IT STARTS WITH A SOCIAL COST OF CARBON

BUS 33701: Energy Policy Practicum

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Abstract

The social cost of carbon is the present value of future harm caused by an incremental ton of carbon dioxide emissions. It is difficult to estimate the social cost of carbon, because carbon emissions, climate change, and economic harm are related through complex processes that are not fully understood. Additionally, the rate at which to discount future harm is contentious and critical to the magnitude of the present value. We evaluate several approaches to estimating the social cost of carbon, including the 2013 U.S. Government estimate of $42 per metric ton of CO_2 (in 2020). We discuss the political economy and feasibility of several carbon policy options. We conclude that despite, and because of, the uncertainty in climate science and economics, it is prudent to adopt a carbon policy that is sufficient to induce some transition to cleaner practices today, because of the long lives of carbon infrastructure and the persistence of energy consuming behaviors. The ideal policy is a uniform global carbon tax, because it would minimize emissions leakage around the world and provide more cost certainty for firms.

1. The Foundations of a Social Cost of Carbon

The social cost of carbon is the present value of future harm caused by an incremental ton of carbon dioxide emissions. The burning of an incremental ton of emissions marginally affects climate change on the planet by slightly raising temperatures, changing rainfall patterns, affecting storm intensity, and so on. These effects are projected to reduce output of the global economy on net, through their impact on sectors such as health, agriculture, and real estate. The social cost of carbon ideally characterizes with one number the magnitude and proximity of harm from incremental emissions, though it does not directly reflect important underlying factors such as the distribution of harm across regions and sectors and the potential for catastrophic outcomes. While it is abstract in nature, the social cost of carbon is a critical number to inform carbon policy making.

Any carbon policy would attempt to correct the market failures which lead to excessive emissions. Emissions are a negative externality, the harmful side effect of burning fuels. Economic theory predicts that activities with associated negative externalities will be oversupplied if their social costs are not internalized. Without a carbon price, emitters are not charged for releasing carbon into the atmosphere and have no incentive to reduce emissions. Also, the earth's atmosphere is a public good, both non-rivalrous and non-excludable. As such, it is likely to be degraded without policy intervention, because its conservation is in no individual's rational interest.

Standard economic policy prescriptions exist to alleviate these issues. If energy-burning practices were priced to reflect their total cost to society, economic efficiency would be reached through the profit-maximizing behaviors of emitters and consumers. Determining carbon's social cost is therefore the first step to reaching an economically efficient policy response to climate change. A modest value of the social cost of carbon (say a few dollars per ton of CO_2) would have little effect on today's choice of fuels and energy consumption, but a high value would make carbon intensive practices such as burning coal and petroleum expensive relative to other fuels, leading to more significant substitution to cleaner fuels and lower energy consumption in general. A wide range of responses could be efficient, depending on the magnitude of the social cost of carbon.

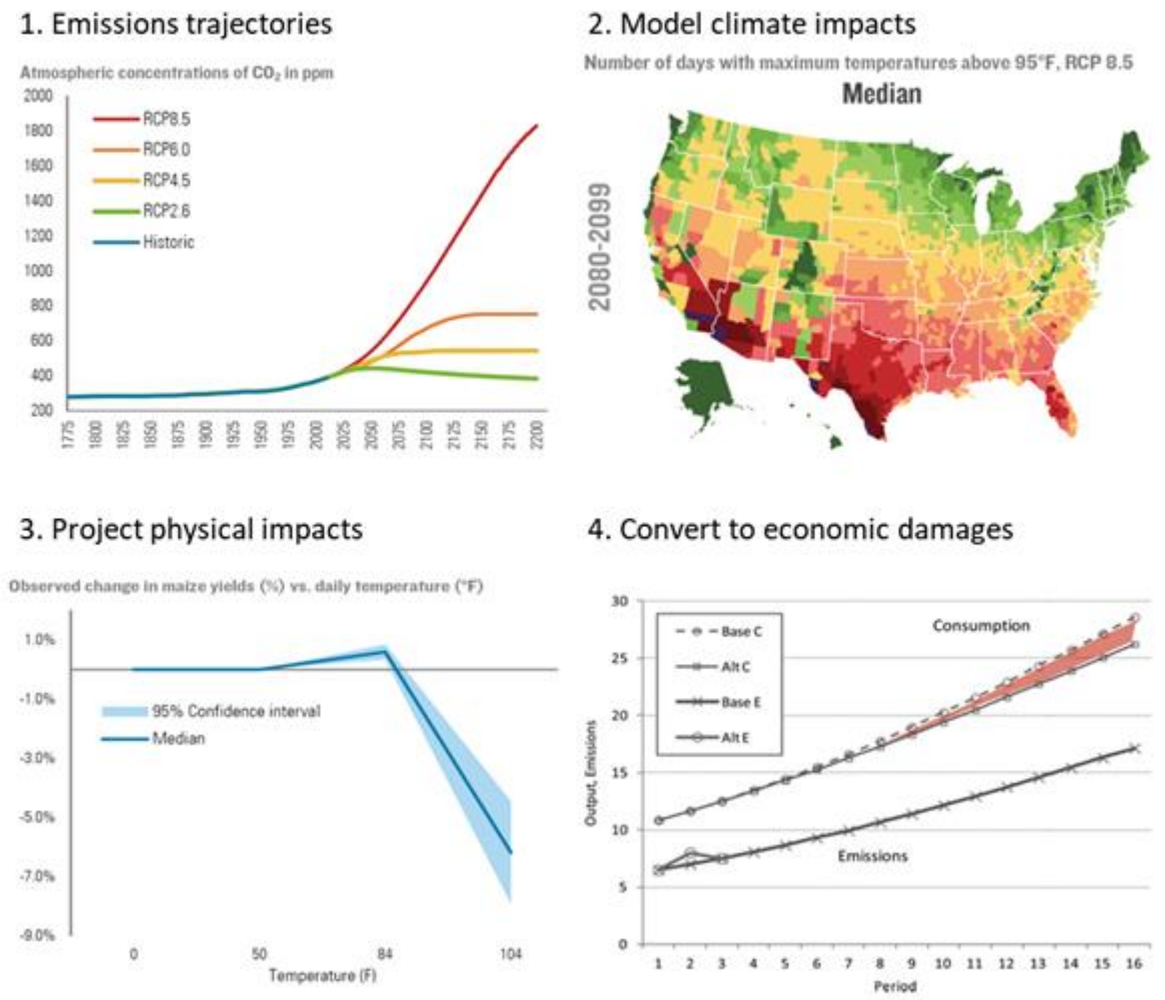
The purpose of this paper is to summarize the current state of knowledge pertaining to the social cost of carbon and discuss potential carbon-reduction policies and their trade-offs. The paper is structured as follows: in Section 2, we summarize how the social cost of carbon is estimated, showing that it is no simple feat. Section 3 discusses the political economy of carbon policies both in the United States and internationally. Section 4 highlights the importance of global coordination in mitigating climate change, and evaluates three potential carbon policies: taxation, cap-and-trade, and command and control regulation. Using lessons drawn from these analyses, we then outline the ideal policy response to climate change, a uniform global carbon tax.

2. *Estimating the Social Cost of Carbon*

Carbon emissions, climate change, and economic harm are related through complex processes. Although the scientific understanding of climate change has improved significantly over the last several decades, there remains a considerable range in estimates for the social cost of carbon (SC-CO_2). Integrated assessment models (IAMs) have been the main tool to estimate the SC-CO_2 since the early 1990s. A next generation IAM, the Spatial Empirical Global-to-Local Assessment System (SEAGLAS), is being developed at the University of Chicago. This section of the paper will discuss in turn each of the major steps involved in calculating the SC-CO_2.

There are five conventional steps to estimating the SC-CO_2:

1. Use socioeconomic trajectories (population and GDP) to estimate emissions trajectories of CO_2 and other greenhouse gases (GHG)
2. Model climate impacts of GHG using climate models
3. Project physical impacts in a number of sectors (e.g. sea level rise and agriculture)
4. Convert environmental impacts into economic damages (e.g. a percentage of GDP)
5. Discount damages to reflect present value



(1, 2, 3: Houser et al., 4: Nordhaus 2013)

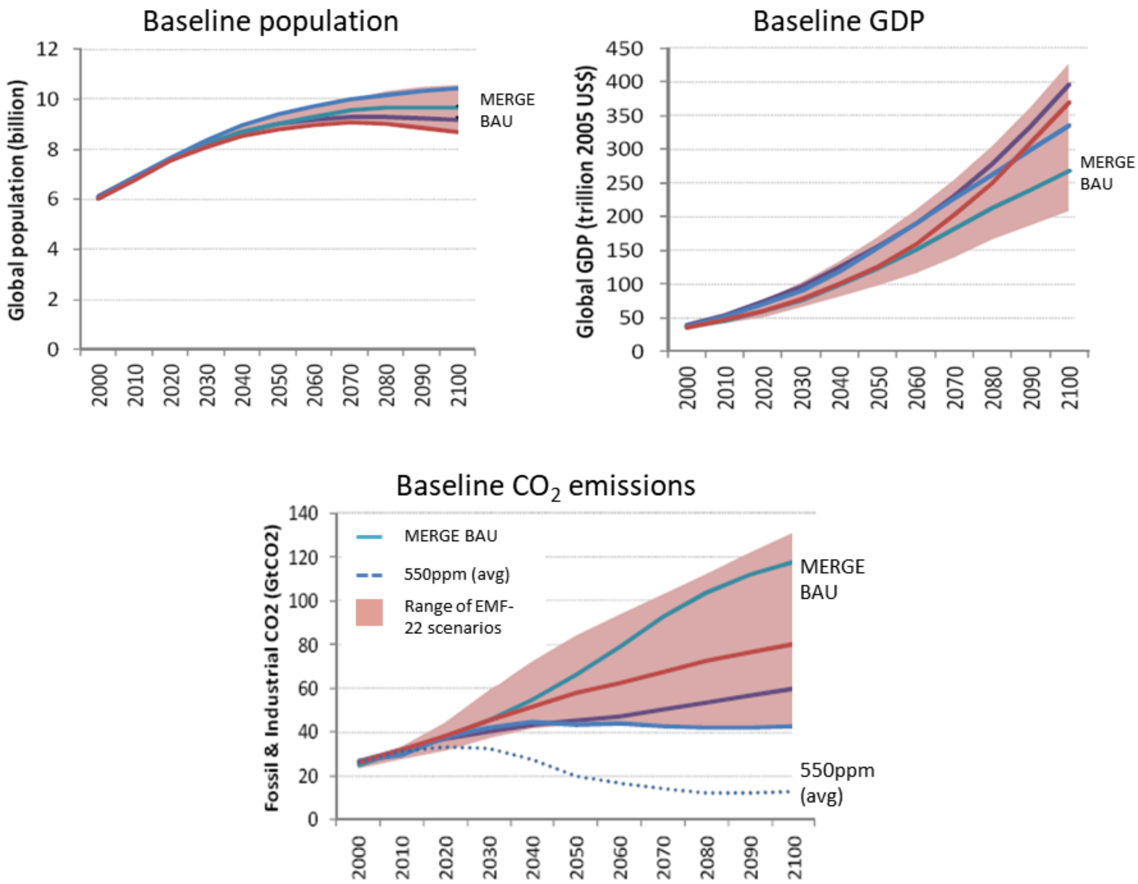
To determine the SC-CO_2, an IAM or another model is first run using a baseline socioeconomic and emissions scenario, and the resulting climate and economic projections (usually consumption) are captured. The model is run again with a pulse of CO_2 emissions at some point in time, and the difference in consumption between the two runs gives the economic damages over time (illustrated in the bottom right panel of the figure on the previous page). Economic damages are then discounted to reflect the present value of the future harm caused by incremental emissions, the SC-CO_2.

Common SC-CO_2 estimations therefore consider harm of climate change that is carried out on the market economy. Other factors, such as potential agricultural shocks, ecosystem disruption, and civil conflict are not usually included; indeed, many of the most important risks associated with climate change fall on ecological systems which are not captured in the calculation. Including impacts from these factors would lead to a higher value for the SC-CO_2 (Houser et al. p.132). One factor that might lead to a lower value for the SC-CO_2 is the possibility of an affordable, scalable mitigation technology that could reduce the impact of bad climate outcomes. One such technology is stratospheric aerosol injection, a type of climate engineering (or geoengineering). A discussion of geoengineering opportunities is presented by Britto, Bent, Craven, and Lilovich, published by the Energy Policy Institute of Chicago (Britto et al.).

2.1 Socioeconomic Trajectories

The first step to estimating the SC-CO_2 is to make projections of population, GDP, and CO_2 emissions over the modeling horizon. This is no easy task, as the modeling horizon usually extends to the end of the century at minimum, and can extend for hundreds of years. Socioeconomic trajectories (or scenarios) come from a number of different sources. For example, DICE 2016 uses UN estimates for population projections and a survey of experts for the projected growth in per capita output. FUND uses the EMF14 Standardized Scenario for population and per capita income, and includes alternative scenarios from the Intergovernmental Panel on Climate Change (IPCC) SRES study.

The U.S. Government Interagency Working Group (Interagency 2010) whose study produced the \$42/ton SC-CO_2 estimate, used a set of socioeconomic scenarios from the EMF 22 International Scenarios study, published in 2009 (Clarke et al.). These scenarios were the latest available peer-reviewed scenarios for socioeconomic projections. In that study, ten teams used integrated assessment models to explore emissions mitigation scenarios to meet certain targets of CO_2 emissions (e.g. 550 ppm), an alternate approach to estimating the SC-CO_2. The Working Group used the business-as-usual (BAU) trajectories from four models (MiniCAM, MESSAGE, IMAGE, and MERGE "optimistic"). A fifth trajectory was created by averaging the trajectories of the four models under scenarios in which the concentration of CO_2e was mitigated to 550 ppm. The scenarios comprise a very wide range of CO_2 emissions trajectories, and modest ranges of GDP and population trajectories.

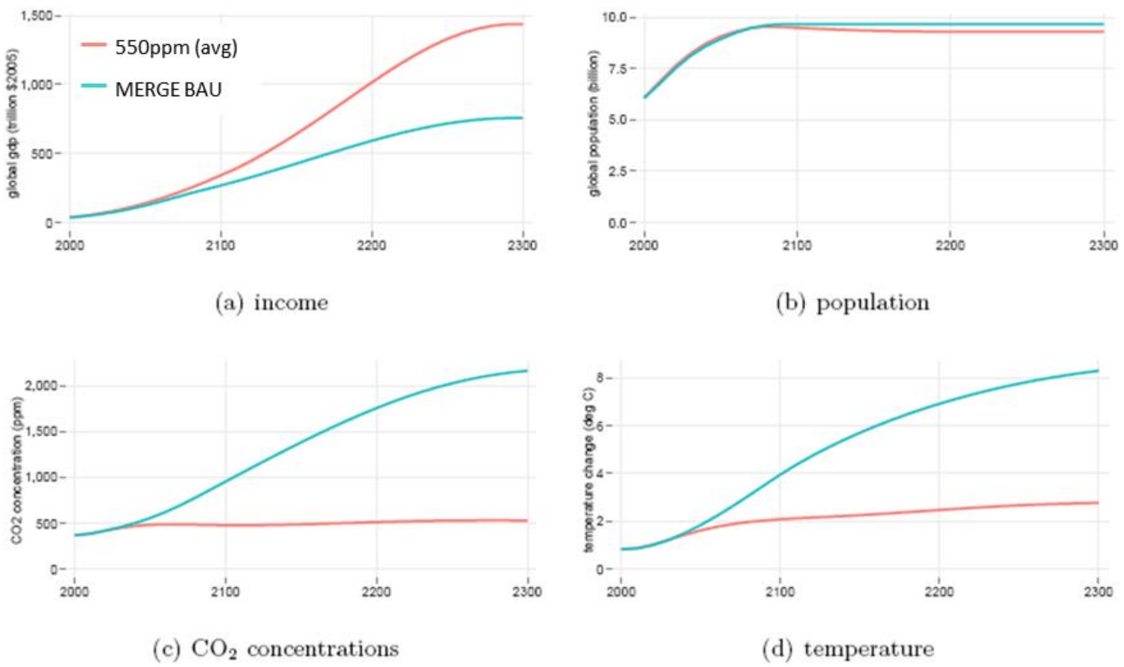


Socioeconomic trajectories included in 2010 Working Group study (two are labeled for further discussion) (Rose p.18)

Since the EMF 22 modeling period ended at 2100, the Working Group made a set of assumptions to extend the projections to the end of its modeling horizon in 2300. To extend the trajectories, the Working Group assumed that population growth rate declines linearly to zero in 2200, GDP per capita growth rate declines linearly to zero in 2300, and the declining fossil and industrial carbon intensity growth rate (CO_2/GDP) is maintained from 2100 through 2300.

The charts on the next page show the Working Group's extended trajectories of GDP and population, along with resulting CO_2 concentration and temperature, for two of the five Working Group scenarios. "MERGE BAU" refers to the business as usual forecast from the MERGE "optimistic" case. "550ppm (avg)" is the scenario in which CO_2 concentration is mitigated to 550 ppm (the average of four separate mitigation scenarios). These are the highest and lowest CO_2 emissions scenarios, respectively.

The temperature chart indicates the range in projected temperature increase from these widely differing emissions scenarios, which gives a rough sense for the importance of socioeconomic and emissions trajectories on projected climate change using the DICE climate model. The range of temperature change is about 2ºC to 4ºC in 2100, and 2.5ºC to 7ºC in 2200.



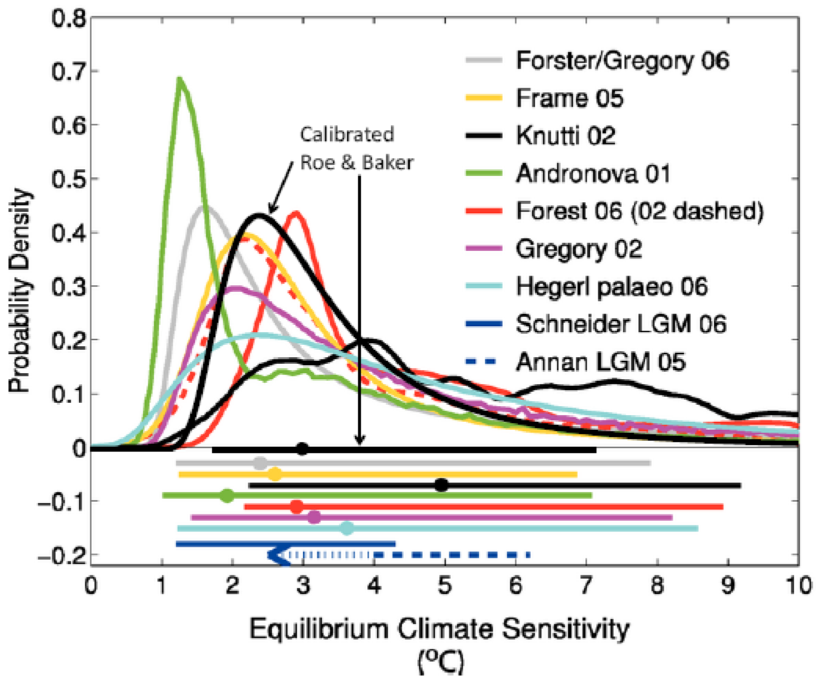
Socioeconomic trajectories and CO_2 concentration extended to year 2300, projected temperature change (DICE) (Diaz p.19)

SEAGLAS, the next-generation IAM, uses the latest peer-review scenarios, which were developed by the Integrated Assessment Modeling Consortium and used for the IPCC Fifth Annual Report (AR5). They are referred to as “Representative Concentration Pathways” (RCPs, i.e. CO_2 concentration trajectories). RCPs link more naturally with CO_2 concentration targets issued from international discussions such as the Paris Agreement, but are essentially an equivalent input for modeling damages.

2.2 Climate Modeling

Projecting the impact of CO_2 emissions on the earth's climate is a challenging exercise. The earth's climate system has a number of feedback effects, meaning that an increase in global average temperatures could cause compounding impact to the climate system. Examples of feedback effects from temperature increases include changes in cloud characteristics, increase in atmospheric water vapor, and decreasing reflectivity of the earth's surface due to snow and ice melting. Not all of the underlying mechanisms driving feedback effects in the climate system are understood from first principles. Without this knowledge, engineering models must be used to estimate the range of possible climate outcomes, instead of defining the range using a theoretical approach.

The Equilibrium Climate Sensitivity (ECS) is defined as the long-term change in global average temperature from a doubling of CO_2 concentration from pre-industrial levels. After CO_2 concentrations level off, atmospheric and ocean processes are projected to reach equilibrium over a period of hundreds or thousands of years, and this response is captured by the ECS. Without feedback effects, the ECS is relatively simple to calculate; its value would be about 1.2ºC. Projecting feedback effects with engineering models leads to a considerable range in projected values. The chart shows ECS distributions from nine studies published from 2000 to 2006, along with the Working Group's Calibrated Roe & Baker distribution. The studies all have a very large range of possible values for the ECS.



(Interagency 2010 p.14)

The IPCC concluded the following regarding the ECS in its Fourth Assessment Report (AR4) on climate change:

Basing our assessment on a combination of several independent lines of evidence… including *observed climate change and the strength of known feedbacks simulated in [global climate models], we conclude that the global mean equilibrium warming for doubling CO_2, or 'equilibrium climate sensitivity', is likely to lie in the range 2ºC to 4.5ºC, with a most likely value of about 3ºC. Equilibrium climate sensitivity is very likely larger than 1.5ºC. For fundamental physical reasons as well as data limitations, values substantially higher than 4.5ºC still cannot be excluded, but agreement with observations and proxy data is generally worse for those high values than for value in the 2ºC to 4.5ºC range.* (Pachauri et al. 2007).

Note that the IPCC avoids defining probabilities in its statement. The technical reason for using qualitative descriptors is that uncertainty could not be formally quantified in the estimation approach, a meta-analysis of existing studies. The Working Group followed the IPCC's guidance but was forced to infer probabilities from the IPCC's conclusion to make a distribution of the ECS. It interpreted the "most likely" (3ºC) as the median, and "likely" (2ºC to 4.5ºC) as having a two-thirds probability. It also bounded the ECS below 0ºC and above 10ºC. It calibrated four distributions that satisfied these criteria. The Working Group selected the calibrated Roe and Baker distribution because it was based on a theoretical understanding of the climate system response and because it had the largest right tail, which the team believed better matched the studies underlying the IPCC report. The mean of the distribution is about 3.5ºC.

