8

Cost-Benefit Analysis

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Key Findings

Key findings of this chapter include the following:

CBA Basics

- Cost-benefit analysis (CBA) is an economic tool that can help determine if the social benefits over the lifetime of a government project exceed its social costs.

- In the climate change debate, CBA is used to answer questions about the costs and benefits of climate change, the use of fossil fuels, and specific measures to mitigate, rather than adapt to, climate change.

- Integrated assessment models (IAMs) are a key element of cost-benefit analysis in the climate change debate. They are enormously complex and can be programmed to arrive at widely varying conclusions.

- A typical IAM has four steps: emission scenarios, future CO_2 concentrations, climate projections and impacts, and economic impacts.

- IAMs suffer from propagation of error, sometimes called cascading uncertainties, whereby uncertainty in each stage of the analysis compounds, resulting in wide uncertainty bars surrounding any eventual results.

- The widely cited "social cost of carbon" calculations produced during the Obama administration by the Interagency Working Group on the Social Cost of Carbon have been withdrawn and are not reliable guides for policymakers.

- The widely cited "Stern Review" was an important early attempt to apply cost-benefit analysis to climate change. Its authors focused on worst-case scenarios and failed to report profound uncertainties.

Assumptions and Controversies

- Most IAMs rely on emission scenarios that are little more than guesses and speculative "storylines." Even current greenhouse gas emissions cannot be measured accurately, and technology is likely to change future emissions in ways that cannot be predicted.

- IAMs falsely assume the carbon cycle is sufficiently understood and measured with sufficient accuracy as to make possible precise predictions of future levels of carbon dioxide (CO_2) in the atmosphere.

- Many IAMs rely on estimates of climate sensitivity – the amount of warming likely to occur from a doubling of the concentration of atmospheric carbon dioxide – that are too high, resulting in inflated estimates of future temperature change.

- Many IAMs ignore the extensive scholarly research showing climate change will not lead to more extreme weather, flooding, droughts, or heat waves.

- The "social cost of carbon" (SCC) derived from IAMs is an accounting fiction created to justify regulation of fossil fuels. It should not be used in serious conversations about how to address the possible threat of man-made climate change.

- The IPCC acknowledges great uncertainty over estimates of the "social cost of carbon" and admits the impact of climate change on human welfare is small relative to many other factors.

- Many IAMs apply discount rates to future costs and benefits that are much lower than the rates conventionally used in cost-benefit analysis.

Climate Change

- By the IPCC's own estimates, the cost of reducing emissions in 2050 by enough to avoid a warming of ~2°C would be 6.8 times as much as the benefits would be worth.

- Changing only three assumptions in two leading IAMs – the DICE and FUND models – reduces the SCC by an order of magnitude for the first and changes the sign from positive to negative for the second.

- Under very reasonable assumptions, IAMs can suggest the SCC is more likely than not to be negative, even though they have many assumptions and biases that tend to exaggerate the negative effects of GHG emissions.

Fossil Fuels

- Sixteen of 25 possible impacts of fossil fuels on human well-being are net benefits, only one is a net cost, and the rest are either unknown or likely to have no net impact.

- Wind and solar cannot generate enough dispatchable energy (available 24/7) to replace fossil fuels, so energy consumption must fall in order for emissions to fall.

- Transitioning from a world energy system dependent on fossil fuels to one relying on alternative energies would cost trillions of dollars and take decades to implement.

- The evidence seems compelling that the costs of restricting use of fossil fuels greatly exceed the benefits, even accepting many of the IPCC's very questionable assumptions.

- Reducing greenhouse gas emissions to levels suggested by the IPCC or the goal set by the European Union would be prohibitively expensive.

Regulations

- Cost-benefit analysis applied to greenhouse gas mitigation programs can produce like-to-like comparisons of their cost-effectiveness.

- The cap-and-trade bill considered by the U.S. Congress in 2009 would have cost 7.4 times more than its benefits, even assuming all of the IPCC's assumptions and claims about climate science were correct.

- Other bills and programs already in effect have costs exceeding benefits by factors up to 7,000. In short, even accepting the IPCC's flawed science and scenarios, there is no justification for adopting expensive emission mitigation programs.

- The benefits of fossil fuels far outweigh their costs. Various scenarios of reducing greenhouse gas emissions have costs that exceed benefits by ratios ranging from 6.8:1 to 162:1.

Introduction

The debate over climate change would be advanced if it were possible to weigh, in an even-handed and precise manner, the costs imposed by the use of fossil fuels on humanity and the environment, on the one hand, and the benefits produced by their use on the other. If the costs exceed the benefits, then efforts to force a transition away from fossil fuels are justified and ought to continue. If, on the other hand, the benefits are found to exceed the costs, then the right path forward would be the *energy freedom* path described in Chapter 1 rather than more restrictions on the use of fossil fuels.

Cost-benefit analysis (CBA) can be used to conduct such an investigation. CBA is an economic tool that is widely used in the private and public sectors to determine if the benefits of an investment or spending on a government program exceed its costs (Singer, 1979; Hahn and Tetlock, 2008; Wolka, 2000; Ellig, McLaughlin and Morrall, 2013; OMB, 2013). The history of CBA in shaping public policy was briefly surveyed in Chapter 1, Section 1.2.9.

We apologize in advance to the many researchers and reviewers, especially in the UK, who prefer "benefit-cost analysis" or BCA to "cost-benefit analysis" or CBA. Some researchers distinguish between the two, using CBA to refer only to analyses that rely on the potential compensation test (PCT) and BCA for analyses that rely on willingness to pay (WTP) or willingness to accept (WTA) (see Zerbe, 2008, 2017) but others do not. A Google search for both terms suggests CBA is preferred over BCA by a margin of about 17:1. In keeping with this choice, the two approaches are not distinguished here and results are reported as the ratio of costs to benefits rather than benefits to costs. Except for the final section, where the editors defer to the wishes of a chapter lead author.

Cost-benefit analysis is a complex endeavor typically involving subjective choices about what data to include and what to leave out, how to weigh evidence, and how to interpret results. The discipline is complicated enough to merit its own society, the Society for Benefit-Cost Analysis, and its own journal, *Journal of Benefit-Cost Analysis*. Section 8.1 begins with a brief tutorial on the application of CBA to the climate change debate. It is followed by an introduction to integrated assessment models (IAMs), an explanation of their biggest shortcoming (the "propagation of error" or cascading uncertainty), and reviews of CBAs of global warming produced by the Interagency Working Group on the Social Cost of Carbon (since disbanded) and the British Stern Review.

Section 8.2 examines the assumptions and biases that underlie IAMs. Tracking the order of "blocks" or "modules" in IAMs and drawing on research presented in previous chapters, it shows how errors or uncertainties in choosing emission scenarios, estimating the amount of carbon dioxide that stays in the atmosphere, the likelihood of increases in flooding and extreme weather, and other inputs render IAMs too unreliable to be of any use to policymakers.

Section 8.3 shows how two leading IAMs – the DICE and FUND models – rely on inaccurate equilibrium climate sensitivity rates, low discount rates, and a too-long time horizon (300 years). Correcting only these errors reveals the SCC is most likely negative, even accepting all of the IPCC's other errors and faulty assumptions. In other words, the social benefits of anthropogenic GHG emissions exceed their social cost.

Sections 8.4 summarizes the extensive literature reviews on the impacts of fossil fuels on human well-being conducted for earlier chapters in a single table. It reveals 16 of 25 possible impacts are positive (net benefits), only one is negative (net cost), and the rest are unknown or produce benefits and costs that are likely to offset each other. It presents cost-benefit analyses showing the cost of ending humanity's reliance on fossil fuels would be between 32 and 162 times as much as the hypothetical benefits of a slightly cooler world in 2050 and beyond.

Section 8.5 presents a formula for calculating the cost-effectiveness of GHG mitigation programs using the IPCC's own data and assumptions to produce like-to-like comparisons. The formula reveals a sample of proposed and existing programs has cost-benefit ratios ranging from 7.4:1 to 7,000:1, suggesting that current regulations, subsidies, and tax schemes aimed at reducing GHG emissions are not justified by their social benefits.

Section 8.6 offers a brief conclusion. According to the authors, CBA reveals the global war on energy freedom, which commenced in earnest in the 1980s and reached a fever pitch in the second decade of the twenty-first century, was never founded on sound science or economics. They urge the world's policymakers to acknowledge this truth and end that war.

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8.1 CBA Basics

> *Cost-benefit analysis (CBA) is an economic tool that can help determine if the social benefits over the lifetime of a government project exceed its social costs.*

Section 8.1.1 describes how cost-benefit analysis can be used to answer four key questions in the climate change debate. Section 8.1.2 provides background and an overview of the structure of integrated assessment models (IAMs) and describes how the "propagation of error" or cascading uncertainty renders their outputs unreliable. Sections 8.1.3 and 8.1.4 critique two of the best known attempts to apply CBA to climate change, the U.S. Interagency Working Group on the Social Cost of Carbon (since disbanded) and the British Stern Review. Section 8.1.5 presents a brief conclusion.

8.1.1 Use in the Climate Change Debate

In the climate change debate, CBA is used to answer four distinct questions:

1. Do the benefits from the use of fossil fuels, such as the increase in per-capita income made possible by affordable energy and higher agricultural output due to higher carbon dioxide (CO_2) levels in the atmosphere, exceed the costs it may have imposed, such as reduced air quality and, if they contribute to climate change, damage and harm from floods, droughts, or other severe weather events? (Bezdek, 2014)

2. Do the *social* benefits of either fossil fuels or climate change exceed the *social* cost – that is, do the positive externalities produced by the private use of fossil fuels exceed the negative externalities imposed on others? This is often called the "social cost of carbon" (SCC), calculated as the welfare loss associated with each additional metric ton of CO_2 emitted. (Tol, 2011)

3. Will the benefits of *a particular program* to reduce greenhouse gas emissions or sequester CO_2 by planting trees or injecting the gas into wells for underground storage exceed the costs incurred in implementing that program? (Monckton, 2016)

4. Is the cost-benefit ratio of a particular program to mitigate climate change higher or lower than the cost-benefit ratio of adapting to climate change by investing in stronger levees and dams, finding alternative sources of water, or "hardening" critical infrastructure? This is the *"mitigate versus adapt"* question that is frequently referenced in the Working Group II contribution to the IPCC's Fifth Assessment Report (AR5) (e.g., IPCC, 2014a, Chapter 10, pp. 665–666, 669, 679).

Regarding the first question, about the total private and social costs and benefits of the use of fossil fuels, Chapters 3 and 4 showed how fossil fuels made possible three Industrial Revolutions which in turn made possible large increases in human population, per-capita income, and lifespan (Bradley, 2000; Smil, 2005, 2006; Goklany, 2007; Bryce, 2010, 2014; Gordon, 2016). The benefits continue to accumulate today as cleaner-burning fossil fuels bring electricity to third-world countries and replace wood and dung as sources of heat in homes (Yadama, 2013; Bezdek, 2014). How much of the benefits of that economic transformation should be counted as "private" versus "social" benefits is not immediately apparent, but those benefits cannot be ignored entirely.

Rising atmospheric carbon dioxide concentrations and higher temperatures produce other benefits such as higher agricultural productivity, expanded ranges for most terrestrial animals having economic value such as livestock, and lower levels of human mortality and morbidity traditionally caused by exposure to cold temperatures (see Chapters 4 and 5 and Idso, 2013 for a detailed review of this literature). These well-known and observable benefits must be compared and weighed against cost estimates appearing in CBAs that are much less certain or well documented, many of which could even be judged conjectural.

Forward-looking CBAs must be based on reasonably accurate forecasts of future climate conditions. This requires climate models that take explicit, quantitative account of the principal relevant results in climatology, notably the radiative-forcing functions of CO_2 and other greenhouse gases and the various values of the climate sensitivity parameter. Current climate models have not shown much promise in this regard, as deomonstrated in Chapter 2, Section 2.2.2 (and see Fyfe *et al.*, 2013; McKitrick and Christy, 2018). CBAs also require economic models that can predict future changes in per-capita income, energy supply and demand, rate of technological innovation, economic growth rates in the developed and developing worlds, demographic trends, changes in land use and lifestyles, greenhouse gases other than carbon dioxide, and even political trends such as whether civil and economic freedoms are likely to expand or contract in various parts of the world (van Kooten, 2013).

The IPCC claims it can resolve all these uncertainties. In the Working Group III contribution to AR5, the IPCC says "a *likely* chance to keep average global temperature change below 2°C relative to pre-industrial levels" would require "lower global GHG emissions in 2050 than in 2010, 40% to 70% lower globally, and emissions levels near zero $GtCO_2eq$ or below in 2100" (IPCC, 2014b, pp. 10, 12). Since fossil fuels are responsible for approximately 80% of anthropogenic greenhouse gas emissions, this would require gradually phasing out the use of fossil fuels and banning their use entirely by 2100.

Any effort to calculate the costs and benefits of future climate change confronts fundamental problems inherent in making forecasts in the absence of complete understanding of underlying causes and effects. In such cases, the most reliable method of forecasting is to project a simple linear continuation of past trends (Armstrong, 2001), but this plainly is not what is done by the IPCC or the authors of the models on which it relies. An audit of the IPCC's Fourth Assessment Report conducted by experts in scientific forecasting found "the forecasting procedures that were described [in sufficient detail to be evaluated] violated 72 principles" of scientific forecasting (Green and Armstrong, 2007). The authors found no evidence the scientists involved in making the IPCC's forecasts were even aware of the literature on scientific forecasting.

Cost-benefit analysis of future climate change also must address the effects of dematerialization. As the research by Wernick and Ausubel (2014), Smil (2013), and others cited in Chapter 5 demonstrates, technological change is lowering the energy- and carbon-intensity of manufacturing and goods and services generally in the United States and globally, meaning future emission levels may be lower or less certain than is presently assumed. The cost of reducing emissions is likely to be lower in the future as well, as new technologies emerge to capture and sequester carbon dioxide or generate energy or consumer goods without emissions. As Mendelsohn (2004) writes, "there is no question but that we will learn a great deal about controlling greenhouse gases and about climate change over even the next few decades. The optimal policy is to commit to only what one will do in the near term. Every decade, this policy should be reexamined in light of new evidence. Once the international community has a viable program in place, it is easy to imagine the community being able to adjust their policies based on what new information is forthcoming" (p. 47).

Comparing the costs and benefits of specific mitigation efforts, the third question, requires CBA methodologies that are case-specific, which means they can be applied to specific mitigation projects such as a carbon tax, a carbon trading program, investment in solar photo-voltaic systems, or subsidizing electric cars (Monckton, 2014, 2016). Conducting CBAs of mitigation strategies is complicated by the fact that the possible benefits from mitigation will not be apparent until many years into the future – the models used often claim to be accurate and policy-relevant 100 years and even longer – even though the costs will be incurred immediately and will be ongoing. This makes choosing an appropriate discount rate – the subject of Section 8.2.5.2 – critical to producing an accurate evaluation.

There is considerable uncertainty regarding whether man-made emissions will ever cause a contribution to atmospheric warming of more than 1° or 2°C. Some experts believe costs may begin to exceed benefits if the contribution of man-made emissions is a temperature rise exceeding 2.5°C above pre-industrial levels (Mendelsohn and Williams, 2004; Tol, 2009; Doiron, 2014). If temperatures stop rising before or around that point, due to natural feedbacks or simply because man no longer is producing large quantities of greenhouse gases or because the climate sensitivity to greenhouse gases is lower than the IPCC projects, then enormous expenditures spanning generations will have been entirely wasted.

Because forcing a transition away from fossil fuels to alternative fuels requires raising the price of energy, and the price of energy is closely related to the rate of economic growth, actions taken today to reduce emissions will reduce the wealth of future generations. Thus, investing today to avoid or delay a future hazard that may or may not even materialize may undermine the ability of future generations to cope with climate change (whether natural or man-made) or make further progress in protecting the natural environment from other, real, threats.

The fourth question, which asks if mitigation is preferable to adaptation, is often overlooked by scientists and policymakers alike. Environmentalists who are predisposed to oppose initiatives that shape or alter the natural world view adaptation strategies as insufficient and likely to result in doubling down on past bad behavior that could make the situation worse rather than better (Orr, 2012). However, if future climate change is gradual, unlikely to reach the levels feared by some proponents of the hypothesis, or unlikely to be accompanied by many of the negative impacts thought to occur, then adaptation would indeed be the preferred strategy.

While the cost of adaptation to unmitigated warming is not always case-specific, since it may consist of countless choices made by similarly countless individuals over long periods of time, the cost of mitigation projects can be assessed case by case. This could make direct cost-benefit ratio comparisons of mitigation strategies with adaptation difficult, unless the cost of adaptation to unmitigated global warming can be shown to be lower than even the best mitigation strategies.

The complexity of climate science and economics makes conducting any of these CBAs a difficult and perhaps even impossible challenge (Ceronsky *et al.*, 2011; Pindyck, 2013). In a candid statement alluding to the many difficulties associated with determining the "social cost of carbon," Weitzman remarked, "the economics of climate change is a problem from hell," adding that "trying to do a benefit-cost analysis (BCA) of climate change policies bends and stretches the capability of our standard economist's toolkit up to, and perhaps beyond, the breaking point" (Weitzman, 2015).

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8.1.2 Integrated Assessment Models

> *Integrated assessment models (IAMs) are a key element of cost-benefit analysis in the climate change debate. They are enormously complex and can be programmed to arrive at widely varying conclusions.*

Integrated assessment models (IAMs), as they are used in the climate change debate, are mathematical constructs that provide a framework for combining knowledge from a wide range of disciplines, in particular climate science and economics, to measure economic damages associated with carbon dioxide (CO_2)-induced climate change. In public discourse as well as academic research, this measure is often referred to as the "social cost of carbon" (SCC) which Nordhaus (2011) defines as "the economic cost caused by an additional ton of carbon dioxide emissions (or more succinctly carbon) or its equivalent. In a more precise definition, it is the change in the discounted value of the utility of consumption denominated in terms of current consumption per unit of additional emissions. In the language of mathematical programming, the SCC is the shadow price of carbon emissions along a reference path of output, emissions, and climate change" (p. 2).

The SCC label is regretfully inaccurate since "carbon" exists in several states in the natural environment (including in the human body and in the breath we exhale), it is a basic building block of life on Earth, and the "cost" being estimated is typically only the cost of the effects of climate change attributed to CO_2 and other greenhouse gases emitted by humanity, not the net social and environmental costs *and benefits* of the activities that produce greenhouse gases. Since that is quite a mouthful, the brief but inaccurate moniker "social cost of carbon" has been adopted generally by researchers and is used here.

The building and tweaking of IAMs has become so complex its practitioners, like those who specialize in cost-benefit analysis, have formed their own society, The Integrated Assessment Society, and publish their own academic journal, titled *Integrated Assessment Journal*, dedicated to "issues in how to calibrate and validate complex integrated assessment models" (IAJ, 2018). As noted by Wilkerson *et al*. (2015), there are "dozens of IAMs to choose from when evaluating policy options and each has different strengths and weaknesses, solves using different techniques, and has different levels of technological and regional aggregation. So it is critical that consumers of model results (*e.g.*, scientists, policymakers, leaders in emerging technologies) know how a particular model behaves (and why) before making decisions based on the results."

The three models used by the U.S. government for policymaking prior to 2017 were the Dynamic Integrated Climate-Economy (DICE) model, developed by Yale University economist William Nordhaus (Newbold, 2010; Nordhaus, 2017); the Climate Framework for Uncertainty, Negotiation and Distribution, referred to as the FUND model, originally developed by Richard Tol, an economist at the University of Sussex and now co-developed by Tol and David Anthoff, an assistant professor in the Energy and Resources Group at the University of California at Berkeley (Anthoff and Tol, 2014; Waldhoff *et al.*, 2014); and the Policy Analysis of the Greenhouse Effect (PAGE) model created by Chris Hope and other researchers affiliated with the Judge Business School at the University of Cambridge (Hope, 2006, 2013).

Because of their prominent role in producing SCC estimates, the bulk of the present chapter focuses on IAMs. Section 8.1.2.1 discusses their background and structure and 8.1.2.2 discusses perhaps their biggest problem, the propagation of error (sometimes referred to as the "cascade of uncertainty" due to the chained logic of the computer programming on which they rely). Descriptions of the IAMs used by the U.S. Interagency Working Group on the Social Cost of Carbon and by a UK report – the Stern Review – are presented in Sections 8.1.3 and 8.1.4, and a brief conclusion appears in Section 8.1.5.

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8.1.2.1 Background and Structure

> *A typical IAM has four steps: emission scenarios, future CO_2 concentrations, climate projections and impacts, and economic impacts.*

Prior to the widespread use of modern-day mathematical computer models, questions involving cross-disciplinary issues were generally addressed by scientific panels or commissions convened to bring together a group of experts from different disciplines who would provide their collective wisdom and judgment on the issue at hand. The first formal application of an IAM in global environmental issues was the Climate Impacts Assessment Program (CIAP) of the U.S. Department of Transportation, which examined the potential environmental impacts of supersonic flight in the early 1970s. Other efforts to address global challenges using IAMs followed, but it was not until the 1990s that IAMs proliferated and became commonplace in studies of global climate change.

In an early description and review of these models, appearing as a chapter in the IPCC's Second Assessment Report, Weyant *et al.* explained how "Integrated Assessment Models (IAMs) use a computer program to link an array of component models based on mathematical representations of information from the various contributing disciplines.

This approach makes it easier to ensure consistency among the assumptions input to the various components of the models, but may tend to constrain the type of information that can be used to what is explicitly represented in the model" (Weyant *et al.*, 1996, p. 371). Today there are hundreds of IAMs investigating multiple aspects of the global climate change debate, including the calculation of SCC estimates (Stanton *et al*., 2009; Wilkerson *et al*., 2015).

As shown in Figure 8.1.2.1.1, there are four basic steps to calculating the SCC in an IAM: (1) projecting future CO_2 emissions based on various socioeconomic conditions, (2) calculating future atmospheric CO_2 concentrations based on the predicted emission streams, (3) determining how future CO_2 concentrations will change global temperature and weather, and what impact such changes would have on society, and (4) calculating the economic impact ("monetizing the damages") of weather-related events.

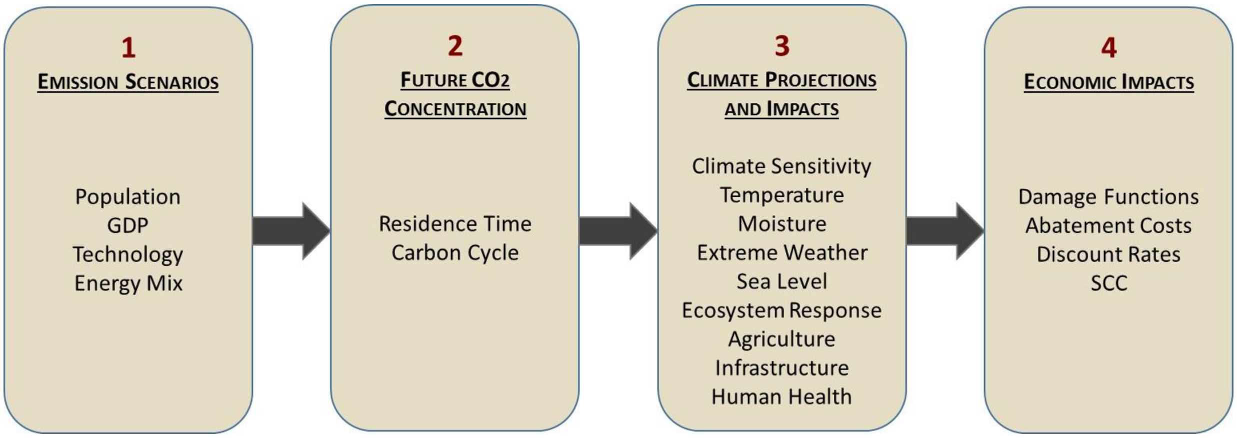
The *Emission Scenarios* block, called *Economic Dynamics* in some models, encompasses the impact = population x affluence x technology (IPAT) equation discussed in Chapter 5, Section 5.2.1. This block usually contains a fairly robust energy module as well as a component representing agriculture, forestry, and livestock.

The *Future CO_2 Concentration* block, also called the *Carbon Cycle* module, contains a model of the carbon cycle that estimates the net increase of carbon in the atmosphere based on what we know of carbon reservoirs, exchange rates, and the residence time of CO_2 in the atmosphere. See Chapter 5, Section 5.1.2 for a tutorial on the carbon cycle.

