exponent. Can be whatever is chosen, simply compares the shape of the regression functions ● IMP - reduction in impacts from adaptation

32	**Weighted impact from discontinuity for region *r* in period *i*** $$WIDIS_{i,r} = IDIS_i * (\frac{PDIS}{100}) * WDIS_r * GDP_{i,r}$$ ● PDIS - Probability of discontinuity
33	**Total weighted impact in period *i* in region *r*.** Calculated as the sum of the weighted effects from temperature rise(WI) and the weighted impact from discontinuity (WDIS). $$WIT_{i,r} = \sum_d WI_{i,d,r} + WIDIS_{i,r}$$
34	**End of analysis period 10 is also the end of analysis year.** $$Yhi_{10} = Y_{10}$$
35	**End of analysis period.** Usually taken as the middle of the last analysis year. $$Yhi_i = \frac{(Y_i + Y_{i+1})}{2}$$
36	**Beginning of analysis period 1** is also the beginning of analysis year 0**.** $$Ylo_1 = Y_0$$
37	**Beginning of analysis period i** is the midpoint between the current analysis year and the last analysis year**.** $$Ylo_i = \frac{Y_i + Y_{i-1}}{2}$$
38	**Aggregated Damage for region *r* in analysis period *i*.** This assumes that the amount of weighted damage is the same for all years included in the same analysis period, which may be a dubious claim. $$AD_{i,r} = WIT_{i,r} * (Yhi_i - Ylo_i)$$
39	**Global Discounted Damage.** Takes into account possible discontinuity impacts and emissions impacts on economic and non-economic impact sectors. $$DD = \sum_{i,r} (AD_{i,r}) * \Pi_{k=1}{}^{i}(1 + dr_{k,r} * \frac{ric}{100})^{-(Y_k - Y_{k-1})}$$ ● dr - Discount rate for costs. A value that is used to discount the costs of policy implementation.

	• ric - Impact discount rate multiplier. A value that is used to discount the costs related to climate change impacts. This is where the Ramsey equation, if used to calculate the discount rate, gets factored in.

Table II.3

40	**Cost of slope adaptation (CS)** $$CS_{d,r} = CS_{d,r=0} * CF_r$$ • CF- regional multiplier. This is an unknown parameter.
41	**Cost of plateau adaptation (CP)** $$CP_{d,r} = CP_{d,0} * CF_r$$
42	**Cost of impact adaptation (CI)** $$CI_{d,r} = CI_{d,0} * CF_r$$ • PLAT - non-negative factor characteristic to an adaptive policy
43	**Total cost of adaptation (AC) in period *i*, for sector *d* and in region *r*** $$AC_{i,d,r} = CS_{d,r} * SLOPE_{i,d,r} + CP_{d,r} * PLAT_{i,d,r} + CI_{d,r} * IMP_{i,d,r}$$
44	**Aggregate adaptive costs (AAC) in period *i*, for sector *d* and in region *r*.** Once again, the costs are assumed to remain constant for all years within the analysis period. $$AAC_{i,d,r} = AC_{i,d,r} * (Yhi_i - Ylo_i)$$
45	**Discounted aggregate adaptive costs (DAC).** Note that there is no impact discount rate multiplier for these costs. $$DAC = \sum_{i,d,r} AAC_{i,d,r} * \Pi_{k=1}{}^{i} (1 + \frac{dr_{k,r}}{100})^{-(Y_k - Y_{k-1})}$$
46	**Adjusting for uncertainty (or unknown factors) in a zero-cost preventative policy.** This essentially means business-as-usual (BAU), referring to the case where society does not take any action to prevent further climate change.

	$$ZC_{i,g,r} = (1 + \frac{EMIT_{g,r}}{100} * \frac{Y_i - Y_0}{Y_{10} - Y_0}) * BAU_{i,g,r}$$ ● EMIT - a stochastic parameter that is used to model the uncertainty associated with future economic growth, policy measures. Essentially is a sensitivity analysis, meant to increase the variance of the results predicted.
47	**Cutback percentage for period i = *1*, for gas *g*, and in region *r*,** by which greenhouse gas emissions (ER) fall below the zero cost emission level. $$CB_{i=1,g,r} = max\{0, ZC_{1,g,r} - ER_{1,g,r}\}$$
48	**Cutback percentage for period *i*, for gas *g*, and in region *r*.** Once cutbacks are made, it is assumed that they cannot be undone. $$CB_{i,g,r} = max\{0, ZC_{i,g,r} - ER_{i,g,r}\}$$
49	**Costs of cheap preventative action (CL) for gas *g*, and in region *r*** $$CL_{g,r} = CL_{g,r=0} * CPF_r$$ ● CPF - regional multiplier.
50	**Additional costs of expensive preventative action (CH) for gas *g*, and in region *r*** $$CH_{g,r} = CH_{g,r=0} * CPF_r$$
51	**Cost of prevention for gas *g*, in analysis year *i*, and region *r*.** $$if\ CB_{i,g,r,} < MAX_{g,r,0}: PC_{i,g,r} = (\frac{CL_{g,r} * MAX_{g,r}}{100} + CL_{g,r} * \frac{CB_{i,g,r} - MAX_{g,r}}{100}) * E_{i=0,g,r}$$ $$Otherwise: PC_{i,g,r} = (\frac{CL_{g,r} * MAX_{g,r}}{100} + (CL_{g,r} + CH_{g,r}) * \frac{CB_{i,g,r} - MAX_{g,r}}{100}) * E_{i=0,g,r}$$

	• MAX - maximum cutback proportion that can be achieved by the cheap control measures
52	**Aggregated preventative costs** $$APC_{i,d,r} = PC_{i,d,r} * (Yhi_i - Ylo_i)$$
53	**Discounted Aggregate preventative costs** $$DPC = \sum_{i,d,r} APC_{i,d,r} * \Pi_{k=1}{}^{i}(1 + \frac{dr_{k,r}}{100})^{-(Y_k - Y_{k-1})}$$