It is worth noting that the ECS is not the only significant metric of climate response. The National Academies of Science, Engineering, and Medicine's Committee on Assessing Approaches to Updating the Social Cost of Carbon suggests that the most relevant single climate metric for the estimation of the SC-CO_2 may be the Transient Climate Response (TCR), that is, the *transient* response of global mean temperature to a doubling of CO_2 emissions (National Academies 2016). The TCR is the more immediate effect of a doubling of CO2 on the climate system, rather than the full equilibration that plays out over many centuries. It more directly links to the magnitude of the SC-CO_2, because damages which are more proximal are weighted more heavily after discounting. The TCR may become a more important metric to compare climate models in the future.

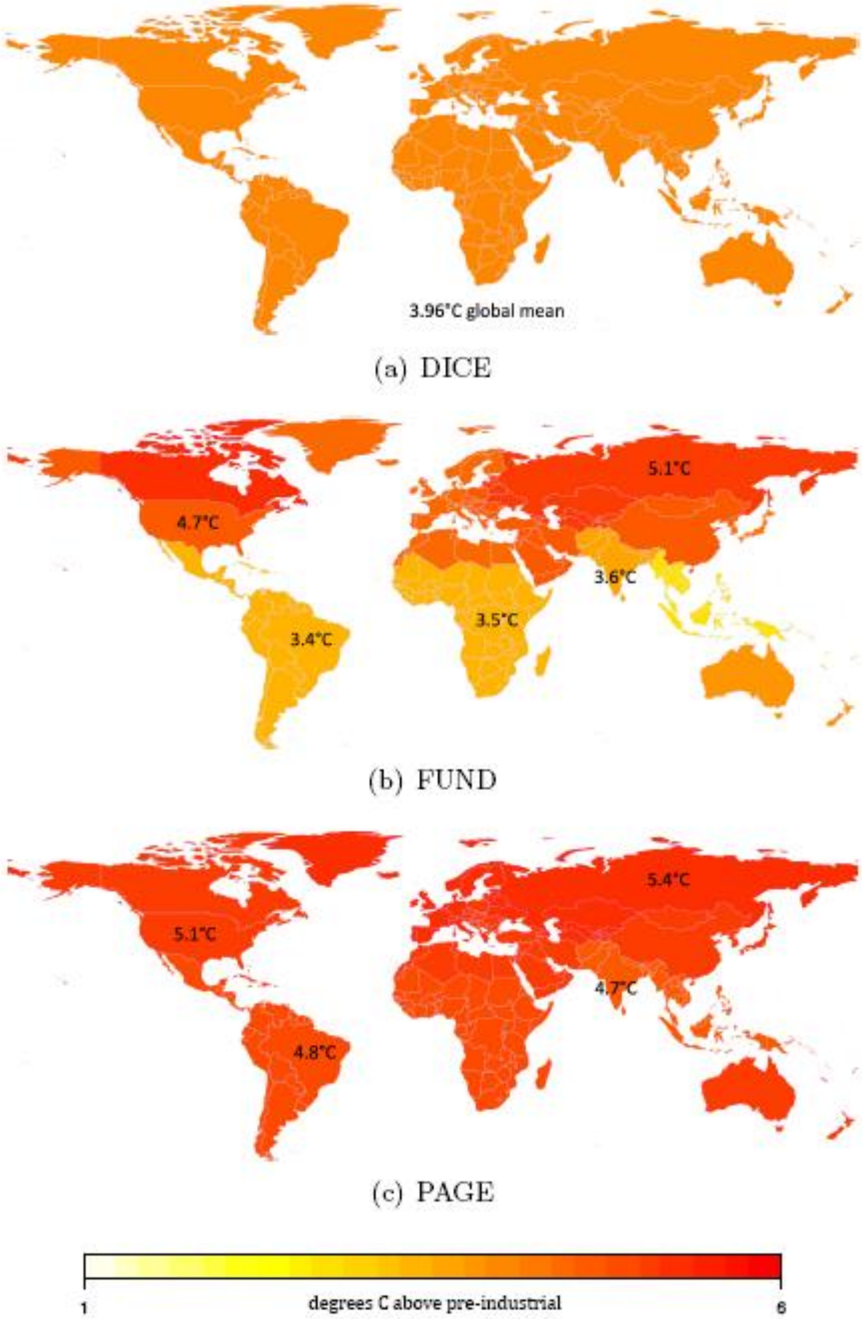
IAM authors use different assumptions for the ECS. DICE 2016 sets the ECS to 3.1ºC, which comes from a meta-analysis of existing studies, similar to the approach of the Working Group (Olsen et al. 2012). FUND 3.5 sets the ECS to 3.0ºC. FUND also defines a distribution for the ECS, as with a number of other input parameters. It uses a gamma distribution with a median of 3.0ºC.

The IAMs include a number of other climate modeling aspects besides the ECS. The figure below gives a comparison of the climate modeling structural characteristics for the IAMs, including details on the carbon cycle, non-CO2 gases, ocean temperature, and other parameters.

Characteristic	DICE	FUND	PAGE
Atmospheric Concentrations			
CO_2	3-box carbon cycle	5-box carbon cycle	1-box carbon cycle
Non-CO_2 Kyoto	Not modeled	CH_4, N_2O, SF_6	Not modeled
Non-CO_2 non-Kyoto	Not modeled	SO_2	SO_2
Radiative forcing			
CO_2 (per doubling)	3.80 W/m^2	3.71 W/m^2	3.81 W/m^2
Non-CO_2 Kyoto	Exogenous	CH_4, N_2O, SF_6	Exogenous
Non-CO_2 non-Kyoto	Exogenous	SO_2	SO_2, non-SO_2 exogenous
Global Mean Surface Temperature	Rate temperature moves toward equilibrium is a function of climate sensitivity & surface temperature modulated by ocean heat uptake	Rate temperature moves towards equilibrium is a function of climate sensitivity	Function of global mean land and ocean temperatures
Ocean Temperatures	2-box (upper and deep ocean)	1-box	1-box
Regional Temperatures	n/a	Implicit with regional damage parameters calibrated to regional temperatures downscaled based on a linear pattern-scale average of 14 global circulation models	Explicit with regional temperatures downscaled according to latitude and landmass adjustment
Global Mean Sea Level Rise	Components (thermal expansion, glacier and small ice cap melt, GIS melt, WAIS melt) computed as functions of temperature and lagged temperature	Computed as a function of temperature and lagged temperature	Computed as a function of temperature and lagged temperature
Time Steps	10-year	1-year	Variable (10-year 2000-2060, 20-year 2060-2100, 100-year 2100-2300)
Implementation of CO_2 Pulse in Year t	Pulse spread equally over the decade straddling year t	Pulse spread equally over the decade from year t forward	Pulse distributed evenly over the two decades preceding and subsequent to year t
Model-Specific Uncertainties Other than ECS (number of parameters; distribution types)	None	11 – normal, truncated normal, triangular, and gamma distributions	10 – triangular distributions

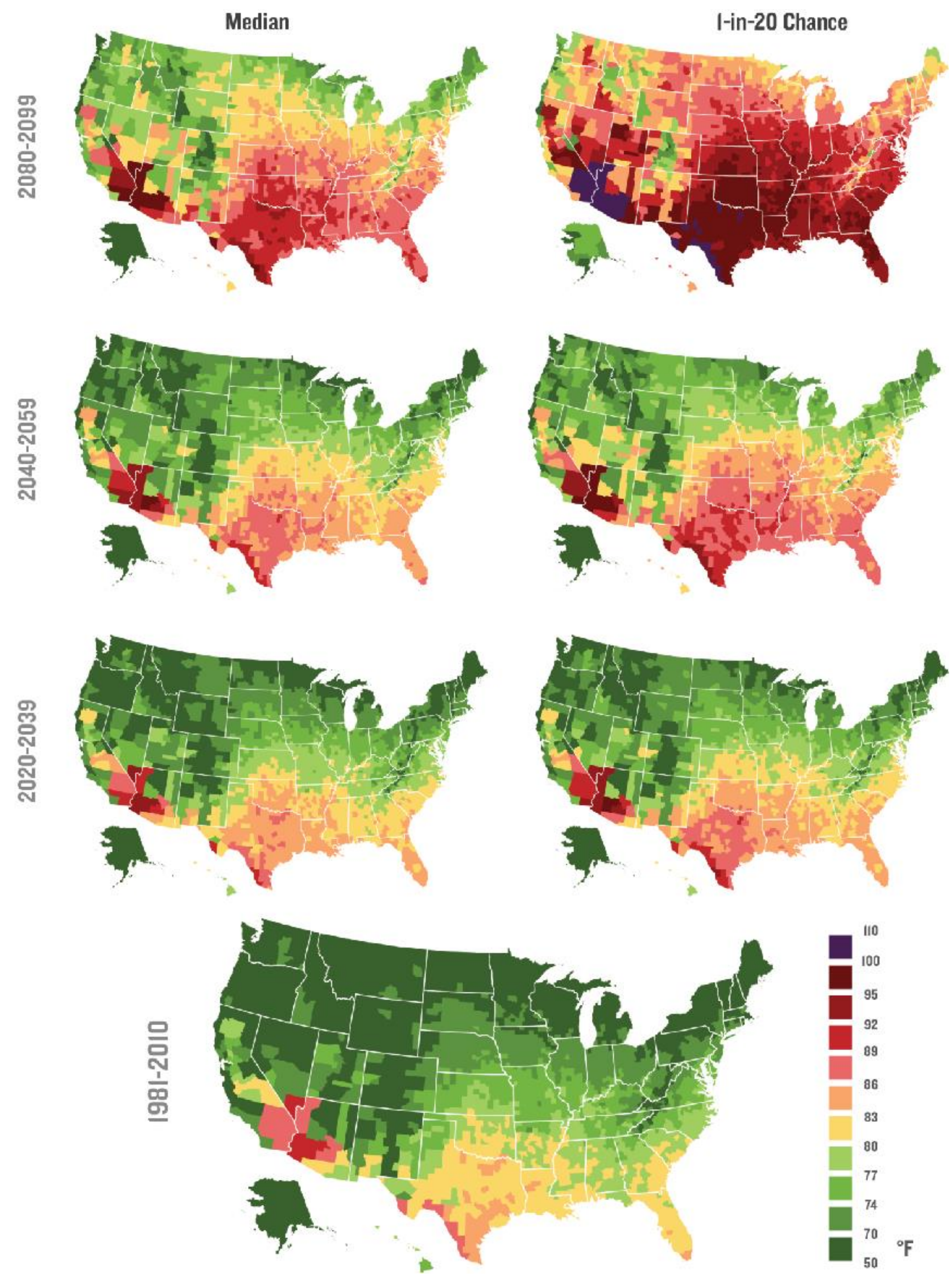
Climate model characteristics of IAMs
(National Academies 2016 p.36)

The IAMs project climate change over very large regions. The chart below compares the projected temperature changes in the three IAMs in year 2100 (under the MERGE scenario). Although the authors attempt to aggregate heterogeneous effects within the regions, it is a challenge with such little granularity built into the models.



Projected temperature change in 2100 from IAMs, MERGE (BAU) Scenario.
(Diaz p.22)

SEAGLAS, the next generation of IAM, uses much more advanced climate modeling. The Coupled Model Intercomparison Project Phase 5 ($CMIP_5$) is an ensemble of 35 different global climate models (GCMs) used by the IPCC in AR5 (Pachauri 2014). The GCMs have a spatial resolution of 70 to 150 miles, which were further downscaled to county level for SEAGLAS. GCMs allow for a better assessment of the heterogeneity of climate impacts, but they are still subject to the underlying uncertainty regarding climate mechanisms that is reflected in the ECS distribution. $CMIP_5$ gives a robust "ensemble of opportunity" of possible climate projections. This provides a good *indication* of uncertainty in climate science, but still cannot be used to technically quantify the uncertainty.



Daily average summer (June, July, August) temperature (F) under RCP 8.5
(Houser et al. p21)

2.3 Physical Impacts and Economic Damages

2.3.1 Integrated Assessment Models

IAMs, first developed in the early 1990s, have been the primary method for estimating the SC-CO_2. Three models were included in the Working Group effort: DICE (Dynamic Integrated Climate and Economy) by William Norhaus, PAGE (Policy Analysis of the Greenhouse Effect) by Chris Hope, and FUND (Climate Framework for Uncertainty, Negotiation, and Distribution) by Richard Tol. IAMs take a high level view of the science and economics of climate change, and by necessity make a large number of assumptions. In instances these are derived from or calibrated to match published studies, and in others they are applied based on the author's judgment.

The figure compares a number of factors in the IAMs. There are stark differences, including the regions and sectors modeled, the shape of the damage functions, assumptions on adaptation, handling of potential catastrophes, and definition of input parameter distributions.

	DICE	FUND	PAGE
History and background	**Dynamic Integrated model of Climate & the Economy** • Developed by William Nordhaus (1992) • Run by EPA as a simulation model (not true DICE) • Based on DICE2010 Excel equations, not current version (2013R) • Open souce: GAMS (and user-friendly Excel) • http://www.econ.yale.edu/~nordhaus/homepage/	Climate **Framework for Uncertainty, Negotiation and Distribution** • Developed by Richard Tol (1990s), David Anthoff co-developer (2006) • Run by Anthoff/Tol for 2010 SCC, by EPA in 2013 • Open source: C# • http://www.fund-model.org/	**Policy Analysis of the Greenhouse Effect** • Developed by Chris Hope (1995) • Run by Hope • Not open source: Excel @Risk • http://climatecolab.org/resources/-/wiki/Main/PAGE
Regions	**1 region:** World	**16 regions:** ANZ, CAM, CAN, CEE, CHI, FSU, JPK, MDE, NAF, SAM, SAS, SEA, SIS, SSA, USA, WEU	**8 regions:** Africa + Middle East, China + CPAsia, EU, FSU + ROE, India + SEAsia, Latin America, Other OECD, USA
Sectors	**2 sectors:** sea level rise, aggregate non-slr	**14 sectors:** sea level rise, agriculture, forests, heating, cooling, water resources, tropical storms, extratropical storms, biodiversity, cardiovascular respiratory, vector borne diseases, morbidity, diarrhea, migration	**4 sectors:** sea level rise, economic, non-economic, discontinuity (e.g., abrupt change or catastrophe)
Regional temperature downscaling	n/a	Regional damage parameters calibrated to regional temperatures downscaled based on linear pattern-scale average of 14 GCMs	Regional temperatures downscaled according to latitude and landmass adjustment
Global mean SLR	Global mean SLR components (thermal expansion, glacier and small ice cap melt, GIS melt, AIS melt) computed as functions of temperature and lagged temperature	Global mean SLR computed as a function of temperature and lagged temperature	Global mean SLR computed as a function of temperature and lagged temperature
SLR damage function	Quadratic function of global SLR (e.g., $DF=\alpha SLR^2$) Drivers: global mean SLR (in turn driven by temperature), income	Additive functions for coastal protection costs, dryland loss, and wetland loss, based on an internal cost-benefit rule for optimal adaptation Drivers: global mean SLR, dryland value, wetland value, topography (elevation, coastlength), protection cost, population density, income density, per capita income	Power function of global SLR (e.g., $DF=\alpha SLR^{0.7}$) Drivers: global mean SLR, regional coastlength scaling factor relative to EU, adaptation capacity and costs, per capita income, income
Non-SLR damage functions	Quadratic function of global temperature (e.g., $DF=\alpha T^2$) Drivers: global mean temperature, income	Uniquely formulated by sector Drivers: global mean temperature, CO_2 concentrations, ocean temperature (for storms), population, income, per capita income, technological change	Power function of regional temperature (e.g., $DF=\alpha T^2$) Drivers: regional temperature, regional scaling factor relative to EU, adaptation capacity and costs, per capita income, income
Adaptation?	Implicit (damages net of adaptation)	Explicit for agriculture & SLR, implicit otherwise (econometric studies of net response to warming)	2 types of exogenous fixed adaptation policy (i.e., constant regardless of climate change and socioeconomics) that reduce impacts for a cost
Climate benefits?	Implicit (damages net of benefits)	Explicit outcome of certain sectoral damage functions (e.g., avoided heating demand, agriculture benefits from CO_2 fertilization)	Assumes small economic benefits at low levels of warming
Catastrophe?	Implicit (via calibration to an expected value of catastrophic loss)	Represented in probabilistic mode via extreme tails of parameter distributions	'Discontinuity' impact occurs with a positive probability linked to temperatures over 3°C
Parameter uncertainty?	Fully deterministic (no uncertain parameters)	50 uncertain parameters (normal, truncated normal, triangular, gamma), vary independently	46 uncertain parameters (triangular), vary independently
Other features		"Dynamic vulnerability" (climate resiliency increases with per capita income)	

Damage function attributes of IAMs
(Diaz p.7)

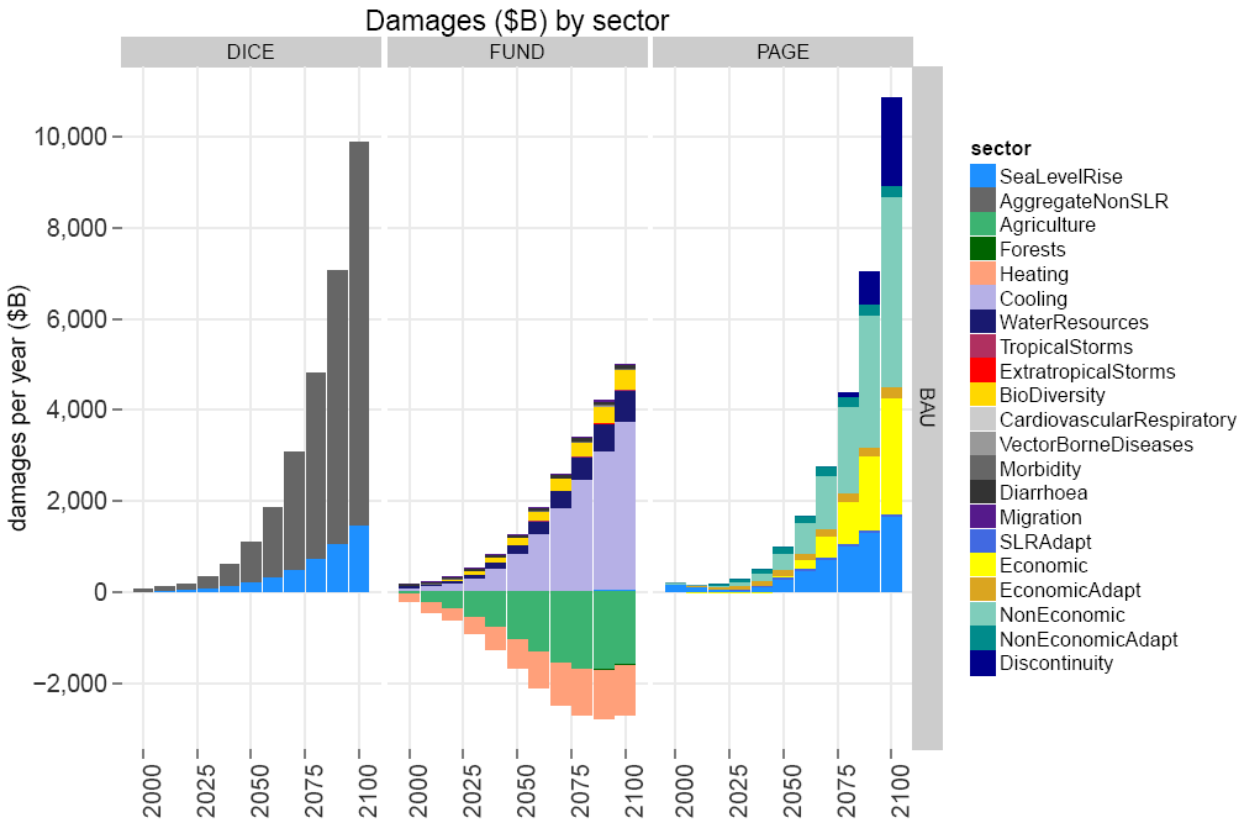
The IAMs use a number of different empirical studies to project physical damages from climate change, which are summarized below. The IAMs define damages across sectors of varying levels of aggregation, with DICE separating only sea-level rise (SLR) from all non-sea-level rise, and FUND using ten different sectors. The studies used are relatively old and surprisingly few given the daunting task of projecting climate damages across the global economy. Diaz also notes several studies which were influenced by previous generations of IAMs (e.g. the Warren et al. study used for economic damages in PAGE was based on four previous IAMs, including DICE-99 and FUND1.6). The author concludes that this leads to some degree of interlinkage between the models.

Model	Damage type	Study	Basis	Interlinkages to SCC models
DICE	Aggregate non-SLR	IPCC (2007), Tol (2009)[1]	Calibration	DICE, FUND, PAGE
	SLR coastal impacts	Undocumented		
FUND	Agriculture	Kane et al. (1992), Reilly et al. (1994), Morita et al. (1994), Fischer et al. (1996), Tsigas et al. (1996)	Calibration	
		Tol (2002b)	Income elasticity	
	Forestry	Perez-Garcia et al. (1995), Sohngen et al. (2001)	Calibration	
		Tol (2002b)	Income elasticity	
	Energy	Downing et al. (1995), (1996)	Calibration	
		Hodgson and Miller (1995)	Income elasticity	
	Water resources	Downing et al. (1995, 1996)	Calibration	
		Downing et al. (1995, 1996)	Income elasticity	
	Coastal impacts	Hoozemans et al. (1993), Bijlsma et al. (1995), Leatherman and Nicholls (1995), Nicholls and Leatherman (1995), Brander et al. (2006)	Calibration	
	Diarrhoea	WHO Global Burden of Disease (2000)	Calibration	
		WHO Global Burden of Disease (2000)	Income elasticity	
	Vector-borne diseases	Martin and Lefebvre (1995), Martens et al. (1995, 1997), Morita et al. (1995)	Calibration	
		Link and Tol (2004)	Income elasticity	
	Cardiovascular and respiratory mortality	Martens (1998)	Calibration	
	Storms	CRED EM-DAT database, WMO (2006)	Calibration	
		Toya and Skidmore (2007)	Income elasticity	
	Ecosystems	Pearce and Moran, (1994), Tol (2002)	Calibration	
PAGE	SLR	Anthoff et al. (2006)[2]	Calibration & income elasticity	FUND
	Economic	Warren et al. (2006)[3]	Calibration	DICE, FUND, PAGE
	Noneconomic	Warren et al. (2006)	Calibration	DICE, FUND, PAGE
	Discontinuity	Lenton et al. (2008), Anthoff et al. (2006), Nordhaus (1994)[4]	Calibration	DICE, FUND
	Adaptation costs	Parry et al. (2009)	Calibration	

[1] Tol 2009 is a meta analysis of the following global damage studies: Nordhaus (1994a), Nordhaus (1994b), Fankhauser (1995), Tol (1995), Nordhaus and Yang (1996), Plambeck and Hope (1996), Mendelsohn, Schlesinger, and Williams (2000), Nordhaus and Boyer (2000), Maddison (2003), Rehdanz and Maddison (2005), Hope (2006), and Nordhaus (2006). These studies themselves report impacts estimated by earlier versions of the SCC models, specifically DICE-94, RICE-96, RICE-99, DICE-99, PAGE95, PAGE2002, and FUND1.6.
[2] Anthoff et al. (2006) is a study of coastal impacts that uses version 2.8 of the FUND model.
[3] Warren et al. (2006) is a review of damage modeling in earlier versions of four integrated assessment models: DICE/RICE-1999, MERGE 1995 and 2004, PAGE2002, and FUNDv2.9.
[4] Nordhaus (1994) is an expert elicitation on climate catastrophes, and is also used as the basis for catastrophic impacts in DICE prior to 2010.