Changes in carbon concentrations are used as inputs into a *Climate Projections and Impacts* block, sometimes called a *Climate Dynamics* module, which attempts to predict changes in global average surface temperature based on an estimate of "climate sensitivity." See Chapter 2, Section 2.5.3 for a discussion of climate sensitivity, and Chapters 1, 2 and 3 of Idso *et al.* (2013) for hundreds of source citations on this issue. In that same block, changes in temperature are determined or assumed to cause specific effects such as extreme weather events and sea-level rise, which in turn are determined or assumed to have adverse effects on agriculture, human health, and human security. See Chapter 2, Sections 2.1 and 2.7, and Chapter 7, Section 7.2, for discussions of these associations and chains of impacts, and more generally NIPCC (2013, 2014) for thousands of source citations on the subject.

Finally, the postulated changes to weather and then damage to property and livelihood are fed into an *Economic Impacts* block, often called the *Damage Function* module, which monetizes the effects, usually expressing them as a change in per-capita income or gross national product (GNP) or economic growth rates, discounts them to account for the length

Figure 8.1.2.1.1
Simplified linear causal chain of an IAM illustrating the basic steps required to obtain SCC estimates



Source: Modified from Parson *et al.*, 2007, Figure ES-1, p. 1.

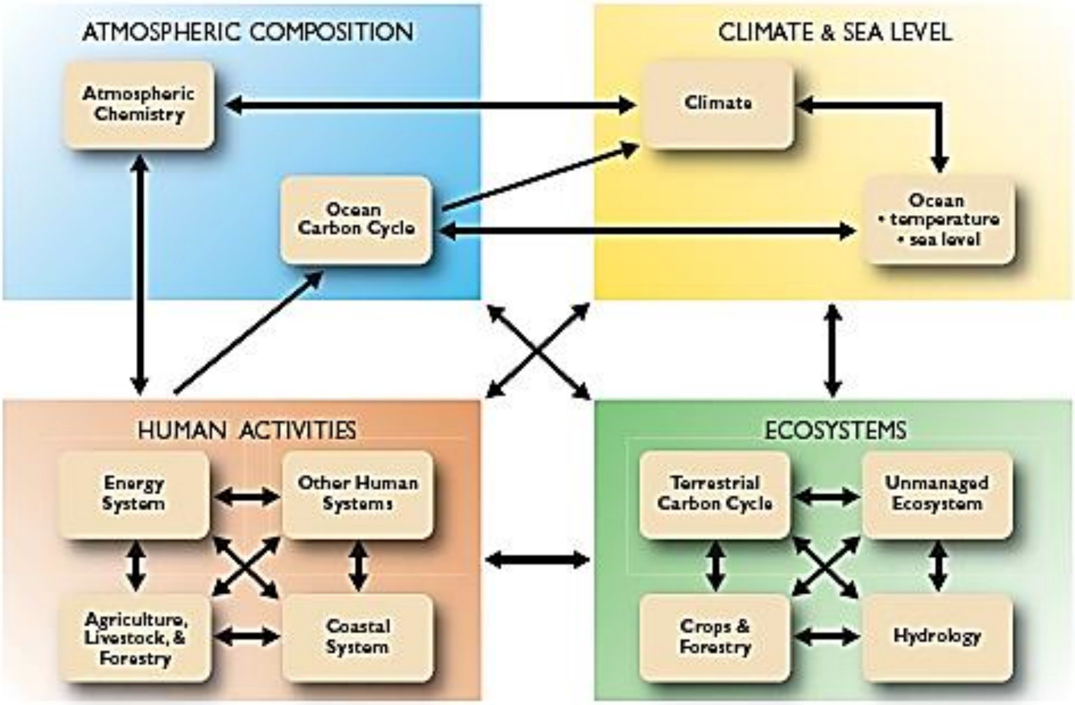
of time that passes before the effects are experienced, calculates the total (global) net social cost (or benefit), divides it by the number of tons of carbon dioxide emitted according to the *Emission Scenarios* block, and produces a "social cost of carbon" typically expressed in USD per metric ton of CO_2-equivalent greenhouse gases.

Models can be more complex than the one shown in Figure 8.1.2.1.1. For example, the model illustrated in Figure 8.1.2.1.2 incorporates an Ocean Carbon Cycle model as well as a terrestrial and atmospheric model. Conceptually, there is no limit to the degree of sophistication that can be built into the IAMs. Computational limits, however, are another matter, and these weigh heavily in optimization models based on computable general equilibrium (CGE) economic modules, such as the DICE model, which compute optimal growth paths by computing thousands of iterations over hundreds of periods.

Model complexity does not necessarily equate to model accuracy or reliability. Illustrating this point, Risbey *et al*. (1996) compared IAMs to a home built from bricks, where the bricks represent the substantive knowledge found in the different disciplines represented in the various IAM modules, and the mortar or "glue" is the modelers' subjective judgements linking the disparate blocks of knowledge together. They wrote,

> Unfortunately, while the bricks may be quite sound and well described, the subjective judgments (glue) are often never made explicit. As a result, it is difficult to judge the stability of the structure that has been constructed. Thus, in the case of integrated assessment, not only do we need criteria for assessing the quality of the individual components of the analysis, we also need criteria that are applicable to the glue or the subjective judgments of the analyst, as also for the analysis as a whole. While criteria for adequacy for the individual components may be obtained from the individual disciplines, a

Figure 8.1.2.1.2
Wiring diagram for integrated assessment models of climate change



Source: Parson *et al.*, 2007, Figure 2.1, p. 23, citing Wyant *et al.,* 1996.

> similar situation does not exist for the 'glue' in the analysis (Risbey *et al.*, 1996, p. 383).

Not only is the "glue" suspect in IAMs, but the blocks themselves are also questionable. Major module limitations include the simplicity of their approach, using only one or two equations associating aggregate damage to one climate variable – in most cases temperature change – which does not recognize interactions among different impacts. More problems include the ability to capture only a limited number of impacts and often omitting those impacts that may be large but are difficult to quantify or show high levels of uncertainty, and presenting damage in terms of loss of income without recognizing capital implications. A particularly difficult problem to solve is the application of "willingness to pay" or "stated preference" quantifications that frequently overstate values relative to observed behavior, since people responding to surveys face no real consequences in terms of required payment for the good or service. This positive "hypothetical bias" is widely noted and discussed in economic literature (e.g., Murphy *et al.*, 2004; Vossler and Evans, 2009; Penn and Hu, 2018). These and other weaknesses described below erode confidence in the ability of IAMs to accurately estimate the "social cost of carbon" in CBAs.

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8.1.2.2 Propagation of Error

> *IAMs suffer from propagation of error, sometimes called cascading uncertainties, whereby uncertainty in each stage of the analysis compounds, resulting in wide uncertainty bars surrounding any eventual results.*

"Propagation of error" is a term introduced in Chapter 2, Section 2.1.1.3, used in statistics to refer to how errors or uncertainty in one variable, due perhaps to measurement limitations or confounding factors, are compounded (or propagated) when that variable becomes part of a function involving other variables that are similarly uncertain. Error propagation through sequential calculations is widely used in the physical sciences to reveal the reliability of an experimental result or of a calculation from theory. As the number of variables or steps in a function increases, uncertainties multiply until there can be no confidence in the calculational outcomes. In academic literature this is sometimes referred to as "cascading uncertainties" or "uncertainty explosions."

Uncertainties in climate science, described in Chapter 2, create major difficulties for IAMs. Although considerable progress has been made in climate science and in the understanding of how human activity interacts with and impacts the biosphere and economy, significant uncertainties persist in each block or module of an IAM. As the model progresses through each of these phases, uncertainties surrounding each variable in the chain of computations are compounded one upon another, creating a cascade of uncertainties that peaks upon completion of the final calculation.

An interesting example of the uncertainty and arbitrariness of damage functions can be shown in a comparison conducted by Aldy *et al*. (2009) of the results of IAM impact studies. They found there was a significant amount of consistency among several disparate studies of the economic impact of a 2.5°C warming by 2100 of average global temperatures compared to pre-industrial levels. Five models predicted economic damages between 1% and 2% of global GDP. However, although the gross damage estimates were similar, *there were huge differences in the estimates of the sources of the damages within each study*. The similar results for the gross damage estimates could have occurred by remarkable coincidence. More likely, the modelers "tuned" their models to arrive at total damage values they knew to be in the range of what other researchers have reported. This is an example of the "herding" behavior documented in Chapter 2, Section 2.2.2.1, and the "tuning" of climate models reported by Voosen (2016) and Hourdin *et al.* (2017).

When confronted with the fact that their models include only a limited number of sectors of the economy, the modelers typically argue any unrepresented sectors would result in even greater damage assessment if included. For example, the IPCC says "Different studies include different aspects of the impacts of climate change, but no estimate is complete; most experts speculate that excluded impacts are on balance negative" (IPCC, 2014, p. 690). However, little evidence is presented to support these claims. In contrast, as shown in previous chapters of this volume, the opposite is more likely to be true. Tunnel vision prevents bureaucracies from searching for evidence that might seem to lower the risk of the problem they are responsible for solving, so the "excluded impacts" are likely to be exculpatory rather than reinforce the government's theory. Publication bias (the tendency of academic journals to publish research that finds associations and not to publish those that do not) means more research is likely to reveal that relationships between climate change and alleged impacts is weaker than currently thought.

IAMs increasingly address the issue of uncertainty by including probability distributions – a range of values around a norm – of the parameters to explicitly address the issue of uncertainty. While this serves to acknowledge that we have no real scientific evidence to support one value over another, their use introduces another bias into IAM results. Since the structure of the damage function is made up of quadratic equations, the results of using probability distributions of equation parameters results in so-called "fat tail" impacts that are larger for higher temperature increases than for lower increases. Multiplying a series of upper-bound estimates results in a phenomenon called "cascading conservatism" (Council of Economic Advisors, 2004, p. 179) or what Belzer (2012, p. 13) calls "cascading bias," leading to risk assessments that are orders of magnitude higher than what observational data suggest.

Many experts have concluded the uncertainty problem affecting IAMs makes them too unreliable to form the basis of public policy decisions. Payne (2014) noted "the activist policy [of reducing CO_2 emissions] depends on a teetering chain of improbabilities" and represents "an extensive chain of assumptions, every one of which has to be true in order for carbon-dioxide-limiting policies to be justified." Pindyck wrote in the *Journal of Economic Literature* in 2013,

> [IAMs] have crucial flaws that make them close to useless as tools for policy analysis: certain inputs (e.g., the discount rate) are arbitrary, but have huge effects on the SCC estimates the models produce; the models' descriptions of the impact of climate change are completely ad hoc, with no theoretical or empirical foundation; and the models can tell us nothing about the most important driver of the SCC, the possibility of a catastrophic climate outcome. IAM-based analyses of climate policy create a perception of knowledge and precision, but that perception is illusory and misleading (Pindyck, 2013a, abstract).

Writing that same year in the *Review of Environmental Economics and Policy,* Pindyck (2013b, p. 6) also observed:

> IAM damage functions are completely made up, with no theoretical or empirical foundation. They simply reflect common beliefs (which might be wrong) regarding the impact of 2°C or 3°C of warming, and can tell us nothing about what might happen if the temperature increases by 5°C or more.

> And yet those damage functions are taken seriously when IAMs are used to analyze climate policy.

Harvard University's Martin Weitzman (2015, pp. 145–6) has commented,

> [D]isconcertingly large uncertainties are everywhere, including the most challenging kinds of deep structural uncertainties. The climate change problem unfolds over centuries and millennia, a long intergenerational human time frame that most people are entirely unaccustomed to thinking about. With such long time frames, discounting becomes ultra-decisive for BCA, and there is much debate and confusion about which long-run discount rate should be chosen.

According to Tapia Granados and Carpintero (2013, p. 40), "The lack of robustness of results of different IAMs indicates the limitations of the neoclassical approach, which constitutes the theoretical base of most IAMs; the variety of so-called ad hoc assumptions (often qualified as 'heroic' by their own authors), and the controversial nature of the methods to estimate the monetary value of non-market costs and benefits (mortality, morbidity, damage to ecosystems, etc.). These features explain why many contributions of this type of macroeconomics-oriented IAMs have been criticized for their dubious political usefulness and limited scientific soundness."

Tapia Granados and Carpintero then presented several important shortcomings of IAMs, most of which have been discussed previously: (1) a lack of transparency to explain and justify the assumptions behind the estimates, (2) questionable treatment of uncertainty and discounting of the future, (3) assumption of perfect substitutability between manufactured capital and "natural" capital in the production of goods and services, and (4) problems in the way IAMs estimate monetary costs of non-market effects, which can lead to skepticism about policies based on the results of the models. In another blunt assessment, Ackerman *et al*. (2009, pp. 131–2) wrote:

> [P]olicy makers and scientists should be skeptical of efforts by economists to specify optimal policy paths using the current generation of IAMs. These models do not embody the state of the art in the economic theory of uncertainty, and the foundations of the IAMs are much shakier than the general circulation models that represent our best current understanding of physical climate processes. Not only do the IAMs entail an implicit philosophical stance that is highly contestable, they suffer from technical deficiencies that are widely recognized within economics.

Even the latest contributors to the IPCC's assessment reports agree. According to the Working Group II contribution to Chapter 10 of the Fifth Assessment Report (AR5), "Uncertainty in SCC estimates is high due to the uncertainty in underlying total damage estimates (see Section 10.9.2), uncertainty about future emissions, future climate change, future vulnerability and future valuation. The spread in estimates is also high due to disagreement regarding the appropriate framework for aggregating impacts over time (discounting), regions (equity weighing), and states of the world (risk aversion)." As the result of such uncertainties, they say,

> Quantitative analyses have shown that SCC estimates can vary by at least approximately two times depending on assumptions about future demographic conditions (Interagency Working Group on the Social Cost of Carbon, 2010), at least approximately three times owing to the incorporation of uncertainty (Kopp *et al.,* 2012), and at least approximately four times owing to differences in discounting (Tol, 2011) or alternative damage functions (Ackerman and Stanton, 2012) (IPCC, 2014, p. 691).

According to the IPCC, "In sum, estimates of the aggregate economic impact of climate change are relatively small but with a large downside risk. Estimates of the incremental damage per tonne of CO_2 emitted vary *by two orders of magnitude,* with the assumed discount rate the main driver of the differences between estimates. The literature on the impact of climate and climate change on economic growth and development has yet to reach firm conclusions. There is agreement that climate change would slow economic growth, by a little according to some studies and by a lot according to other studies. Different economies will be affected differently. Some studies suggest that climate change may trap more people in poverty" (*Ibid.,* p. 692–693, italics added).

For the foreseeable future, IAM analyses will be saddled with the fact that the degree of uncertainty within the various computational stages is immense – especially when the most significant input is subjective (*i.e.*, the discount rate). For all practical purposes the errors inherent to IAMs render their use as policy tools highly questionable, if not irresponsible. They are simply not capable of providing realistic estimates of the SCC, nor can they justify GHG emission reduction policies.

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8.1.3 IWG Reports

> *The widely cited "social cost of carbon" calculations produced during the Obama administration by the Interagency Working Group on the Social Cost of Carbon have been withdrawn and are not reliable guides for policymakers.*

On March 28, 2017, President Donald Trump issued an executive order ending the U.S. government's endorsement of estimates of the "social cost of carbon" (SCC) (Trump, 2017). The executive order, which also rescinded other legacies of the Obama administration's environmental agenda, read in part:

> Section 5. Review of Estimates of the Social Cost of Carbon, Nitrous Oxide, and Methane for Regulatory Impact Analysis.
>
> (a) In order to ensure sound regulatory decision making, it is essential that agencies use estimates of costs and benefits in their regulatory analyses that are based on the best available science and economics.

(b) The Interagency Working Group on the Social Cost of Greenhouse Gases (IWG), which was convened by the Council of Economic Advisers and the OMB Director, *shall be disbanded*, and the following documents issued by the IWG shall be withdrawn as no longer representative of governmental policy:

(i) Technical Support Document: Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866 (February 2010);

(ii) Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis (May 2013);

(iii) Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis (November 2013);

(iv) Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis (July 2015);

(v) Addendum to the Technical Support Document for Social Cost of Carbon: Application of the Methodology to Estimate the Social Cost of Methane and the Social Cost of Nitrous Oxide (August 2016); and

(vi) Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis (August 2016).

(c) Effective immediately, when monetizing the value of changes in greenhouse gas emissions resulting from regulations, including with respect to the consideration of domestic versus international impacts and the consideration of appropriate discount rates, agencies shall ensure, to the extent permitted by law, that any such estimates are consistent with the guidance contained in OMB Circular A-4 of September 17, 2003 (Regulatory Analysis), which was issued after peer review and public comment and has been widely accepted for more than a decade as embodying the best practices for conducting regulatory cost-benefit analysis (Trump, 2017).

It is not unusual for a president to rescind his predecessor's executive orders, and Trump's predecessor relied heavily on executive orders to implement his anti-fossil-fuel agenda. Disbanding the Interagency Working Group (IWG) sent a clear signal that the president did not want to see the "social cost of carbon" concept kept alive by agency bureaucrats.

The IWG was comprised of representatives from 12 federal agencies brought together specifically to come up with a number – the alleged damages due to climate change caused by each ton of CO_2 emitted by the use of fossil fuels – that could be used to support President Barack Obama's war on fossil fuels (IER, 2014, p. 2). It was an example of the "seeing like a state" phenomenon reported by Scott (1998) and discussed in Chapter 1, Section 1.3.4, when government agencies succumb to pressure to find what they believe their overseers want them to find. IWG utilized experts from numerous agencies who explored technical literature in relevant fields, discussed key model inputs and assumptions, considered public comments, and then duly produced some stylized facts to meet the government's needs.

The first IWG report, issued in 2010, put the social cost of carbon in 2010 at between \$4.70 and \$35.10 per metric ton of CO_2, depending on the discount rate used (5% for the lower estimate and 2.5% for the higher estimate) (IWG, 2010). The numbers were based on the average SCC calculated by three IAMs (DICE, PAGE, and FUND) and three discount rates (2.5%, 3%, and 5%). A fourth value was calculated as the 95th percentile SCC estimate across all three models at a 3% discount rate and was included to characterize higher-than-expected impacts from temperature change in the tails of the SCC distribution. See Figure 8.1.3.1.

New versions of the three IAMs prompted IWG to recalculate and publish revised SCC estimates in 2013, shown in Figure 8.1.3.2 below (IWG, 2013). In this follow-up exercise, IWG did not revisit other methodological decisions so no changes were made to the discount rate, reference case socioeconomic and emission scenarios, or equilibrium climate sensitivity. Changes in the way damages are modeled were confined to those that had been incorporated into the latest versions of the models by the developers themselves and reported in the peer-reviewed literature.

The IWG's new estimates for the SCC in 2010 ranged from \$11 to \$52 per metric ton of CO_2, once again depending on the discount rate used, considerably higher than its previous estimate. The

Figure 8.1.3.1
Estimates of the social cost of carbon in 2007 dollars per metric ton of CO_2 from the IWG's 2010 report

Discount Rate Year	5.0% Avg	3.0% Avg	2.5% Avg	3.0% 95th
2010	4.7	21.4	35.1	64.9
2015	5.7	23.8	38.4	72.8
2020	6.8	26.3	41.7	80.7
2025	8.2	29.6	45.9	90.4
2030	9.7	32.8	50.0	100.0
2035	11.2	36.0	54.2	109.7
2040	12.7	39.2	58.4	119.3
2045	14.2	42.1	61.7	127.8
2050	15.7	44.9	65.0	136.2

Source: IWG, 2010.

Figure 8.1.3.2
Estimates of the social cost of carbon in 2007 dollars per metric ton of CO_2 from the IWG's 2013 report

Discount Rate Year	5.0% Avg	3.0% Avg	2.5% Avg	3.0% 95th
2010	11	33	52	90
2015	12	38	58	109
2020	12	43	65	129
2025	14	48	70	144
2030	16	52	76	159
2035	19	57	81	176
2040	21	62	87	192
2045	24	66	92	206
2050	27	71	98	221

Source: IWG, 2013.

new, higher SCC estimates were used by the U.S. government for the first time in a June 2013 rule on efficiency standards for microwave ovens (U.S. Department of Energy, 2013). IWG's SCC estimates were fiercely criticized by experts in the climate change debate. Much of the criticism focused on the IAMs it used as the basis of its estimates – an average of the DICE, FUND, and PAGE models – and since those models are critiqued later in this chapter (see Section 8.3), there is no need to repeat that analysis here.

The Institute for Energy Research (IER), in comments submitted to the Office of Management and Budget in 2014, offered a stinging critique of SCCs in general, making many of the points made in the previous section, and then focused specifically on IWG's process for arriving at an SCC estimate. The IER authors wrote:

> The most obvious example of the dubious implementation of the SCC in federal cost/benefit analyses is the ignoring of clear [Office of Management and Budget (OMB)] guidelines on how such analyses are to be quantified. Specifically, OMB requires that the costs and benefits of proposed policies be quantified at discount rates of 3% and 7% (with additional rates being optional), and OMB also requires that the costs and benefits be quantified at the domestic (not global) level. In practice, the Working Group and agencies that have relied on its estimates of the SCC have simply ignored these two clear OMB guidelines (IER, 2014, p. 12).

Similar points were made in comments submitted by Michaels and Knappenberger (2014). When Heritage Foundation researchers re-ran two of the three IAMs using the 7% discount rate, the SCC dropped by more than 80 percent in one of the models and actually went negative in the other (Dayaratna and Kreutzer, 2013, 2014). The authors of the IER comment went on to say, "No one is arguing that the Working Group or federal agencies should be prohibited from reporting results using a low discount rate. Rather, the public deserves to know what the results would be, were the cost/benefit calculations performed at a 7% discount rate, as OMB guidelines clearly require," and "This omission of a 7% figure masks just how dependent the SCC is on discount rates" (IER, 2014, p. 12) The importance of choosing proper discount rates is discussed in detail later in this chapter (see Section 8.2.5.2).

The IWG's decision to include in its cost-benefit analysis estimates of the global costs (and presumably benefits) of climate change reflected the fact that the three IAMs it chose to rely on attempt to find a global cost rather than a cost specific to the United States. But not only does this violate the purpose of CBA as set forth in national policy guidelines, it also produces false results by disregarding the "leakage" problem reported in Chapter 1, Section 1.2.10, which found reducing emissions in the United States by 10 metric tons could cause emissions by other countries to increase between 1.2 and 13 tons (Brown, 1999; Babiker, 2005).

A net reduction of 10 tons assuming the lower of the two estimates would require an emissions reduction by the United States of 11.4 tons, so the IWG estimate of the SCC is too low. The second estimate means no reductions by the United States, no matter how high, will lead to a net reduction in global emissions since emissions in other countries rise faster than reductions in the United States. In choosing to use a global estimate of damages in its SCC, the IWG disregarded an extensive body of literature on leakage rates by industry, by type of program, and by country (Fischer *et al.*, 2010).

Finally, the IER researchers also observe that "According to Cass Sunstein, the man who convened the SCC Working Group, 'Neither the 2010 TSD [Technical Support Document] nor the 2013 update was subject to peer review in advance, though an interim version was subject to public comment in 2009' [Sunstein, 2013]. This is a direct violation of the administration's stance on 'Transparency and Open Government' [Obama, 2009]" (IER, 2014, p. 19).

For all these reasons, the Trump administration was right to withdraw the social cost of carbon calculations produced during the Obama administration by the Interagency Working Group on the Social Cost of Carbon.

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and off mode for microwave ovens. *Federal Register* **78** (116): 10 CFR Parts 429 and 430.

8.1.4 The Stern Review

The widely cited "Stern Review" was an important early attempt to apply cost-benefit analysis to climate change. Its its authors focused on worst-case scenarios and failed to report profound uncertainties.

The Economics of Climate Change: The Stern Review was prepared for the British government by Nicholas Stern, professor of economics and government at the London School of Economics, released in October 2006, and published by Cambridge University Press in 2007 (Stern *et al.,* 2007). Commonly known as the Stern Review, it claimed "using the results from formal economic models, the Review estimates that if we don't act, the overall costs and risks of climate change will be equivalent to losing at least 5% of global GDP each year, now and forever. If a wider range of risks and impacts is taken into account, the estimates of damage could rise to 20% of GDP or more."

The Stern Review's findings were markedly different from prior works on the subject and thus led to questions as to how and why its authors came to such a radically different conclusion. It did not take long for researchers to determine the disparity and the report was quickly refuted (Byatt *et al*., 2006; Mendelsohn, 2006; Nordhaus, 2006; Tol and Yohe, 2006). Nevertheless, the report was heralded throughout the policy world and continues to be frequently cited as justification for enacting CO_2 emission reduction policies. Following are some key shortcomings of the report.

Uncertainty. Uncertainties all along the chain of calculations are poorly expressed or not acknowledged at all, creating the appearance of a specific and certain finding (such as the numbers cited above) even though its conclusions could be off by an order of magnitude or even reverse sign. This sort of rhetoric is tolerated in the "gray literature" – policy research and commentary that is not peer-reviewed – but it should not then be presented as an authoritative scientific report.