Empirical studies used to calibrate IAM damages
(Diaz p.17)

The structural differences of the IAMs are further apparent by comparing the undiscounted climate damages by sector (MERGE scenario). Interestingly, among the number of FUND sectors with empirical studies, the most significant damage is simply increased cooling costs, which are partly offset by reduced heating costs. The PAGE model separates sea level rise, economic, and non-economic impacts, plus the costs of adaptation in each sector. PAGE also has a discontinuity (tipping point) when the global temperature reaches 3ºC in 2080.

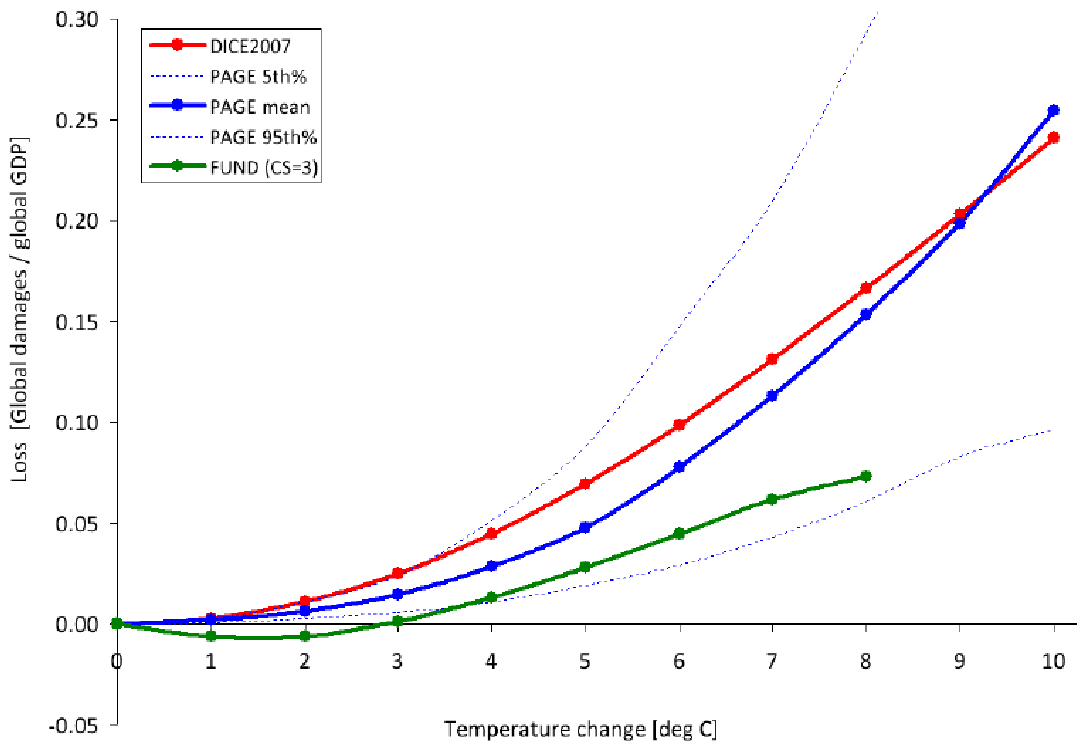


Projected sectoral climate damages to 2100, MERGE (BAU) scenario.
(Diaz p.25)

Total damages for the IAMs are shown below versus the increase in global average temperature. The PAGE model includes the 5th and 95th percentile estimates of the Monte Carlo forecasts given the default uncertainty ranges for numerous parameters, including the ECS discussed previously.

The damage functions have similar trends and roughly the same magnitudes, perhaps suggesting more agreement in the general nature of climate damages than is warranted.

Nevertheless, it is worth noting that IAMs suggest relatively small climate impacts, at least in this century. As discussed in Section 2.1, by 2100 the increase in temperatures across the five Working Group socioeconomic scenarios is roughly 2ºC to 4ºC. The range of damages across this temperature range, expressed as a percentage of world GDP, is about 0% (FUND model at 2ºC) to about 4% (DICE model at 4ºC). This inter-model base case comparison gives a sense of the magnitude of expected damages but does not reflect quantifiable uncertainty.



Base case damage functions from IAMs
(Interagency 2010 p.9)

2.3.2 SEAGLAS

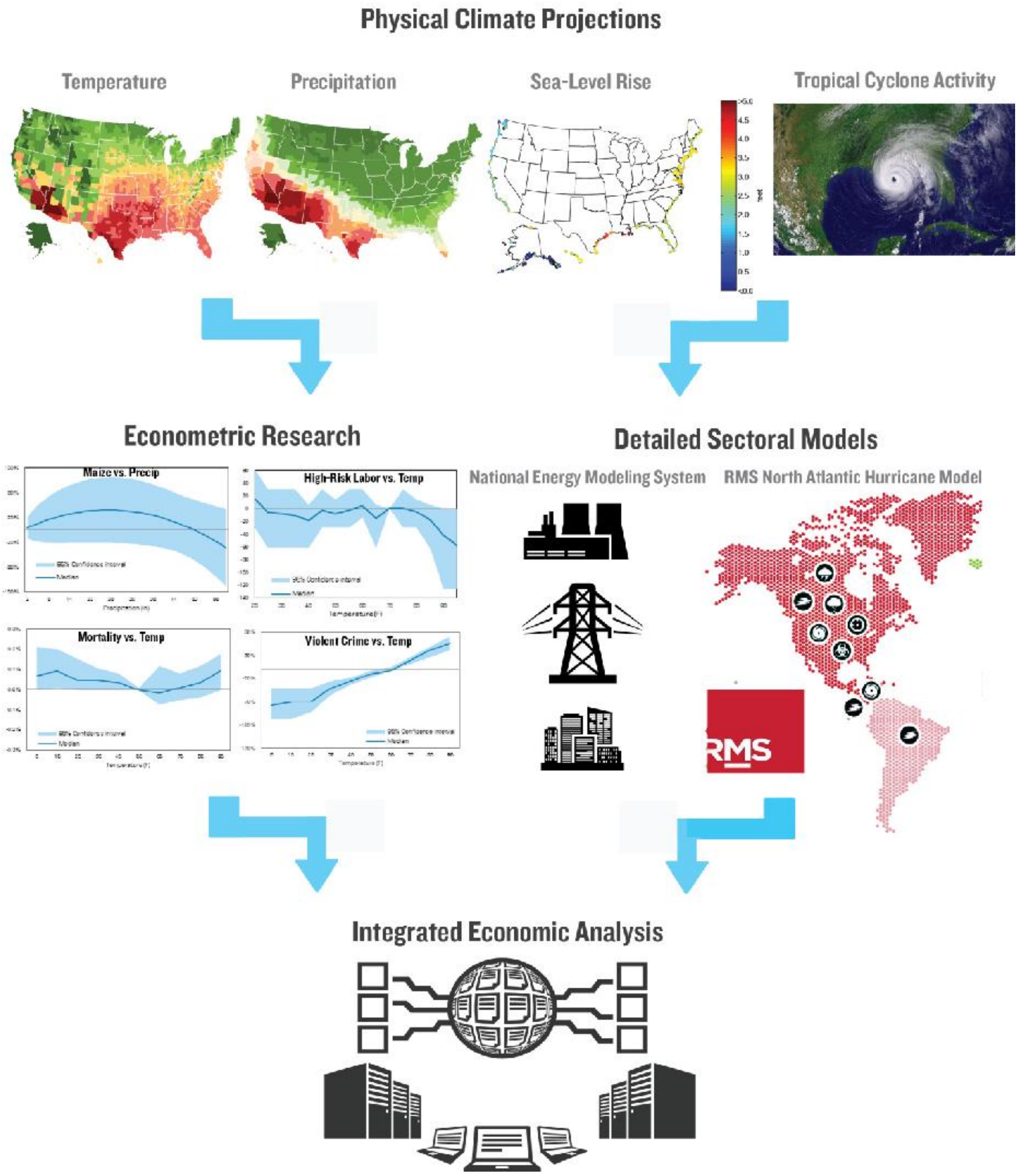
As mentioned previously, the IAMs have been criticized for drawing on different studies and implementing and extrapolating them in different ways. The next generation IAM, SEAGLAS, addresses many of these criticisms. SEAGLAS uses a consistent, transparent, empirical approach to assess damages and gives a better, though not complete, sense of the uncertainty in climate and physical impacts. Climate projections have been made for the United States, and the work is being extended globally. From global impacts, a more robust SC-CO_2 can be determined.

Four “Representative Concentration Pathways” (RCPs, i.e. CO_2 trajectories), were applied from IPCC AR5. These are named RCP2.6, RCP4.5, RCP6.0, and RCP8.5, in order of increasing CO_2 concentration. RCP8.5 represents a business as usual scenario.

For climate modeling, SEAGLAS used the $CMIP_5$ ensemble of 35 GCMs discussed previously. The climate projections were downscaled to county level using a technique called bias-corrected spatial disaggregation (BCSD). This technique uses the historical variability in climate patterns at the more local (county) level to refine the projections at model resolution level. Downscaling adds to the uncertainty in the GCM projection, but is useful for implementing county-level physical impacts.

SEAGLAS recognized that the $CMIP_5$ ensemble does not represent a probability distribution, so the authors adjusted the ensemble to reflect the distribution of climate projections from the MAGICC model in the year 2100. MAGICC is a simple climate model that imitates the results of more complex GCMs; its parameters were calibrated to match the IPCC’s estimated ECS distribution discussed previously. The $CMIP_5$ ensemble was adjusted to reflect the estimated distribution from MAGICC in two ways. First, the projections of different GCMs were weighted differently. Second, “model surrogates” were created to populate the tails of the distribution that were not captured in the original ensemble. The surrogates were created by scaling the results of other GCMs, maintaining the spatial patterns. By matching the distributions of MAGICC, the $CMIP_5$ ensemble was made to approximate a probability distribution of temperature change (Hauser et al. p.16).

The figure gives an overview of SEAGLAS. Detailed climate projections for temperature, precipitation, and sea level rise link with econometric research and sectoral models to make county-level damage projections over time. In projecting physical impacts, the authors placed an emphasis in capturing the statistical uncertainty in underlying empirical studies, focusing "on [risks] where there is a solid basis for assessment and where sector-level impacts are of macroeconomic significance" (p8). This included coastal, agriculture, labor, energy, crime, and mortality impacts.

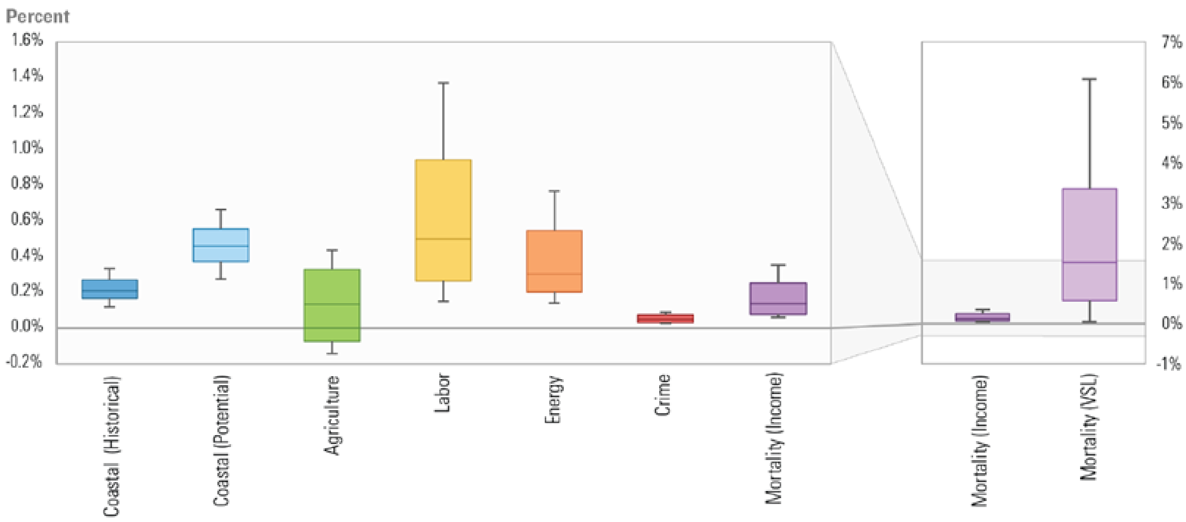


SEAGLAS
(Hauser et al. p.5)

Approximating climate uncertainty as estimated by the MAGICC model and maintaining statistical uncertainty in the empirical physical impact studies allows for a more meaningful description of uncertainty on climate damages than has been captured to date (p.5). However, it is important to emphasize that uncertainty is still not totally captured.

The results for U.S. damages versus U.S. GDP in years 2080-2099 are shown. The categories sum to less than 2 percent of GDP, which is similar in magnitude to IAM damages, although the results are substantially more credible and clear. The results do not account for adaptation, though the study outlines a method to use historical adaptation across regions as a function of wealth to project future adaptation.

A critical assumption for mortality impacts is whether to use discounted future wages or the "value of statistical life" (VSL). Applying the VSL ($7.9 million per person, EPA 2010) yields about ten times higher mortality-related damages and roughly doubles the total climate damages, as is captured in the far right panel of the figure (p.108).



Direct costs and benefits of temperature change under RCP8.5 (BAU) in the United States as a share of GDP, 2080-2099. (Hauser et al. p.116)

It is clear that SEAGLAS is a significant improvement to climate damage modeling, and after global damages are tallied it will give a more reliable estimate of SC-CO_2. However, due to the uncertainty inherent in climate modeling, the statistical uncertainty in empirical studies of physical impacts, and the choice of discount rate (discussed ahead), the range in SC-CO_2 will likely remain large.

2.3.3 *Expert Survey*

Robert Pindyck is a vocal critic of the IAM approach, arguing that the IAM creates "a perception of knowledge and precision that is illusory" (Pindyck p.2). Pindyck advocates the use of expert elicitation to determine the SC-CO_2 because it is more transparent and simpler than using an IAM, and relies on the opinions of a broad group rather than an individual analyst. The survey featured seven questions related to emissions growth and climate damages. In the survey they were elaborated upon in more depth, while they are only briefly summarized below.

The first four pertained to questions related to a business-as-usual emissions scenario:

1. Most likely average growth rate of world GHG emissions over the next 50 years
2. Most likely climate-caused percentage reduction in world GDP in year 2066
3. Probability of reduction in world GDP in year 2066 of 2% or greater, 5% or greater, 10% or greater, 20% or greater, 50% or greater
4. Most likely percentage reduction in world GDP in year 2150

The last three questions pertained to abatement, discount rate, and the researcher's expertise:

5. Most likely average growth rate of world GHG emissions needed to prevent (reduce the probability to near zero) a reduction in GDP of at least 20%
6. What discount rate should be used to evaluate future costs and benefits from GHG abatement?
7. Is your expertise primarily in climate science, economics, or in both?

The online survey was sent to 6,833 published climate scientists and economists. Approximately 1,000 of those contacted responded (p.20). Tellingly, "about 400" of the responses had to be dropped for nonsensical answers, or 40% of all responses. A few given examples are GDP loss greater than 100%, discount rates greater than 50%, and probabilities greater than one (p.23). The error rate casts doubt on the approach, as many researchers either did not give sufficient attention to the questions or struggled to translate climate impacts into the requested dimensions.

The survey gives the following information, with the notation used in the study:

m_0 – expected growth rate of emissions under BAU (1)
m_1 – reduced growth rate of emissions needed to avoid a 20% GDP impact (5)
z_1 – most likely percentage impacts under BAU in 2066 (2)
z_2 – most likely percentage impacts under BAU in 2150 (4)
R – discount rate (6)
$F(z_1^*)$ – probabilities of various climate impacts in 2066 (3)
ϕ – damage term used to fit probability distributions. $\phi = -\ln(1 - z)$

> ϕ is unconstrained at the upper end, so fat-tailed distributions (e.g., Generalized Pareto) can be compared to thin-tailed distributions (e.g., Gamma), whereas z is constrained $0 \leq z \leq 1$ (p 6)

β – dynamic adjustment parameter, used to create damage equation from z_1 and z_2

> $z_2 = z_1[1 - e^{-\beta t}]$

For a number of reasons, the author calculates the average SC-CO_2, rather than the marginal SC-CO_2 determined by the IAMs. Most importantly, the marginal SC-CO_2 cannot be calculated without an IAM. The approach is to define a probability distribution of GDP impacts under BAU, define the change in emissions growth which would truncate the distribution at z_1 = 20%, and create a truncated distribution by setting the probability of z_1 = 20% to one and shifting up the probabilities for z_1 < 20%. The difference between the distributions is the benefit of emissions reduction, which has an associated reduction in emissions flow. Using the dynamic adjustment parameter, the damage distribution is projected out. Using the discount rate R, the damages are discounted back to present values. The average SC-CO_2 equals the benefits of abatement which "truncate the distribution" divided by the present value of emissions reductions required (p.10). By pivoting calculations around the survey response for the probability of GDP impacts greater than 20%, the elicitation focuses on catastrophic events to some degree.

The table below shows the averaged parameters from seven groupings of respondents, with N respondents in each, after dropping responses outside the 5th or 95th percentiles. The "High Confidence" group was self-identified in the survey. It is very surprising that $E(z_1)$, the expected GDP impact in 2066 under BAU emissions, is about 12% for all respondents, and roughly the same across groups. Climate models predict a BAU temperature increase of about 2–2.5ºC by this time, which the base-case IAMs project will cause a far smaller impact to GDP, about 0–2%.

Parameter/ Distribution	All Respond.	All – High Confidence	Economists	Climate Scientists	North America	Europe	Developing Countries
N	534	230	157	307	269	229	53
$\bar{z}_1$	.1203	.1309	.1003	.1182	.1204	.1229	.1061
$\bar{z}_2$	.2923	.3062	.2648	.2977	.2904	.3024	.2368
β	.0024	.0034	.0022	.0020	.0026	.0021	.0047
$\bar{m}_0$	.0234	.0246	.0203	.0239	.0231	.0214	.0242
$\bar{m}_1$	−.0178	−.0200	−.0172	−.0175	−.0179	−.0183	−.0123
$\bar{R}$	.0293	.0261	.0273	.0313	.0294	.0260	.0414
Gamma:							
SCC	208.5	107.6	148.6	199.9	207.3	341.4	107.3
R^2	.3692	.1954	.4201	.2319	.1013	.2270	.2769
Lognormal:							
SCC	278.1	135.2	261.8	260.2	271.7	456.7	163.1
R^2	.3843	.2079	.4315	.2463	.1123	.2385	.2964
Pareto:							
SCC	15.0	4.0	22.2	11.4	8.6	21.5	5.0
R^2	.1899	.1648	.3586	.1848	.2054	.1888	.1399
Frechet:							
SCC	295.0	137.9	348.1	270.2	278.4	481.9	181.7
R^2	.3765	.1986	.4271	.2390	.1053	.2286	.2962

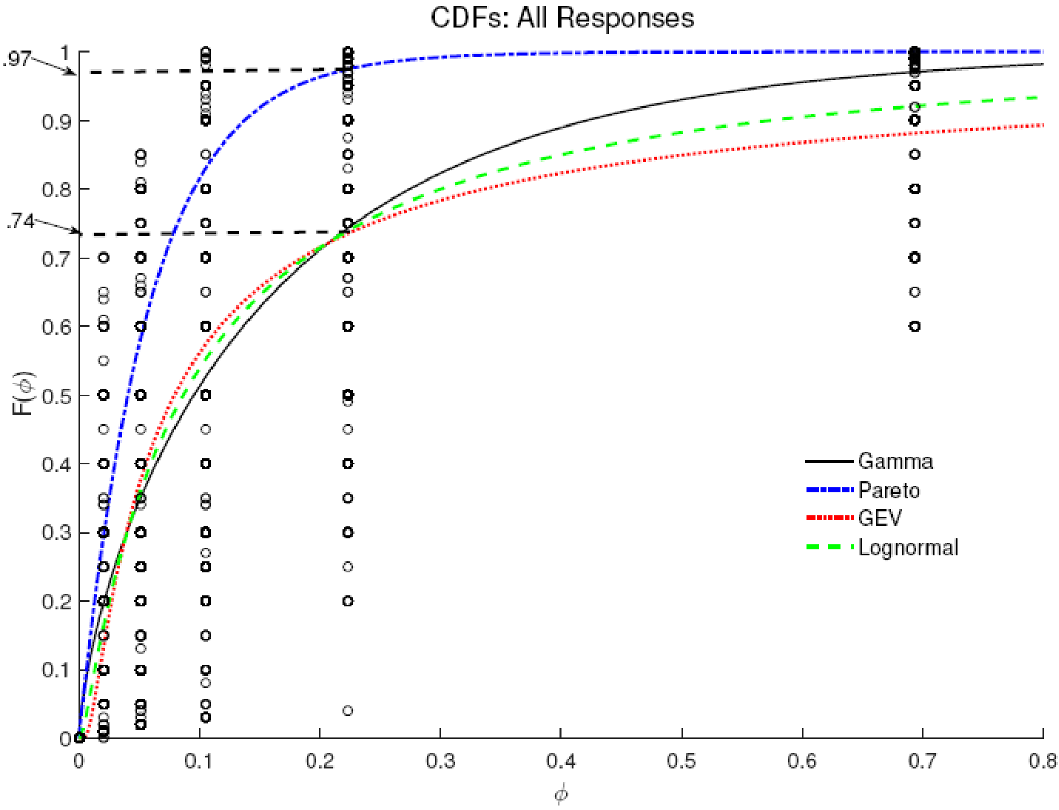
(Pindyck p.29)

The discrepancy between experts and IAMs calls into question how an expert might even surmise climate impacts. A pessimistic theory is that the expected damages elicited in Question 2 were influenced by the range of damage estimates provided in Question 3, the median of those being 10%. An equally important estimate is m_1, the amount of emission growth needed to curtail the impact distribution – effectively, to avoid any catastrophic event. Again, this would be a very difficult value to estimate and it is not clear that it could be effectively determined by expert elicitation.