Emission Scenarios. The Stern Review uncritically endorses the IPCC's future emissions scenarios, which have been widely criticized as problematic and based on flawed economic analyses to which no probabilities have been assigned (Henderson, 2005). As an example, the Stern Review considers only one baseline of demographic change over the next two centuries, which assumes rapid population growth in lower latitudes. Further, the scenario assumes an anemic growth in per-capita income of only 1.3% per year instead of recent growth rates of approximately 3%. This blend of assumptions creates a future full of billions of poor people living in regions deemed most sensitive to warming. Had the Stern Review assumed economic growth to continue at just 2%, and if population growth rates continued to slow, there would actually be a reduction in the poorest and most vulnerable rural populations in these lower latitudes.

Climate Impacts. The Stern Review consistently exaggerates the potential impacts of climate change, giving much more weight and credence to worst-case future climate scenarios. The report assumes powerful positive feedbacks will cause temperatures to increase more rapidly than previously thought, especially throughout the twenty-second century. The central assumption is temperatures might rise 2° to 5°C by 2100, and then by another 2°C by 2200. But the report also raises the possibility warming might be as high as 10° to 11°C by 2100, in which event the global cost is estimated to be as high as 5% to 20% of GDP.

Much of the economic damages are expected to result from increasing extreme weather events, which gain in magnitude and frequency and time in the Stern Review. Observational evidence, in contrast, shows no conclusive relationship between extreme weather events and global warming, with much of the literature suggestive that such events will decline as temperatures warm (see Chapter 2 and references in NIPCC, 2013, Chapter 7). Estimated annual climate-related damages in the Stern Review amount to only 0.2% of GDP at present but rise to 5% of GDP in 2200. This translates to around $70 billion in damages in 2000 to a staggering $23 trillion per year by 2200. There is no evidence to suggest climate impacts could possibly reach this height.

Discount Rate. The Stern Review utilized an extremely low value for the discount rate, just 1.4%. As discussed in some detail in Section 8.2.5.2, the application of such a low value will inherently produce a very high SCC (one dollar of damage in 2200 is worth six cents in 2000 if discounted at 1.4%, but worth only 0.03 cents if discounted at 4%). The authors of the Stern Review argue for using the 1.4% value, which is only 0.1% above the rate of growth of consumption in their analysis, saying it is "ethically proper" – they consider using a higher discount rate to be unfair to future generations. In fact, using a low discount rate to justify draconian reductions on CO_2 emissions today would reduce the welfare of all generations by slowing economic growth today and for decades to come. Further, by using a low discount rate, the Stern Review placed too much near-term significance on events that may occur only far into the future.

Another problem concerning the discount rate was pointed out by Mendelsohn (2006, p. 43), who wrote

> Despite arguing for the low discount rate in the impact analysis, the report does not use it when evaluating the cost of mitigation. To be consistent, the opportunity cost of investing in mitigation must also be valued using the same discount rate as was used to determine the cost of climate change. Because investing in mitigation substitutes for investing in other activities that can earn the market rate of interest, society loses the income that it could have gained from other valuable projects. Assuming that we use the historic rate of return of 4% (that the mitigation program does not drive up interest rates), the value of $1 of abatement is $2.9 when evaluated at a discount rate of 1.4%. The mitigation costs reported in the study need to be multiplied by a factor of three to be consistent with how the damages are calculated.

No Adaptation. Despite discussing the importance of human adaptation to climate change at various points in the report, the influence of adaptation on welfare damages is not taken into account. As Mendelsohn (2006, p. 44) once again critiqued: "[T]he report's estimates of flood damage costs from earlier spring thaws do not consider the probability that people will build dams to control the flooding. Farmers are envisioned as continuing to grow crops that are ill suited for new climates. People do not adjust to the warmer temperatures they experience year after year, and they thus die from heat stroke. Protective structures are not built along the coasts to stop rising sea levels from flooding cities. No public health measures are taken to stop infectious diseases from spreading." The result is that "compared to studies that include adaptation, the [Stern] report overestimates damages by more than an order of magnitude" (*Ibid.*).

Emission Abatement. The Stern Review concedes a present-day high cost of abatement. To reach the stabilization goal of 550 ppm, which corresponds to a two-thirds reduction in emissions by 2050, a carbon tax on the order of $168 per ton would need to be implemented, amounting to a rough estimate of $8.9 trillion per year, which is 6.5% of GDP, or a displaced investment worth about 20% of GDP. The Stern Review reassures its readers these costs will be reduced over time by technological advancements that will drive the costs to only 3% of GDP in 2020 and 1% in 2050. But the costs of technologies do not always fall over time.

Mendelsohn (2006, p. 46) wrote, "Many technologies have been abandoned precisely because their costs have not fallen. Moreover, one must be careful projecting how far costs will fall because one will eventually exhaust all the possible improvements that can be made. One of the critical linchpins of the Stern Report is that technical change will drive down the cost of abatement six-fold by 2050."

Carbon recapture remains a costly, unproven technology and there are multiple problems with renewable technology (see Chapter 3). To meet the Stern Review's goals, Mendelsohn notes, an area covering some 5 million to 10 million hectares of land would be needed for solar panels (in sunny locations), 33 million hectares would be needed to install two million additional wind turbines, and a whopping 500 million additional hectares of land would be needed to increase energy production from biofuels (Mendelsohn, 2006, p. 45). And, despite the increased pressure these actions would place on land, the Stern Review assumes they would have no impact on the price of land, nor on the industries from which the land presumably would be taken (agriculture, timber, and tourism).

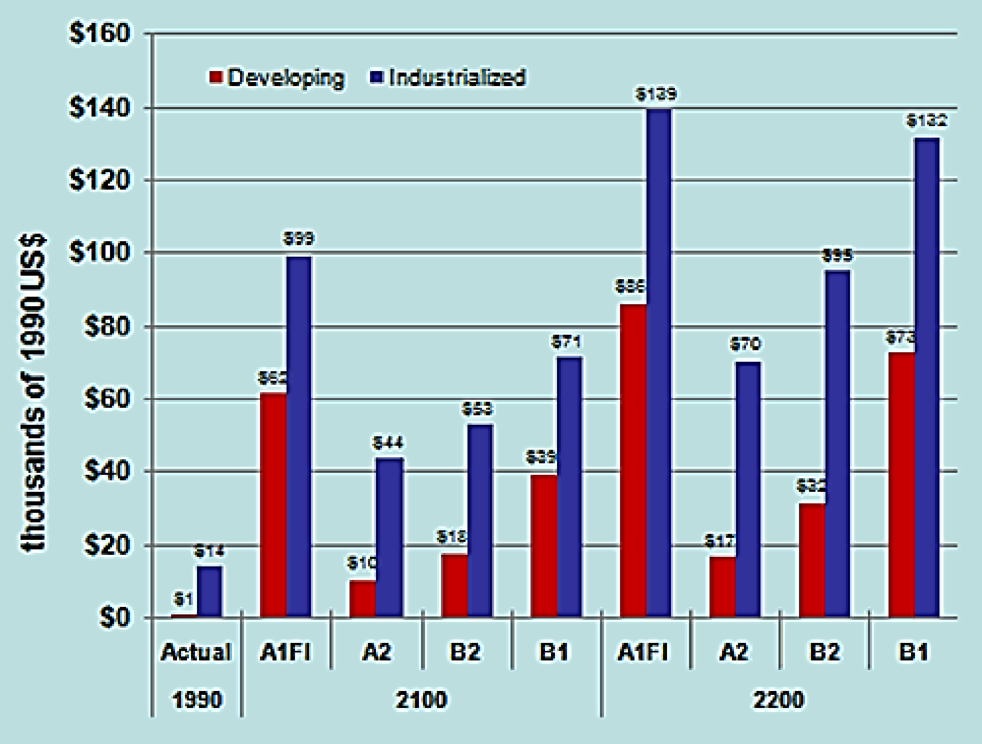
Economic Impact. Because of its errors in emission scenarios, estimates of climate impact, use of improper discount rates, and failure to consider adaptation, the Stern Review's claim that unabated global warming would produce large negative economic impacts "now and forever" is not credible. Unlike most other studies, the Stern Review attempts to account for non-market (*i.e.*, environmental) impacts as well as the risk of catastrophe (see, *e.g.*, Freeman and Guzman, 2009, p. 127). Tol observes, "[The Stern Review's] impact estimates are pessimistic even when compared to other studies in the gray literature and other estimates that use low discount rates" (Tol, 2008, p. 9).

Goklany (2009) used the Stern Review's four emission scenarios (taken from the IPCC's Third Assessment Report (TAR)) and its inflated estimates of the damages caused by global warming (expressed as a loss of GDP) for developing and industrialized countries to produce estimates of per-capita income in 2100 and 2200 *net of the cost of global warming* – in other words, subtracting the Stern Review's estimate of income loss attributed to unabated global warming – and compared them to actual 1990 per-capita income (both Stern's and the IPCC's baseline year). His findings appear in Figure 8.1.4.1.

In Figure 8.1.4.1, the net GDP per capita for 1990 is the same as the actual (unadjusted) GDP per capita (in 1990 US dollars, using market exchange rates, per the IPCC's practice). This is consistent with using 1990 as the base year for estimating changes in globally averaged temperatures. The average global temperature increases from 1990 to 2085 for the scenarios are as follows: 4°C for AIFI, 3.3°C for A2, 2.4°C for B2, and 2.1°C for B1. For context, in 2006, GDP per capita for industrialized countries was $19,300; the United States, $30,100; and developing countries, $1,500.

For 2100, the unadjusted GDP per capita accounts for any population and economic growth assumed in the IPCC scenarios from 1990 (the base year) to 2100. For 2200, Goklany assumed the unadjusted GDP per capita is double that in 2100, which is equivalent to a compounded annual growth rate of 0.7%, less than the Stern Review's assumed annual growth rate of 1.3%. Thus, Goklany's calculation substantially understates the unadjusted GDP per capita and, therefore, also the net per-capita GDP in 2200. The costs of global warming are taken from the Stern Review's 95th percentile estimates under the "high climate change" scenario, which is equivalent to the IPCC's warmest scenario (A1F1). Per the Stern Review, these costs amount to 7.5% of global GDP in 2100 and 35.2% in 2200. These losses are adjusted downwards for the cooler scenarios per Goklany (2007).

Figure 8.1.4.1
Net GDP per capita, 1990–2200, after accounting for losses due to global warming as estimated by the Stern Review, for four IPCC emission and climate scenarios



A1FI, A2, B2, and B1 are four emission scenarios for the years 2100 and 2200 as postulated by IPCC TAR arranged from the warmest (A1FI) on the left to the coolest (B1) on the right. Per-capita income growth rate is explained in the text. *Source:* Goklany, 2009.

Figure 8.1.4.1 shows that even accepting the Stern Review's unrealistic assumptions and highest damage estimates, and despite assuming an economic growth rate in the absence of global warming that is *less* than the already low rate assumed by the Stern Report, for populations living in countries currently classified as "developing," net GDP per capita (after accounting for global warming) will be 11 to 65 times higher in 2100 than it was in the base year. It will be even higher (18 to 95 times) in 2200.

Goklany's calculation also found that industrialized countries will have net GDP per capita three to seven times higher in 2100 than in 1990. In 2200 it will be five to 10 times higher. Net GDP per capita in today's developing countries will be higher in 2200 than it was in industrialized countries in the base year (1990) under all scenarios, despite any global warming. *That is, regardless of any global warming, populations living in today's developing countries will be far better off in the future than people currently inhabiting today's industrialized countries.* This is also true for 2100 for all but the "poorest" (A2) scenario.

Under the warmest scenario (A1FI), the scenario that prompts much of the apocalyptic warnings about global warming, net GDP per capita of inhabitants of developing countries in 2100 ($61,500) will be double that of the United States in 2006 ($30,100), and almost triple in 2200 ($86,200 versus $30,100). (All dollar estimates are in 1990 US dollars.)

In other words, if the Stern Review's pessimistic scenario were to come about, people everywhere – even in developing countries – would be wealthy by today's standards, and their ability to cope with and adapt to climate change will be correspondingly higher.

* * *

In conclusion, at the time of its publication in 2007 the Stern Review was a serious attempt to estimate the social costs and benefits of climate change. Written by a distinguished author (and team of assistants), it was and still is accepted as being at least close to the mark by many policymakers and activists around the world. But the report was not even close to the mark.

Admitting and reporting uncertainty is what separates scholarship from propaganda. For the authors of the Stern Review not to admit or reveal the cascade of uncertainties that render their predictions wholly implausible is not excusable. To manipulate economic growth and discount rates to arrive at headline-grabbing numbers that invoke fear is not the best way to advance an informed public debate. Painting a picture of widespread poverty and despair a century from now, when its own data show people living in developing countries would be *11 to 65 times better off in 2100 than they were in 1990*, suggests at best sleight of hand rather than transparency. In short, the Stern Review set back, rather than advanced, global understanding of the consequences of climate change.

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8.1.5 Conclusion

Cost-benefit analysis (CBA) is a well-established practice in finance and economics, and its application to fossil fuels, climate change, and environmental regulations should be welcomed. Decisions need to be made, but they are being made without a full appreciation of the costs and benefits involved, who will bear the costs and when they might arrive, and other key factors that need to be considered. Integrated assessment models (IAMs) attempt to fill this gap by combining what is known about climate change – the carbon cycle, climate sensitivity, and the residence time of CO_2 in the atmosphere, for example – with economic models that monetize the possible consequences of climate change. These models can be simple or complex; complexity is no guarantee of a superior ability to forecast the future, and may have the opposite effect.

The problem with IAMs is that they are not reliable. This is the result of cascading uncertainties in each block or module of the models, a problem that cannot be solved by more computer power, more data, or averaging the outputs of multiple models. Even small amounts of uncertainty in, say, the residence time of CO_2 in the atmosphere or the cost of adaptation in future years, produces false signals that get amplified year after year as the model is run, making predictions 50 years or 100 years distant purely speculative.

A second problem with IAMs is the judgments that act as the “glue” between the modules. Those judgments are subjective and can be “tuned” to produce practically any result their modelers like: a low “social cost of carbon” estimate if the intent is to avoid having to pay for polluting the commons with greenhouse gases that may injure future generations, or a higher estimate if the intent is to justify punitive regulations on fossil fuel producers and users. Certainly this latter was the case with the SCC estimates produced by the now-disbanded Interagency Working Group and the Stern Review.

Later in this chapter, Section 8.3 reports two attempts made to correct some of the biggest mistakes that appear in IAMs. The exercise is useful if only to reveal how unrealistic current models are and to give policymakers a basis for rejecting calls that they act on the current models’ flawed and exaggerated forecasts.

8.2 Assumptions and Controversies

Each of the four modules of a typical integrated assessment model (IAM) relies on assumptions about and controversial estimates of key data, processes, and trends. Efforts to use the models to apply cost-benefit analysis (CBA) to climate change are consequently deeply compromised. In this section the major assumptions and controversies in each model are identified and errors documented.

8.2.1 Emission Scenarios

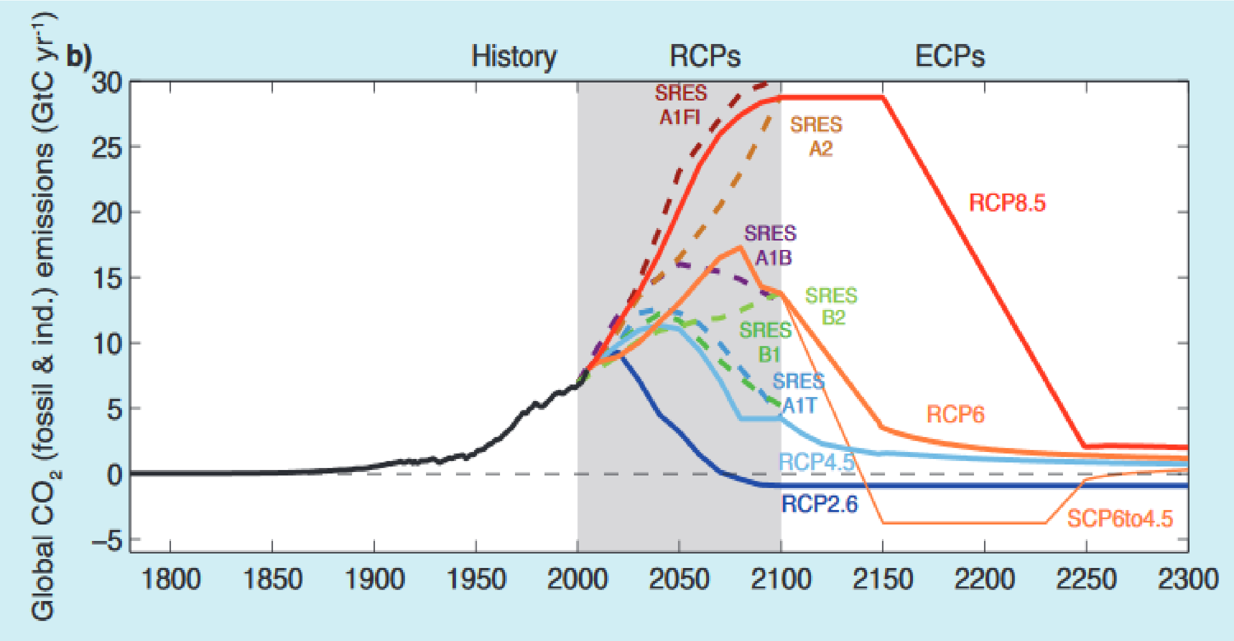
> *Most IAMs rely on emission scenarios that are little more than guesses and speculative “storylines.” Even current greenhouse gas emissions cannot be measured accurately, and technology is likely to change future emissions in ways that cannot be predicted.*

As illustrated in Figure 8.1.2.1.1, the first step in an IAM is to project future changes in human greenhouse gas emissions. The *Emission Scenarios* block, called *Economic Dynamics* in some models, encompasses the impact = population x affluence x technology (IPAT) equation discussed in Chapter 5, Section 5.2.1.

Scenarios (or “storylines,” as the IPCC has called them in the past) of future CO_2 emissions are generated by forecasting economic growth rates and their related emissions. Prior to 2013, most IAMs and “gray literature” such as the Stern Review relied on emission scenarios called “SRESs,” named after the IPCC’s 2000 *Special Report on Emissions Scenarios* that proposed them (IPCC, 2000). In 2013, those scenarios were superseded by “representative concentration pathways” (RCPs) used in the Fifth Assessment Report (IPCC, 2013, Chapters 1 and 12). As the IPCC explains, “Representative Concentration Pathways are referred to as pathways in order to emphasize that they are not definitive scenarios, but rather internally consistent sets of time-dependent forcing projections that could potentially be realized with more than one underlying socioeconomic scenario. The primary products of the RCPs are concentrations but they also provide [estimates of] gas emissions” (IPCC, 2013, p. 1045).

Each RCP starts with projections of emissions of four greenhouse gases (carbon dioxide, methane, nitrous oxide, and chlorofluorocarbons (CFCs)) obtained from the Coupled Model Intercomparison Project (CMIP), an international effort to achieve

Figure 8.2.1.1
Greenhouse gas emissions in IPCC's four representative concentration pathways (RCPs) from 1765 to 2300



Source: IPCC, 2013, Box 1.1, Figure 3b, p. 149.

consensus on inputs to IAMs. According to CMIP's website, "CMIP provides a community-based infrastructure in support of climate model diagnosis, validation, intercomparison, documentation and data access. This framework enables a diverse community of scientists to analyze [global climate models] in a systematic fashion, a process which serves to facilitate model improvement. Virtually the entire international climate modeling community has participated in this project since its inception in 1995" (CMIP, 2018). CMIP is funded by the U.S. Department of Energy.

Total global annual anthropogenic emissions of greenhouse gases, measured as CO_2 equivalents, are estimated for the past two centuries (starting "around 1765") and forecast from the present for approximately 300 years (to the year 2300). The IPCC's forecast appears as Figure 8.2.1.1, reprinted from Working Group I's contribution to AR5 (IPCC, 2013, p. 149).

The IPCC's four RCPs are titled RCP2.6, RCP4.5, RCP6, and RCP8.5, named after radiative forcing (RF) values of cumulative anthropogenic CO_2 and CO_2 equivalents by the year 2100 relative to pre-industrial values (2.6, 4.5, 6.0, and 8.5 W/m^2, respectively). Whether these emissions would actually have these radiative forcing values is discussed in Section 8.2.3 below. IPCC's switch from SRESs to RCPs seems designed to direct attention away from the complexity and uncertainty of its estimates of past, current, and future emissions. Accepting an RCP amounts to accepting a black box that produces easy and "consistent" answers to questions about concentrations and radiative forcing, questions IAM modelers have great difficulty answering without admitting to great uncertainty.

The IPCC's RCPs allow it to say none of its scenarios depends on "one underlying socioeconomic scenario" (IPCC, 2013, p. 1045). This makes challenging their credibility more difficult, but doesn't make any scenario more credible. Apparently, no change in population or economic (consumption) growth, war, natural disaster, or appearance of a new technology for emissions control or efficiency can discredit any one of the RCPs because they no longer rely explicitly on real-world events that might affect these variables. Instead, they rest on an amalgam of IAMs reported in 23 published reports (see sources cited for Table 12.1 on pp. 1048–49). This resembles the IPCC's decision to rely on the DICE, FUND, and PAGE models for its cost-benefit analysis. But what is convenient for modelers is not necessarily good science. Once again, averaging the outputs of models that share common flaws does not produce results more accurate than any one model can produce.

Forecasting future emissions is no easy task given the crude and often simplified parameterizations utilized by IAMs to mimic the global economy (Lemoine and Rudik, 2017). The key is to accurately portray the quantity of current and annual future emissions by properly estimating future population and economic growth and changes in technology and productivity, and predicting seemingly unpredictable events such as changes in government policies, wars, scientific and medical breakthroughs, and more. Few self-described "futurists" can accurately predict such things a year or two in advance. None can predict them across decades or even centuries, as the IPCC attempts to do.

Even measuring *current* emissions is an extremely complex and difficult exercise. Because natural sources (oceans and vegetation) produce massive amounts of CO_2 relative to human emissions, their background presence makes the measurement of anthropogenic emissions on the ground impossible. As reported in Chapter 5, Section 5.1.2, human CO_2 emissions account for only about 3.5% (7.8 Gt divided by 220 Gt) of the carbon entering the atmosphere each year and so, with about 0.5% (1.1 Gt divided by 220 Gt) from net land use change, natural sources account for the remaining 96.0%. The residual of the human contribution the IPCC believes remains in the atmosphere after natural processes move the rest to other reservoirs is as little as 1.17 Gt per year (15% of 7.8 Gt), just 0.53% of the carbon entering the atmosphere each year (IPCC, 2013, p. 471, Figure 6.1). This is less than two-tenths of 1% (0.195%) of the total amount of carbon thought to be in the atmosphere.

Of course, the IPCC does not actually measure CO_2 emissions, since there are millions of sources (billions if humans are counted). Virtually all emission estimates coming from CMIP and therefore the IPCC are not observational data, but stylized facts standing in for unknown quantities that can only be estimated by models and formulas homogenizing disparate and often poorly maintained databases. As the IPCC says, "the final RCP data sets comprise land use data, harmonized GHG emissions and concentrations, gridded reactive gas and aerosol emissions, as well as ozone and aerosol abundance fields" (p. 1046).

Not all countries are able to keep accurate records of economic activity, much less emissions of a dozen gases. "Informal economies" constitute a large part of the economies of many developing and even industrial countries, and little is known about their use of natural resources or emissions. It is thought that 50% of the world's workforce works in informal markets and are likely to escape government regulations and reporting requirements (Jutting and de Laiglesia, 2009). If their use of energy and emissions are comparable to use in the formal economy, then an economy as large as that of China and Japan *combined* is largely invisible to government data collectors. This source of uncertainty is never reported by IAM modelers.

Some countries, including major emitters such as China and Russia, routinely manipulate data regarding economic growth and investment to hide economic woes from their citizens or exaggerate their success to other world leaders. Martinez (2018) observes that totalitarian regimes have "a stronger incentive to exaggerate economic performance (years of low growth, before elections, after becoming ineligible for foreign aid)" which might be observed in their reporting of "GDP sub-components that rely on government information and have low third-party verification." To measure this deception, he compared satellite images of changes over time in electric lights in free and authoritarian countries to their reported economic growth rates during the same period. He found that "yearly GDP growth rates are inflated by a factor of between 1.15 and 1.3 in the most authoritarian regimes" (Martinez, 2018; see also Ingraham, 2018). According to Freedom House, an organization that monitors democracy and authoritarianism around the world, countries designated as "free" in 2013 represented only 40% of the global population (Freedom House, 2014).

With respect to economic growth, IAMs typically assume compound annual global economic growth rates for the period 1995 to 2100 that range between 1.48% and 2.45%, with an average baseline rate of growth of 2.17%. Spreadsheets with the various parameters for the created scenarios can be found on a website maintained by the Energy Modeling Forum at Stanford University (Energy Modeling Forum, 2018). These rates of growth are not particularly high, especially when compared to global growth rates over the past 50 years. The International Energy Agency (IEA) assumes that world GDP, in purchasing power parity (PPP), will grow by an average of 3.4% annually over the period 2010–2030 (IEA, 2017). Similarly, the U.S. Energy Information Agency (EIA) forecasts that from 2015 to 2040, real world GDP growth averages 3.0% in its Reference case (EIA, 2017). If a warmer world is also a more prosperous world, as countless historians have documented was the case in the past (see the review in Chapter 7), then even these projected rates will be too low and along with them, forecasts of future greenhouse gas emissions.

More rapid-than-expected technological change would have the opposite effect of faster-than-expected economic growth. Thanks to the spread of electrification, technology-induced energy efficiency, and the emergence of natural gas as a vigorous competitor to coal for electricity production in the United States (and likely in other countries in the future), the correlation between economic growth (consumption) and greenhouse gas emissions has weakened since the end of the twentieth century (Handrich *et al.*, 2015). Emissions in industrialized countries generally, and especially in the United States, have slowed or even fallen despite population and consumption growth, evidence of the "dematerialization" reported by Ausubel and Waggoner (2008), Goklany (2009), Smil (2013), and others cited in Chapter 5.

In conclusion, most IAMs rely on emission scenarios that are little more than guesses and speculative "storylines." Even current greenhouse gas emissions cannot be measured accurately, and technology is likely to change future emissions in ways that cannot be predicted.

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8.2.2 Carbon Cycle

> *IAMs falsely assume the carbon cycle is sufficiently understood and measured with sufficient accuracy as to make possible precise predictions of future levels of carbon dioxide (CO_2) in the atmosphere.*

As illustrated in Figure 8.1.2.1.1, the second step in an IAM is to compute the trajectory of global atmospheric CO_2 concentrations based on the emission scenarios calculated in Step 1. The *Future CO_2 Concentration* block, also called the *Carbon Cycle* module, contains a model of the carbon cycle that estimates the net increase of carbon in the atmosphere based on what is known about carbon reservoirs, exchange rates, and the residence time of CO_2 in the atmosphere.

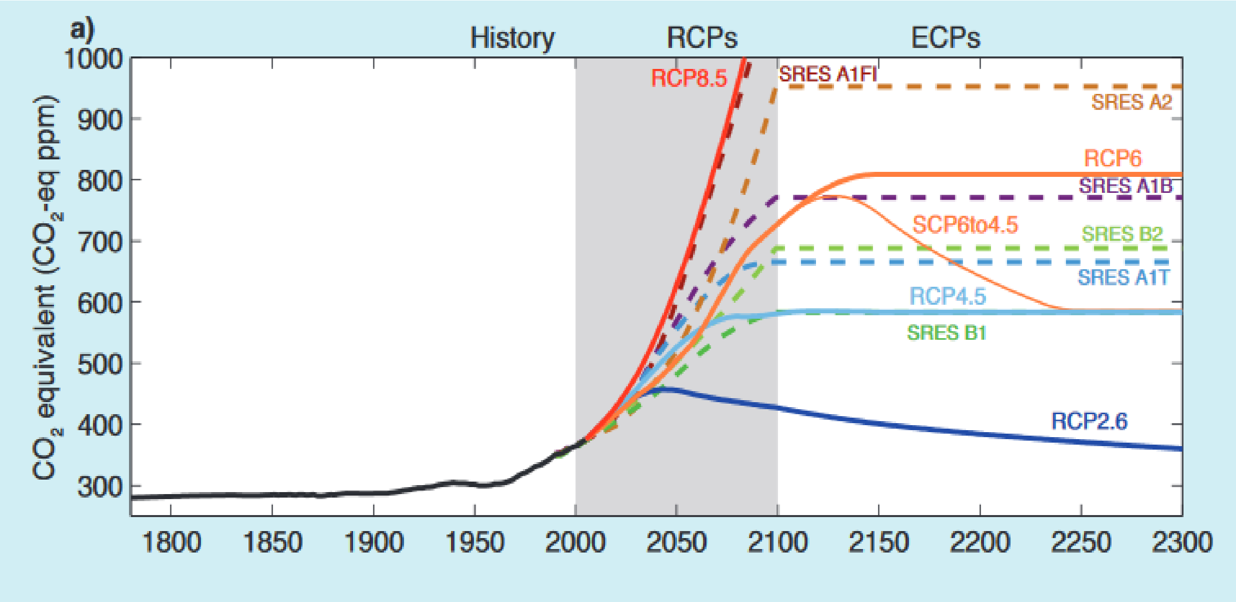
The IPCC describes the carbon cycle in some detail in Chapter 6 of the Working Group I contribution to AR5 (IPCC, 2013, pp. 465–570), but for its cost-benefit analysis it relies on a single carbon cycle model provided by CMIP. The IPCC uses it to estimate how much anthropogenic carbon dioxide remains in the atmosphere and how it affects future atmospheric concentrations. Figure 8.2.2.1, reprinted from Working Group I's contribution to AR5, illustrates historical and projected estimated atmospheric CO_2 concentrations for the four RCPs from 1800 to 2300 (IPCC, 2013, p. 149).

How accurate or certain is the carbon cycle model provided by CMIP for this part of the IPCC's cost-benefit analysis? The IPCC itself says "a single carbon cycle model with a representation of carbon-climate feedbacks was used in order to provide consistent values of CO_2 concentration for the CO_2 emission provided by a different IAM for each of the scenarios. This methodology was used to produce consistent data sets across scenarios *but does not provide uncertainty estimates for them*" (*Ibid.*, p. 1046, italics added). Estimates without uncertainty estimates should be a red flag for all serious researchers.

As described in more detail in Chapter 5, Section 5.1.2, carbon is stored in four reservoirs: soil, rocks, and sediments, oceans and lakes, plants and animals, and the air. The amount of carbon in each reservoir and the rates of exchange among reservoirs are not known with certainty. Estimates vary in the literature (e.g., Ruddiman, 2008; Falkowski *et al.*, 2000; IPCC, 2013, p. 471). Falkowski *et al.* admitted, "Our knowledge is insufficient to describe the interactions between the components of the Earth system and the relationship between the carbon cycle and other biogeochemical and climatological processes" (Falkowski *et al.*, 2000).

Carbon moves from soil, rocks, and sediment into the air via natural oxidation, bacterial processing, degassing from midocean ridges and hotspot volcanoes, seepage of crude oil and natural gas from land and the ocean floor, the weathering of rocks, and

Figure 8.2.2.1
Historical and projected estimated atmospheric CO_2 concentrations, 1765–2300



Source: IPCC, 2013, Box 1.1, Figure 3, p. 149.

burning of fossil fuels. Just how much carbon is released naturally from the lithosphere in any given year is uncertain. According to Burton *et al.* (2013, p. 323), "the role of CO_2 degassing from the Earth is clearly fundamental to the stability of the climate, and therefore to life on Earth. Notwithstanding this importance, the flux of CO_2 from the Earth is poorly constrained. The uncertainty in our knowledge of this critical input into the geological carbon cycle led Berner and Lagasa (1989) to state that it is the most vexing problem facing us in understanding that cycle."

According to Wylie (2013), estimates of volcanic degassing rose from around 100 million metric tons of CO_2 per year in 1992 to 600 million metric tons in 2013, a six-fold increase in two decades. According to Aminzadeh *et al.* (2013, p. 4), "What is the volume of hydrocarbon seepage worldwide? The Coal Oil Point seeps are a large source of air pollution in Santa Barbara County, California. Those seeps are similar in many ways to the seeps discussed in this volume. When multiplied by any reasonable assumption of seep numbers worldwide, it is easy to imagine that natural seepage of oil in the range of thousands of barrels per day and gas leakage of hundreds of millions of cubic feet per day is not unreasonable."

In 2003, a U.S. National Research Council report titled *Oil in the Sea III* acknowledged "the inputs from land-based sources are poorly understood, and therefore estimates of these inputs have a high degree of uncertainty," and "estimating the amount of natural seepage of crude oil into the marine environment involves broad extrapolations from minimal data." It nevertheless estimated the annual global oil seepage rate to be between 200,000 and 2,000,000 tons (60 and 600 million gallons) (NRC, 2003). Since the NRC report was produced, extensive use by the oil industry of 3D seismic data, manned submersibles, and remotely operated vehicles has revealed more seeps than previously assumed to exist, suggesting natural seepage of hydrocarbons from the ocean floor may be understated by the IPCC and other research bodies (Roberts and Feng, 2013, p. 56).

Oceans are the second largest reservoir of carbon, containing about 65 times as much as the air. The IPCC and other political and scientific bodies assume roughly 50% to 70% (note the range) of the CO_2 produced by human combustion of fossil fuels is absorbed and sequestered by the oceans, most of the remainder is taken up by plants and animals (terrestrial as well as aquatic), and what's left remains in the air, contributing to the slow increase in atmospheric concentrations of CO_2 during the modern era.

Earth's atmosphere (air) is the fourth and smallest reservoir, estimated to hold approximately 870 gigatons of carbon (GtC). (Note this estimate is generated by mathematical formulas and is not observational data.) As mentioned in the previous section, the total human contribution, including net land use change (primarily agriculture and forestry), is only about 4.3% of total annual releases of carbon into the atmosphere (IPCC, 2013, p. 471, Figure 6.1). The residual of the human contribution that the IPCC believes remains in the atmosphere after natural processes move the rest to other reservoirs is just 0.53% of the carbon entering the air each year. It is less than two-tenths of 1% (0.195%) of the total amount of carbon thought to be in the atmosphere, per Ruddiman (2008). Given uncertainties in the sizes of the reservoirs and the exchange rates among them, it is proper to ask if this residual is measurable, and if not, if it exists at all.

The IPCC apparently assumes atmospheric CO_2 concentrations would be stable, decade after decade and century after century, *but for* anthropogenic emissions. Yet research suggests 500 million years ago the atmosphere's CO_2 concentration was approximately 20 times higher than it is today, at around 7,500 ppm. Two hundred million years later it declined to close to the air's current CO_2 concentration of just over 400 ppm, after which it rose to four times that amount at 220 million years before present (Berner, 1990, 1992, 1993, 1997; Kasting, 1993).

During the middle Eocene, some 43 million years ago, the atmospheric CO_2 concentration is estimated to have dropped to a mean value of approximately 385 ppm (Pearson and Palmer, 1999), and between 25 to nine million years ago, it is believed to have varied between 180ppm and 290 ppm (Pagani *et al*., 1999). This latter concentration range is essentially the same in which the air's CO_2 concentration oscillated during the 100,000-year glacial cycles of the past 420,000 years (Fischer *et al*., 1999; Petit *et al*., 1999). While the natural processes that have driven these changes in CO_2 are not likely to operate over the shorter time scales of an IAM, they nonetheless demonstrate the natural world can and does influence the atmosphere's CO_2 content.

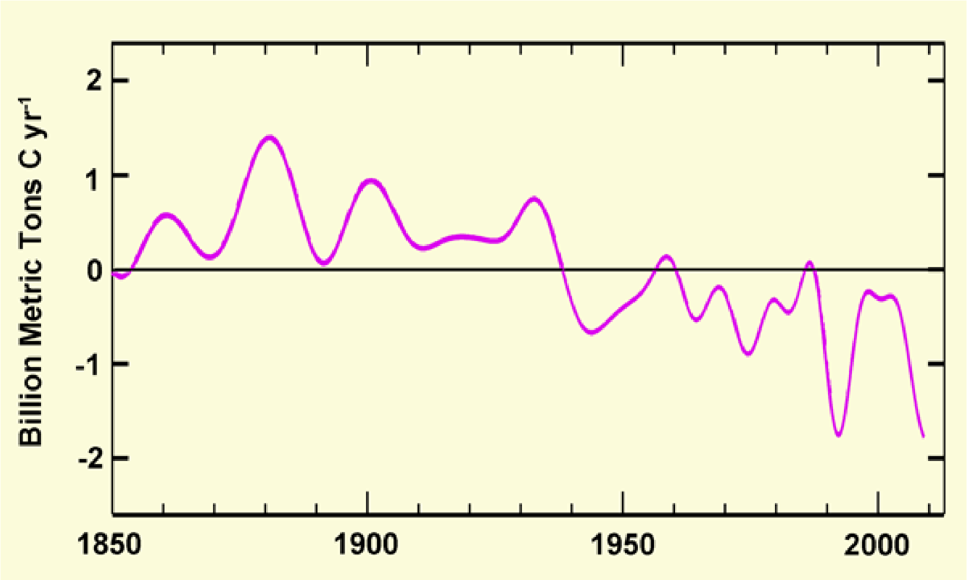
But there is also evidence nature's carbon cycle can impact atmospheric CO_2 at the shorter time periods that matter to IAMs. Joos and Bruno (1998) used ice core data and direct observations of atmospheric CO_2 and ^{13}C to reconstruct the histories of terrestrial and oceanic uptake of anthropogenic carbon over the past two centuries. They discovered that, whereas the land and ocean biosphere typically acted as a source of CO_2 to the atmosphere during the nineteenth century and the first decades of the twentieth century, it subsequently "turned into a sink." In another study, Tans (2009) employed measurements of atmospheric and oceanic carbon contents, along with reasonably constrained estimates of global anthropogenic CO_2 emissions, to calculate the residual fluxes of carbon (in the form of CO_2) from the terrestrial biosphere to the atmosphere (+) or from the atmosphere to the terrestrial biosphere (-), obtaining the results depicted in Figure 8.2.2.2.

As Figure 8.2.2.2 illustrates, Earth's land surfaces were a net *source* of CO_2-carbon to the atmosphere until about 1940, primarily because of the felling of forests and the plowing of grasslands to make way for expanded agricultural activities. From 1940 onward, however, the terrestrial biosphere has become, in the mean, an increasingly greater *sink* for CO_2-carbon, and it has done so despite all the many real and imagined assaults on Earth's vegetation that have occurred over the past several decades, including wildfires, disease, pest outbreaks, deforestation, and climatic changes in temperature and precipitation, more than compensating for any of the negative effects these phenomena may have had on the global biosphere.

Such findings, which do "not depend on models" but "only on the observed atmospheric increase and estimates of fossil fuel emissions," led Tans (2009) to conclude, "suggestions that the carbon cycle is becoming less effective in removing CO_2 from the atmosphere (*e.g.*, LeQuere *et al*., 2007; Canadell *et al*., 2007) can perhaps be true locally, but they do not apply globally, not over the 50-year atmospheric record, and not in recent years." Tans continues, "to the contrary," and "despite global fossil fuel emissions increasing from 6.57 GtC in 1999 to 8.23 in 2006, the five-year smoothed global atmospheric growth rate has not increased during that time, which requires more effective uptake [of CO_2] either by the ocean or by the terrestrial biosphere, or both, to satisfy atmospheric observations."

Confirming evidence has come from Ballantyne *et al*. (2012), who used "global-scale atmospheric CO_2 measurements, CO_2 emission inventories and their full range of uncertainties to calculate changes in global CO_2 sources and sinks during the past fifty years." The five U.S. scientists say their mass balance

Figure 8.2.2.2
Five-year smoothed rates of carbon transfer from land to air (+) or from air to land (-) vs. time



Source: Adapted from Tans (2009).

analysis shows "net global carbon uptake has increased significantly by about 0.05 billion tonnes of carbon per year and that global carbon uptake doubled, from 2.4 ± 0.8 to 5.0 ± 0.9 billion tonnes per year, between 1960 and 2010." See Figure 8.2.2.3 for the authors' plot of their findings.

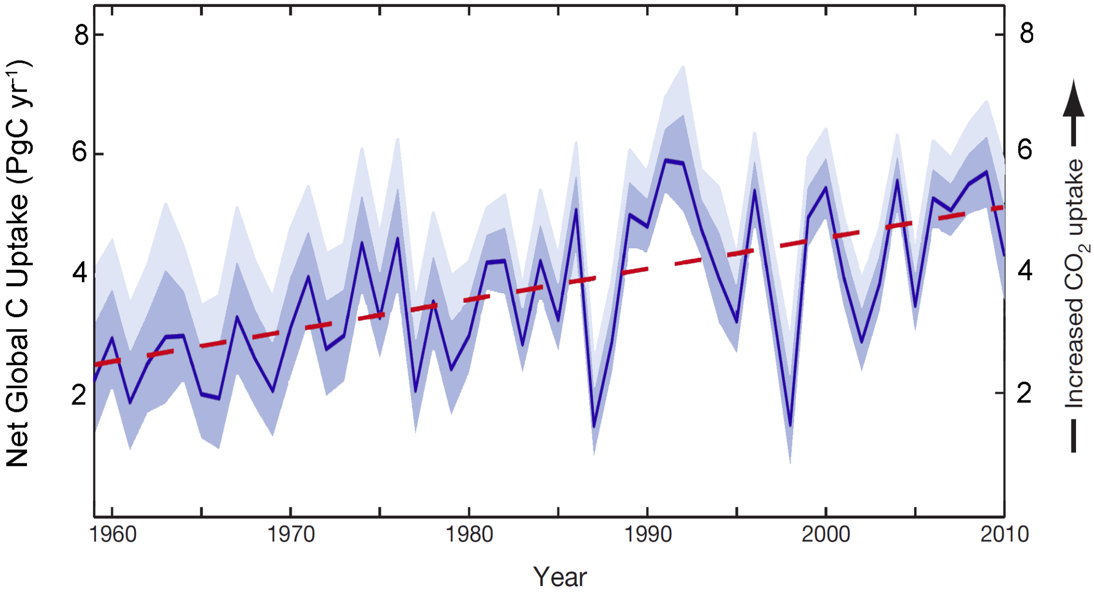
Commenting on the significance of their findings, Ballantyne *et al*. (2012) wrote in the concluding paragraph of their *Nature* article, "although present predictions indicate diminished C uptake by the land and oceans in the coming century, with potentially serious consequences for the global climate, as of 2010 there is no empirical evidence that C uptake has started to diminish on the global scale." In fact, as their results clearly indicate, just the *opposite* appears to be the case, with global carbon uptake actually doubling over the past half-century. When estimating future concentrations of atmospheric CO_2, IAMs must reconcile model projections of diminished future C uptake by the land and oceans with past observations that indicate land and ocean uptake is being enhanced.

As for the *cause* of this increased removal of CO_2 from the atmosphere, it is primarily the product of Earth's rising atmospheric CO_2 content itself. Thousands of studies demonstrate the photosynthetic response of terrestrial and aquatic plants is enhanced at higher CO_2 concentrations via a phenomenon known as the *aerial fertilization effect* of CO_2 (Idso *et al*., 2014; Idso, 2018). As Earth's atmospheric CO_2 content has risen since the beginning of the Industrial Revolution, so too has the magnitude of its aerial fertilization effect. This enhancement of terrestrial and oceanic productivity, in turn, has led to an increase in the average amount of CO_2 annually being sequestered from the atmosphere into the land and ocean biosphere, as illustrated in Figures 8.2.2.2 and 8.2.2.3. And that upsurge in sequestration impacts the atmosphere's CO_2 concentration, reducing it from what it would have been without the fertilization effect.

The carbon cycle modules utilized within IAMs must correctly capture all the detailed workings of the global carbon cycle – and how those workings are influenced by both natural and anthropogenic factors – or their estimates of future atmospheric CO_2 concentrations will be wrong. And if those estimates

Figure 8.2.2.3

Annual global net carbon (C) uptake by Earth's lands and oceans (solid blue line) for 1959–2010



The linear trend (dashed red line) and 1σ (dark shaded bands) and 2σ (light shaded bands) uncertainties are also shown. *Source:* Adapted from Ballantyne *et al*. (2012).

are inaccurate, so will be the projected impacts of future climate that depend on them. No current IAM incorporates this moderating influence of the aerial fertilization effect on future CO_2 concentrations.

In conclusion, IAMs falsely assume the carbon cycle is sufficiently understood and measured with sufficient accuracy as to make possible precise predictions of future levels of CO_2 in the atmosphere.

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8.2.3 Climate Sensitivity

> *Many IAMs rely on estimates of climate sensitivity – the amount of warming likely to occur from a doubling of the concentration of atmospheric carbon dioxide – that are too high, resulting in inflated estimates of future temperature change.*

As illustrated in Figure 8.1.2.1.1, the third step in an IAM is to project future changes in global surface temperatures and weather for a given atmospheric CO_2 concentration. Changes in carbon concentrations are used as inputs into a *Climate Projections and Impacts* block, sometimes called a *Climate Dynamics* module, which attempts to predict changes in global average surface temperature.

Equilibrium climate sensitivity (ECS) was discussed in some detail in Chapter 2. It is broadly defined as the equilibrium global mean surface temperature change following a doubling of atmospheric CO_2 concentration. In its Fifth Assessment Report (AR5), the IPCC decided on "a range of 2°C to 4.5°C, with the CMIP5 model mean at 3.2°C" (IPCC, 2013, p. 83). Having estimated the increase in atmospheric CO_2 concentrations caused by emissions in its four Representative Concentration Pathways (RCP), the IPCC used its climate sensitivity estimate to calculate recent past and future radiative forcing, and then the resulting changes to average global surface temperatures, for each RCP. Figure 8.2.3.1 shows the IPCC's estimates for 1950 to 2100. Figure 8.2.3.2 shows the IPCC's RCP estimates for 1765 to 2500. (That is not a typo: The IPCC believes it can hindcast to before the American Revolutionary War and forecast the impact of human greenhouse gas emissions 600 years in the future.)

The IPCC predicts the increase in global average surface temperature by the end of the twenty-first century, relative to the average from year 1850 to 1900, due to human greenhouse gas emissions is "*likely* to exceed 1.5°C for RCP4.5, RCP6.0, and RCP8.5 (*high confidence*). Warming is likely to exceed 2°C for RCP6.0 and RCP8.5 (*high confidence*), more likely than not to exceed 2°C for RCP4.5 (*high confidence*), but *unlikely* to exceed 2°C for RCP2.6 (*medium confidence*). Warming is *unlikely* to exceed 4°C for RCP2.6, RCP4.5, and RCP6.0 (*high confidence*) and is *about as likely as not* to exceed 4°C for RCP8.5 (*medium confidence*)" (IPCC, 2013, p. 20). The IPCC illustrates its forecast with the graph reprinted as Figure 8.2.3.3 below.

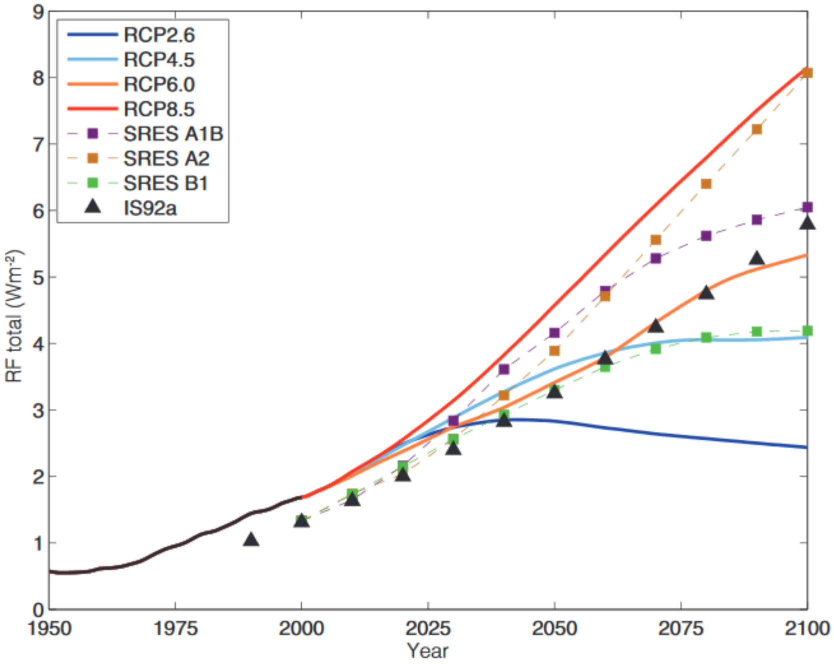
A better rendering of predicted future global average surface temperatures, in this case forecast by the DICE Model, one of the IAMs relied on by the IPCC, is shown in Figure 8.2.3.4.

How credible are these estimates of climate sensitivity and the temperature changes attributed to them? The Nongovernmental International Panel on Climate Change (NIPCC, 2013) says its best guess of ECS is 0.3°C to 1.1°C, about two-thirds lower than the IPCC's. Figure 2.1.4.1 in Chapter 2 presented a visual representation of estimates of climate sensitivity appearing in scientific research papers published between 2011 and 2016. According to Michaels (2017), the climate sensitivities reported in that figure average ~2.0°C (median) with a range of ~1.1°C (5^{th} percentile) and ~3.5°C (95th percentile). The median is high than NIPCC's 2013 estimate but still more than one-third lower than the estimate used by the IPCC.