Four distributions were fit to the probabilities of various GDP impacts in 2066 ($F(z_1^*)$) from all responses in each group. Although the Pareto distribution was included to give a distribution with fatter tails, its best fit was usually obtained with very thin tails, resulting in the lowest SC-CO_2 among distributions. The author compares the R^2 values to assess the best distribution for each set of responses. There is a large range of SC-CO_2 values depending on the grouping and distribution, but the typical responses of \$100-\$300 are quite high, driven by the high expected damages given in survey responses.

The chart below shows the assigned probabilities of various GDP impacts for all respondents and the four fitted probability distributions (except those outside of the 5^{th} to 95^{th} percentiles). The damage term ϕ values correspond to the survey GDP impacts in 2066 of 2%, 5%, 10%, 20%, and 50%, respectively (expressed as $\phi = -\ln(1 - z_1)$). The highlighted dashed lines show the probability in each calibrated distribution of a 20% impact to GDP ($\phi = .223$) occurring in 2066. Discounting the Pareto distribution because of its poor fit ($R^2 = .19$), the expected probability is about 26% (1 – .74).

Again, the expert responses were combined to project a relatively high chance of extreme climate damages, with a 26% chance of a 20% or greater impact to GDP in less than 50 years. This is a totally different view than comes out of the IAMs.



(Pindyck p.32)

Besides its seemingly high bias, the approach can give a wide range of answers due to its dependency on higher probability, high impact damages. For example, using the only the 5th to 95th percentile of responses from all researchers, the SC-CO_2 is \$278.1 for the lognormal distribution (the best fit). If the range is reduced to the 10th to 90th percentile, the SC-CO_2 drops to \$217.2, again using the lognormal distribution. This indicates that the answer is sensitive to the most pessimistic respondents.

To summarize, the Pindyck approach gives a useful overview of the beliefs of numerous climate scientists and economists. But while the survey represents a broad range of views on the problem, there are clear limitations to human intuition on such complex interactions between the climate and the economy. Absent readily calculable damages and abatement, respondents may be subject to biases resulting from, for example, the choice architecture used in the survey. Survey participants are self-selecting and may represent a relatively pessimistic view. The probability-impact distributions of damages are sensitive to high estimates, making the SC-CO_2 even more subject to pessimistic views.

SEAGLAS directly addresses many of Pindyck's criticisms of the IAMs and appears to be a better way forward to estimating the SC-CO2 than expert elicitation.

2.4 Discount Rates

A seemingly unsolvable, but worthwhile debate is being waged about the proper rate at which to discount economic damages from climate change. This section will provide a brief background on the purpose of discounting and its importance to the social cost of carbon, identify the major schools of thought on how to discount climate damages, and provide recommendations where appropriate on how these methods could be improved to reduce ambiguity in the magnitude of the social cost of carbon.

2.4.1 Discounting and its Importance

The first questions that need to be answered are, what is a discount rate and why is it important? In short, a discount rate is the expected return on an investment, given its risk (uncertainty of the benefits). In economics terminology, it reflects society's marginal rate of substitution between consumption in different time periods i.e. today vs. tomorrow, or 100 years from now when we might experience adverse impacts to our society from climate change. A high discount rate suggests we value consumption today and therefore must be compensated with a high rate of return in order to defer consumption to a future period, due to the uncertainty in utility of consuming in the future. The two key components of the discount rate are:

- Time value of money: A dollar today is worth more than a dollar tomorrow because if I don't spend that dollar I can invest it in a risk free security usually a U.S. government T-bill and earn a guaranteed rate of return r on my investment. Thus I will have $\$1(1+r)^t$ dollars at time t.

- Risk: If instead I invest in a non risk free asset i.e. where there is uncertainty that I get the full $\$1(1+r)^t$, then rationally I would demand a different value for r to compensate me for this uncertainty.

Economic damages from climate change must be discounted to reflect the fact they occur far into the future, and carry a high degree of uncertainty. In addition, the forecasted damages do not occur instantaneously, they occur as a stream over many years. To convert this stream of damages to one present value (the SC-CO_2), we must discount them into today's dollars using an appropriate rate r. As per Greenstone (2013) the discount rate r is used to calculate the present value of the stream of damages in the year when the additional unit of carbon was released.

The discount rate has such a profound impact on the SC-CO_2 because the benefits/damages from emitting carbon today can last for centuries. To provide context, if emitting carbon today were to cause \$1Mm of future damages in time T, the present value of those damage would be the following under different cases for r and T. Notice how many of these numbers are within \$0-\$1000 in today's dollars.

Value of $1Mm over very large time horizons

Rate	Years						
	100	150	200	250	500	1000	2000
1%	3.697E+05	2.248E+05	1.367E+05	8.311E+04	6.907E+03	4.771E+01	2.276E-03
3%	5.203E+04	1.187E+04	2.707E+03	6.176E+02	3.814E-01	1.455E-07	2.116E-20
5%	7.604E+03	6.631E+02	5.783E+01	5.043E+00	2.543E-05	6.467E-16	4.182E-37
7%	1.152E+03	3.912E+01	1.328E+00	4.509E-02	2.033E-09	4.133E-24	1.708E-53

For further reference the table below from the Working Group displays the impact different discount rates have on the SC-CO_2 calculation; it's large.

Social cost of CO_2 estimates for 2010 by model, socioeconomic trajectory, and discount rate (in 2007 dollars)

		Discount rate			
Model	**Socioeconomic reference scenario**	**5% Mean**	**3% Mean**	**2.5% Mean**	**3% 95th percentile**
DICE	IMAGE	10.8	35.8	54.2	70.8
	MERGE Optimistic	7.5	22.0	31.6	42.1
	Message	9.8	29.8	43.5	58.6
	MiniCAM	8.6	28.8	44.4	57.9
	550 ppm average	8.2	24.9	37.4	50.8
PAGE	IMAGE	8.3	39.5	65.5	142.4
	MERGE Optimistic	5.2	22.3	34.6	82.4
	Message	7.2	30.3	49.2	115.6
	MiniCAM	6.4	31.8	54.7	115.4
	550 ppm average	5.5	25.4	42.9	104.7
FUND	IMAGE	−1.3	8.2	19.3	39.7
	MERGE Optimistic	−0.3	8.0	14.8	41.3
	Message	−1.9	3.6	8.8	32.1
	MiniCAM	−0.6	10.2	22.2	42.6
	550 ppm average	−2.7	−0.2	3.0	19.4

To conclude, the discount rate is a very important piece of the SC-CO_2. If a high discount rate is assumed when discounting damages, the SC-CO_2 will be very low no matter how extensive damages are, due to the high discount factor. Alternatively if a low or near zero discount rate is chosen the SC-CO_2 will be an extraordinarily high number which suggests society should defer consumption and invest heavily in climate abatement today. The common controversies with each approach will be examined in the following section.

2.4.2 Schools of Thought on Discounting Climate Damages

There are two main approaches to determining the appropriate discount rate for climate damages, and thus a Social Cost of Carbon. They are the Descriptive Approach; which suggests using a rate based on observable returns on real assets (i.e. bonds, commodities, equities etc), and Prescriptive approach; where the choice of rate is largely influenced by the moral or philosophical judgement of the analyst on what level of importance should be placed on the well-being of future generations ability to consume.

Primer: The Ramsey Equation

Frank P. Ramsey, a British economist, created a framework in 1928 for optimal allocation across generations using a rate based on savings/consumption preferences, amongst other inputs. This "Ramsey Equation" can be used to analyze intergenerational consumption and underlies some arguments for determining appropriate discount rates for carbon related damages.

As per EPA (2010) discounting over line time horizons is complicated by three factors:

1. The "investment horizon" is longer than what is reflected in observed interest rates that are used to guide private discounting decisions

2. Future generations are without a voice in the current policy process are affected

3. Compared to intragenerational time horizons, intergenerational investment horizons involve greater uncertainty

Policies with long time horizons involve costs/investments that are born by the current generation to achieve benefits that will accrue to likely unborn future generations. The Ramsey equation provides a framework to balance how individuals should consume and/or reinvest economic output over time in order to optimize the NPV of the utility they obtain from consuming in current and future periods (EPA 2010).

Ramsey Equation: $r = ng + p$

As per EPA (2010) the Ramsey equation implies the market interest rate *(r)* is equivalent to the pure rate of time preference *(p)* plus the elasticity of marginal utility *(n)* times the consumption growth rate *(g)*.

(p) The pure rate of time preference measures the rate at which individuals discount their own utility over time, i.e. how valuable future well-being is compared to the present. A low *(p)* means that actors will prefer saving instead of consuming, while a high value means actors prefer consuming today. For example, if *(p)* is very high then actors must be compensated with a very large reward or benefit in order to defer consumption today.

(n) The elasticity of marginal utility reflects the change in marginal utility (from consumption) due to a given change in consumption

(g) The consumption growth rate is the long-term growth rate for consumption.

Multiplying *(n)* and *(g)* reflects the fact that marginal utility of consumption will change as the level of consumption changes. As consumption grows, future generations will be richer. Due to the diminishing marginal utility of consumption, consumption in future periods will be given less weight than today. This discount factor is in addition to the pure rate of time preference *(p)*.

The Descriptive Approach

The descriptive approach, first outlined by Arrow et al (1996), arrives at the discount rate by observing market rates of return achievable by investors on assets today, and by observing people's saving vs. consumption choices over time. As per Greenstone et al (2013), advocates of the descriptive approach claim realizable market rates of return are appropriate because expenditures made today to mitigate GHG emissions are financed out of current consumption like any other investment. Nordhaus (2007) articulates a powerful argument for this approach stating that if climate damages are not discounted using market rates, society will end up over-investing (or under-investing) in low yielding greenhouse gas abatement strategies (and therefore over-invest in carbon emitting project), at the expense of the higher yielding investments. The result of this over-investment is a reduction in conventional capital (due to a switch towards climate abatement investments), combined with only a slight increase in climate capital due to low yields, resulting in an overall reduction in wealth and consumption, inducing harm to society. A number of studies/researchers have implemented the descriptive approach in conducting analysis on the SC-CO_2 including:

- Michael Greenstone et al (2013) *Developing a Social Cost of Carbon for US Regulatory Analysis: A Methodology and Interpretation*. This group actually chose three certainty equivalent discount rates of 5% to reflect market returns, 3% to reflect the after tax risk free rate, and 2.5% to reflect the fact that climate judgements may have an "insurance" property, may be uncertain over time, and to appease the prescriptive approach crowd.

- William Nordhaus (2007) *The Stern Review on the Economics of Climate Change*. Nordhaus uses a rate of 5.5% based on observed real rates of return. Nordhaus updated his analysis in 2014 to a discount rate of 4.5%, and again updated his analysis in 2016 using a consumption discount rate of 5.25%, which declines over time to a rate of 3.75% by year 2100.

- Topel Murphy & Becker (2011) *On the Economics of Climate Policy* critique. The authors debate numerous approaches and drawbacks to using market rates of return, especially for investments with "insurance" properties such as certain scalable technologies, and damages that have very concentrated impacts in certain regions, or "fat tail" catastrophic events that could require different discounting. However they ultimately recommend using a market rate of return because this represents the opportunity cost of such investments, despite obvious drawbacks and implicit assumptions made when choosing different asset classes to represent "the market".

- Weitzman (2007) *The Stern Review of the Economics of Climate Change critique*. Weitzman advocates for an approach using observable market rates of return, similar to Nordhaus. He presents many similar arguments that it is sub-optimal to allocate such a low discount rate to climate damages, as they will result in sub-optimal capital allocation and worsen society. He does admit that under situations with uncertain future rates, a lower discount rate may be appropriate.

Pros and Cons

The descriptive approach provides an economically sound rationale for arriving at a discount rate for climate damages, however it is not without flaws. Currently there is a reason no consensus exists today amongst the world's leading financiers, policymakers, and economists. The pros and cons of this approach will be explored below.

We will start by examining tradeoffs in utilizing the Ramsey Equation. The main drawback is no hard data exists to compute *(p)*, The pure rate of time preference. In addition, it is likely this value is different across societies and cultures, exacerbating the problem. As per Greenstone et al (2013), most papers in the climate change literature adopt values for η in the range of 0.5 to 3 (Weitzman cites plausible values as those ranging from 1 to 4), although not all authors articulate whether their choice is based on prescriptive or descriptive reasoning. Dasgupta (2008) argues that η should be greater than 1 and may be as high as 3, since η equal to 1 suggests a savings rate that does not conform to observed behavior. Most papers in the climate change literature adopt values for ρ in the range of 0 to 3 percent per year. The very low rates tend to follow from moral judgments involving intergenerational neutrality. A commonly accepted approximation for *g* is around 2 percent per year. Economists are left to infer *(p)* by empirically measuring the other variables in the equation, including *(r)* and then backing into *(p)*. As per Frederick (2003) who attempted to study the implied rate of substitution between current and future lives, there was little evidence that the public values current lives more than future. The disparity of the results are in the table below:

Table 3. Implied rate of substitution (of future lives for current lives).

		No. of future lives = 1 current life		
Question format	Time horizon	Cropper, Aydede, and Portney (1994)[a]	Johanneson and Johansson (1997)[b]	Present study[c]
Binary choice	100	45	>243	≈45
Binary choice	25	6	25	≈6
Matching	100			≈3
Rating	100			≈1
Equity	100			<1
Total	25			≈1
Sequence	25			<1

The main benefit of using observable rates of return on financial or other assets is they represent the opportunity cost of capital, and discounting future damages at these rates in theory will ensure optimal allocation of capital and optimize future generations consumption and well being. See the numerical example below where an assumed market rate of 6% is compared to a rate of 1.5% for discounting damages (Topel, 2016). Assume $100 of damages occurs at time *t*=100. The present value of the damages using the two assumed rates are:

r =.015 ➔ *PV(100,.015) = $22.31.* Pretty big.
r =.060 ➔ *PV(100,.06) = $0.24.* Really small

However, a more interesting case occurs when you consider the potential benefit gained from investing that $22.31 at the market rate for 100 years. The result is:

r=.06➔*FV($22.31,.06) = $9000.*

The question then becomes, would you rather have invested that $22.31 today and prevented $100 worth of future damages, or received $9000 worth of future wealth? The answer seems rather obvious.

However a few key issues present themselves. *i.* Due to heterogeneity in returns, the vexing question becomes, what asset or market is an appropriate benchmark? *ii.* Without knowing the correlation between damages and our economic cycle, a wide range of rates is applicable. *iii.* If uncertainty in the discount rate is persistent (e.g., the rate follows a random walk), then it will result in certainty-equivalent discount rate that declines over time. *iv.* Is using a constant "smoothing" rate even appropriate to discount potential "trigger" events, whereby a catastrophic impact to consumption is realized. The so called "Dismal Theorem" popularized by Weitzman (2009) articulates such a situation.

i. As per Greenstone et al (2013) with heterogeneous returns to gold, oil, stock indices, corporate bonds, government bonds, public works projects, private equity etc. which is the proper rate to use. Additional questions are; should the pre-tax or after-tax rate be used, is using an observed return on American assets applicable to discount damages that will also impact China (and vice versa).

ii. Modern finance principles suggest that asset returns or discount rates, are a function of the time value of money plus the asset's systematic sensitivity to market movements (usually a major stock index like the S&P 500) which is measured by a Beta (B). The question is, are climate damages negatively correlated with market movements, not correlated at all, or positively correlated? Negative correlation is a particularly interesting case, suggesting as per Topel et al (2011) pricing carbon today and thus abating emissions, provides an "insurance" benefit that does not pay off in good times, but really pays off when we need it most. If positive correlation is true, then long run returns on a broad (potentially global) equity or asset index would be appropriate. If there is no correlation, then using a risk free rate such as the long US treasury bond is appropriate, and if the correlation is negative, then a rate lower than risk free is appropriate.

Even if correlation with known, heterogeneity between regions still results in a broad range of potential risk free rates:

	Historical Asset Returns				
	US Treasury 10 YR	*Bank of Japan 10 YR*	*10 Yr German Bund*	*Bank of China 10 YR*	*India 10 YR*
Yield	2.28%	0.04%	0.41%	3.70%	6.67%
Low: 0.04%		**Median:** 2.28%		**High:** 6.67%	

The same problem persists if correlation was known to be positive:

Region	Equity Risk Premiums
Africa & Mid East	9.15%
Australia, NZ & Canada	5.69%
Latin America & Caribbean	10.36%
Japan	6.69%
US	5.69%
Europe	6.81%
Emerging Markets	8.22%
Small Asia (No India, China & J	7.93%
India	9.05%
China	6.55%
Global	7.08%

iii. As per Greenstone et al (2013) Weitzman (1998) showed theoretically and Newell and Pizer (2003) and Groom et al. (2007) confirmed empirically that discount rate uncertainty can have a large effect on net present values. They claim that uncertainty in the discount rate is persistent (e.g., the rate follows a random walk), then it will result in certainty-equivalent discount rate that declines over time. Consequently, lower discount rates tend to dominate over the very long term. This phenomenon is illustrated in the tables below for an investment yielding $1000 in various years in the future.

Value	$1,000.00					
Year	**1**	**2**	**10**	**11**	**100**	**101**
Uncertain Discount Rate Case ($1000)						
Rate	1%	1%	1%	1%	1%	1%
Likelihood	50%	50%	50%	50%	50%	50%
Discount Factor	1.010	1.020	1.105	1.116	2.705	2.732
NPV(e)	$990.05	$980.20	$904.84	$895.83	$367.88	$364.22
Rate	7%	7%	7%	7%	7%	7%
Likelihood	50%	50%	50%	50%	50%	50%
Discount Factor	1.070	1.145	1.967	2.105	867.716	928.456
NPV(e)	$932.39	$869.36	$496.59	$463.01	$0.91	$0.85
E(NPV)	$961.22	$924.78	$700.71	$679.42	$184.40	$182.53
Implied Discount Factor	1.0403426	1.08134	1.427121	1.471836	5.4231211	5.4784132
Implied Rate	4.034%	3.988%	3.621%	3.576%	1.705%	1.698%

This table clearly shows that from years 1 - 101 the implied discount rate declines over time when there is uncertainty in the estimates.

Certain Discount Rate Case ($1000)						
Rate	4%	4%	4%	4%	4%	4%
Likelihood	100%	100%	100%	100%	100%	100%
Discount Factor	1.040	1.082	1.480	1.539	50.505	52.525
NPV	$960.79	$923.12	$670.32	$644.04	$18.32	$17.60
Implied Discount Factor	1.0408108	1.083287	1.491825	1.552707	54.59815	56.826343
Implied Rate	4.081%	4.081%	4.081%	4.081%	4.081%	4.081%

This table demonstrates how the implied rate stays constant when no uncertainty is present.

iv. Under the Dismal Theorem (Weitzman (2014) using any sort of normally distributed structure for analyzing climate change, potentially planet-altering events are not given any significant attention in estimating damages. The dismal theorem assumes that the probability of such events (i.e. a state of zero consumption, contained deep in the tails of a damage distribution) are actually fat tailed due to uncertainty about the estimates. This analysis is important as it raises potential issues with the constant rate “damage smoothing” approaches. By discounting these low probability, very high impact outcomes at market rates, we assign them a present value close to 0. The question becomes, if the damage distribution were to be fat tailed, will we have made the required investments today to adequately mitigate potential catastrophes, suggesting a lower discount rate is needed.

The Prescriptive Approach

The prescriptive approach reflects the personal beliefs and judgements of the analysts, Greenstone (2013). In essence, it allows the analyst to select a rate they think is morally and sometimes, logically defensible. Adopters of the prescriptive approach such as Stern (2007) generally use a very low discount rate for climate damages, claiming it is unethical to prioritize our well-being over that of future generations.

Studies and whitepapers adopting the prescriptive approach:

- Stern (2007) used the Ramsey equation with parameters p = 0.001and n =1and g=.013 that resulted in a rate of 1.4%. The derived SC-CO_2 from this analysis was: $85 (Stern 2007)

Advantages claimed by Prescriptive approach supporters are about taking the moral high ground; future generations are not here to defend their own interests, therefore we should treat their interests as equal to ours based on moral obligation. Additionally they claim using a larger discount rate reduces potentially enormous future damages to a near 0 value if they are far into the future. Lastly because chosen rates are usually very low, resulting in a very high SC-CO_2, The Prescriptive Approach motivates action towards climate change.

One aspect of the SC-CO_2 that the prescriptive approach seems best suited to is dealing with "catastrophic events." Weitzman (2014) in his *Fat tails and the Social Cost of Carbon* outlines scenarios where highly disruptive carbon induced climate events will result in damages so catastrophic that the SC-CO_2 approaches infinity, no matter what the discount rate. The prescriptive approach may prove an ideal way to account for these types of events as they are deemed so undesirable (Becker, Murphy, Topel, 2011) that we would be willing to sacrifice significant consumption today to reduce their probability, or impact. Using a lower discount rate as adopted by many prescriptive approach supporters may result in the necessary behavioral change and investment policy today due to the inflated SC-CO_2.