Also reported in Chapter 2, Christy and McNider (2017), relying on the latest satellite temperature data, put the transient climate response (ΔT_{LT} at the time CO_2 doubles) at +1.10 ± 0.26 K, which they say "is about half of the average of the IPCC AR5 climate models of 2.31 ± 0.20 K. Assuming that the net remaining unknown internal and external natural forcing over this period is near zero, the mismatch since 1979 between observations and CMIP-5 model values suggests that excessive sensitivity to enhanced radiative forcing in the models can be appreciable."

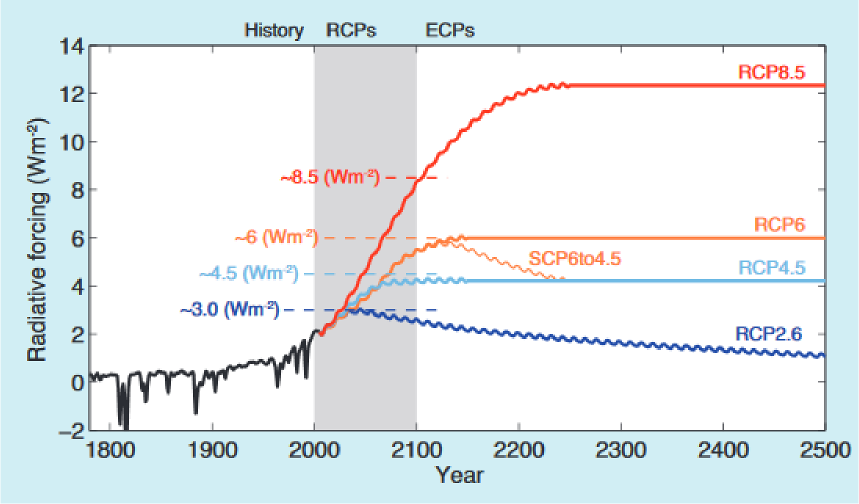
The fact that the climate models relied on by the IPCC tend to "run hot" is demonstrated in Figure 8.2.3.5, showing the results of 108 climate model runs during the 20-year and 30-year periods ending in 2014 (Michaels and Knappenberger, 2014). The blue bars show the number of runs that predicted a specific maximum trend in °C/decade, while the red and yellow lines point to the actual observed trend during those periods. Remarkably, every model predicted maximum temperature increases higher than the observed 20-year trend and nearly all of them ran "hotter" than the observed 30-year trend. All of these models were specifically tuned to reproduce the twentieth century air temperature trend, an exercise at which they clearly failed.

Figure 8.2.3.1
Historical and projected total anthropogenic radiative forcing (RF) (W/m^2) relative to preindustrial (around 1765) between 1950 and 2100



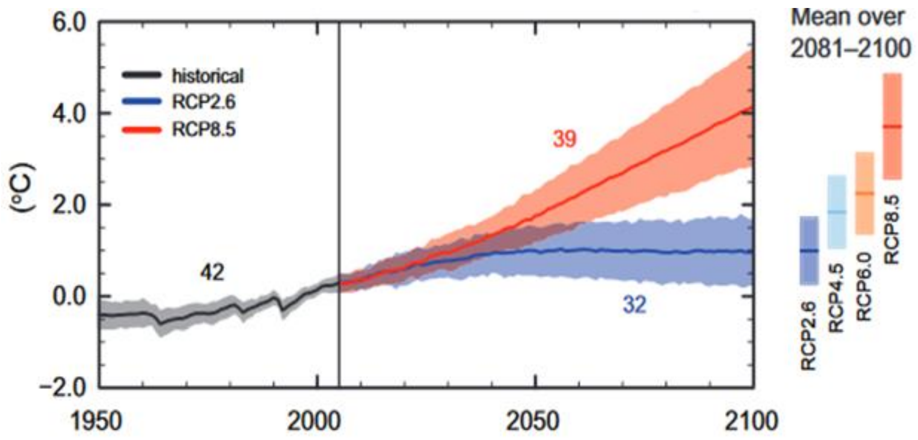
Source: IPCC, 2013, p. 146.

Figure 8.2.3.2
Estimated total radiative forcing (RF) (W/m^2) (anthropogenic plus natural) for four RCPs and extended concentration pathways (ECPs) from around 1765 to 2500



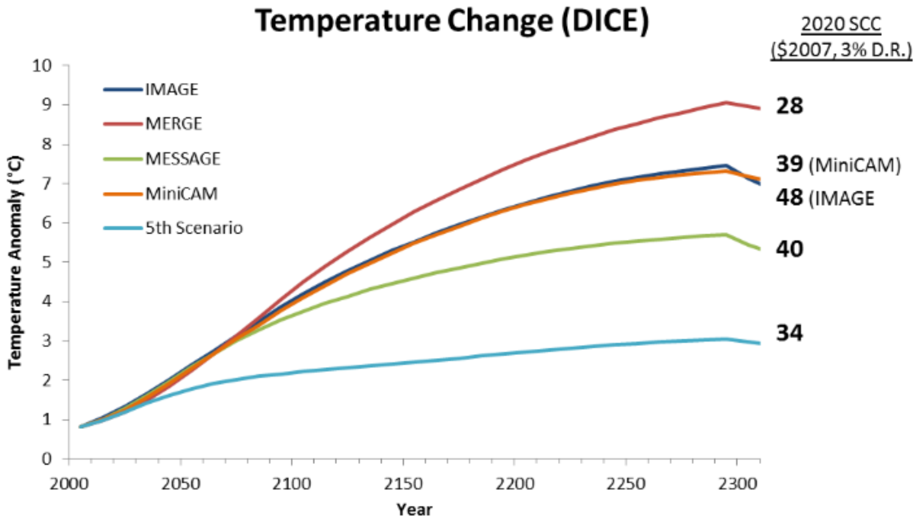
Source: IPCC, 2013, p. 147, citing Meinshausen *et al.*, 2011.

Figure 8.2.3.3
IPCC estimated historical and global average surface temperature changes for four RCPs, 1950–2100



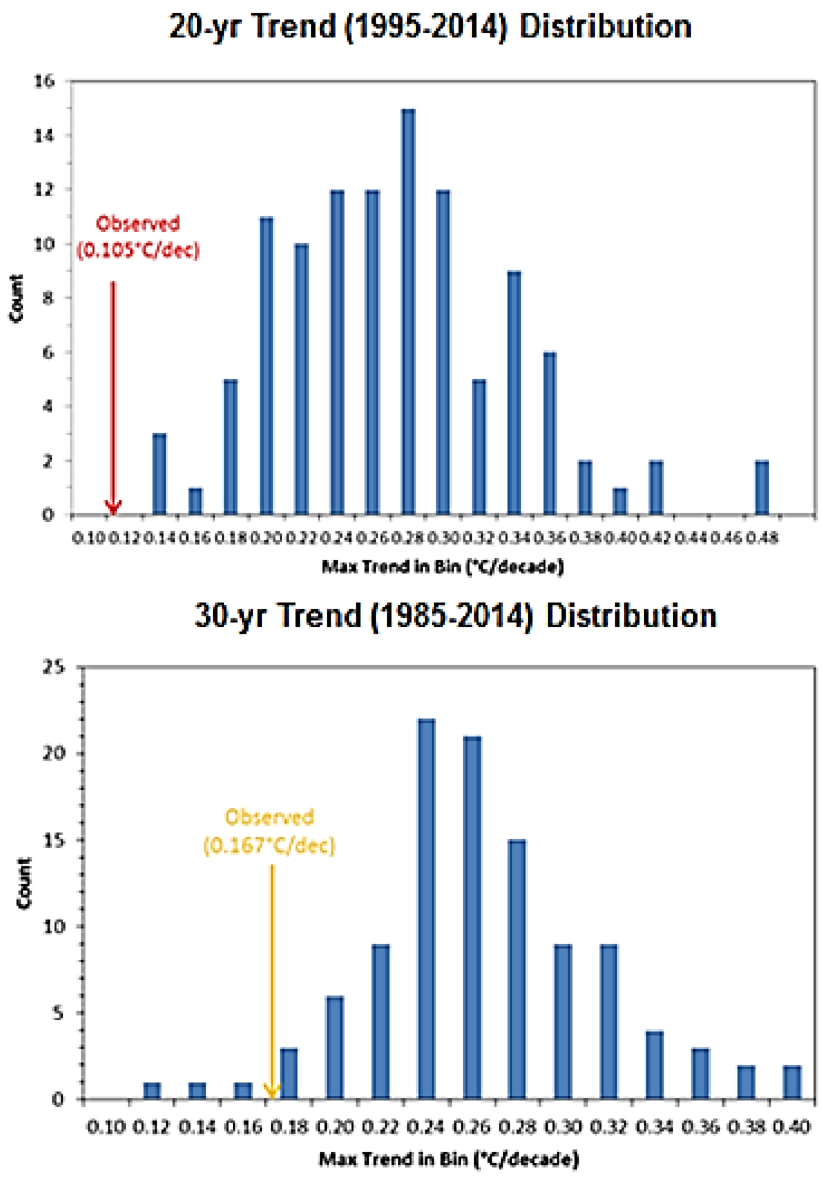
CMIP5 multi-model simulated time series from 1950 to 2100 for change in global annual mean surface temperature relative to 1986-2005. The mean and associated uncertainties for 2085-2100 are given for all RCP scenarios as colored vertical bars. *Source:* IPCC, 2013, p. 21.

Figure 8.2.3.4
Future temperature changes for the years 2000–2300, projected by the DICE model for each of the five emissions scenarios used by the 2013 IWG social cost of carbon estimate



Temperature changes are the arithmetic average of the 10,000 Monte Carlo runs from each scenario. The 2020 value of the SCC (in $2007) produced by the DICE model (assuming a 3% discount rate) is included in the upper right of the figure. DICE data provided by Kevin Dayaratna and David Kreutzer of The Heritage Foundation. *Source:* Michaels and Knappenberger, 2014, p. 4.

Figure 8.2.3.5
20- and 30-year trend distributions from 108 climate model runs versus observed change in temperature



Source: Michaels and Knappenberger, 2014

Critics of the models used by the IPCC have produced their own estimates (e.g., Spencer and Braswell, 2008; Lindzen and Choi, 2011; Monckton *et al.* 2015). Monkton *et al.* (2015) cited 27 peer-reviewed articles "that report climate sensitivity to be below [IPCC's] current central estimates." Their list of sources appears in Chapter 2 of the present volume as Figure 2.5.3.1.

No one actually knows what the "true" climate sensitivity value is because it is, like so many numbers in the climate change debate, a stylized fact: a single number chosen for the sake of convenience for those who make their living modeling climate change. The number is inherently uncertain for much the same reason it is impossible to know how much CO_2 is emitted into the air every year or how much of it stays there, which is the enormous size of natural processes relative to the "human signal" caused by our CO_2 emissions (Frank, 2015). See Chapter 2, Section 2.2.3 for a discussion of climate sensitivity, and more generally NIPCC (2013) for hundreds of source citations on this complex matter.

The IPCC's estimate of climate sensitivity is very likely to be too high, which invalidates its temperature forecasts and consequently any IAMs that rely on its forecasts. But the IPCC is not the only participant in the climate debate that is wrong. Deep uncertainty about the dynamics of climate means it is probably impossible to reliably estimate climate sensitivity.

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8.2.4 Climate Impacts

> *Many IAMs ignore the extensive scholarly research showing climate change will not lead to more extreme weather, flooding, droughts, or heat waves.*

The *Climate Projections and Impacts* module of Integrated Assessment Models (IAMs) that contains the estimate of climate sensitivity also contains formulas linking changes in temperature to specific climate impacts such as extreme weather events and sea-level rise, violent conflict over water or other scarce resources, negative health effects caused by exposure to heat or diseases spread by mosquitoes, ticks, and other parasites, loss of livelihoods (economic displacement), and more.

Efforts to link global warming to these alleged harms are crippled by cascading uncertainty, described in Section 8.1.2.2, whereby the errors or uncertainty in one variable are compounded (propagated) when that variable becomes part of a function involving other variables that are similarly uncertain, as well as cascading bias, explained in Chapter 6, Section 6.3.1, whereby upper-limit risk estimates are multiplied by each other resulting in estimates orders of magnitude greater than what empirical data suggest. Coming late in the sequence of calculations in an IAM, the *Climate Projections and Impacts* module already has to manage the uncertainties infecting earlier modules, so modelers cannot say with confidence that one additional metric ton of CO_2 released into the air will result in any warming at all. When they try to document an association, they add even more links and more uncertainties to a logical chain that already defies reason.

Since all the climate impacts alleged by the IPCC were addressed in previous chapters, we avoid repetition by only briefly discussing them here. Monetizing the impacts of climate change, the last nodule of an IAM, is addressed in Section 8.2.5.

Extreme Weather

According to the IPCC, "sea level rise and increased frequency of extreme events increases the risk of loss of lives, homes, and properties, and damages infrastructure and transport systems" (IPCC, 2014, Table 12-1, p. 761). But as reported in Chapter 2, Section 2.3.1, researchers have failed to find a convincing relationship between higher surface temperatures over the past 100 years and increases in the frequency or severity of extreme weather events (Maue, 2011; Alexander *et al.*, 2006; Khandekar, 2013; Pielke Jr., 2013, 2014). Instead, the number and intensity of extreme events wax and wane often in parallel with natural decadal or multidecadal climate oscillations.

Legates (2014) writes, "Current state-of-the-art General Circulation Models (GCMs) do not simulate precipitation well because they do not include the full range of precipitation-forming mechanisms that occur in the real world. It is demonstrated here that the impact of these errors are not trivial – an error of only 1 mm in simulating liquid rainfall is equivalent to the energy required to heat the entire troposphere by 0.3°C. Given that models exhibit differences between the observed and modeled precipitation that often exceed 1 mm day, this lost energy is not trivial. Thus, models and their prognostications are largely unreliable" (abstract).

Basic meteorological science suggests a warmer world would experience fewer storms and weather extremes, as indeed has been the case in recent years. Khandekar and Idso concluded, "It is clear in almost every instance of each extreme weather event examined, there is little support for predictions that CO_2-induced global warming will increase either the frequency or intensity of those events. The real-world data overwhelmingly support an opposite conclusion: Weather will more likely be less extreme in a warmer world (Khandekar and Idso, p. 810).

Sea-level Rise

The IPCC says "for countries made up entirely of low-lying atolls, sea level rise, ocean acidification, and increase in episodes of extreme sea surface temperatures compromise human security for present or future higher populations. With projected high levels of sea level rise beyond the end of this century, the physical integrity of low-lying islands is under threat" (IPCC, 2014, p. 775). But as was documented in Chapter 2, Section 2.3.3, sea level rise for the past thousand years it is generally believed to have averaged less than seven inches per century, a rate that is functionally negligible because it is frequently exceeded by coastal processes like erosion and sedimentation (Parker and Ollier, 2017; Burton, 2012). Local sea-level trends vary considerably because they depend on tectonic movements of adjacent land and other local factors. In many places vertical land motion, either up or down, exceeds the very slow global sea-level trend. Consequently, at some locations sea level is rising much faster than the global rate, and at other locations sea level is falling.

Curry (2018) writes, "Tide gauges show that sea levels began to rise during the 19th century, after several centuries associated with cooling and sea level decline. Tide gauges also show that rates of global mean sea level rise between 1920 and 1950 were comparable to recent rates." Her review of recent research found "there is no consistent or compelling evidence that recent rates of sea level rise are abnormal in the context of the historical records back to the 19th century that are available across Europe" and "There is not yet convincing evidence of a fingerprint on sea level rise associated with human-caused global warming."

Agriculture

In its *Summary for Policymakers* for the Working Group II contribution to AR5, the IPCC says "For the major crops (wheat, rice, and maize) in tropical and temperate regions, climate change without adaptation is projected to negatively impact production for local temperature increases of 2°C or more above late-20th-century levels, although individual locations may benefit (*medium confidence*) (IPCC, 2014b, pp. 17–18). But as explained in Chapter 2, Section 2.3.5 as well as in great depth in Chapter 5, this forecast is at odds with the fact that CO_2 is plant food and most plants benefit from warmer surface temperatures. Food production has been growing faster than population growth thanks to the technologies of the Green

Revolution and the Gene Revolution and the aerial fertilization effect caused by the combustion of fossil fuels (FAO, 2015; Idso, 2013).

The IPCC acknowledges that "food security is determined by a range of interacting factors including poverty, water availability, food policy agreements and regulations, and the demand for productive land for alternative uses (Barrett, 2010, 2013)." Blurring the issue of causation by using one of the "expressions of uncertainty" identified in Section 7.2, the IPCC says "many of these factors are themselves *sensitive to* climate variability and climate change" (IPCC, 2014a, p. 763, italics added). The IPCC identifies incidents where "food price spikes have been associated with food riots," but then cites literature attributing those riots to other factors. It ends with a remarkable example of combining words that seem to convey certainty ("critical elements," "robust evidence," and "associated with") with an admission of complete uncertainty: "Food prices, food access, and food availability are critical elements of human security. There is robust evidence that food security affects basic-needs elements of human security and, in some circumstances, is associated with political stability and climate stresses. But there are complex pathways between climate, food production, and human security and hence this area requires further concentrated research as an area of concern" (IPCC, 2014a).

In other words, the relationship between climate and food supply and security is so nuanced there likely is no causal relationship between them. Why, then, does it appear in the IPCC's table purporting to show climate impacts on human security?

Public Health

The IPCC claims "Until mid-century, projected climate change will impact human health mainly by exacerbating health problems that already exist (*very high confidence*). Throughout the twenty-first century, climate change is expected to lead to increase in ill-health in many regions and especially in developing countries with low income, as compared to a baseline without climate change (*high confidence*)" (IPCC, 2014b, p. 19). Chapter 4 explains how medical science and empirical data both contradict that forecast. Warmer temperatures are associated with net health benefits, as is confirmed by empirical research in virtually all parts of the world, even those with tropical climates (Gasparrini *et al.,* 2015; Seltenrich (2015).

An extensive medical literature contradicts the claim that malaria will expand across the globe or intensify in some regions as a result of rising global surface temperatures (Reiter, 2008; Zhao *et al.,* 2016). Concerns over large increases in mosquito-transmitted and tick-borne diseases such as yellow fever, malaria, viral encephalitis, and dengue fever as a result of rising temperatures are similarly unfounded. While climatic factors do influence the geographical distribution of ticks, temperature and climate change are not among the significant factors determining the incidence of tick-borne diseases (Gething, 2010).

Fossil fuels have been an essential part of the campaign to reduce diseases and extend human life since the start of the Industrial Revolution. While somehow avoiding or slowing rising global temperatures would almost assuredly not improve public health, it is certain that restricting access to fossil fuels would *harm* public health.

Violent Conflict

In the *Summary for Policymakers* for the Working Group II contribution AR5, the IPCC claims "Climate change indirectly increases risks from violent conflict in the form of civil war, inter-group violence, and violent protests by exacerbating well-established drivers of these conflicts such as poverty and economic shocks (*medium confidence*). Statistical studies show that climate variability is significantly related to these forms of conflict. … Climate change over the 21st century will lead to new challenges to states and will increasingly shape national security policies (*medium evidence, medium agreement*) (IPCC, 2014, p. 12).

This strong language, common in the IPCC's summaries for policymakers, is not repeated in Chapter 12 of the Working Group II contribution to AR5. There, one reads:

> [B]oth the detection of a climate change effect [on the incidence of violent conflicts] and an assessment of the importance of its role can be made only with *low confidence* owing to limitations on both historical understanding and data. Some studies have suggested that levels of warfare in Europe and Asia were relatively high during the Little Ice Age (Parker, 2008; Brook, 2010; Tol and Wagner, 2010; White, 2011; Zhang

> *et al*., 2011), but for the same reasons the detection of the effect of climate change and an assessment of its importance can be made only with *low confidence*. There is no evidence of a climate change effect on interstate conflict in the post-World War II period (IPCC, 2014, p. 1001).

The extensive literature review presented earlier in the current volume, in Chapter 7, Sections 7.3 and 7.4, demonstrates a consensus among historians that warmer temperatures in the past clearly *reduced* the incidence of violent conflict by resulting in more food production, food security, and faster income growth (increasing the opportunity cost of wars), and facilitating more trade. Gleditsch and Nordås (2014) write, "there is no consensus in the scholarly community about such dire projections of future climate wars; in fact most observers conclude that there is no robust and consistent evidence for an important relationship between climate change and conflict."

Conflicts over scarce resources most frequently arise when they are treated as common property without the sort of management described by Ostrom (1990, 2005, 2010) and her international network of researchers. The way to reduce such conflicts is not to try to control the weather, but to empower people with technologies and wealth so they can turn such "tragedies of the commons" into "opportunities of the commons" (Boettke, 2009).

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8.2.5 Economic Impacts

> *The "social cost of carbon" (SCC) derived from IAMs is an accounting fiction created to justify regulation of fossil fuels. It should not be used in serious conversations about how to address the possible threat of man-made climate change.*

As illustrated in Figure 8.1.2.1.1, the final step in an integrated assessment model (IAM) is to project the economic impacts of climate change due to anthropogenic greenhouse gas emissions. The *Economic Impacts* block, also called the *Damage Function* module, monetizes the damages fed to it by the *Climate Projections and Impacts* block or module. The effects, usually expressed as a change in per-capita income, gross national product (GNP), or economic growth rates, are discounted to account for the length of time that passes before the effects are experienced. Formulas aggregate, weigh, and calculate the total (global) net social cost (or benefit), divide it by the number of tons of carbon dioxide emitted according to the *Emission Scenarios* block, and produce a "social cost of carbon" (SCC) typically expressed in USD per metric ton of CO_2-equivalent greenhouse gas.

Coming at the very end of the sequence of calculations in an IAM, the *Economic Impacts* module is most affected by uncertainties infecting earlier modules. By now, the propagation of error first described in Section 8.1.2.2 is so great that modelers cannot say with confidence whether supposed impacts having to do with weather, sea-level rise, agriculture, and human security will be positive, negative, or nonexistent. Nevertheless, dollar figures are assigned and the models are run in classic GIGO ("garbage in, garbage out") style.

Whereas *climate* impacts have been addressed in great depth in previous chapters of this volume and in previous volumes in the *Climate Change Reconsidered* series, *economic* impacts have not. Therefore, there are fewer references in this section to previous chapters or books. Section 8.2.5.1 addresses the IPCC's findings concerning economic impacts, and Section 8.2.5.2 addresses the issue of choosing a discount rate.

8.2.5.1 The IPCC's Findings

The IPCC's effort to monetize the impacts of climate change appears mainly in Chapter 10 of Working Group II's contribution to AR5 titled "Key Economic Sectors and Services." That chapter, as Gleditsch and Nordås note, "is quite modest when it comes to the global economic effects expected to result from global warming" (Gleditsch and Nordås, 2014, p. 85). From the chapter's executive summary (with two paragraph breaks added to facilitate reading):

> Global economic impacts from climate change are difficult to estimate. Economic impact estimates completed over the past 20 years vary in their coverage of subsets of economic sectors and depend on a large number of assumptions, many of which are disputable, and many estimates do not account for catastrophic changes, tipping points, and many other factors.
>
> With these recognized limitations, the incomplete estimates of global annual economic losses for additional temperature increases of ~2°C are between 0.2 and 2.0% of income (±1 standard deviation around the mean) (*medium evidence, medium agreement*). Losses are more likely than not to be greater, rather than smaller, than this range (*limited evidence, high agreement*). Additionally, there are large differences between and within countries.
>
> Losses accelerate with greater warming (*limited evidence, high agreement*), but few quantitative estimates have been completed for additional warming around 3°C or above. Estimates of the incremental economic impact of emitting carbon dioxide lie between a few dollars and several hundreds of dollars per tonne of carbon (*robust evidence, medium agreement*). Estimates vary strongly with the assumed damage function and discount rate (IPCC, 2014, p. 663).

The IPCC adds "for most economic sectors, the impact of climate change will be small relative to the impacts of other drivers (*medium evidence, high agreement*). Changes in population, age, income, technology, relative prices, lifestyle, regulation, governance, and many other aspects of socioeconomic development will have an impact on the supply and demand of economic goods and services that is large relative to the impact of climate change" (IPCC, 2014, p. 662).

Saying "the impact of climate change will be small relative to the impacts of other drivers," even "changes in … relative prices, lifestyle," is a major concession to what real data show. It is at odds with the tone and narrative of every IPCC *Summary for Policymakers* since publication of the first IPCC assessment report in 1990. It is certainly at odds with the spin put on the release of AR5 by the IPCC and the breathless headlines it generated (e.g., "UN Panel Issues Its Starkest Warning Yet on Global Warming" (Gillis, 2014), "Threat from Global Warming Heightened in Latest U.N. Report" (Reuters, 2014), and "Fossil Fuels Should be 'Phased Out by 2100' says IPCC" (BBC, 2014).