However the prescriptive approach has some well documented drawbacks. As highlighted by Nordhaus (2007), when prescriptivists justify their usually low discount rate with the Ramsey Equation, i.e. as Stern did in his 2007 paper with a rate of 1.4%, the assumptions often conflict with observed behaviors and preferences for consumption vs. saving. In Nordhaus's critique in *The Stern Review on the Economics of Climate Change* (2007) he points out that Stern's values imply nearly a 100% increase over observed savings rates.

The problem with using near zero discount rates is illustrated in the graph below where the Stern carbon tax projections are overlaid of Nordhaus's Dice model. The downfall with the Stern proposal is that even though much of damages occur well into the future, we pay an exorbitant cost to prevent them today, resulting in the steep cost curve below that will be imposed on society. Using a market rate that increases as the damages become closer in time means that today resources will be allocated to high yielding projects and the allocation to climate will increase over time as those benefits become nearer leading to a growing cost of the externality.

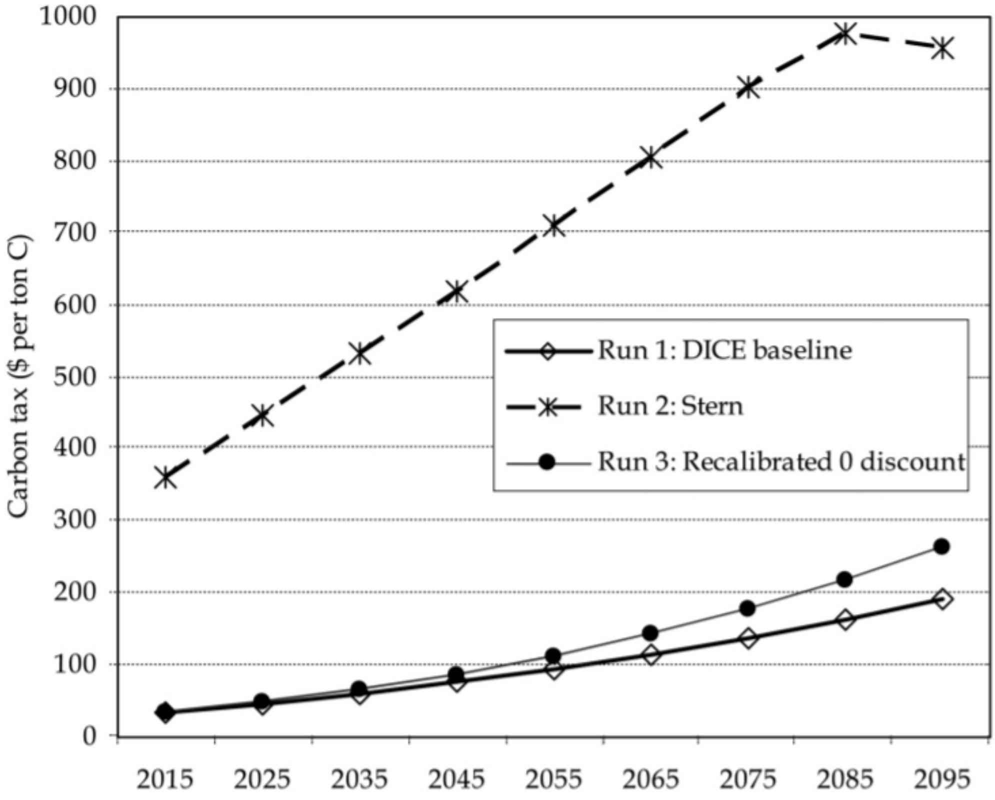


Figure 1. Optimal Carbon Tax in Alternative Runs

Note: This shows the calculated optimal carbon tax, or price that equilibrates the marginal cost of damages with the marginal cost of emissions, in the different runs. These numbers are slightly below the estimated social cost of carbon for the uncontrolled runs. Figures are 2005 U.S. international prices per ton carbon. To get prices per ton of carbon dioxide, the number should be divided by 3.67. The period is the decade centered on the year shown.

Another common argument for using low discount rates is it avoids the marginalizing impacts a high rate will have on very large, but far into the future damages, which could lead to insufficient emissions abatement. However as per Nordhaus (2007) the flip side of this argument is that when using near-zero discount rates, more than half of *discounted* damages occur after the year 2800, where our estimating capability is very inaccurate.

Heterogeneity across analysts, geographies, countries, and consumers, owners amongst many other actors becomes even more complex when using the prescriptive method. Knowing the SC-CO_2 is a global phenomenon, would the moral judgements of billions of inhabitants of planet Earth arrive at remotely similar values? Likely not, and then the question becomes, how can the judgement of a select few analysts and policy makers be used to influence such a large number of people.

2.4.3 Major Needs to Rationalize Estimates

We have created some suggestions that if implemented will increase confidence in the SC-CO_2. Note not all of these suggestions appear feasible at this time and we have identified them as such (although we are open to suggestions).

We would like to note that we do not perceive the prescriptive approach as a viable approach to discounting. This statement would hold even if the prescriptive approach supporters claimed a very high rate was appropriate (today all claim one that is quite low). We feel that the economic argument showing how misallocation of capital hurts society proves it is inferior. Furthermore we feel making policy decisions that impact potentially billions of people based on the judgements of one or few analysts is not a fair solution.

- Most ideal would be to conduct a study to estimate the correlation of climate damages to market returns. If answered, this would allow much narrower convergence on a range of rates and settle many arguments (should we treat climate investments like investing in a giant insurance policy, or like any other investment opportunity). Without answering this question we do not see significant progress made on this debate. Although this seems infeasible given the lack of data to use if even one potential scenario was eliminated (such as the positive correlation scenario as suggested by Greenstone (2017)) estimates could narrow. As a second best alternative we suggest elaborating on the sensitivity approach taken by the Working Group in 2010 and 2013 because arguments using the descriptive method can be made for a range of discount rates in absence of an answer to the correlation question.

- To address the heterogeneity in returns across geographies discount damages on a regional basis using regional discount rates.

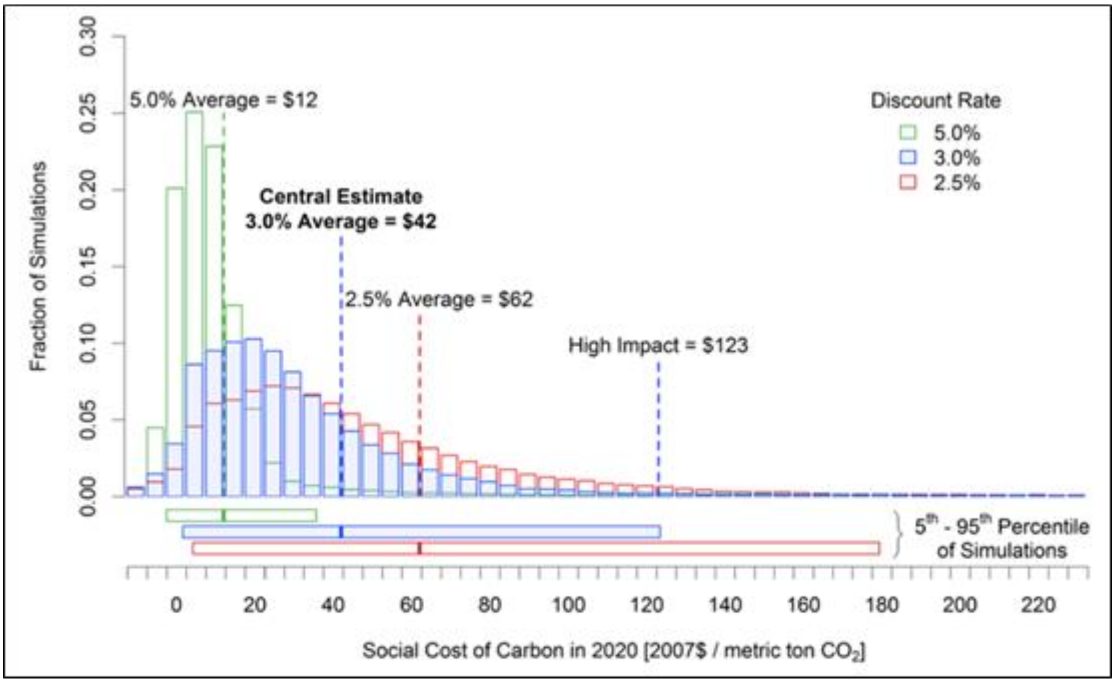
There are no “needs” to improve estimates with the prescriptive method, each analyst is entitled to their own judgements about time preference and the relative importance of current/future generations.

Conclusions

It is likely that this debate will range until the SC-CO_2 itself becomes obsolete. Due to our tendency for risk aversion, and the high level of uncertainty regarding the price of carbon, we favor using a lower discount rate than market rates of return given that paying for carbon emissions today is very similar to buying insurance on our future consumption. In addition, given empirical research that discount rate uncertainty following a random walk results in a declining uncertainty equivalent we think a rate lower than market is more than justified. That said, without an empirical understanding of correlation of damages with the economy we recommend also using a sensitized approach to picking discount rates to inform cost/benefit analysis. We are conscious that such an approach will likely increase the range of estimates.

2.5 U.S. Government Approach

For its estimate of the SC-CO_2, the Working Group used the latest version of the three selected IAMs (Interagency 2010, Interagency 2016). It used these models using their default assumptions and settings, with the exception of a few commonly imposed assumptions. First, Working Group used five socioeconomic scenarios from the EMF-22 modeling exercise. Second, it created a Roe and Baker distribution for the ECS, calibrated to the guidance of the IPCC in AR4 and broadly consistent with a meta-analysis of ECS studies. Third, it applied discount rates of 2.5, 3, and 7 percent. For each IAM, scenario, and discount rate, 10,000 simulations were run, sampling from the ECS distribution and the numerous probabilistically defined parameters in the FUND and PAGE models. Thus, 150,000 runs were generated for each discount rate (3 IAMs, 5 socioeconomic trajectories, 10,000 runs, 3 discount rates). The distributions of SC-CO_2 are shown separately for each discount rate.



Monte Carlo Distributions for SC-CO_2 in 2020 (2007$)
(Interagency 2016 p.5)

The Monte Carlo was repeated for pulses in year 2010, 2020, 2030, 2040, and 2050, to determine the SC-CO_2 across different points in time. The mean of each year's "multi-model ensemble" was calculated separately for each discount rate. A "High Impact" value, meant to represent the right tail of the damage distribution, was calculated as the 95th percentile SC-CO_2 using a discount rate of 3%. Five year intervals were interpolated from the ten year intervals.

The SC-CO_2 escalates over time because the incremental damages increase as "physical and economic systems become more stressed in response to greater climatic change, and because

GDP is growing over time and many damage categories are modeled as proportional to gross GDP" (Interagency 2016 p.16). The SC-CO_2 values are in 2007 USD per metric ton of CO_2. The "central value" is the average SC-CO_2 using a discount rate of 3 percent, or $42/ ton of SC-$CO_2$ in 2020.

Year	5% Average	**3% Average**	2.5% Average	High Impact (95th Pct at 3%)
2010	10	**31**	50	86
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

Central values of SC-CO_2 through time
(Interagency 2016 p.5)

The Working Group's first estimation was conducted in 2010, and it was updated with the latest IAMs in 2013 (the analysis discussed here). In 2010 the Working Group used DICE-07, FUND3.5, and PAGE-02; in 2013 it used DICE-10, FUND 3.8, and PAGE-09. The socioeconomic trajectories, ECS distribution, and discount rates were kept the same. The central value of SC-CO_2 increased from $26.3/ ton to $42/ ton in 2020, reflecting the increasing damages in the updated IAM versions (3 percent discount rate, 2007$).

The table shows various percentiles from the resulting distributions of SC-CO_2 in 2020, for each IAM and socioeconomic scenario, at a 3% discount rate. The range within each row reflects the range in SC-CO_2 due to ECS and the numerous probabilistic IAM parameters of PAGE and FUND. The range across rows reflects the range due to socioeconomic scenarios, which seem to be a second-order effect. The range across tables reflects the range due to IAM used.

Percentile	1st	5th	10th	25th	50th	Avg	75th	90th	95th	99th
Scenario	PAGE									
IMAGE	4	7	9	17	36	87	91	228	369	696
MERGE Optimistic	2	4	6	10	22	54	55	136	222	461
MESSAGE	3	5	7	13	28	72	71	188	316	614
MiniCAM Base	3	5	7	13	29	70	72	177	288	597
5th Scenario	1	3	4	7	16	55	46	130	252	632
Scenario	DICE									
IMAGE	16	21	24	32	43	48	60	79	90	102
MERGE Optimistic	10	13	15	19	25	28	35	44	50	58
MESSAGE	14	18	20	26	35	40	49	64	73	83
MiniCAM Base	13	17	20	26	35	39	49	65	73	85
5th Scenario	12	15	17	22	30	34	43	58	67	79
Scenario	FUND									
IMAGE	-13	-4	0	8	18	23	33	51	65	99
MERGE Optimistic	-7	-1	2	8	17	21	29	45	57	95
MESSAGE	-14	-6	-2	5	14	18	26	41	52	82
MiniCAM Base	-7	-1	3	9	19	23	33	50	63	101
5th Scenario	-22	-11	-6	1	8	11	18	31	40	62

Estimates for SC-CO2 in 2020, 3% Discount rate (2007$)
(Interagency 2016 p.26)

While it is tempting to interpret the results as describing probability around SC-CO_2, it must be remembered that the IAMs do not capture uncertainty meaningfully. The results are a reflection of the spread in ECS combined with the varying IAM techniques and parameter distributions, and only give a sense for what the SC-CO_2 might be. Nevertheless, the results represent the best information available at the time and yield a central value for the SC-CO_2, $42/ ton, which would both lead to reasonable mitigation efforts and be unlikely to significantly disrupt the economy (as indicated by abatement cost curve estimates, see p.65).

2.6 Catastrophic Events

Climate impacts projected by the IAMs are relatively modest at the end of the century and reflect manageable damages in areas like increased electricity demand and property effects of modest sea-level rise. Weitzman imagines the social cost of carbon in an altogether different light: "spending money now to slow global warming should not be conceptualized primarily as being about optimal consumption smoothing so much as an issue about how much insurance to buy to offset the small chance of a ruinous catastrophe that is difficult to compensate by ordinary savings” (Weitzman 2007 p.3).

The Working Group noted that any quantification of tipping points would lead to a potentially dramatic increase in the social cost of carbon. It lists the following possible tipping points: disruption of the Indian Summer Monsoon, dieback of the Amazon Rainforest and boreal forests, collapse of the Greenland Ice Sheet and the West Antarctic Ice Sheet, reorganization of the Atlantic Meridional Overturning Circulation [i.e. the Gulf Stream], strengthening of El Niño-Southern Oscillation, and the release of methane from melting permafrost (Interagency 2010 p.31).

Nordhaus explains that DICE does not deal explicitly with such catastrophes, because “there is virtually no basis for determining the size, timing, or probability of such events or the economic damages that would ensue”. He notes scientific, economic, and algorithmic obstacles to including tipping points in models (Nordhaus 2013 p.298). However, the IAM models do include a limited, conceptual treatment of catastrophes. DICE has an adjustment factor for non-monetized and potentially catastrophic damages. PAGE defines the probability distribution of a discontinuity above a certain threshold temperature. FUND has elements of catastrophic damages included in certain sectors (p.300).

Weitzman describes thinking about catastrophic events as “moving into the unknown territory of subjective uncertainty where our probability estimates of the probability distributions themselves becomes increasingly diffuse because the frequencies of rare events in the tails cannot be pinned down by previous experiences, past observations, or computer simulations” (p.20). Pindyck concludes from his survey approach that the possibility of such catastrophic climate outcome is the “main driver” of the magnitude of SC-CO_2 (Pindyck p.2).

The SC-CO_2 could be determined from a catastrophe-avoidance approach, if the tipping point was known. One could model supply and demand elasticities, mitigation activities, and so on, to estimate the social cost needed to stay below the concentration ceiling. This approach was used in the EMF-22 modeling exercise (Clarke et al.). Alternatively, a concentration pathway could be enforced under a cap-and-trade scheme, and the social cost would be determined by the market, reflected in the price of a CO_2 emissions permit. However, it is difficult to commit to a catastrophe-avoidance approach with no clear basis by which to set a threshold. The Paris Agreement threshold of 450 ppm was devised to give a 50% chance of staying below 2ºC and avoid “dangerous” climate change, but there is little evidence that this specific target is meaningful. If all that is known is that fewer emissions are better, then determining the SC-CO_2 by estimating and discounting future harm (as discussed in previous sections) may be more appropriate.

Possible catastrophes represent the largest threats of climate change and should continue to be studied. However, even if catastrophic damages could be estimated with any confidence, excluding them from the SC-CO_2 calculation may be reasonable if scalable geoengineering technologies are deployable to mitigate the worst of such damages.

3. *Political Economy and Carbon Policies*

There are significant domestic and international political challenges to implementing carbon abatement policies. In this section, we outline several of them to give the context in which policy choices must be considered. In-depth political analysis is beyond the scope of this paper.

3.1 United States

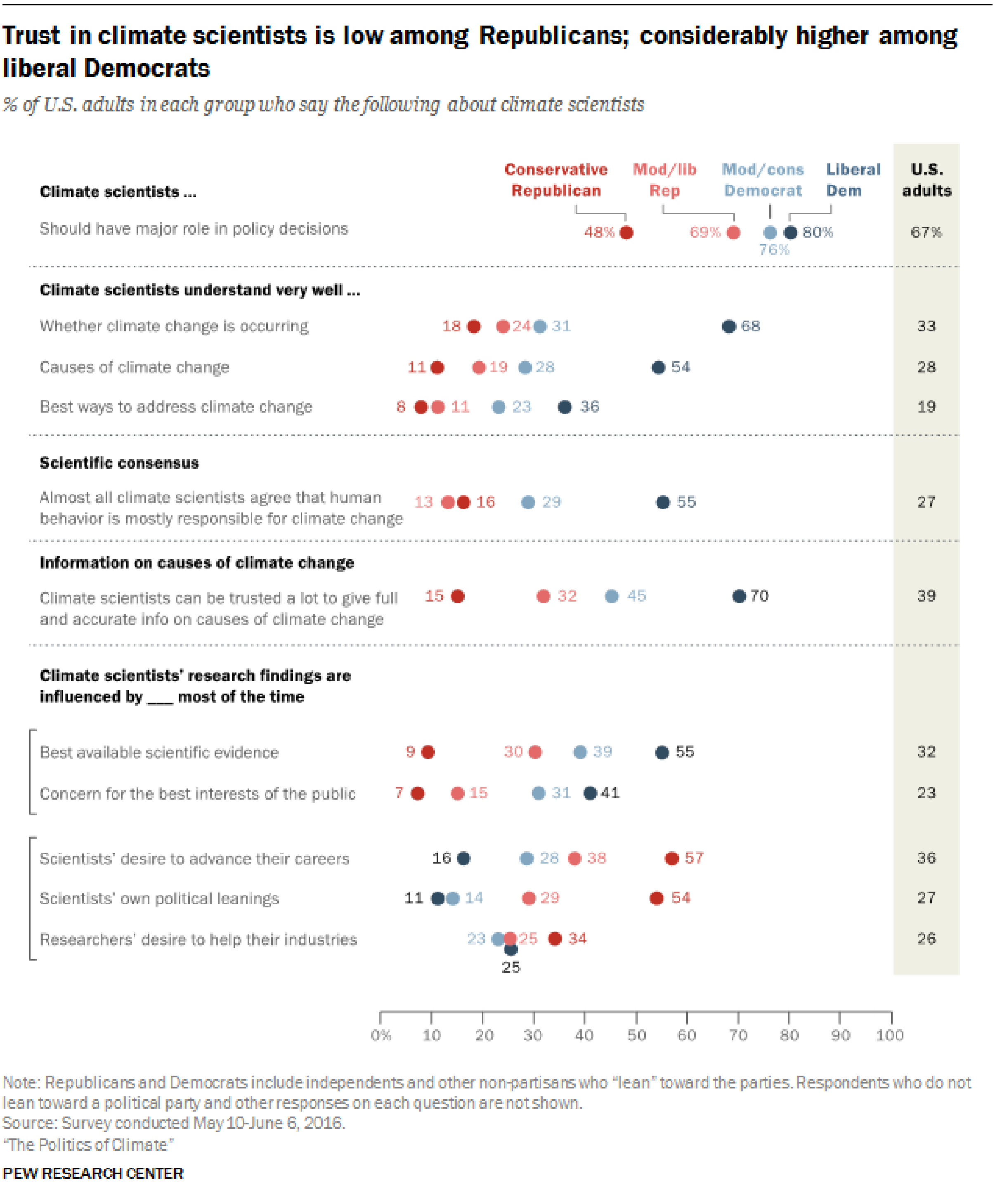
Climate change has been a contentious issue in the United States, with a surprising lack of popular *acknowledgement* of anthropogenic climate change, let alone willingness to address it. Several decades ago, climate policy seemed politically feasible. In 1990, President George H. W. Bush successfully proposed the sulfur dioxide (SO_2) cap-and-trade program, implemented in the Clean Air Act Amendments of 1990. Conservatives hailed the relatively novel market-based approach to environmental regulation. The Bush Administration also (unsuccessfully) advocated a global CO_2 emissions trading in international discussions, suggesting early recognition of the risks of climate change. In recent years, climate change has become a significantly more partisan issue.

First, we give an overview of public opinion towards climate change and carbon policies. Then we address the domestic opposition to carbon policies from the perspective of conservative ideology, the geographic distribution of carbon emissions, and industry interests.

3.1.1 Public Opinion

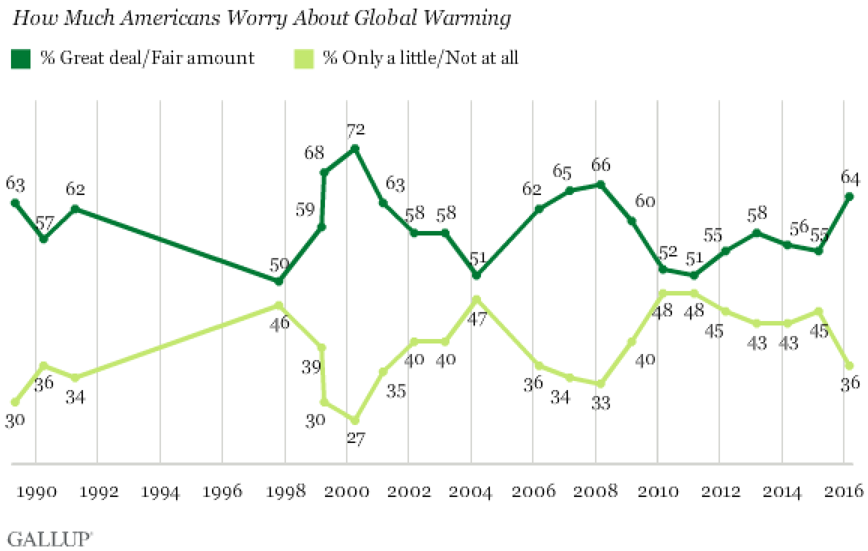
The processes underlying the causes and effects of climate change are not the most intuitive. We can neither see carbon dioxide in the atmosphere nor feel salient harm from fractional-degree increases in global average temperature. It is difficult to imagine much of anything about the distant future, yet people are told to believe far-reaching projections about the climate and economy made from today's models. These factors help explain the doubts of many regarding climate change, especially from those who are skeptical towards scientists and economists in general. Compare the distant, somewhat abstract harm from climate change to the immediate, localized harm from acid rain that drove the SO_2 trading program in 1990.

Pew Research Center polling suggests that the vast majority of Republicans, plus many moderates and Democrats, do not trust the competence or motives of climate scientists. The results also demonstrate the partisan divide that exists on climate issues.



(http://www.pewinternet.org/2016/10/04/the-politics-of-climate/, accessed 6/3/2017)

Gallup polling shows that Americans do worry about climate change, with 50-70% worrying at least a “fair amount” over the last few decades. However, many people may be more worried about the strength of the economy, as is suggested by the dips in the amount of worry about global warming during recessions in 2000-04 and 2008-10. In January 2010, in the midst of the recession and around the time when the Waxman-Markey bill for an economy-wide CO_2 cap-and-trade program flopped in the Senate, the Pew Research Center polled Americans on the importance of 21 issues, and climate change ranked *last* (New Yorker p19).

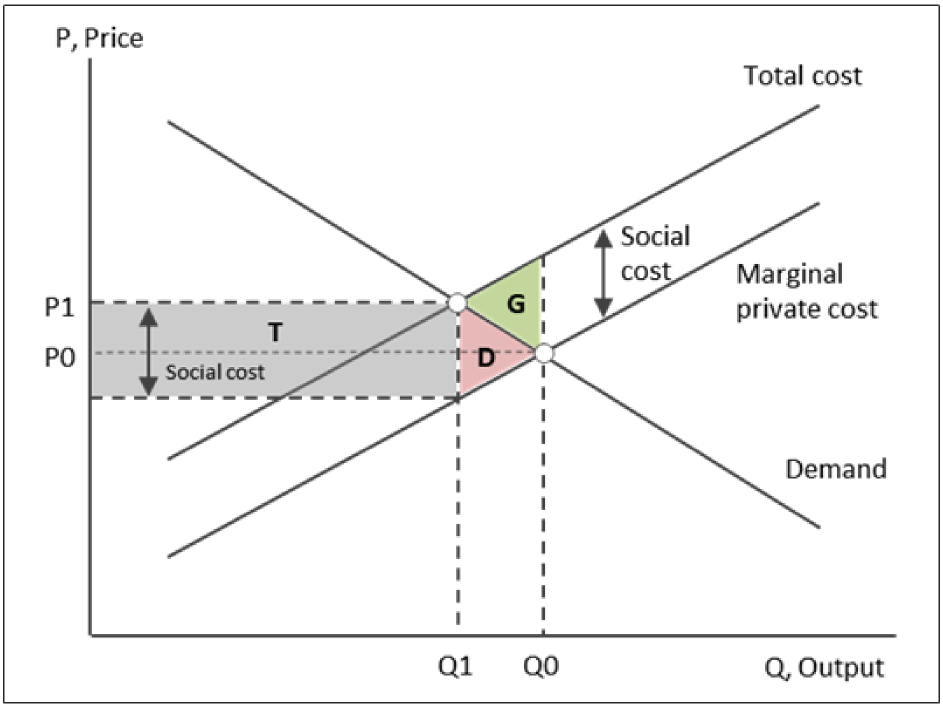


(http://www.gallup.com/poll/190010/concern-global-warming-eight-year-high.aspx, accessed 6/3/17)

3.1.2 Conservative Ideology

A person with conservative views may oppose government intervention to reduce emissions *even if* fully accepting some value for the social cost of carbon. This is because the required amount of government intervention is large relative to the amount of net benefit to society.

Consider the following hypothetical supply and demand example for electricity.



Supply and demand curves illustrating net benefits and tax revenue under a carbon policy.
(Based on Kevin Murphy lecture)

Today's equilibrium would be (Q_0, P_0), reflecting only the private cost of generating electricity. Internalizing the externality by, for example, imposing a carbon tax equal to the social cost of carbon (k), would move the equilibrium to (Q_1, P_1). The reduction in emissions represents a social value of G + D, where D represents the deadweight loss of the policy and G represents the net gain to society. The purpose of the policy is therefore to obtain G. However, in order to obtain G, the carbon tax would have be imposed on all Q_1 units of electricity output, creating a large amount of government tax revenue, T. T is not the cost of the policy, but is the major issue for a conservative. The ratio of G to T can be approximated as:

$$\frac{G}{T} \approx \frac{½\,(\mathrm{Q}_0 - \mathrm{Q}_1) * \Delta\mathrm{k}}{\mathrm{Q}_1 * \Delta\mathrm{k}} \approx ½\ \%\Delta\mathrm{Q}$$

Here the relevant change in quantity is not to electricity, but to the carbon emitted by generating electricity. Nevertheless, supply and demand should be relatively inelastic, so the change in quantity should be small. If we assume that imposing the tax created a 10% reduction in carbon emissions from electricity, this implies the ratio of G/T of only 5%. That is, the tax revenues generated are 20 times larger than the net gain of the policy. If a person believed that at least 5% of the tax revenues would be wasted by government inefficiency (or rent-seeking behavior by firms to avoid the tax), one would conclude that the tax would be a net loss, despite the gain from reduced emissions. While some claim a Pigouvian tax on carbon could be used to reduce distortionary taxes on income, creating an additional benefit or "double dividend", a conservative is unlikely to see it in this light.

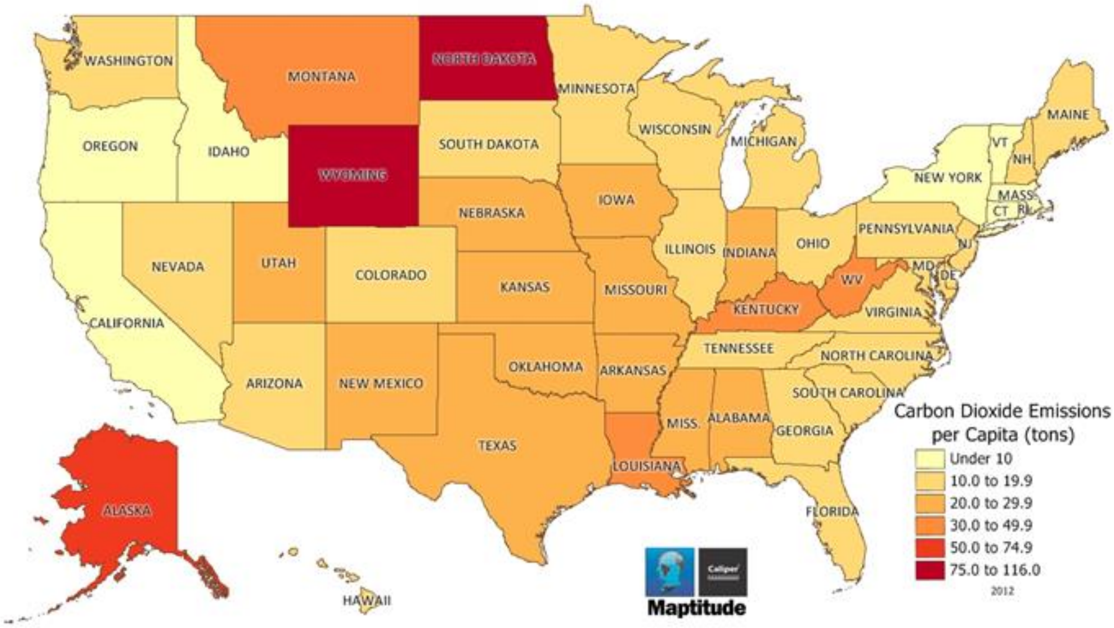
Of course, the same issue would apply to a cap-and-trade program if the permits were auctioned, with the same revenue T generated by the government. A better plan from this perspective might be to freely allocate permits to producers, although this would overcompensate producers at the expense of consumers and likely induce significant rent-seeking in the allocation process (producers gain the top half of T and lose the bottom half of D).

Command and control regulations attempt to achieve the same reductions albeit in a less efficient matter. Such regulation would circumvent conservative issues with the magnitude of government revenues, but would also come with their own costs and inefficiencies, addressed in a later chapter.

3.1.3 Geographic Distribution of Carbon Emissions

The next potential opposition to carbon policies comes from likely distributional consequences. The chart below shows each state's CO_2 emissions per capita in 2012, which range from about 10 tons to 116 tons per year. Per capita emissions are caused by a number of factors but include higher energy consumption in more rural areas (e.g. from increased driving) and the inputs to electricity generation (e.g. coal in Wyoming and North Dakota vs. hydro and renewables in California and the Pacific Northwest). At $40/ ton, this represents an annual tax ranging from $400 to over $4640 per person. Households would not pay the whole bill, but the variance indicates that the effects of the tax will be unequal across the country.

These distributional effects could be masked under the partisanship of climate politics. Many low emissions states, such as California and New York, happen to be more Democratic, while the host of higher emissions states in the middle of the country happen to be more Republican. In general, emissions per capita are lower in large cities, which tend to have more liberal populations. Analysis of anti-carbon legislation voting has found statistically significant effect of a district's carbon intensity on the vote, even after controlling for ideology (Gragg p.15). Thus, carbon policies will probably need to address distributional consequences to obtain wide support.

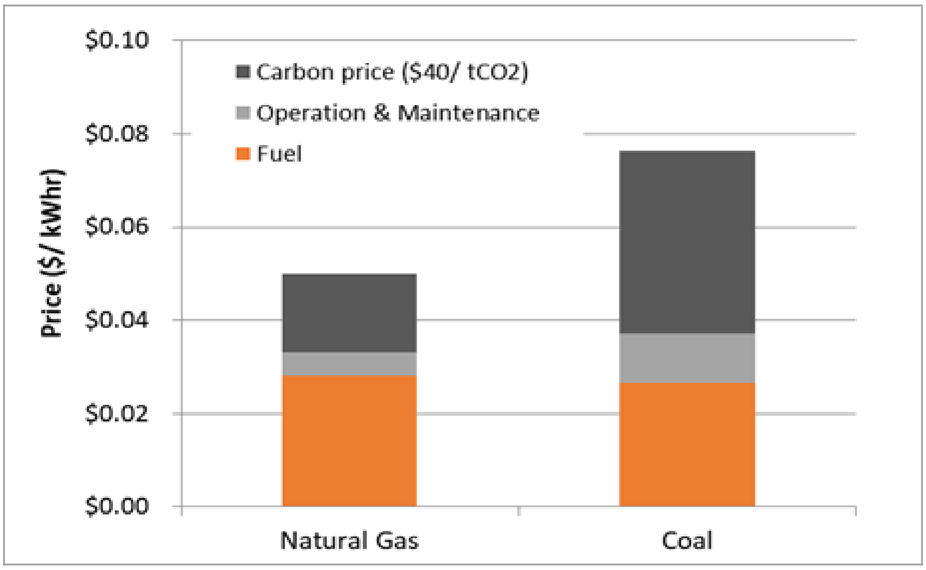


Data from US Energy Information Administration 2012. Accessed from:
http://www.caliper.com/featured-maps/maptitude-state-per-capita-carbon-dioxide-emissions-map.html

3.1.4 Industry Interests

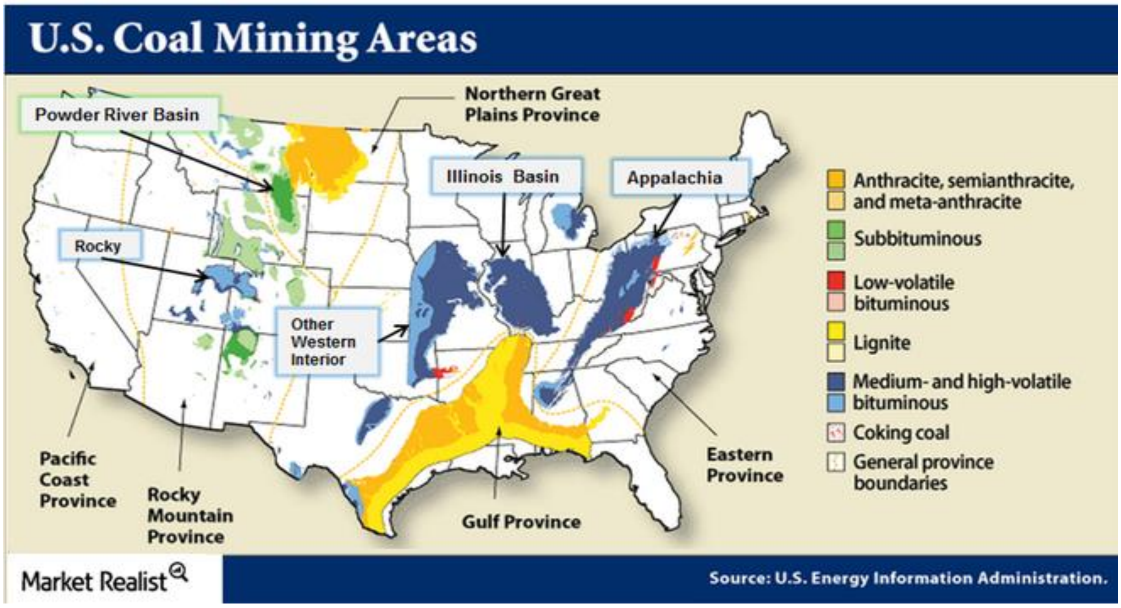
Many industry groups appeared more willing than Congress to adopt the Waxman-Markey cap-and-trade legislation in 2010 (Lizza). Although part of the willingness may have been bought by over-allocating allowances, many industries may not be clear losers from climate policies. For example, major oil and gas companies have supported global carbon taxation (in public), partly because they stand to benefit from the continued transition from coal to natural gas. Additionally, the manufacturing sector, which could suffer from higher energy prices, especially if the tax is not applied globally, stands to benefit from increased development of renewable energy and energy storage systems.

The coal industry appears to be the clear loser of carbon policies. Natural gas has already replaced coal significantly over the last ten years, as prices have fallen and abundant low-cost supplies have been discovered in shales. A carbon tax would further advantage natural gas relative to coal, which emits about 2.5 times more CO_2 per kWhr of electricity. The chart below suggests the effect of a $40/ ton carbon tax on wholesale electricity prices ($40 was chosen for simplicity).



Wholesale electricity prices suggested by a $40/ton carbon tax Fuel
O&M costs from 2015 EIA Average Power Plant Operating Expenses for Major U.S. Investor-Owned Electric Utilities, Carbon Price author's calculations. (https://www.eia.gov/tools/faqs/faq.php?id=74&t=11)

Most of the country's coal production comes from the Powder River Basin in Wyoming and across the Appalachia region. Coal interests have strong influence in political swing states such as Pennsylvania, Ohio, and Indiana. Politicians from these areas will likely support their constituents by opposing carbon policies.



(EIA, accessed from http://library.intellectualtakeout.org/faqs/coal-frequently-asked-questions-faq)

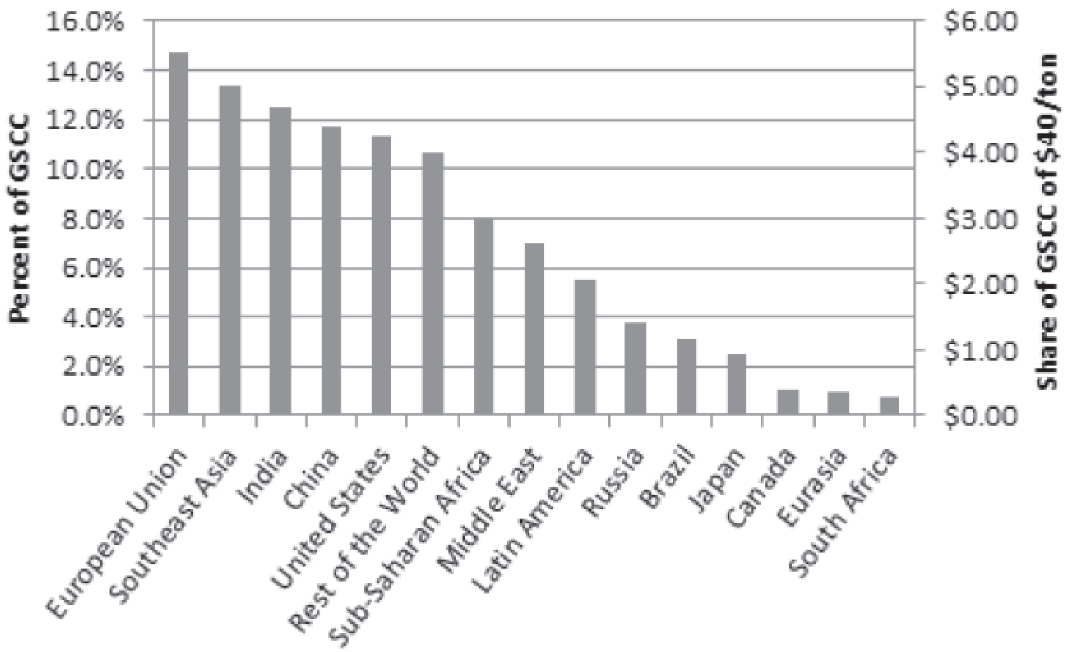
Of course, a carbon tax could also lead to the development of improved carbon capture technologies, which would allow for coal to be burned cleanly well into the future.

3.2 International

International cooperation is a key component of carbon policies. In its estimate of the SC-CO_2, the Working Group noted that only about 10% of abatement benefits are realized in the United States, with the remaining 90% realized in the rest of the world (Interagency 2010 p.16). It is key to recognize that the U.S. does not directly benefit from the majority of its own abatement, *and* that the U.S. benefits from a fraction of the abatement of every other country.

The Working Group argues that if no country can solve the climate change problem on its own, countries should agree to use the global SC-CO_2 for pricing carbon, under a coordinated global action. If each country were to count only its domestic benefits from abatement, efforts would fall far short of the optimal reduction suggested by the SC-CO_2. Thus, international cooperation is critical to effectively reducing emissions.

The chart below shows how a global SC-CO_2 "GSCC" of $40/ ton is allocated across regions as assessed by the three IAMs. Note that the sum of the region social costs equals the global social cost. Nordhaus states that the domestic SC-CO_2 values "are roughly proportional to discounted GDPs, with deviations based on geographic differences in climate sensitivity" (Kotchen p.5).



(Kotchen p.6)

Kotchen argues that countries with higher projected climate damages would advocate a strategic SC-CO_2 *higher* than global, since they have higher marginal benefits of abatement (Kotchen p.22). He considers a number of international voting scenarios and concludes that the internationally negotiated $SC\text{-}CO_2$ would be a value near the global $SC\text{-}CO_2$, given that countries were sufficiently concerned about climate change and recognized a similar value for the global $SC\text{-}CO_2$. However, there are significant challenges to enforcing a global carbon tax or cap-and-trade scheme.

Disparity in wealth presents the largest obstacle. Environmental policies are a normal good (i.e. demand for them increases with wealth), as evidenced by the lower levels of environmental protection in the developing world. All else being equal, developing countries would prefer to allocate resources to pulling their citizens out of poverty rather than fighting climate change. The Paris Agreement recognized this by establishing a flow of payments of $100 billion from developed countries to developing ones, equal to about half of the annual revenues generated by a tax of $40/ ton in the United States.

Second is disparity in climate impacts. For example, Bangladesh is likely to suffer severe flooding from any amount of sea level rise, while Russia and Canada may enjoy more moderate temperatures, better for certain types of agriculture and reducing mortality rates from very cold winters. Likewise, Europe may face more significant risks than the U.S., due to possible cooling from the reorganization of the Gulf Stream current. Due to these challenges, effective international cooperation is perhaps unlikely to occur without significant transfers between countries and complex international negotiations.

Mechanisms for enforcement are critical to holding parties to international agreements. The most promising tool is a border tax on carbon emissions. To illustrate how this would work, consider compliant Country A and non-compliant Country B. If Country A taxes Country B's imports based on the carbon emissions related to production of goods, it collects Country B's would-be carbon tax, obliging Country B to tax carbon itself and keep the revenue. The risk of a border tax is a negative impact on the state of international trade, which would offset benefits of emissions reduction.

4. *Policymaking and the Social Cost of Carbon*

There is no doubt that the task of calculating the most accurate, or optimal social cost of carbon will prove a long-term endeavor. But there should also be no doubt that this social cost is greater than zero; the Interagency Working Group currently pegs the SC-CO_2 at $42 per ton of CO_2-equivalent emitted. While the impacts of climate change are the subject of deep uncertainty, we do know these have the potential to be very harmful. Given humanity's preference for risk aversion, the *attempt* to price carbon represents a critical first step towards optimizing between carbon-driven economic productivity and carbon-driven environmental degradation. The more accurate the SC-CO_2, the greater will be the efficacy of any climate change policy. If used to inform global policymaking, an accurate carbon price would in theory cause the most efficient, world-economy-wide re-optimization of greenhouse gas emissions that account for the productive economic, and harmful environmental, potential of carbon.

So, what is the ideal coordinated policy response to climate change? Across the world, policy to date has taken many forms. In order of decreasing theoretical economic efficiency, these include carbon taxation, which in some form has been enacted in numerous sovereign jurisdictional bodies across the world; emissions markets, as utilized for carbon emissions within the European Union, and for sulfur-dioxide emissions in the United States; and command and control environmental regulations, which under the Obama Administration were regularly utilized in the United States. With each policy option comes tradeoffs between efficacy, efficiency, and political feasibility. The aim of this section is to outline mechanisms and prerequisites for global coordination in mitigating climate change, evaluate the success of these three existing climate change policy frameworks, and outline the ideal future policy response to climate change, and in light of the challenges that faces, describe other potential solutions.