There is another, even bigger, admission in AR5 that undermines its narrative of an impending climate crisis. The authors of the Working Group II contribution admit climate change "may be due to natural internal processes or external forcings such as modulations of the solar cycles, volcanic eruptions, and persistent anthropogenic changes in the composition of the atmosphere or in land use" (IPCC, 2014, Background Box SPM.2). While this may be obvious to all climate scientists, the IPCC Working Group I has *defined* "climate change" as referring only to changes attributable to human activities, either the release of greenhouse gas emissions (primarily by the use of fossil fuels) or by changes in land use (primarily agriculture and forestry). But Working Group II says "attribution of observed impacts in the WGII AR5 generally links responses of natural and human systems to observed climate change, *regardless of its cause*" (IPCC, 2014, p. 4, italics added). In a footnote, they add, "the term attribution is used differently in WGI and WGII. Attribution in WGII considers the links between impacts on natural and human systems and observed climate change, regardless of its cause. By comparison, attribution in WGI quantifies the links between observed climate change and human activity, as well as other external climate drivers" (*Ibid.*).

This is an important clarification with considerable consequences for IAM modelers. It means the "climate impacts" IPCC describes, often at great length and most likely to be reported by media outlets and featured by environmental advocacy groups in their fundraising appeals, may be due to natural causes ("solar cycles, volcanic eruptions") and not be attributable to human activities. Why, then, would IAM modelers incorporate any of them in models intended to forecast "the social cost" of human carbon emissions? Nearly all IAMs make a major error by relying on IPCC data for their inputs.

Rather than produce its own IAM to estimate economic impacts, the IPCC surveyed the IAM literature and, in a fashion similar to what the Interagency Working Group did in the United States, reported an average of the findings. Its estimates of the social cost of carbon (SCC), reported in Table 10-9 of the Working Group II contribution to AR5, are reproduced as Figure 8.2.5.1.1 below. Note that *all these IAMs use IPCC anecdotes and scenarios as inputs into their damage function modules*, so these IAMs are not independent research or confirmation of IPCC's findings.

The IPCC chose to report a range of discount rates, from 0% to 3%, starting lower than and not extending as high as what was used by the IWG (2.5% to 5%) and lower than many experts in the field recommend. (This is the topic of Section 8.2.5.2 below.) Its estimate of the SCC at the 3% discount rate is $40 per metric ton for all studies and $33 for studies published since the Fourth Assessment Report (AR4) published in 2007, figures within IWG's range of $11 to $52 reported in 2013, and the second figure is even a perfect match with IWG's estimate assuming a 3% discount rate. The proximity is neither coincidence nor evidence of accuracy, however, given the herding tendency of model builders and their shared assumptions (Park *et al.*, 2014).

The economic impact of global warming also can be expressed as a measure of lost income or consumption over time, typically expressed as per-capita gross domestic product (GDP). The IPCC says "the incomplete estimates of global annual economic losses for additional temperature increases of ~2°C are between 0.2 and 2.0% of income," with only "*medium evidence, medium agreement*" (IPCC, 2014, p. 663). Oddly, this estimate appears in the executive summary of the chapter but nowhere in the body of the chapter. Presumably this is the lost income growth over a 50-year period (the time required for temperatures to increase ~2°C). (This interpretation of the IPCC's very terse statement of its finding is from Gleditsch and Nordås (2014, p. 85), who cite Tol (2014a) for support.)

The order of magnitude separating the IPCC's low and high estimates is proof that this is little more than a guess. The IPCC admits this, saying "The literature on the impact of climate and climate change on economic growth and development has yet to reach firm conclusions. There is agreement that climate change would slow economic growth, by a little according to some studies and by a lot according to other studies. Different economies will be affected differently" (IPCC, 2014, p. 693).

The economic impacts forecast by the three main IAMs the IPCC uses were plotted by the Interagency Working Group in 2010 in a figure that is reproduced below as Figure 8.2.5.1.2. For a 4°C increase in temperatures by the end of the century – a midpoint in the IPCC's range "from 3.7°C to 4.8°C compared to pre-industrial levels" (IPCC, 2014b., p. 8) – the three IAMs find an annual consumption loss of about 1%, 3%, and 4.5%. For a 2°C warming – IPCC's estimate for the year 2050 – the PAGE and DICE models forecast consumption losses of about 0.5% and 1% while the FUND model forecasts a consumption *benefit* of about 1% of GDP. See Figure 8.2.5.1.2. The models average about a 0.5% consumption loss, the number we can use for a cost-benefit ratio.

The IPCC's attempt to conduct a cost-benefit analysis of global warming illustrates the profound difficulty confronting such endeavors. The IPCC's admissions of uncertainty are explicit and could hardly be more emphatic; from the executive summary previously cited, "Global economic impacts from climate change are difficult to estimate. … [They] depend on a large number of assumptions, many of which are disputable, and many estimates do not account for catastrophic changes, tipping points, and many other factors" (IPCC, 2014). The IPCC's decision not to build its own IAM speaks volumes as well. The IPCC reports many efforts to monetize the impact of climate change on specific sectors of the economies of many nations, including energy (supply, demand, transport and transmission, and macroeconomic impacts), water services, transportation, recreation and tourism, insurance and financial services, and "other primary and secondary economic activities" including agriculture, forestry, fisheries, and mining. The estimates come from hundreds of sources, many of them "gray literature" meaning they were not peer reviewed. Most estimates are country-specific and would need to be extrapolated to produce global estimates, an exercise fraught with uncertainties. All estimates cover different time periods (long, short, decades ago, or more recent) and use different methodologies (often formulas applied to limited sets of observational data). Most have not been replicated.

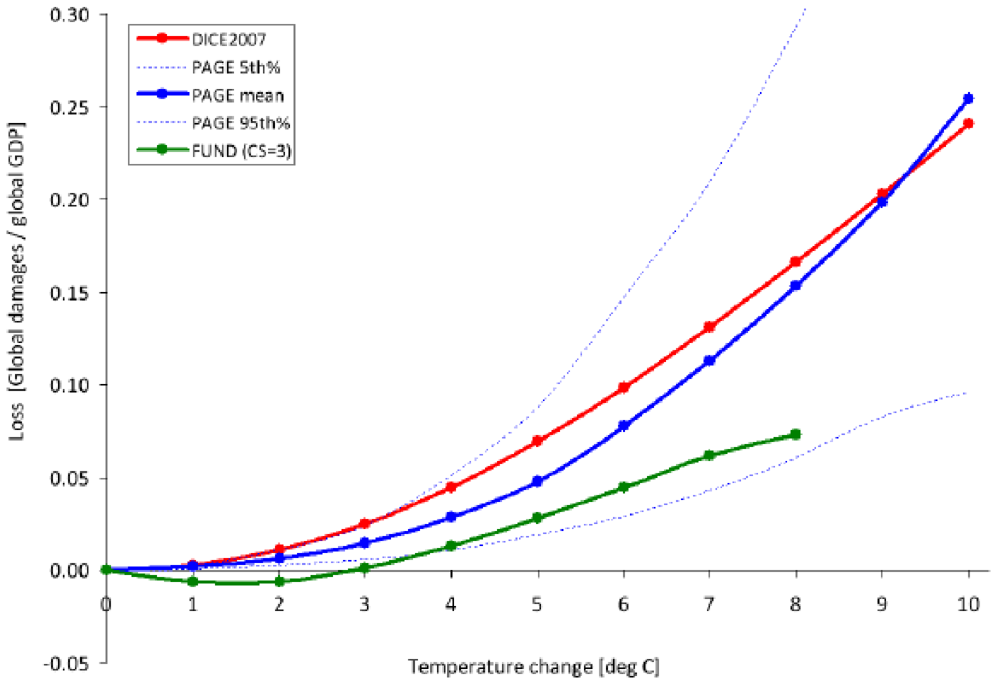
To perform a cost-benefit analysis, the IPCC would need to aggregate these extensive but disparate and often unreliable data on these individual economic sectors, an impossible task. The

Figure 8.2.5.1.1
Social cost of carbon estimates reported in AR5

PRTP	Post-AR4			Pre-AR4			All studies		
	Avg	SD	*N*	Avg	SD	*N*	Avg	SD	*N*
0%	270	233	97	745	774	89	585	655	142
1%	181	260	88	231	300	49	209	284	137
3%	33	29	35	45	39	42	40	36	186
All	241	233	462 (35)	565	822	323 (49)	428	665	785 (84)

"PRTP" is pure rate of time preference (discount rate). Columns titled "N" report the number of findings using each of three discount rates (0%, 1%, and 3%). The number of studies surveyed before and after publication of AR4 and the total number of unique studies is reported in parenthesis at the bottom of the "N" columns. "Avg" is the average social cost of carbon in dollars per metric ton of carbon dioxide equivalent greenhouse gas emissions as reported by the studies, "SD" is standard deviation (a measure of variability around the mean). *Source:* IPCC, 2014, Table 10-9, p. 691, citing Section SM10.2 of the on-line supplementary material.

Figure 8.2.5.1.2
Annual consumption loss as a fraction of global GDP in 2100 due to an increase in annual global temperature in the DICE, FUND, and PAGE models



Source: IWG, 2010, Figure 1A, p. 9.

insurmountable problems it would have faced did not disappear when it decided to rely on IAMs created by others. *The DICE, PAGE, and FUND modelers faced the same challenges* but went ahead and produced unreliable estimates anyway.

Averaging the results of multiple IAMs does not raise the probability of finding an SCC estimate or impact on economic growth that is accurate. As Frank observed, "systematic error does not average away with repeated measurements. Repetition can even increase error. When systematic error cannot be eliminated and is known to be present, uncertainty statements must be reported along with the data" (Frank, 2016, p. 338).

In a review of IAMs, Warren *et al*. (2006) concluded, "The assumption of a quadratic dependence of damage on temperature rise is even less grounded in any empirical evidence. Our review of the literature uncovered no rationale, whether empirical or theoretical, for adopting a quadratic form for the damage function – although the practice is endemic in IAMs." Similarly, Pindyck has lamented,

> IAM damage functions are completely made up, with no theoretical or empirical foundation. They simply reflect common beliefs (which might be wrong) regarding the impact of 2°C or 3°C of warming, and can tell us nothing about what might happen if the temperature increases by 5°C or more. And yet those damage functions are taken seriously when IAMs are used to analyze climate policy (Pindyck, 2013a, p. 16).

Also troubling is that these functions are usually based on only one country or region because the literature on the topic of environmentally induced costs is very limited, except in agriculture. For example, as described by Mastrandrea (2009):

> Market and non-market damages in DICE are based on studies of impacts on the United States that are then scaled up or down for application to other regions. Many of the estimates to which market damages in PAGE are calibrated are also based on an extrapolation of studies of the United States. Only FUND uses regional and sector-specific estimates. However, in some sectors these estimates also originate in one country, or may be dominated by estimates from one region. For example, in the energy sector, the sector which accounts for most of the economic damages in FUND, estimates for the UK are scaled across the world.

Summing up the cumulative effects of the many shortcomings that prevent IAMs from being able to accurately determine the economic impacts of climate change, Pindyck writes:

> … the greatest area of uncertainty concerns the economic impact (including health and social impacts) of climate change. The economic loss functions that are part of most IAMs are essentially ad hoc. This is not surprising given how little we know – in terms of both theory and data – about the ways and extent to which changes in temperature and other climate variables are likely to affect the economy. In fact, the economic impact of climate change may well be in the realm of the "unknowable." This in turn means that IAM-based analyses of climate change may not take us very far, and the models may be of very limited use as a policy tool (Pindyck, 2013b, p. 17).

Assuming *arguendo* that the IPCC's estimate of the economic impacts of global warming in 50 or 100 years is accurate, how should it be interpreted? The IPCC's estimate of the impact of a surface temperature increase of ~2°C (from pre-industrial levels), a loss of 1% of GDP around the year 2050, is *less than the expected global economic growth rate in about four months.* A single recession, even a very short and mild recession, would have a larger impact, and several are likely to occur before 2050.

Other than their choice of a low discount rate, the authors of Chapter 10 of Working Group II's contribution to AR5 may be out-of-step with the rhetoric and tone of other chapters of the WGII contribution to AR5, *but that is a good thing.* While the authors of other chapters seemed to think it their duty to compile anecdotes of human suffering due to extreme weather and natural disasters and to speculate that such events will become more frequent in the future due to human interference in the climate, the authors of Chapter 10 took more seriously their duty to prove the links in the logical chain behind such claims (even while accepting the IPCC's distorted views in the emission scenarios and carbon cycle modules), and then to monetize the harms.

One of the two lead authors of Chapter 10, Richard S.J. Tol, is the creator of the FUND model, one of the three IAMs most prominent in the climate change literature. Significantly, Tol resigned from the IPCC shortly before AR5 was released. He explained why in a blogpost on April 25, 2014:

> In the earlier drafts of the SPM, there was a key message that was new, snappy and relevant: **Many of the more worrying impacts of climate change really are symptoms of mismanagement and under-development.** This message does not support the political agenda for greenhouse gas emission reduction. Later drafts put more and more emphasis on the reasons for concern about climate change, a concept I had helped to develop for AR3. Raising the alarm about climate change has been tried before, many times in fact, but it has not had an appreciable effect on greenhouse gas emissions. I reckoned that putting my name on such a document would not be credible – my opinions are well-known – and I withdrew (Tol, 2014b, boldface in original).

Economics, as explained in Chapter 1, uses data about prices and investment returns to make objective what are otherwise only subjective impressions, preferences, and anecdotes. When applied to the impacts of climate change, economics can reveal the true net costs of climate change, should it occur and provided the data that enter earlier modules in the IAMs are accurate. Even with the IPCC's thumb on the scale in this respect, it is remarkable to see how small the economic consequences of climate change would be.

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8.2.5.2 Discount Rates

As discussed in Chapter 1, Section 1.2.8, the selection of a discount rate (referred to in the U.K. as the "social time preference rate" or STPR) is one of the most controversial issues in the climate change debate (Heal and Millner, 2014; Weitzman, 2015).

According to the U.K. Treasury's *Green Book*, a STPR has two components:

- "time preference" – the rate at which consumption and public spending are discounted over time, assuming no change in per capita consumption. This captures the preference for value now rather than later.

- "wealth effect" – this reflects expected growth in per capita consumption over time, where future consumption will be higher relative to current consumption and is expected to have a lower utility (H.M. Treasury, 2018, p. 101).

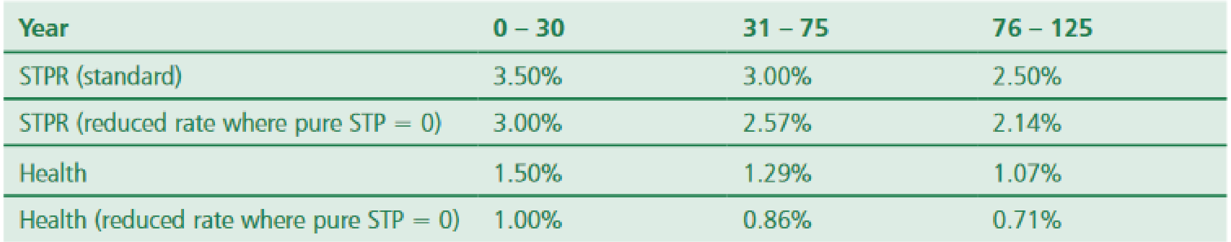
The STPR is expressed as an equation, $r = \rho + \mu g$, where r is the STPR, ρ (rho) is time preference comprising pure time preference (δ, delta) and catastrophic risk (L), and μg is the wealth effect, derived as the marginal utility of consumption (μ, mu), multiplied by expected growth rate of future real per capita consumption g. In 2018, the *Green Book* put the three variables at $\rho = 1.5\%$; $\mu = 1.0$; and $g = 2\%$, so $0.015 + 1 \times 0.02 = 3.5\%$. However, the *Green Book* recommends a lower rate of 1.5% for "risk to health and life values" because "the 'wealth effect', or real per capita consumption growth element of the discount rate, is excluded." The STPR also should "decline over the long term," says the *Green Book*, "due to uncertainty about future values of its components." The result is a range of STPRs which it summarizes in the table reproduced as Figure 8.2.5.2.1 below.

Many IAMs and reports in the "gray literature" use rates similar to the *Green Book's* long-term health rates – 0.71% to 1.07% – which are much lower than those used in any other area of public policy. While different rates are appropriate for different kinds of analysis, it seems the practice of using extremely low rates (and even zero) was adopted early on in the climate change debate to draw attention to what was thought to be an under-appreciated long-term problem. Over time, much of the urgency about the issue has been removed as temperatures have risen less than expected and the predicted climate impacts have failed to materialize. The high cost of mitigation has become better understood, strengthening the case that investments in emissions mitigation should compete on equal footing with spending on other long-term public needs such as education, health care, and infrastructure.

The IPCC originally endorsed discount rates much higher than those recommended by the *Green Book*. The IPCC's Third Assessment Report (IPCC, 2001) said the following about discount rates:

> For climate change the assessment of mitigation programmes and the analysis of impacts caused by climate change need to be distinguished. The choice of discount rates applied in cost assessment should depend on whether the perspective taken is the social or private case.
>
> *For mitigation effects*, the country must base its decisions at least partly on discount rates that reflect the opportunity cost of capital. In developed countries rates around 4%–6% are probably justified. Rates of this level are

Figure 8.2.5.2.1
Declining long term social time preference rate (STPR)



Year	0 – 30	31 – 75	76 – 125
STPR (standard)	3.50%	3.00%	2.50%
STPR (reduced rate where pure STP = 0)	3.00%	2.57%	2.14%
Health	1.50%	1.29%	1.07%
Health (reduced rate where pure STP = 0)	1.00%	0.86%	0.71%

Source: H.M. Treasury, 2018, Table 8, p. 104.

> in fact used for the appraisal of public sector projects in the European Union (EU) (Watts, 1999). In developing countries the rate could be as high as 10%–12%. The international banks use these rates, for example, in appraising investment projects in developing countries. It is more of a challenge, therefore, to argue that climate change mitigation projects should face different rates, unless the mitigation project is of very long duration. These rates do not reflect private rates of return, which typically need to be considerably higher to justify the project, potentially between 10% and 25%.
>
> *For climate change impacts*, the long-term nature of the problem is the key issue. The benefits of reduced [greenhouse gas (GHG)] emissions vary with the time of emissions reduction, with the atmospheric GHG concentration at the reduction time, and with the total GHG concentrations more than 100 years after the emissions reduction. Any "realistic" discount rate used to discount the impacts of increased climate change impacts would render the damages, which occur over long periods of time, very small. With a horizon of around 200 years, a discount rate of 4% implies that damages of USD1 at the end of the period are valued at 0.04 cents today. At 8% the same damages are worth 0.00002 cents today. Hence, at discount rates in this range the damages associated with climate change become very small and even disappear (Cline, 1993)" (IPCC, 2001, p. 466).

There are two main points to be taken from this passage. First, investments in mitigation should be held to the same standard as other investments, public or private, to ensure capital flows to its highest and best use. For developing countries, the IPCC suggests using discount rates as high as 10% to 12%. Second, "the range of dangers associated with climate change become very small and even disappear" as the chosen discount rate increases. It should therefore come as no surprise that governments and other proponents of immediate action to slow or stop climate change favor the use of lower discount rates. At higher (and likely more appropriate) discount rates, there is no economic rationale for immediate action.

In 2001, the IPCC cited a survey by Weitzman (1998) of 1,700 professional economists suggesting they believe "lower rates should be applied to problems with long time horizons, such as that being discussed here," and Weitzman "suggests the appropriate discount rate for long-lived projects is less than 2%" (IPCC, 2001, p. 467). In the eyes of some, discounting at all is unethical (Broome, 2004, 2012; Heal, 2009; Stern, 2014). They claim it violates intergenerational neutrality, causing future generations to be held as less valuable than the current one. But this logic seems flawed since the cost of reducing greenhouse gas emissions to benefit future generations must be compared to other investments *that would also benefit future generations*. Nearly any investment in capital and services that raises productivity and produces wealth will benefit future generations.

Weitzman (2007) and a team of other economists (Arrow *et al.*, 2013) have sided with a declining discount rate based on a formula called the Ramsey discounting formula, in which benefits realized in the immediate future (one to five years) might be discounted at 4%, those in the medium future (26–75 years) at 2%, and those in the distant future (76–300 years) at 1%. But once again, this seems counter-intuitive. Making investments in emission reductions that yield less than the return on alternative investments impoverishes future generations (Birdsall and Steer, 1993; Klaus, 2012). As Robert Mendelsohn wrote in 2004, "if climate change can only earn a 1.5% return each year, there are many more deserving social activities that we must fund before we get to climate. Although climate impacts are long term, that does not justify using a different price for time" (Mendelsohn, 2004).

Other economists argue for discount rates higher than the Ramsey formula. Carter *et al.* wrote, "because our knowledge of future events becomes more uncertain as the time horizon is extended, discount rates should if anything increase rather than diminish with time" (Carter *et al.*, 2006). The passage of time diminishes the odds that any specific event, whether harmful (cost) or desirable (benefit), will come to pass. It is therefore logical to discount the possibility of ever seeing a benefit whose delivery is decades or even a century distant. In the climate debate, delivery of the benefit can be foiled by even small changes in population, consumption, technology, politics, and international affairs that can (following the IPCC's chain of logic) change emission scenarios, hence atmospheric concentrations of CO_2, hence climate impacts, and hence economic impacts.

Another reason to believe discount rates should be high rather than low for benefits realized in the far future is because future generations will be much wealthier than people are today and therefore better able to cope with the risks that might accompany climate change. "There is a general consensus among economists that future generations will be able to deal with the average impacts of climate change relatively uneventfully," writes Litterman (2013, p. 38). At an annual per-capita income growth rate of 2.8% (the average over the past 50 years), average personal income will be four times as high as today in 50 years and 16 times as high in 100 years. In the latter case, even the world's poor will be wealthier than middle-income wage earners today, giving them access to mobility, air conditioning, and other forms of adaptation to climate hazards that currently may be beyond their reach (Goklany, 2009).

Nigel Lawson reports the rate the British Treasury set for public-sector projects was 6% during his time as U.K. Chancellor, and he is skeptical of the justification for a subsequent reduction to 3.5%, pointing out the private-sector rate is considerably higher (Lawson, 2008, p. 84). The issue, he observes, is not what would be an appropriate rate for developed countries, but what rate should be applied to a global project, and as the IPCC admits in the excerpt above, normal rates in developing countries are considerably higher.

The U.S. Office of Management and Budget (OMB) guidelines for base-line analysis state, "Constant-dollar benefit-cost analyses of proposed investments and regulations should report net present value and other outcomes determined using a real discount rate of 7%. This rate approximates the marginal pretax rate of return on an average investment in the private sector in recent years" (OMB, 1992, p. 9). Another commonly referenced benchmark is the return on U.S. Treasury notes, which at the time of this writing was 3.14% (Bankrates.com, 2018).

Economists generally reject the notion that climate change should be singled out for unique treatment, arguing the assessment of present values of future benefits/costs rests on principles that are rational and immutable (*e.g.*, Mendelsohn, 2004). Although expenditures can be viewed very differently in terms of diverse politics, moral philosophy, or ethics, they contend discount rates used for inter-temporal calculations should be around the real rate of return on capital, because only that rate represents the true opportunity cost of investments in climate mitigation (Nordhaus, 1998; Murphy, 2008). According to Kreutzer (2016),

> What, then, is the best reasonable return on investment? While one cannot predict what future rates will be, past rates of return on broad indexes are an excellent guide. The return on the Standard & Poor's 500 from 1928 to 2014 was 9.60 percent. Over this time inflation was a compounded 3.1 percent. The real rate of return would be the difference, 6.5 percent per year. Another source estimates the return for all stocks in the U.S. from 1802 to 2002 and gets the same 6.5 percent real return on capital. Yet another source calculates the real return on stocks between 1802 and 2002 to be 6.8 percent per year. These estimates reflect the returns after corporate income taxes are paid. Adjusting for corporate profits taxes increases these rates to between 7.5 percent and 9.9 percent.

Kreutzer concludes, "In any event, the 7 percent discount rate that is part of the Office of Management and Budget's guidance does not seem too high" (*Ibid.*).

The exception that seems to draw many researchers away from this consensus is Sir Nicholas Stern, whose 2007 Stern Review based its analysis on a discount rate of roughly 1.4% or even as low as 0.1% (Stern, 2007; Stern Review team, 2006). Stern justifies his rate as follows:

> The most straightforward and defensible interpretation (as argued in the Review) of [the utility discount factor] δ is the probability of existence of the world. In the Review, we took as our base case δ = 0.1%/year, which gives roughly a one-in-ten chance of the planet not seeing out this century. [Annual per-capita consumption growth] is on average ~1.3% in a world without climate change, giving an average consumption or social discount rate across the entire period of 1.4% (being lower where the impacts of climate change depress consumption growth) (Dietz *et al.*, 2007).

Stern assumes a one-in-ten probability that anthropogenic global warming will bring the world to an end by 2100, the social discount rate would indeed be vanishingly different from zero. But that doomsday scenario defies logic as well as climate science and economics. Carbon dioxide's effect on climate and then climate change's effect on human well-being are likely to be small relative to other human needs and priorities, even well past the end of the twenty-first century. Investing in efforts to mitigate their effects ought not be raised above other needs without sound scientific and economic justification. Stern's focus on an utterly implausible scenario makes his advice on a discount rate unreliable.

The detailed analyses of the risk of anthropogenic climate change presented earlier in this chapter and in previous chapters make a strong case that there is nothing special or unique about climate change that would justify an exceptional discount rate. Estimates of future costs and benefits and investments in emission reductions should be discounted at the same rate as other costs, benefits, and investment opportunities that face similar uncertainties. Special pleading or exception-making opens the door for bad public policy choices, thereby undermining the goals of CBA in the first place.

Finding the right discount rate has major consequences for estimating the human welfare impacts of climate change. The debate over choosing an appropriate discount rate is certainly worth having, but opponents of using a constant discount rate of approximately 7%, as recommended by OMB, Kreutzer, and others, have a tough position to defend.

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8.3 Climate Change

Previous sections of this chapter have shown how cascading uncertainty cripples integrated assessment models (IAMs). All five steps in an IAM – emission scenarios, carbon cycle, climate sensitivity, climate impacts, and economic impacts – rely on assumptions and controversial assertions that undermine the credibility of these academic exercises. They are, as Pindyck (2013) wrote, "close to useless as tools for policy analysis."

Assuming *arguendo* that IAMs get some aspects of the climate change problem right, this section begins with a summary of what the IPCC in its Fifth Assessment Report says the models show. It is seldom noted that the IPCC's estimates of the cost of reducing greenhouse gas emissions is reported in the Working Group III report while the benefits appear in the Working Group II report. What happens when those two estimates are compared? Section 8.3.1 answers that question.

Sections 8.3.2 and 8.3.3 report what happened when Dayaratna *et al.* (2017) re-ran two of the three IAMs relied upon by the IPCC to estimate the "social cost of carbon" using different assumptions regarding climate sensitivity, discount rates, and number of years being forecast. (The researchers also were interested in examining the robustness of the IPCC's third model, the PAGE model (Hope, 2013, 2018), but the author of that model, Chris Hope, insisted on co-authorship of any publications that would be written in exchange for providing his codes, so that model was not studied.)

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8.3.1 The IPCC's Findings

> *By the IPCC's own estimates, the cost of reducing emissions in 2050 by enough to avoid a warming of ~2°C would be 6.8 times as much as the benefits would be worth.*

The IPCC's estimate of the economic impact of unmitigated climate change was discussed in some detail in Section 8.2.5.1. Working Group II's contribution to AR5 put the cost of unmitigated climate change at between 0.2% and 2.0% of annual global GDP for a warming of approximately 2°C by 2050 (IPCC, 2014a, p. 663). Presumably this is the lost income growth over a 50-year period (the time required for temperatures to increase ~2°C) (Gleditsch and Nordås, 2014, p. 85). A mean cost estimate might be 1% (2.2 / 2), but this is higher than what the IPCC's IAMs forecast (see Figure 8.2.5.1.2). For a 2°C warming the PAGE and DICE models forecast consumption losses of about 0.5% and 1% while the FUND model forecasts a consumption *benefit* of about 1% of GDP. The models average about a 0.5% consumption loss. Avoiding this cost would be the *benefit* of reducing emissions sufficiently to keep the warming from occurring.

The Working Group III contribution to AR5 puts the *cost* of reducing greenhouse gas emissions enough to avoid more than 2°C warming by 2100 at 1.7% of global GDP in 2030, 3.4% in 2050, and 4.8% in 2100 (IPCC, 2014b, Table SPM.2, p. 15). These are "global mitigation costs" discounted at 5% per year and do not include the possible benefits or costs of climate impacts.

Working Group III says without mitigation, "global mean surface temperature increases in 2100 from 3.7°C to 4.8°C compared to pre-industrial levels" (IPCC, 2014b, p. 8). But Working Group II doesn't offer an estimate of the cost of unmitigated climate change much higher than ~2°C, saying "losses accelerate with greater warming (*limited evidence*, *high agreement*), but few quantitative estimates have been completed for additional warming around 3°C or above. … Estimates vary strongly with the assumed damage function and discount rate" (IPCC, 2014a, p. 663). On this point we can agree with the IPCC: Accurately forecasting economic costs and benefits more than 40 or 50 years distant is impossible.

The ratio of the IPCC's estimates of the costs and benefits of reducing emissions sufficiently to prevent more than 2°C warming by 2050 is 6.8:1 (3.4/0.5). This seems as close to a cost-benefit ratio as one can derive from the IPCC's voluminous research and commentary on impacts and mitigation. Reducing emissions would cost approximately seven times as much as any possible benefits that might come from a slightly cooler world in 2050 and beyond. This means the IPCC itself makes a strong case *against* reducing emissions before 2050. But given all the errors in the IPCC's analysis documented in this and earlier chapters, a better cost-benefit ratio is in order.

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8.3.2 DICE and FUND Models

> *Changing only three assumptions in two leading IAMs – the DICE and FUND models – reduces the SCC by an order of magnitude for the first and changes the sign from positive to negative for the second.*

The two publicly available models used by the U.S. Interagency Working Group (IWG) for policymaking prior to 2017 were the Dynamic Integrated Climate-Economy (DICE) model (Newbold, 2010; Nordhaus, 2017), and the Climate Framework for Uncertainty, Negotiation and Distribution (FUND) model (Anthoff and Tol, 2014; Waldhoff *et al.*, 2014; Tol and Anthoff, 2018). Examination of the DICE and FUND models by Dayaratna *et al.* (2017) revealed they are especially sensitive to three parameters chosen by IWG: discount rates, equilibrium climate sensitivity, and the number of years being forecast. IWG simply chose not to run the models with the 7% discount rate required by the U.S. Office of Management and Budget (OMB, 1992) and recommended by many economists as recounted in Section 8.2.5.2. So Dayaratna *et al.* ran the models themselves. As previously mentioned, a third model, PAGE, was not used due to the author's insistence of co-authorship, precluding independent analysis.

Equilibrium climate sensitivity (ECS) was discussed in detail in Chapter 2 and in Section 8.2.3. The ECS distribution used by IWG was published in the journal *Science* 11 years ago (Roe and Baker, 2007). Rather than being based on empirical data, this distribution was calibrated to assumptions made by IWG. Since it was published, studies regarding ECS distributions have found a significantly lower probability of extreme global warming (see Figure 8.2.3.5 and Otto *et al.*, 2013; Lewis, 2013; and Lewis and Curry, 2015). Dayaratna *et al.* (2017) re-ran the

DICE and FUND models with these new ECS estimates.

The IWG also chose to run the DICE and FUND models with time horizons of 300 years, which defies credibility. The “cascade of uncertainty” identified earlier in this chapter grows greater with every year, making predictions beyond even one or a few decades speculative. Three centuries is far beyond the horizon of any credible scientific or economic model. As seen in the outputs reported below, reducing the horizon by half, to a still-unbelievable 150 years, dramatically changes the SCC.

When Dayaratna *et al.* (2017) ran the DICE model using a 7% discount rate but retaining the Roe and Baker ECS estimate and 300-year horizon, the social cost of carbon (SCC) estimates ranged from $4.02 per marginal ton of CO_2eq generated in 2010 to $12.25 in 2050, dramatically less than the estimates produced when lower discount rates are assumed. For example, between a 2.5% and a 7% discount rate, the SCC falls by more than 80% in 2050. The reductions in SCC for other years are also quite substantial. The results appear in (A) in Figure 8.3.2.1.

Figure 8.3.2.1
Re-running the DICE model with truncated time horizon

Year	**Discount Rate**			
	2.50%	**3%**	**5%**	**7%**
(A) DICE model SCC estimates using outdated Roe-Baker (2007) ECS distribution and 300 year time horizon				
2010	$46.57	$30.04	$8.81	$4.02
2020	$56.92	$37.79	$12.10	$5.87
2030	$66.52	$45.14	$15.33	$7.70
2040	$76.95	$53.25	$19.02	$9.85
2050	$87.69	$61.72	$23.06	$12.25
(B) DICE model SCC estimates using outdated Roe-Baker (2007) ECS distribution with time horizon truncated at 150 years				
2010	$36.78	$26.01	$8.66	$4.01
2020	$44.41	$32.38	$11.85	$5.85
2030	$50.82	$38.00	$14.92	$7.67
2040	$57.17	$43.79	$18.36	$9.79
2050	$62.81	$49.20	$22.00	$12.13
(C) Percentage change in DICE model’s SCC estimates using outdated Roe-Baker (2007) ECS distribution after truncating time horizon to 150 years				
2010	-21.04%	-13.43%	-1.77%	-0.20%
2020	-21.98%	-14.32%	-2.10%	-0.27%
2030	-23.60%	-15.82%	-2.66%	-0.39%
2040	-25.71%	-17.78%	-3.45%	-0.60%
2050	-28.37%	-20.28%	-4.58%	-0.94%

Running the DICE model using the 7% discount rate and truncating the time horizon to 150 years instead of 300 years significantly reduced SCC estimates for model runs using low discount rates while leaving the SCC estimates for the 7% discount rate relatively unchanged. The absolute values appear in (B) and the percentage change from (A) to (B) appears in (C) in Figure 8.3.2.1.

Dayaratna *et al.* (2017) also found the DICE model is sensitive to the choice of its equilibrium climate sensitivity distribution. Running the model with the Otto *et al.* (2013) ECS instead of the out-of-date Roe-Baker (2007) ECS revealed an SCC with a 7% discount rate of between $2.80 (2010) and $8.29 (2050), a decline by some 30%. (D) in Figure 8.3.2.2 presents the absolute values and (E) shows the percentage change from (A) in Figure 8.3.2.1.

Dayaratna *et al.* (2017) also ran the DICE model using the Lewis and Curry (2015) ECS distribution instead of the outdated Roe-Backer (2007) ECS distribution and found similar lower SCC results and large percentage changes at all discount rates as shown in (F) and (G) in Figure 8.3.2.3.

These reductions in SCC estimates are due to a very simple aspect of the ECS distribution used. The outdated Roe-Baker distribution has a significantly higher probability of high-end global warming than these more up-to-date distributions. For example, the probability of a temperature increase greater than 4° Celsius is slightly above 0.25 under the outdated Roe-Baker distribution; under the Otto *et al.* (2013) and Lewis and Curry (2015) distributions, this probability is less than 0.05. As a result, model simulations draw more from such extreme cases of global warming using the Roe-Baker distribution, and those extreme cases manifest themselves in higher estimates of the SCC.

Similarly, Dayaratna *et al.* (2017) re-ran the FUND model using the 7% discount rate and replacing the outdated Roe-Baker (2007) ECS distribution with the more recent Otto *et al.* (2013) and Lewis and Curry (2015) ECS distributions. The FUND model's estimates of SCC start out slightly lower than the DICE model because it includes some social benefits attributable to enhanced agricultural productivity due to increased CO_2 fertilization. With a 7% discount rate and updated ECS distributions, the FUND model reports a slightly negative SCC for all years from 2010 to 2050 ranging from $-0.14 per metric ton to -$1.12. See (H), (I), and (J) in Figure 8.3.2.4 for the SCC estimates for all four discount rates and three ECS distributions.

Figure 8.3.2.2
Re-running the DICE model with Otto et al. (2013) ECS distribution

Year	Discount Rate			
	2.5%	3%	5%	7%
(D) DICE model SCC estimates using Otto *et al.* (2013) ECS distribution				
2010	$26.64	$17.72	$5.73	$2.80
2020	$32.65	$22.32	$7.82	$4.04
2030	$38.33	$26.74	$9.88	$5.26
2040	$44.54	$31.63	$12.24	$6.69
2050	$51.19	$36.91	$14.84	$8.29
(E) Percentage change in DICE model's SCC estimates after switching from the outdated Roe-Baker (2007) to Otto *et al*. (2013) ECS distribution				
2010	-42.79%	-41.00%	-35.02%	-30.39%
2020	-42.63%	-40.93%	-35.37%	-31.20%
2030	-42.38%	-40.77%	-35.52%	-31.71%
2040	-42.12%	-40.61%	-35.65%	-32.13%
2050	-41.62%	-40.20%	-35.62%	-32.33%

Figure 8.3.2.3
Re-running the DICE model with the Lewis and Curry (2015) ECS distribution

Year	Discount Rate			
	2.5%	3%	5%	7%
(F) DICE model SCC estimates using Lewis and Curry (2015) ECS distribution				
2010	$23.62	$15.62	$5.03	$2.48
2020	$28.92	$19.66	$6.86	$3.57
2030	$33.95	$23.56	$8.67	$4.65
2040	$39.47	$27.88	$10.74	$5.91
2050	$45.34	$32.51	$13.03	$7.32
(G) Percentage change in DICE model's SCC estimates after switching from the outdated Roe-Baker (2007) to Lewis and Curry (2015) ECS distribution				
2010	-49.28%	-48.00%	-42.91%	-38.31%
2020	-49.19%	-47.98%	-43.31%	-39.18%
2030	-48.96%	-47.81%	-43.44%	-39.61%
2040	-48.71%	-47.64%	-43.53%	-40.00%
2050	-48.30%	-47.33%	-43.50%	-40.24%

Re-running the DICE and FUND models with these reasonable changes to discount rates and equilibrium climate sensitivity reveals several things:

(a) The models relied on by the IPCC, EPA, and other government agencies depend on factors whose values violate conventional cost-benefit analysis (low discount rates), rely on outdated and invalidated data (the Roe-Baker (2007) ECS estimate), or lie outside the range of plausibility (the 300-year horizon);

(b) Altering only these three variables is sufficient to reduce the SCC to less than $10 in the DICE model (e.g from $87.69 to $7.32 in 2050) and to change its sign from positive to negative in the FUND model (e.g. from $42.98 to -$-0.53 in 2050);

(c) Using the FUND model – the only model that takes into account potential benefits from CO2 emissions – the estimates of the SCC are close to zero or even negative under very reasonable assumptions, suggesting that climate change may offer more benefits than costs to society.

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Figure 8.3.2.4
Re-running the FUND model using Roe-Baker (2007), Otto *et al.* (2013), and Lewis and Curry (2015)

Year	**Discount Rate**			
	2.50%	**3%**	**5%**	**7%**
(H) FUND model SCC estimates using outdated Roe-Baker (2007) ECS distribution				
2010	$29.69	$16.98	$1.87	-$0.53
2020	$32.90	$19.33	$2.54	-$0.37
2030	$36.16	$21.78	$3.31	-$0.13
2040	$39.53	$24.36	$4.21	$0.19
2050	$42.98	$27.06	$5.25	$0.63
(I) FUND model SCC estimates using Otto *et al.* (2013) ECS distribution				
2010	$11.28	$6.27	$0.05	-$0.93
2020	$12.66	$7.30	$0.36	-$0.87
2030	$14.01	$8.35	$0.74	-$0.75
2040	$17.94	$11.08	$1.50	-$0.49
2050	$19.94	$12.69	$2.21	-$0.14
(J) FUND model SCC estimates using Lewis and Curry (2015) ECS distribution				
2010	$5.25	$2.78	-$0.65	-$1.12
2020	$5.86	$3.33	-$0.47	-$1.10
2030	$6.45	$3.90	-$0.19	-$1.01
2040	$7.02	$4.49	-$0.18	-$0.82
2050	$7.53	$5.09	$0.64	-$0.53

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8.3.3 A Negative SCC

> *Under very reasonable assumptions, IAMs can suggest the SCC is more likely than not to be negative, even though they have many assumptions and biases that tend to exaggerate the negative effects of GHG emissions.*

The negative SCC estimates produced by the FUND model are interesting and warrant further discussion. Since SCC is presented as a cost, a negative estimate signifies more social benefits than social costs associated with greenhouse gas emissions, and therefore such emissions are net beneficial for the planet. As these models are estimated via Monte Carlo simulation, Dayaratna *et al.* (2017) were able to compute the probability of a negative SCC. Their findings are summarized in (A), (B), and (C) in Figure 8.3.3.1.

There are a few noteworthy points from these results. First, with a 7% discount rate and updated ECS range, the probability ranges from 54% to 73% that the SCC is negative. Even with lower discount rates the probability of a negative SCC ranges from 22.8% to 60.1%. Even using the outdated Roe-Baker distribution, with a 7% discount rate there is a greater probability of a negative SCC than a positive SCC through 2040.

These results may be one of the reasons the IWG researchers chose not to report a 7% discount rate in their analysis. Acknowledging that the combustion of fossil fuels – the main source of anthropogenic CO_2 emissions – likely causes more social benefits than social harms would hardly have aided the Obama administration in its "war on coal." That result would more plausibly support efforts to protect the nation's coal-powered electric generation capacity, something Obama's successor is pursuing (Cama, 2017; Dlouhy, 2018).

The analysis by Dayaratna *et al.* (2017) makes clear that estimates of the social cost of carbon are sensitive to changes to assumptions and a few key variables. Although these models are interesting to explore in academic research, they are not robust enough for use in setting regulatory policy. Fortunately, the Trump administration disbanded the IWG and halted use of SCC estimates in regulatory policy (Trump, 2017). Future administrations, both in the United States and elsewhere in the world, would benefit from doing the same.

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8.4 Fossil Fuels

Efforts to calculate the "social cost of carbon" (SCC) routinely underestimate the cost of reducing humanity's reliance on fossil fuels by excluding the private benefits of fossil fuels and then the opportunity cost of foregoing those benefits. As was mentioned at the start of this chapter, in Section 8.1.2, the SCC label is typically applied only to the cost of the net effects of climate change attributed to CO_2 and other greenhouse gases emitted by humanity.

But to ignore this opportunity cost is obviously wrong. In its 2017 report to Congress, the U.S. Office of Management and Budget (OMB) said "cost-benefit analysis as required by EO 12866 remains the primary analytical tool to inform specific regulatory decisions. Accordingly, except where prohibited by law, agencies must continue to assess and consider *both the benefits and costs* of regulatory and deregulatory actions, and issue such actions only upon a reasoned determination that benefits justify costs" (OMB, 2018, p. 51, italics added).

It should have occurred to the IWG economists that the integrated assessment models (IAMs) they chose to rely on for the SCC estimates failed to meet OMB's requirement, and not only by failing to report costs using a 7% discount rate and by comparing domestic costs with global benefits, as reported in Section 8.1.4. IAMs *by design* monetize only the costs of climate change attributable to anthropogenic greenhouse gas emissions. The DICE model

Figure 8.3.3.1
Probability of a negative Social Cost of Carbon (SCC) estimate

Year	**Discount Rate**			
	2.5%	**3%**	**5%**	**7%**
(A) Probability of negative SCC estimates for DICE and FUND models using outdated Roe-Baker (2007) ECS distribution				
2010	0.087	0.121	0.372	0.642
2020	0.084	0.115	0.344	0.601
2030	0.08	0.108	0.312	0.555
2040	0.075	0.101	0.282	0.507
2050	0.071	0.093	0.251	0.455
B. Probability of negative SCC estimates for DICE and FUND models using Otto *et al.* (2013) ECS distribution				
2010	0.278	0.321	0.529	0.701
2020	0.268	0.306	0.496	0.661
2030	0.255	0.291	0.461	0.619
2040	0.244	0.274	0.425	0.571
2050	0.228	0.256	0.386	0.517
(C) Probability of negative SCC estimates for DICE and FUND models using Lewis and Curry (2015) ECS distribution				
2010	0.416	0.450	0.601	0.730
2020	0.402	0.432	0.570	0.690
2030	0.388	0.414	0.536	0.646
2040	0.371	0.394	0.496	0.597
2050	0.354	0.372	0.456	0.542

deliberately excludes *any benefits* from climate change, while the FUND model includes only the benefits from aerial CO_2 fertilization (Dayaratna and Kreutzer, 2013, 2014). They omit entirely the extensive benefits produced by the use of fossil fuels, and hence the opportunity cost of losing those benefits. Consequently, while IAMs might be used to monetize one or a few of the many costs and benefits arising from the use of fossil fuels, they are not a true CBA (Pindyck, 2013).

The rest of this section attempts to produce more accurate cost-benefit ratios for the use of fossil fuels. Section 8.4.1 reviews all the impacts of fossil fuels identified earlier in this chapter and in other chapters of this book and finds 16 benefits and only one net cost. Section 8.4.2 produces realistic estimates of the cost of reducing GHG emissions by the amounts recommended by the IPCC and according to a goal set by the European Union. Section 8.4.3 produces new cost-benefit ratios using the findings from the IPCC, the Interagency Working Group, and Bezdek (2014, 2015). The authors find the cost of reducing humanity's reliance on fossil exceeds the benefits by ratios as low as 6.8:1 to as high as 160:1.

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Section 8.4.1 Impacts of Fossil Fuels

Sixteen of 25 possible impacts of fossil fuels on human well-being are net benefits, only one is a net cost, and the rest are either unknown or likely to have no net impact.

The authors of the Working Group II contribution to the IPCC's Fifth Assessment Report (AR5) reported hundreds of studies allegedly documenting the impacts of climate change on humanity, but they did not attempt to aggregate those impacts, observing that differences in methodology, geographical areas, time periods, and outputs made such a meta-analysis impossible. Instead, they opted to summarize the possible impacts in a table (Assessment Box SPM.2 Table 1 in the Summary for Policymakers (IPCC, 2014a, pp. 21–25).

The authors of the current volume follow the IPCC's lead by producing the table shown in Figure 8.4.1.1 summarizing the findings of previous chapters regarding the impacts of fossil fuels on human well-being. Possible impacts appear in alphabetical order, their net impact (benefit, cost, no net impact, or unknown) appear in the second column, brief observations on the impacts appear in the third column, and chapters and sections of chapters in which the topics are addressed appear in the fourth column of the table.