4.1 International Climate Agreements

That the atmosphere is insensitive to national boundaries means international coordination, followed by collective action, is necessary if climate change is to be mitigated. The importance of international climate pacts, like the Paris Agreement, cannot be understated. These underline a global commitment towards resolving climate change. Such commitment is entirely necessary as the efforts of any one country alone will be insufficient, as it requires global buy-in. In addition, maximizing the effectiveness and efficacy of the SC-CO_2 requires that it is incorporated at parity across the world. For this reason, supranational climate agreements have a important role to play in the future of climate change policy. Without these, the required global buy-in will not occur. Only with such coordination can the collective action problem be defeated.

Public opinion, manifesting itself more as public concern regarding the issue of climate change, has dictated that on both national and international levels, policy-makers make efforts to curb greenhouse gas emissions. Since 1992 the United Nations has hosted annual international climate negotiations with that specific goal, the most recent being COP21, when in December 2016 the Paris Agreement was signed. The consensus is that, while pledges made by individual nations may not be enough to prevent the worst of climate change, it remains a concrete accomplishment, and a source of optimism, due to the fact sovereign nations successfully came to an agreement on a quintessential collective action problem. The *Accord de Paris* is the first of many climate agreements that will likely be necessary to cover issues related to international carbon pricing and/or trade, two key missing ingredients from the Paris Agreement.

4.1.1 The Paris Agreement

The Paris Agreement in many respects represents the new global roadmap for tackling climate change. In differing contexts, it has been hailed as a ‘landmark’, a ‘milestone’, a ‘big leap’, and quite simply ‘historic’. Yet, the agreement alone will not prevent significant damage from climate change; even if all national emissions reductions pledges are entirely met, atmospheric temperatures will likely see a post-Industrial Revolution increase of over 3°C, the results of which could potentially be calamitous. At its core, Paris provides a roadmap for dealing with climate change that is constrained by realities economic and political, which in turn makes its goals more reasonable, and attainable.

Amongst these goals is the call for a ‘peaking’ of global greenhouse gas emissions ‘as soon as possible’ with the caveat that developing countries may take longer to arrive at their zenith. Indeed, it is the very heterogeneity in responsibility for, and impact of, climate change across the world that will likely be a major sticking point in international climate agreements moving forward. Why shouldn’t South Asia and Africa, for example, grow rich the same way the current OECD band did, on the back of fossil fuels? The economic productivity of carbon is undisputed, given that it has driven much of the growth in richer nations since the Industrial Revolution. In this regard, it might be unfair to impose carbon constraints on today’s underdeveloped, or still developing, nations, yet the global nature of climate change means that this potential conflict cannot be ignored.

The Agreement recognizes this reality too; first, through the allowance for developing nations’ emissions to peak ‘later’, and, second, through pledges by developed nations to provide \$100 bn a year, by 2020, to aid climate change adaption and mitigation efforts in their developing counterparts. Such financial assistance is imperative if developing countries are to meet both development and environmental goals concurrently. A potential problem lies in the fact that in order for this, and other proposed policies, to become legally binding, the Paris Agreement must be ratified by at least 55 nations representing 55% of global greenhouse gas emissions. This represents one reason why President Trump’s announcement of the United States’ withdrawal from The Paris Agreement is concerning. Not only is the United States a significant current and historic contributor to emissions, it plays a global leadership role at world forums.

The Agreement in its current form includes the emissions reduction plans of 186 nations through 2025 or 2030, and a stipulation requiring all countries update these plans with stricter targets by 2020, and every five years thereafter. Additionally, nations are required to monitor, verify, and report their greenhouse gas emissions in a single global accounting system. Countries would be required to provide regular reports of all anthropogenic carbon emissions, by source, in a bid to ensure maximal transparency and allow all parties to keep detailed track of their progress. An external 'carbon verification' body, charged with the task of validating countries' reported emissions reductions, has been suggested, but the specifics of both this body and the single global accounting system have yet to be confirmed. We feel this process, from reporting through verification, is essential for this, or any future climate agreement to hold real weight.

The Paris Agreement is comprehensive; it has drawn greenhouse gas emissions reductions pledges from countries representing 95% of global emissions; it outlines plans for the monitoring of future emissions; and it provides financial assurances for poorer nations who face the daunting, and unknown, task of achieving economic growth with constraints on carbon usage. However, further agreements are necessary for several reasons. First, the aforementioned carbon reporting and verification process must be planned out in detail. Second, national emissions reductions pledges must continue to be tightened over time. Third, trade in environmental goods must expand, and future climate agreements would be more effective if they included stipulations for free trade in low-carbon technology. Finally, nations must engage in discussion on a uniform, international carbon price.

4.1.2 The Future of Climate Agreements

Of importance too is the formation of further bilateral, multilateral, or regional agreements. These should cover both climate change mitigation and adaptation measures, and would serve to support and strengthen the overarching global framework. Agreements at such scales hold additional effectiveness given the fact that the harmful impacts of emissions and climate change are likely to hit on regional, rather than national, levels. These deals would allow particularly concerned or vulnerable regions to pool efforts and resources, and through policy-alignment maximize their collective effort towards mitigating climate change. Smaller-scale agreements, involving fewer signatories, would prove less challenging to ratify, while serving to reaffirm national commitments towards the environment, build trust between economies through cross-country policy alignment, and aid the momentum of global climate negotiations.

Any comprehensive supranational climate agreement must further include stipulations pertaining to international trade, for two reasons. The first relates to the accounting of national emissions; comprehensiveness of international trade networks across the world mean that goods consumed in one nation may comprise of parts created in many others, and, that goods produced in one nation may ultimately be consumed in another. Should the carbon footprint of a product then be counted in the country of production, or country of consumption? What about the volume of greenhouse gas emissions that arise from the transportation of goods across borders, that increases with international trade? Such issues should be ironed out else they complicate efforts to foster the trust required to coordinate international climate policy. Secondly, trade in environmental goods, defined as those relevant to climate change mitigation, must expand, and these markets be left as free as possible. For a global diffusion of low-carbon technology to occur, it needs to be economically feasible, a feat atypical of emerging technologies. Therefore, it is imperative that the cost of green technology falls globally. One way to achieve this is to remove trade barriers such as tariffs, which, given globalized value chains, can add much to the cost of final products. Another way is through a global proliferation in the use of such emerging, low-carbon technologies. Such proliferation would be easier to accomplish if the carbon emissions arising from production were priced uniformly worldwide, and would drive down the relative cost of low-carbon technology.

International climate agreements thus represent a critical part of the process of mitigating climate change. It is important, however, that progress doesn’t stop here. The Agreement contains loopholes that must be addressed, while there remains much to be gained if there was increased alignment in regional climate policy aims, as well as free trade dispensations for low-carbon factors of production. A uniform, global social cost of carbon has a big part to play in this process.

4.2 Carbon Taxation

Having priced carbon, the most efficient subsequent policy would be to enact a global tax on carbon emissions equivalent to the social cost of carbon. A tax on carbon emissions equivalent to the SC-CO_2 *fully internalizes* the greenhouse gas externality. This tax will favor low-carbon production methods, which ideally will become more cost-effective over time. Global emissions will re-optimize at a lower level as the global economy reduces its carbon footprint. From an economic perspective, accounting for the damages caused by carbon in this way represents a critical component of the optimal solution to anthropogenic climate change.

Economic consensus represents, however, only one side of the equation. Taxes are unpopular by nature, and rarely in practice does economic theory play out as smoothly as it purports to. Leaving aside the potential for disagreement on the specific SC-CO_2 used across nations (once again, highlighting the importance of international agreements), any national policy utilizing a carbon tax will face three main hurdles: concerns over its inherently regressive distributional effects; the need for the public recognition of the importance of climate action; and the opposition it will face from various interest groups. We begin this section by evaluating the carbon tax policies of Australia and British Columbia, in terms of both their implementation and eventual impact, keeping in mind the importance of the three hurdles listed above. Utilizing these lessons, we then postulate how the future of carbon taxation might function, in a manner that is politically feasible and sufficient in its achievements such that we successfully mitigate the issue of climate change.

4.2.1 Australian Carbon Tax: Political Chaos and Powerful Interests

The Australian experience with carbon taxation perfectly illustrates the political complications of such a policy. The passage of the 2011 *Clean Energy Act* saw the institution of a national carbon tax in July 2012 by then-Prime Minister Julia Gillard's minority coalition government (which included the Australian Greens, a pro-environmental party). It was repealed two years later by Tony Abbott, who in winning the 2013 Federal Election ran on a campaign that included a promise to "axe the tax".

The initial implementation of the carbon tax arrived on the back of a decade of shifting public perception over the importance of the issue of climate change. Spurred by such public opinion and the controversy created by the long-term refusal of then-Prime Minister John Howard's Liberal-National government to ratify the Kyoto Protocol, the opposition Australian Labor Party leader Kevin Rudd called for a significant cut to the country's greenhouse gas emissions, calling climate change *"the greatest moral, economic, and social challenge of our time"*. Rudd won the 2007 Australian Federal Election, with an emissions trading scheme (ETS) amongst his policy proposals, and things seemed to be heading in the right direction.

But, politics. Rudd's proposed ETS, scheduled to come into effect in July 2010, was voted down in Parliament in August 2009. During revisions to the proposal (and indeed throughout the entire lifespan of the tax), powerful groups composed of conservative political parties, and mining and natural resource companies lobbied especially heavily against any climate action. They succeeded: by April 2010, Rudd announced a hold to the ETS proposal, citing a lack of parliamentary support, and was within months dumped by his party. Julia Gillard assumed leadership of Labor, promising to review the ETS proposal of her predecessor. With a public still greatly concerned about climate change, Gillard won a minority government during the 2010 Federal Election in coalition with the Greens, who favored a tax over the mooted cap-and-trade. Under pressure from this faction, Gillard's electoral promise of a re-evaluated ETS turned into a proposal for a carbon tax, again, slated to start in July 2012.

Then-opposition leader Tony Abbott, already against the environmental policy stance of Gillard's predecessor Rudd, labelled this turnaround a "historic betrayal". In late 2011, the *Clean Energy Act*, which included stipulations for a carbon tax, passed the Senate, but anger never subsided over her perceived flip-flop. The carbon tax existed for two years; in the process, aggressively negative (but unfounded) media campaigns were launched by pro-carbon interests and conservative groups about the tax and its effects, and Gillard was herself usurped as party leader as her political capital kept dwindling. Rudd, once again, took up the reins as Labor leader, and ahead of the 2013 Federal Election announced the carbon tax would be scrapped in favor of another ETS, this to commence in 2014. Abbott took issue with this, suggesting an ETS was in fact carbon tax, but by a different name. Labelling the election a referendum on the tax, and having campaigned to “axe” it, Abbott won the election. By July 2014 the carbon tax was repealed.

The effects of the policy, however, belied the negative coverage it faced from the hands of carbon interests and conservative groups. Initially set at $23 per ton of carbon emitted, the tax was applied to 500 of Australia’s biggest polluters, covering electricity generation, mining, and certain industrial sectors. In the first nine months of the tax’s existence, the share of coal in electricity generation fell by almost 20% and the share of renewables increased by 28%. The overall emissions intensity of the electricity market fell by over 5%, emissions from electricity generation were down 9%, and by 7% amongst all companies subjected to the tax. Wholesale electricity prices rose, reflecting the increase in investment in renewable energy technology and its growing role in electrical generation (Australian Government, 2014).

To address the distributional concerns associated with the carbon tax, income tax rates were reduced for those earning under the median (roughly AUD$65,000 a year) and the tax-free threshold was more than tripled, from AUD$6,000 to AUD$18,200. Direct payments, utilizing over half the tax revenue, were made to middle- and low-income households to assist them in coping with price increases that would occur as firms passed the incidence of the tax on to consumers. In addition, revenue was dedicated towards research and development of renewable energy technology (already a market failure of its own), as well as towards funds focused on biodiversity, low-carbon agriculture, small business development, and indigenous community support (Australian Government, 2012). These stipulations all aimed at mitigating the theoretically negative redistributive effects of a carbon tax. It is an unfortunate reality that despite the seedlings of hope offered by the impacts of the carbon tax and a public in favor of climate action, political maneuvering and the influence of notable interests played a role in ensuring the first repeal of a national carbon tax in history.

4.2.2 British Columbian Carbon Tax: Revenue Neutrality

In many regards, carbon taxation in the Canadian province of British Columbia has proven a success. In effect since 2008, it covers greenhouse gas emissions arising from fossil fuels burned in electricity generation, heating, and transportation, or 70% of the province’s total. Its origins are critical; 2007 public opinion polls found environmental issues to be foremost in voters’ minds, behind only concerns pertaining to healthcare (Harrison, 2013). In 2008, driven by a state aim to cut greenhouse gas emissions by a third between 2007 and 2020, the ruling Liberal Party introduced a revenue-neutral carbon tax starting at $\$10/\text{t-CO}_2e$, rising by \$5 a year, and peaking at $\$30/\text{t-CO}_2e$ in 2012. A key part of this tax policy was a system of redistribution, where amongst its other progressive components, income tax rates were reduced by 5% for the two lowest tax brackets; while corporations and small businesses across the board saw 1-percentage-point tax rate cuts.

During the 2009 provincial elections, the Liberals defeated the New Democratic Party, whose platform included a repeal of the carbon tax in favor of a replacement cap-and-trade market. The effects of the tax vindicated the voters' decision. Five years after the initial implementation of the tax, per-capita fossil fuel consumption had fallen by 17.4% (while growing by 3% in the rest of Canada), with reductions occurring across all fuel types, for a total per-capita emissions reduction of 13%. Over the same time period, British Columbia outperformed the national average in terms of GDP growth. While its combination of redistributive tax shifts, are theoretically revenue-neutral, evidence shows that the government returned $500m in excess of what it raised from the carbon tax, on top of corporate and income tax cuts (Harrison, 2013; Smart Prosperity, 2012).

Although the effects of the tax tailed off (indeed, emissions began to rise) after 2012, with the price of carbon frozen at \$30/t-CO_2e, Canadian Prime Minister Justin Trudeau in October 2016 announced that by 2018, all provinces must adopt a carbon-pricing scheme put into effect through either a carbon tax or emissions trading market. Under his proposal, carbon prices across provinces must exceed a government-mandated minimum of \$10/t-CO_2e in 2018, and must increase by \$10 a year to \$50/t-CO_2e in 2022.

British Columbia's carbon tax gives evidence for the elasticity of energy consumption with respect to carbon emissions in the short run. The tax should lead to more reduction in emissions in the long run, as supply and demand become somewhat more elastic. Trudeau's proposal would provide evidence of elasticities up to $50/ton; this would be informative for policymakers in the United States, since current estimates of the SC-CO_2 are in this range. Additionally, concurrent and positive economic impacts in provinces adopting revenue-neutral tax policies may be suggestive of any double dividend, though it would likely be hard to trace.

The experience of British Columbia with carbon taxation represents a situation in which public support resulted in good politics and policy, to the overall benefit of environmental and social welfare.

4.2.3 The Future of Carbon Taxation

At the start of Section 4, we proposed that taxes are unpopular due to historical inefficiencies in government expenditure: not every tax dollar collected by governments is spent efficiently. However, unlike an income tax, which is distortionary and can result in large deadweight loss, a carbon tax is Pigouvian: it corrects market failures by forcing emitters to internalize the cost of their greenhouse gas emissions. Without such internalization, the externality imparts harm on society; therefore a carbon tax that curbs emissions provides a benefit to society greater than the deadweight loss it imposes.

If designed to be revenue-neutral, the double-dividend hypothesis suggests a carbon tax may be used to increase economic surplus. The first of these 'dividends' relates to the positive health and environmental effects that arise as a result of reduced emissions, and the second from the redistributive aspects of a revenue-neutral carbon tax, through reductions in existing distortionary taxes such as income or corporate taxes. The theory being: governments can offset other sources of tax revenue with carbon tax revenue. Additionally, in many nations where subsidies exist for environmental goods, or regulations exist to curb greenhouse gas emissions, a third dividend might even exist. The implementation of a revenue-neutral carbon tax that fully captures the greenhouse gas externality would remove the need for less-economically-efficient environmental policies that existed in its absence. Such a carbon tax could provide a net positive benefit to society, making it much easier to sell politically and economically. As an example, British Columbia's revenue-neutral carbon tax offers explicit, practical evidence of the double-dividend in action through reductions in both taxes and emissions. It would be wise for any future carbon taxation policy to include this feature of revenue-neutrality.

Therefore, the optimal solution to this externality is to combine a globally-uniform Pigouvian tax on carbon emissions with revenue-neutrality, enabled through progressive domestic redistribution by reducing distortionary taxes such as on individual and corporate income. The Pigouvian nature of the tax corrects the negative externality. Uniformity in the global price of carbon eliminates opportunities for cross-country arbitrage in carbon-intensive activity, and accounts for the scientific fact that emissions, wherever they originate, inflict the same amount of damage on the environment. Lastly, the concept of revenue-neutrality serves to alleviate the political hesitation regarding taxation. There is substantial negative stigma associated with the word "tax" because they have inherently regressive properties. This redistributive aspect of the policy, through reductions in existing taxes and direct cash transfers to low-income households, if properly communicated, should eliminate this negative perception. There do however, still remain several critical questions that need to be answered for the implementation of a globally-uniform carbon tax to be considered practical.

The first of these relates once more to the importance of international coordination; setting the foundations for international acquiescence is imperative, and this requires trust, shared motivations, and collective action. It is important that the future of climate agreements sets the foundation for global policy alignment, and, in the case of a globally-uniform carbon tax, the first objective should be for nations to come to an agreement on what the chosen SC-CO_2 should be. This figure must fully capture the externality costs of emissions and be void of any political manipulation in its determination. The next step is to balance the impact on developing nations. For underdeveloped nations to pay for carbon-use the same tax that developed countries pay is certainly unfair; those currently developed have historically relied on carbon for economic growth without accounting for the damages it causes. We propose allowing stipulations within the Paris Agreement, which call for financial contributions from developed to developing countries, to address this issue. Note we are not calling for carbon tax revenues to fund such contributions, unless that particular developed country feels that course of action is appropriate.

Further redistribution could occur in the form of technology transfer programs from developed to developing nations. This would help mitigate the carbon-intensity of production in developing nations by lowering barriers to acquiring low-carbon technology, especially if paired with comprehensive free trade agreements. We also hope the proposed carbon tax stimulates further investment in research and development of low-carbon technology (a more implicit market failure; see Stavins, 2011), enabling a more cost-effective transition away from fossil fuels. Lastly inefficient preexisting environmental legislation such as command-and-control regulations, and subsidies for low-carbon technologies and factors of production, can also be reduced. In conclusion, a uniform, global tax on carbon has the potential to introduce efficiency gains that domino throughout the global economy, enhancing the political feasibility of the policy itself.

The final issue that we seek to analyze with regard to the implementation of a global carbon tax relates to whether such a policy ought to be applied on an origin-basis, or destination-basis. The key distinction here is that the former implies that tax jurisdiction is asserted over where the good is produced, and the latter where it is consumed. Understanding the right position to take should be rooted in what is theoretically most efficient from an economic perspective. First, we have to account for the fact we live in a globalized world. For this reason, production location decisions are based on theories of comparative and absolute advantage, which is to say that iPhones are manufactured in China, for example, because its most efficient to do so there. Any policy we enact must minimize any distortions to production location decisions, since those are already dictated by what is most economically efficient. Of course, a uniform global tax on carbon would impose the same costs on a producer regardless of whether they are based in Dhaka or Denver. Upon first glance it is apparent that an origin-based system would be highly regressive (across countries), considering the fact that much of global production presently occurs in less-developed nations, and much of global consumption in developed ones.

A destination-basis system, whereby taxes are imposed on the carbon content of final products, on the other hand forces consumers to consider the carbon-intensity of their consumption choices. This would affect demand patterns for all goods, from cars and solar panels to the quantity of beef forgone for tofu on the dinner table. One-time taxation of the consumption of a good, in affecting consumer demand, would thus cause a re-optimization of product market equilibria across the world, benefitting more sustainable, less carbon-intensive production practices. This in turn incentivizes a shift towards low-carbon production processes by producers, who face increasing marginal costs and threats to profitability compared to low-carbon competitors. This shift would be made easier through technology transfer programs, and free-trade dispensations for environmental goods: two features we have previously highlighted as imperative for any coordinated future climate change policy.

An additional implication relates to the inherently progressive nature of this choice of tax incidence: given that the majority of consumption today occurs in more developed nations, it is they who will face the majority of the “tax burden”. Given the benefits derived in these nations from unpriced and unabated historical carbon consumption, there exists an element of fairness in such a proposal, enhancing the political feasibility of a global tax on carbon, insofar as buy-in from the developing world is concerned. Further, within less-developed nations, such a destination-basis system remains progressive because higher income households are responsible for the bulk of consumption. Ultimately this structure ensures that the burden is felt more by those countries, and individuals within those countries, with higher carbon footprints, who are more able to cope with the incidence of the tax. We do acknowledge that wealthy individuals or nations acting in their self-interest, will likely oppose such a provision and this structure will have to be carefully thought through.

In this section, we have proposed a *revenue-neutral, globally-uniform, destination-basis carbon tax* as the optimal response to climate change. Recognizing potential impediments to the enactment of such a policy, from redistributive concerns to issues of political feasibility, studying the carbon tax policies of Australia and British Columbia, and postulating how a global carbon tax might play out, we find that at least from a theoretical economic standpoint there are several potential efficiency gains from such a proposal. We say this with caution, however, as there remain many issues that might stand in the way of a successful implementation of a global carbon tax. International coordination in climate policy aims, including a consensus on the correct valuation of the social cost of carbon, is necessary, the specifics of domestic and international redistributive policies must be negotiated; and the importance of global public buy-in cannot be understated. Without these, an issue like climate change will remain a partisan issue, and the collective action necessary to mitigate it will never occur.

4.3 Carbon Trading

Cap-and-trade is the other market-based solution to pricing CO_2 emissions. In cap-and-trade, governments set a cap on emissions, instead of a tax. A market for trading emissions permits, or allowances, is created to make the scheme efficient. In an efficient market, each firm will buy or sell permits until its marginal cost of abatement is equal to the price of the permit, so abatement is achieved at the minimum cost. If the emissions cap is set at the optimal level, then this permit price will equal the SC-CO_2. In the supply and demand chart for electricity presented in Section 3.1.2, the same equilibrium (Q_1, P_1) is achieved with a tax set equal to the SC-CO_2 or an emissions cap set equal to Q_1.

Cap-and-trade systems have a several advantages over taxation systems, but we find that the most significant are political. First, legislators have the issuance of allowances as a political tool. Under a trading system, allowances may be auctioned, freely allocated, or issued using a combination of both. If transaction costs are not excessive, then the efficient outcome will be reached irrespective of how allowances are allocated, although allocation has clear distributional consequences (Coase Theorem). Thus, within a fixed emissions cap, the government has a negotiation tool for regions and industries that may needed to pass legislation. Of course, exemptions could be made under a tax, but these would compromise the optimal emissions implied by the tax. Freely allocating permits could make cap-and-trade more desirable to conservatives, since it avoids the creation of large amounts of government tax revenue. However, as mentioned in the Political Economy section, freely allocating all permits overcompensates firms.

Partly related is the advantage that cap-and-trade may reduce political challenges towards new taxes. Under the Obama Administration, tax legislation of all kinds was fiercely debated along strong partisan lines. Any carbon tax bill faces this extra challenge, even if it claims to be revenue-neutral. Further, debating a carbon tax leads to debate on the value of the SC-CO_2, with its many underlying assumptions. Debating carbon cap-and-trade leads to a discussion of emissions cuts and permit allocation, which may be a more politically feasible way to frame the idea. However, opponents to carbon policies have branded cap-and-trade as “cap-and-tax”, because an auctioned permit system is practically a tax. This slogan was part of the opposition to the 2009 Waxman-Markey bill for an economy-wide CO_2 cap-and-trade program in the U.S.

The biggest challenge to cap-and-trade is the fluctuations in permit prices. Supply and demand for energy, and thus CO_2, are inelastic in the short run, so small shifts in quantity lead to relatively large shifts in price. Prices would also be subject to regulators who periodically adjust the emissions cap, or a long-term cap schedule that would be unable to anticipate supply and demand trends. There are two solutions to price variance under cap-and-trade. The first is intertemporal banking of permits, wherein firms may borrow or save permits to smooth volatility. The second is setting a permit price ceiling and floor. The government would enact the ceiling by issuing new permits at some high price, for times of tight supply. It would enact the floor by buying permits at some low price, for times of excess supply. The price ceiling and floor would allow for more certainty on prices, but would also reduce forces of market efficiency.

Fluctuating prices is particularly an issue for an economy-wide carbon policy, because carbon infrastructure lasts for many decades. Uncertainty in the long term price of a permit might tend to delay investments needed to overhaul the energy sector. A tax would also be subject to regulatory or legislative intervention, but while in effect it would make it give firms more certainty on costs, facilitating investment decisions.

We examine the mostly successful history of the SO_2 cap-and-trade program in the U.S., to demonstrate the advantages and disadvantage of this policy option.

4.3.1 United States: Sulfur Dioxide Trading System

The SO_2 allowance trading system in the United States was a response to growing concern about acid rain in the late 1980s, especially in the Northeastern U.S., caused by SO_2 and NO_x emissions from burning "dirty" coal (Schmalensee). It was passed under George H. W. Bush Administration in the Clean Air Act Amendments of 1990. The cap-and-trade system was novel at the time and represented the conservative solution to environmental regulation. Most environmental laws since the Clean Air Act of 1970 had been command and control regulations, with varying degrees of efficiency with regards to the cost of emissions reduction. Many in the environmental community preferred command and control regulations and were hostile to the notion of trading "rights to pollute" (p.103). The trading program had a Phase I (1995-1999) limited to the 263 highest polluting coal-fired electric power plants, and a Phase II (after 2000) covering nearly the entire fleet of fossil-fuel power plants in the continental U.S.

Interesting in the context of considering the social cost of carbon, it was noted that there were "no credible estimates of economic benefits" of different emissions target levels. Instead, the target was roughly at the "elbow" of the abatement cost curve (p105). This target was set to allow for a significant amount of abatement without severely impairing social welfare.

Allowance allocation was used as a political tool when drafting legislation; there was noted value of "being able to allocate free allowances to address differential economic impacts across regions, states, and Congressional districts" (p106). Allowances were also auctioned by the EPA.

The program was a major success in the first decade of implementation, allowing for a 15-90% cost savings over counterfactual command and control policies. SO_2 emissions from electric power plants decreased 26% between 1990 and 2004, largely due to input substitution and mixing (i.e. burning more coal from western basins with lower SO_2 content) and installed scrubbers (flue gas desulfurization devices).

The ex-post benefits of SO_2 abatement were significantly higher than expected, though they mostly came from unanticipated areas. The ecological benefits, the initial reason for passing the policy, were actually relatively small, because it "takes much longer than thought to reverse the acidification of ecosystems" (p109). On the other hand, the human health benefits of reduced levels of airborne fine sulfate particles, which were not known until well after the program was implemented, turned out to be enormous. The estimated benefits in the U.S. of SO_2 reduction are on the order of \$0.5 billion annually for ecosystem effects, whereas reduced mortality accounts for \$50 to \$100 billion annually, roughly *one hundred times* greater benefits. Compare these with annual costs of \$0.5 to \$2 billion, and the program appeared to be of enormous net benefit.

Estimated Annual US Benefits and Costs of the SO_2 Allowance Trading Program; Title IV, Clean Air Amendments of 1990
(billions of US 2000 Dollars)

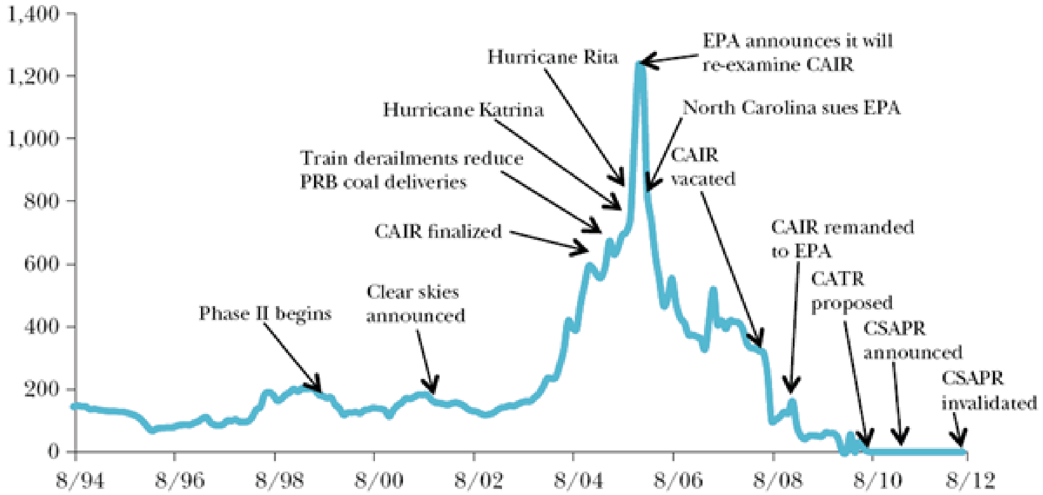
Benefits	
Mortality	50–100
Morbidity	3–7
Recreational visibility	2–3
Residential visibility	2–3
Ecosystem effects	0.5
Total	**59–116**
Costs	**0.5–2.0**
Net benefits	**58–114**

Source: Burtraw, Krupnick, Mansur, Austin, and Farrell (1998); Burtraw (1999); Chestnut and Mills (2005); Banzhaf, Burtraw, Evans, and Krupnick (2006).

(Schmalensee p.110)

Next we turn to allowance prices. These were stayed relatively stable for the first ten years of the program, between roughly $80 and $200/ ton. In 2004 and 2005 there was a large spike in prices, eventually exceeding $1200 per ton. The increase was caused primarily by the Clean Air Interstate Rule (CAIR), proposed under President George W. Bush in 2005, which effectively reduced the emissions cap by two-thirds. It was exacerbated by supply factors related to Hurricane Katrina and railroad track failure affecting shipments of low-sulfur coal. Prices plunged in 2006 when the EPA announced it would re-examine the CAIR. Prices dropped further in 2008 due to a challenge on the CAIR, which led the Obama Administration in 2011 to propose an alternative rule to limit emissions to replace the CAIR with the Cross-State Air Pollution Rule (CSAPR), which severely limited interstate trading. Now, prescriptive regulations at the state level have driven emissions to well below the cap. Although permits are still auctioned the price is basically $0.

SO_2 Allowance Prices and the Regulatory Environment, 1994–2012
(1995 dollars per ton)



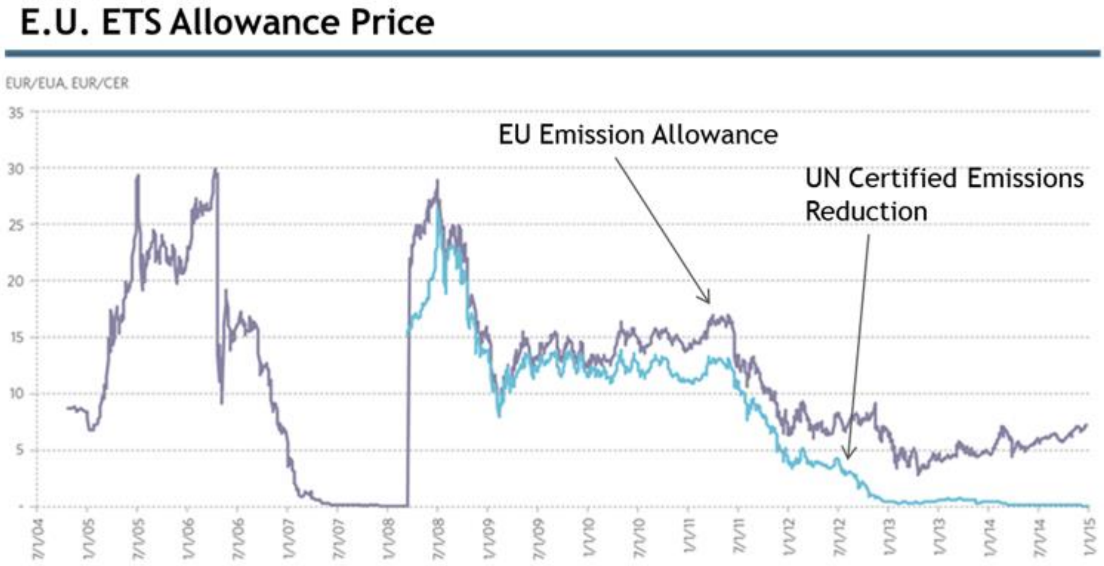
Source: Data on spot prices compiled by Power & Energy Analytic Resources (PEAR) Inc. from Cantor Fitzgerald until September 11, 2001, and from ICAP United thereafter.
Notes: CAIR is "Clean Air Interstate Rule." CATR is "Clean Air Transport Rule." CSAPR is "Cross-State Air Pollution Rule."

(Schmalensee p.114)

The SO_2 trading system efficiently lowered SO_2 emissions and created large benefits to public health. However, the interference of other policies is suggestive of the reality of politics in the U.S. It may be unrealistic to expect any carbon policy to be left intact over many presidential administrations and congressional sessions without interference. Also, the volatility of permit prices is indicative of potential issues with a carbon cap-and-trade system.

4.3.2 European Union: Emissions Trading Scheme

We turn to the European Union Carbon Dioxide Emissions Trading Scheme (ETS) to further illustrate volatility in allowance prices, the main weakness of cap-and-trade programs over a tax. The chart shows the allowance price for CO_2 in the ETS and for a UN Certified Emissions Reduction (CER). CERs are used to finance UN certified carbon offset projects (e.g. reforestation), often in developing countries.



Allowance prices in E.U. ETS, €/ton CO2,
sourced from: http://www.climate2020.org.uk/role-carbon-trading

The ETS currently covers more than 11,000 factories, power plants, and other installations. Phase I took place from 2005 to 2007, Phase II from 2008 to 2012, Phase III is planned for 2013 to 2020, and a Phase IV is planned for 2021 to 2028. In Phase I, most allowances were freely allocated. By 2013, approximately 60% of allowances were auctioned, with the percentage set to grow over time.

The low permit price in 2007 and 2008 is blamed on an excess supply of allowances, caused in part by the modest reduction goals of Phase I of the program. Prices rebounded at the start of Phase II, though they tapered downward starting in late 2008, in part due to the recession which lowered energy demand. Allowance prices have remained quite low in Phase III. Critics of the program point out that the prevailing carbon price has generally been too low to induce much reduction by itself. However, the EU’s goal at the start of ETS was to reach a 21% reduction in emissions by 2020. It reached that goal in 2014, so clearly other measures have been successful.

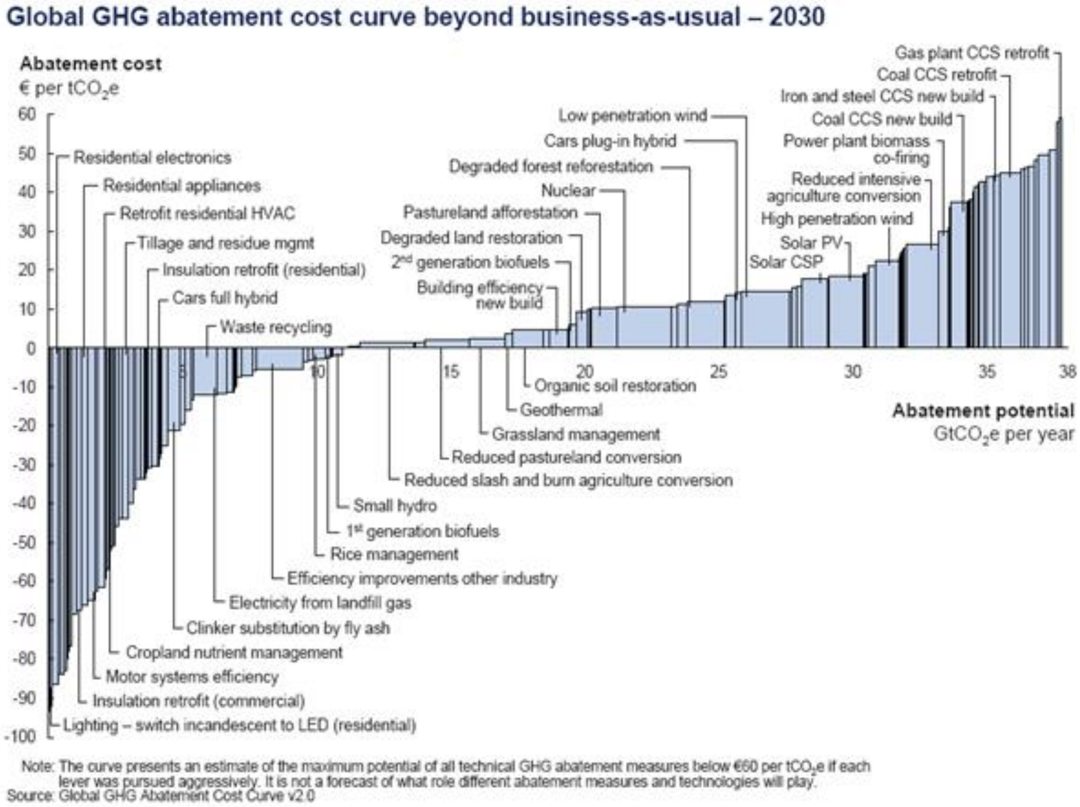
Allowance prices are subject to an ongoing struggle among different interests, and the challenge of forecasting supply and demand. It seems that it would be simpler to pick a reasonable price and establish that as a tax instead.

4.4 Command and Control Regulation

Finally, we discuss command and control, or prescriptive, regulations. Command and control regulations enact standards, caps, mandates, or other restrictions to reduce emissions, often focusing on specific industries or practices. Flexible, outcomes-based prescriptive regulations can lead to relatively efficient outcomes on narrow problems; however, we believe these will be less effective in economy-wide reduction in CO_2 emissions because abatement opportunities are so varied.

To indicate the types of activities that may be incentivized by a global carbon price, we show the cost curve of CO_2 abatement estimated in 2013 by McKinsey & Company, a consultancy (McKinsey 2009). The cost curve was built by estimating the abatement potential in a number of different activities and technologies if each option is successfully pursued in the period from 2010 to 2030 (i.e. have been "driven down the cost curve" over that time). The cost (€/ton CO_2) is the weighted average cost over the 2010 to 2030 time period of each opportunity. The chart sums 38 Gt CO_2e of possible abatement in 2030, relative to a business as usual scenario of 70 Gt CO_2e per year.

First, negative cost options indicate that agency and behavioral issues limit certain value-adding abatement activities today. These are certainly areas where prescriptive regulations may be appropriate. The point from the remainder of the chart is that a number of abatement activities and technologies will likely be needed to significantly reduce global CO_2 emissions. Reductions include 14 Gt of energy efficiency, 12 Gt of low-carbon energy supply, and 12 Gt of forestry and agriculture. Critically, command and control regulations are unlikely to envisage or incentivize the different pathways to these solutions. As a result, they will achieve fewer reductions in emissions or create significantly more cost.



(McKinsey p.27)

4.4.1 Regulatory Action under the Obama Administration

In 2007, the Supreme Court ruled that the EPA was required to regulate CO_2 and other GHG emissions. As a result, it must include CO_2-related costs and benefits in regulatory impact analyses, or RIAs.

After the Waxman-Markey bill was defeated in the U.S. Senate in 2010, the Obama Administration and Congress gave up on serious attempts to pass a broad carbon tax or cap-and-trade legislation. Instead, the Obama Administration implemented regulations through the EPA, Department of Energy (DOE), and Department of Transportation (DOT) to enact carbon-reducing policies. It used the SC-CO_2 to conduct the cost-benefit analysis for the programs. The figure shows a list of proposed or final regulations through 2012 (notably excludes the Clean Power Plan of 2014). The CO_2 benefits are separated, calculated using the 2010 U.S. Government estimate of the SC-CO_2 (averaging about $35 per ton over the evaluation period). For standards on vehicle fuel economy, power plants (“stationary sources”), and appliances, the CO_2 reduction benefits were significant.

Agency	Rule	Date	Total Benefits (Billions of \$)	Total CO_2 Benefits (Billions of \$)	CO_2 as Share of Total Monetized Benefits (%)
EPA	Final Cross-State Air Pollution Rule (CSAPR) (vacated by courts, in review)	8/8/2011	183.3	.6	.3
EPA/DOT	Final Light Duty Vehicle GHG Standards (2017–25)	10/15/2012	126.0	46.6	37.0
EPA/DOT	Final Light Duty Vehicle GHG Standards (2012–16)	5/7/2010	58.4	17.0	29.1
EPA	Final MATS Rule	2/16/2012	57.7	.4	.6
EPA	Final Boiler MACT (CO2 disbenefits)	12/20/2012	42.5	(.0)	−.1
EPA	Proposed GHG Standards for New Stationary Source EGUs	4/13/2012	21.4	11.0	51.3
EPA	Final Cement NESHAP/NSPS (CO2 disbenefits) (under reconsideration)	9/9/2010	11.5	.0	.2
DOE	Final ECS for Residential Refrigerators and Freezers	9/15/2011	9.9	9.0	91.0
EPA/DOT	Final Medium-Heavy Duty Vehicles GHG Standards	9/15/2011	7.3	5.7	78.1
DOE	Final ECS for Fluorescent Lamp Ballasts	11/14/2011	1.3	1.3	96.6
DOE	Final ECS for Residential Water Heaters	4/16/2010	.2	.2	95.3
DOE	Proposed ECS for Battery Chargers and External Power Supplies	3/27/2012	.1	.1	94.1
DOE	Final ECS for Small Electric Motors	4/9/2010	.1	.1	95.2
DOE	Final ECS for Residential Dishwashers	5/30/2012	.1	.1	96.6
EPA	Final Sewage Sludge Incinerators NSPS/Emissions Guidelines (CO2 disbenefits)	3/21/2011	.0	(.0)	−.3
EPA	Proposed (supplemental) NESHAP: Mercury Cell Chlor-Alkali Plants Amendments	3/14/2011	.0	.0	21.1

Note.—The estimates in this table generally exclude fuel or energy savings from benefits. They are based on the government's central SCC value from the 2010 study of \$22 per ton for 2015 reductions in 2005\$. EPA = Environmental Protection Agency; DOT = Department of Transportation; DOE = Department of Energy; GHG = greenhouse gases; MATS = Mercury and Air Toxics Standards; NESHAP = National Emission Standards for Hazardous Air Pollutants; NSPS = New Source Performance Standards; ECS = Energy Conservation Standards; NESHAPS = National Emission Standards for Hazardous Air Pollutants. Data were provided by the staff of the US Environmental Protection Agency.

(Nordhaus 2013 p.304)

However, the CO_2 benefits expressed may be overstated due to leakage. That is, the emissions may just shift somewhere else. Since any rule or standard applies to a small part of the economy, substitution in production and consumption and carbon intensity across different sectors will cause leakage to occur (Nordhaus 2013 p.303).

Another issue with the Obama Administration regulations is that they may not be long-lasting. Significantly, the Clean Power Plan faced numerous legal challenges and was almost immediately put up for review by the incoming Trump Administration. Legislation with bipartisan support is probably necessary if there is any chance for a policy to induce significant emissions reductions over the long term.

Conclusion

For the foreseeable future, the range in estimates for the social cost of carbon is likely to remain large. Nevertheless, researchers should continue to improve projections of climate damages and explore the potential for catastrophic events. Given the uncertainty, policymakers should consider central estimates for the social cost of carbon along with abatement cost curves, ultimately choosing a price that is supported by projections, sufficient to induce mitigation, and not excessively harmful to the economy. The 2013 U.S. Government estimate of $42 per metric ton of CO_2 (in 2020) appears to meet these criteria.

The ideal policy would be a uniform global carbon tax. It would minimize emissions leakage around the world and ensure that carbon has a stable price, giving greater certainty on investments. Carbon tax revenues could provide a "double dividend" if used to offset distortionary taxes, but must also address distributional consequences across income levels and regions. International negotiations must address differences in willingness to pay between countries, given disparities in economic development and magnitudes of expected climate-related harm. International cooperation over long periods is a major obstacle, but border taxes are a promising option for enforcement.

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