Figure 8.4.1.1
Impact of fossil fuels on human well-being

Impact	Benefit or Cost	Observations	Chapter References
Acid rain	No net impact	Once feared to be a major environmental threat, the deposition of sulfuric and nitric acid due to smokestack emissions, so-called "acid rain," was later found not to be a threat to forest health and to affect only a few bodies of water, where remediation with lime is an inexpensive solution. The fertilizing effect of nitrogen deposition more than offsets its harms to vegetation. Dramatic reductions in SO_2 and NO_2 emissions since the 1980s mean "acid rain" has no net impact on human well-being today.	5.1, 6.1
Agriculture	Benefit	Fossil fuels have contributed to the enormous improvement in crop yields by making artificial fertilizers, mechanization, and modern food processing techniques possible. Higher atmospheric CO_2 levels are causing plants to grow better and require less water. Numerous	3.4, 4.1, 5.2, 5.3, 7.2, 8.2

		studies show the aerial fertilization effect of CO_2 is improving global agricultural productivity, on average by at least 15%.	
Air quality	Benefit	Exposure to potentially harmful chemicals in the air has fallen dramatically during the modern era thanks to the prosperity, technologies, and values made possible by fossil fuels. Safe and clean fossil fuels made it possible to rapidly increase energy consumption while improving air quality.	5.2, Chapter 6
Catastrophes	Unknown	No scientific forecasts of possible catastrophes triggered by global warming have been made. CO_2 is not a "trigger" for abrupt climate change. Inexpensive fossil fuel energy greatly facilitates recovery.	8.1
Conflict	Benefit	The occurrence of violent conflicts around the world has fallen dramatically thanks to prosperity and the spread of democracy made possibly by affordable and reliable energy and a secure food supply.	7.1, 7.3, 8.2
Democracy	Benefit	Prosperity is closely correlated with the values and institutions that sustain democratic governments. Tyranny promoted by zero- sum wealth is eliminated. Without fossil fuels, there would be fewer democracies in the world.	7.1
Drought	No net impact	There has been no increase in the frequency or intensity of drought in the modern era. Rising CO_2 lets plants use water more efficiently, helping them overcome stressful conditions imposed by drought.	2.7, 5.3
Economic growth (consumption)	Benefit	Affordable and reliable energy is positively correlated with economic growth rates everywhere in the world. Fossil fuels were indispensable to the three Industrial Revolutions that produced the unprecedented global rise in human prosperity.	Chapter 3, 4.1, 5.2, 7.1, 7.2, 8.1, 8.2
Electrification	Benefit	Transmitted electricity, one of the greatest inventions in human history, protects human health in many ways. Fossil fuels directly produce some 80% of electric power in the world. Without fossil fuels, alternative energies could not be built or relied on for continuous power.	Chapter 3, 4.1
Environmental protection	Benefit	Fossil fuels power the technologies that make it possible to meet human needs while using fewer natural resources and less surface space. The aerial CO_2 fertilization effect has produced a substantial net greening of the planet, especially in arid areas, that has been measured using satellites.	1.3, Chapter 5
Extreme weather	No net impact	There has been no increase in the frequency or intensity of extreme weather in the modern era, and therefore no reason to expect any economic damages to result from CO_2 emissions.	2.7, 8.2
Forestry	Benefit	Fossil fuels made it possible to replace horses as the primary means of transportation, saving millions of acres of land for forests. Elevated CO_2 concentrations have positive effects on forest growth and health, including efficiency of water use. Rising CO_2 has reduced and overridden the negative effects of ozone pollution on the photosynthesis, growth, and yield of nearly all the trees that have been evaluated experimentally.	5.3
Human development	Benefit	Affordable energy and electrification, better derived from fossil fuels than from renewable energies, are closely correlated with the United Nations' Human Development Index and advances what the IPCC labels "human capital."	3.1, 4.1, 7.2
Human health	Benefit	Fossil fuels contribute strongly to the dramatic lengthening of average lifespans in all parts of the world by improving nutrition, health care, and human safety and welfare. (See also "Air quality.")	3.1, Chapter 4, 5.2
Human settlements /migration	Unknown	Forced migrations due to sea-level rise or hydrological changes attributable to man-made climate change have yet to be documented and are unlikely since the global average rate of sea-level rise has not accelerated. Global warming is as likely to decrease as increase the number of people forced to migrate.	7.3, 8.2

Ocean acidification	Unknown	Many laboratory and field studies demonstrate growth and developmental improvements in aquatic life in response to higher temperatures and reduced water pH levels. Other research illustrates the capability of both marine and freshwater species to tolerate and adapt to the rising temperature and pH decline of the planet's water bodies.	5.5
Oil spills	Cost	Oil spills can harm fish and other aquatic life and contaminate drinking water. The harm is minimized because petroleum is typically reformed by dispersion, evaporation, sinking, dissolution, emulsification, photo-oxidation, resurfacing, tar-ball formation, and biodegradation.	5.1
Other market sectors	No net impact	The losses incurred by some businesses due to climate change, whether man-made or natural, will be offset by profits made by other businesses taking advantage of new opportunities to meet consumer wants. Institutional adaptation, including of markets, to a small and slow warming is likely.	1.2, 7.2
Polar ice melting	Unknown	What melting is occurring in mountain glaciers, Arctic sea ice, and polar icecaps is not occurring at "unnatural" rates and does not constitute evidence of a human impact on the climate. Global sea-ice cover remains similar in area to that at the start of satellite observations in 1979, with ice shrinkage in the Arctic Ocean offset by growth around Antarctica.	2.7
Sea-level rise	No net impact	There has been no increase in the rate of increase in global average sea level in the modern era, and therefore no reason to expect any economic damages to result from it. Local sea levels change in response to factors other than climate.	2.7, 8.2
Sustainability	Benefit	Fossil fuels are a sustainable source of energy for future generations. The technology they support makes sustainable development possible. Rising prosperity and market forces also are working to ensure a practically endless supply of fossil fuels.	1.5, 5.2
Temperature-related mortality	Benefit	Extreme cold kills more people than extreme heat, and fossil fuels enable people to protect themselves from temperature extremes. A world made warmer and more prosperous by fossil fuels would see a net decrease in temperature-related mortality.	4.2
Transportation	Benefit	Fossil fuels revolutionized society by making transportation faster, less expensive, and safer for everyone. The increase in human, raw material, and product mobility was a huge boon for humanity, with implications for agriculture, education, health care, and economic development.	4.1
Vector-borne diseases	No net impact	Warming will have no impact on insect-borne diseases because temperature plays only a small role in the spread of these diseases. The technologies and prosperity made possible by fossil fuels eliminated the threat of malaria in developed countries and could do the same in developing countries regardless of climate change.	4.6
Water resources	Benefit	While access to water is limited by climate and other factors in many locations around the world, there is little evidence warming would have a net negative effect on the situation. Fossil fuels made it possible for water quality in the United States and other industrial countries to improve substantially while improving water use efficiency by about 30% over the past 35 years. Aerial CO_2 fertilization improves plant water use efficiency, reducing the demand for irrigation.	5.2, 5.3

Twenty-five climate impacts appear in Figure 8.4.1.1. Some general observations are possible:

- *Net benefits:* 14 impacts (agriculture, air quality, conflict, democracy, economic growth (consumption), electrification, environmental protection, forestry, heat-related mortality, human development, human health, sustainability, transportation, and water resources) are benefits, meaning their net social benefits exceed their social costs.

- *No net impact:* Six impacts (acid rain, drought, extreme weather, other market sectors, sea-level rise, and vector-borne diseases) are either not being intensified or made more harmful by anthropogenic climate change or are likely to have offsetting benefits resulting in no net impacts.

- *Unknown costs and benefits:* Four impacts (catastrophes, human settlements/migration, ocean acidification, and polar ice melting) are not sufficiently understood to determine if net costs exceed benefits.

- *Net cost:* Only one impact (oil spills) is likely to have costs that exceed benefits. Although accidental releases of oil into bodies of water do occur and cause damage, their harm is unlikely to be great. Natural seepage from ocean floors exceeds the human contribution by nearly ten-fold and biodegradation quickly diminishes the threat to human health or wildlife (see Atlas, 1995; NRC, 2003; Aminzadeh *et al.,* 2013). Still, we count this as a net cost.

A visualization of the findings in Figure 8.4.1.1 appears in Figure 8.4.1.2. This image is modeled after, but is quite different from, one produced by the U.S. National Oceanic and Atmospheric Administration (NOAA, 2016).

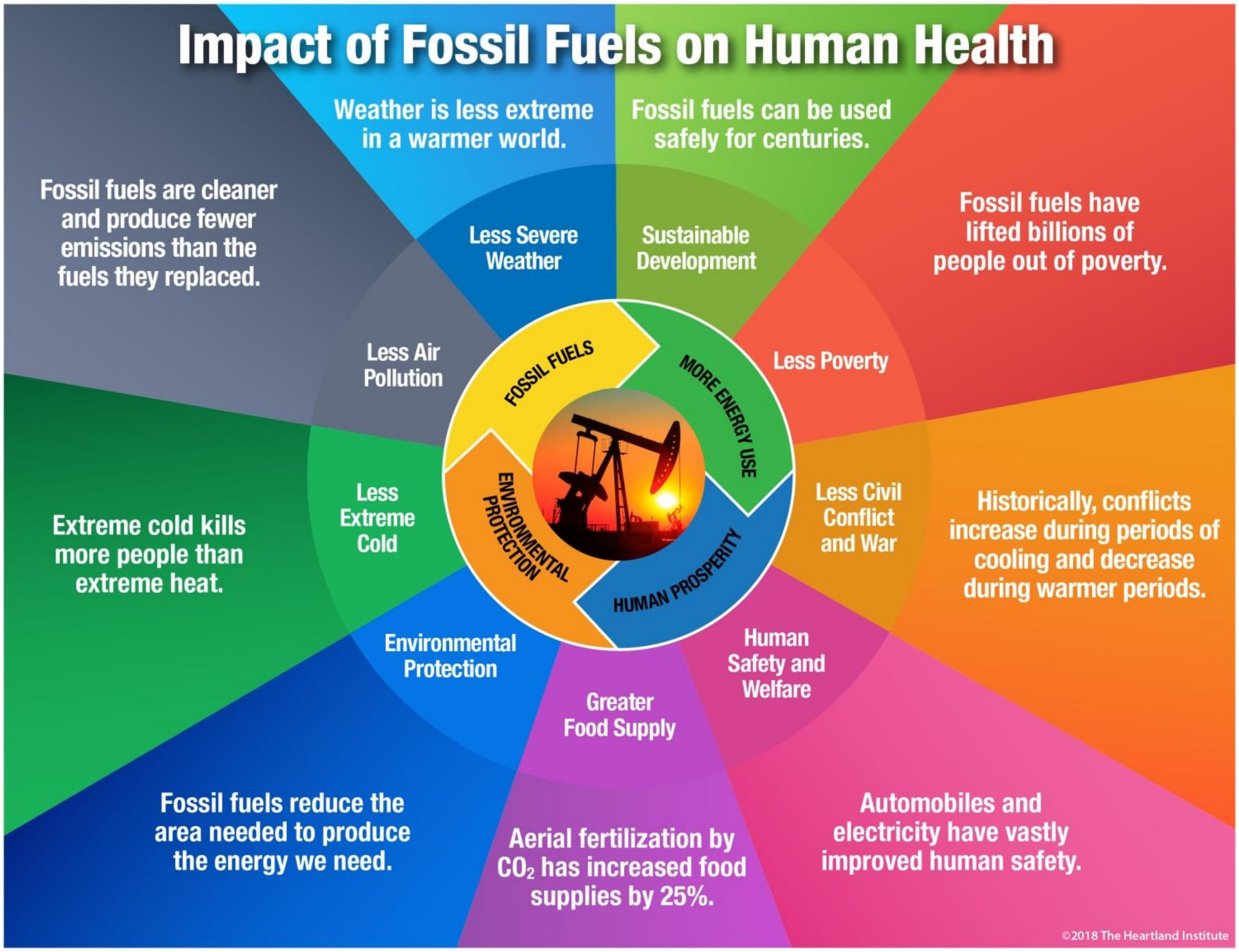
This summary differs dramatically from the opinions expressed by the IPCC, but the reason should be clear: Working Group II did not conduct a cost-benefit analysis of fossil fuels. It was tasked with producing a catalogue of every possible negative consequence of climate change, whether natural or man-made (see Section 8.2.5.1 for a brief comment on that), and did its job with superb attention to detail. But since the chains of causality linking human activity to temperature changes, and then to climate impacts, and finally to human impacts decades and even centuries in the future are long, tenuous, and little more than speculation, WGII's conclusions are necessarily ambiguous: "Global economic impacts from climate change are difficult to estimate. … Estimates vary strongly with the assumed damage function and discount rate … the impact of climate change will be small relative to the impacts of other drivers" (IPCC, 2014, p. 663).

The authors of the current volume asked a different question: "What does observational data show to be the real impacts of the use of fossil fuels on human well-being?" and so reached a different conclusion. Extensive literature reviews have found 14 impacts of the use of fossil fuels are beneficial, meaning their net benefits to society exceed their costs. Six impacts are likely to have neither net benefits nor net costs (benefits offset costs). The net costs or benefits of four impacts are unknown due to our lack of scientific understanding of the processes involved. Only one impact of fossil fuels, oil spills, is likely to be net negative, and it is small relative to natural sources of hydrocarbons in the oceans.

In economic terms, our calculation of net benefits combines private benefits – those enjoyed by individuals and paid for by them – and net social benefits – the benefits enjoyed by people who do not pay for them minus any negative costs imposed on them. This is not a "social cost of carbon" calculation, which by design ignores private costs and benefits. Like the IPCC, we do not attempt to aggregate widely different databases on such diverse impacts. However, private benefits are easier to estimate than social costs thanks to the prices and investment data created by market exchanges, a point explained in Chapter 1, Section 1.2.3. This means the *opportunity cost* of doing without fossil fuels, calculated as a loss of per-capita income or GDP, can be estimated. This calculation is performed in the next section.

Figures 8.4.1.1 and 8.4.1.2 make it clear that the benefits of fossil fuels exceed their cost by a wide margin.

Figure 8.4.1.2
Impact of Fossil Fuels on Human Health



Weather is less extreme in a warmer world.

Fossil fuels can be used safely for centuries.

Fossil fuels have lifted billions of people out of poverty.

Historically, conflicts increase during periods of cooling and decrease during warmer periods.

Automobiles and electricity have vastly improved human safety.

Aerial fertilization by CO_2 has increased food supplies by 25%.

Fossil fuels reduce the area needed to produce the energy we need.

Extreme cold kills more people than extreme heat.

Fossil fuels are cleaner and produce fewer emissions than the fuels they replaced.

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8.4.2 Cost of Mitigation

> *Wind and solar cannot generate enough dispatchable energy (available 24/7) to replace fossil fuels, so energy consumption must fall in order for emissions to fall.*

According to the Working Group III contribution to the IPCC's Fifth Assessment Report, keeping average global surface temperature change to less than 2°C above its pre-industrial level by 2100 requires limiting atmospheric concentrations of CO_2 in 2100 to "about 450 ppm CO_2eq (*high confidence*)," which would require "substantial cuts in anthropogenic GHG emissions by mid-century through large scale changes in energy systems and potentially land use (*high confidence*). Scenarios reaching these concentrations by 2100 are characterized by lower global GHG emissions in 2050 than in 2010, 40% to 70% lower globally, and emissions levels near zero $GtCO_2$eq or below in 2100" (IPCC, 2014b, pp. 10, 12). Emissions can supposedly fall to below zero through the use of "carbon dioxide removal technologies" (*Ibid.*).

Also according to Working Group III, the cost of reducing emissions to meet these goals in the IPCC's best-case scenario – where all countries immediately begin mitigation efforts, adopt a single global carbon tax, and impose no regulations favoring some technologies over others – expressed as a percentage of baseline global gross domestic product (GDP) without climate policies, would be 1% to 4% (median: 1.7%) in 2030, 2% to 6% (median: 3.4%) in 2050, and 3% to 11% (median: 4.8%) in 2100 relative to consumption in baseline scenarios (IPCC, 2014b, pp. 15–16, text and Table SPM.2).

The following sections explain why IPCC's estimate of the cost of a forced transition away from fossil fuels to "near zero … or below in 2100" is too low for two reasons. First, replacing a world energy system currently dependent on fossil fuels to provide more than 80% of primary energy with one relying mostly or entirely on alternative energies would cost far greater sums and take decades to implement. Second, wind and solar face physical limits that prevent them from generating enough dispatchable energy (available 24/7) to replace fossil fuels, so energy consumption must fall in order for emissions to fall. Energy demand is forecast to grow significantly in the twenty-first century, and the opportunity cost of reversing that trend – of reducing rather than increasing per-capita energy consumption – is enormous. Section 8.4.2.1 addresses the first concern, and Section 8.4.2.2 addresses the second.

8.4.2.1 High Cost of Reducing Emissions

> *Transitioning from a world energy system dependent on fossil fuels to one relying on alternative energies would cost trillions of dollars and take decades to implement.*

Chapter 3, Section 3.5, documented at great length the inherent limitations on alternative energy sources and the history of past transitions to new energy sources suggesting the cost of forcing a transition from fossil fuels would be very costly (Smil, 2010; Morriss *et al.*, 2011; Clack *et al.,* 2017). The sheer size of the global energy market makes replacing it massively expensive and time consuming. Smil (2010) notes the global oil industry "handles about 30 billion barrels annually or 4 billion tons" and operates about 3,000 large tankers and more than 300,000 miles of pipelines. "Even if an immediate alternative were available, writing off this colossal infrastructure that took more than a century to build would amount to discarding an investment worth well over $5 trillion – and it is quite obvious that its energy output could not be replaced by any alternative in a decade or two" (p. 140). Later, Smil (2010, p. 148) writes the cost of a transition "would be easily equal to the total value of U.S. gross domestic product (GDP), or close to a quarter of the global economic product."

Wind and solar power face cost, scale, and intermittency problems that make extremely expensive any efforts to increase their share of total energy production to more than 10% or 15% of total production. In particular, their low power density means scaling them up to replace fossil fuels would require alarming amounts of surface space, crowding out agriculture and wildlife habitat with harmful effects on food production and the natural environment. See Chapter 3, Section 3.2, and Chapter 5, Section 5.2, for discussions of these problems and many references there (e.g., Rasmussen, 2010; Hansen, 2011; Kelly, 2014; Bryce, 2014; Smil, 2016; Stacy and Taylor, 2016; Driessen, 2017).

Advocates of rapid decarbonization underestimate the negative consequences of the intermittency of solar and wind power. In a critique of Jacobson *et al.* (2015) and an earlier paper also by Jacobson and a coauthor (Jacobson and Delucchi,

2009) claiming a transition to a 100% renewables future is possible, Clack *et al.* (2017) observe,

> Wind and solar are variable energy sources, and some way must be found to address the issue of how to provide energy if their immediate output cannot continuously meet instantaneous demand. The main options are to (*i*) curtail load (i.e., modify or fail to satisfy demand) at times when energy is not available, (*ii*) deploy very large amounts of energy storage, or (*iii*) provide supplemental energy sources that can be dispatched when needed. It is not yet clear how much it is possible to curtail loads, especially over long durations, without incurring large economic costs. There are no electric storage systems available today that can affordably and dependably store the vast amounts of energy needed over weeks to reliably satisfy demand using expanded wind and solar power generation alone. These facts have led many U.S. and global energy system analyses to recognize the importance of a broad portfolio of electricity generation technologies, including sources that can be dispatched when needed.

Modern economies require a constant supply of electricity 24/7, not just when the sun shines and the wind blows. The grid needs to be continuously balanced – energy fed into the grid must equal energy leaving the grid – which requires dispatchable (on-demand) energy and spinning reserves (Backhaus and Chertkov, 2013; Dears, 2015). This effectively requires that approximately 90% of the energy produced by wind turbines and solar PV cells be backed up by rotating turbines powered by fossil fuels (E.ON Netz, 2005). Today, only fossil fuels and nuclear can provide dispatchable power in sufficient quantities to keep grids balanced.

Similarly, and as explained in Chapter 3, the technology to safely and economically store large amounts of electricity does not exist (Clack *et al.*, 2017), at least not outside the few areas where large bodies of water and existing dams make pumped-storage hydroelectricity possible. The frequent announcements of "breakthroughs" in battery technology have not resulted in commercial products capable of even a small fraction of the storage needs of a transition from fossil fuels (Fildes, 2018). Scholars have even developed a "hype curve" to track how far the claims about new battery technologies overstate their potential and how long it takes for them to achieve commercial success (Sapunkov *et al.*, 2015). See Figure 8.4.2.1.1.

There is no question that fuels superior to coal, oil, and natural gas for some applications already exist or will be found and that their use will increase as new technologies are discovered and commercialized. *Energy freedom* – relying on markets to balance the interests and needs of today with those of tomorrow and to access the local knowledge needed to find efficient win-win responses to climate change – should be permitted to dictate the pace of this transition, not fears of a climate catastrophe and hope for technological breakthroughs.

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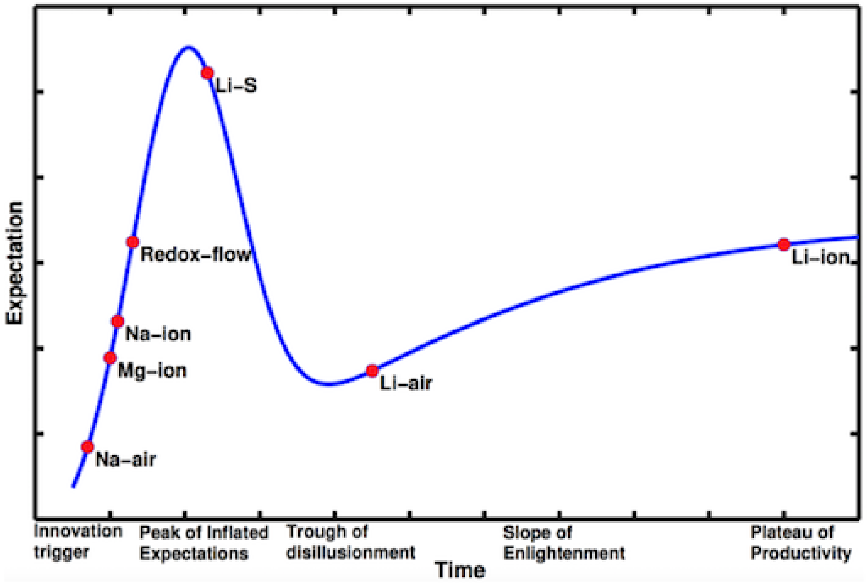
Figure 8.4.2.1.1
The new battery technology "hype cycle"



Source: Sapunkov *et al.*, 2015.

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8.4.2.2 High Cost of Reducing Energy Consumption

> *Reducing greenhouse gas emissions to levels suggested by the IPCC or the goal set by the European Union would be prohibitively expensive.*

If a rapid transition away from fossil fuels is physically impossible due to intermittency and the lack of surface space to accommodate wind turbines, solar panels, and biofuels, or too expensive owing to the trillions of dollars required to replace an energy system delivering energy 24/7 to a global population of 7.4 billion people and the higher levelized cost of electricity (LCOE) produced by alternatives to nuclear power and fossil fuels, what is the alternative? It is, as Clack *et al.* (2007) noted in the previous section, to "curtail load (i.e., modify or fail to satisfy demand) at times when energy is not available." As this section shows, reducing energy consumption would impose even larger social costs than substituting expensive alternatives for inexpensive fossil fuels.

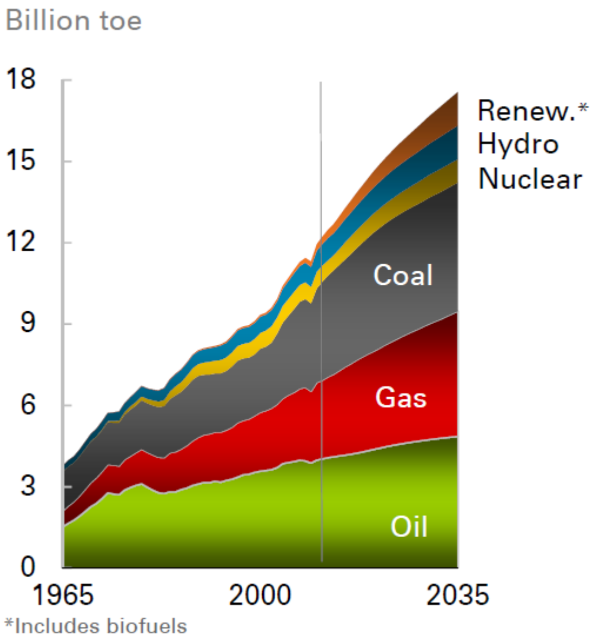
According to *BP Energy Outlook 2035* (BP, 2014[1]), primary energy demand is expected to increase by 41% between 2012 and 2035, with growth averaging 1.5% per annum (p.a.). Growth slows from 2.2% p.a. for 2005–15 to 1.7% p.a. 2015–25 and to just 1.1% p.a. in the final decade. Fossil fuels lose share but they are still the dominant form of energy in 2035 with a share of 81%, compared to 86% in 2012. See Figure 8.4.2.2.1.

Driving this growth in energy demand are rising global population and per-capita consumption. BP forecasts GDP growth (expressed in purchasing power parity (PPP)) averaging 3.5% p.a. from 2012 to 2035. Due to rising energy efficiency and the "dematerialization" trend described in Chapter 5, Section 5.2, energy intensity (the amount of energy required per unit of GDP) declines by 1.9% p.a., and about 36% between 2012 and 2035. BP forecasts the rate of decline in energy intensity post 2020 will be more than double the rate achieved from 2000 to 2010, resulting in a growing decoupling of GDP and energy consumption, as depicted in Figure 8.4.2.2.2.

Despite declining energy intensity, BP projects carbon dioxide (CO_2) emissions will continue to grow at approximately 1.1% p.a., only slightly slower than energy consumption, as shown in Figure 8.4.2.2.3. Figure 8.4.2.2.4 combines the trends shown in the three earlier figures with a common index (1990 = 100) for the x-axis.

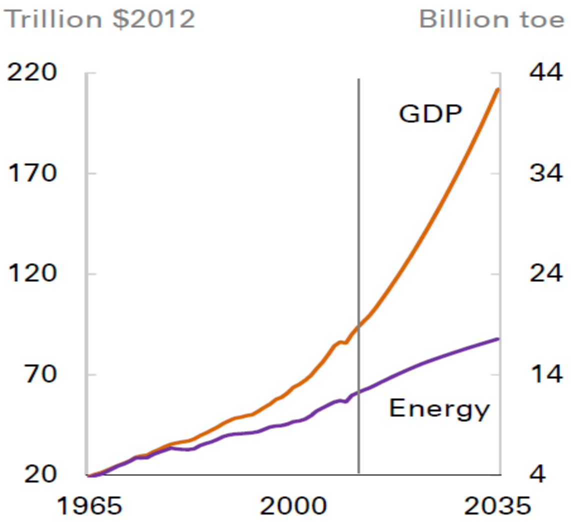
The U.S. Energy Information Administration (EIA) similarly forecasts the world's real GDP will increase 3.5% per year from 2010 to 2040 and world energy consumption will increase 56% between 2010 and 2040 (EIA, 2013, 2014). Like BP, EIA forecasts fossil fuels will continue to supply most of the energy used worldwide. See Figure 8.4.2.2.5.

Figure 8.4.2.2.1
Global energy consumption by type of fuel, actual and projected, in billion tons of oil equivalent (toe), 1965–2035



Source: BP, 2014, p. 12.

Figure 8.4.2.2.2
GDP and energy consumption, actual and projected, 1965–2035



Source: BP, 2014, p. 16.

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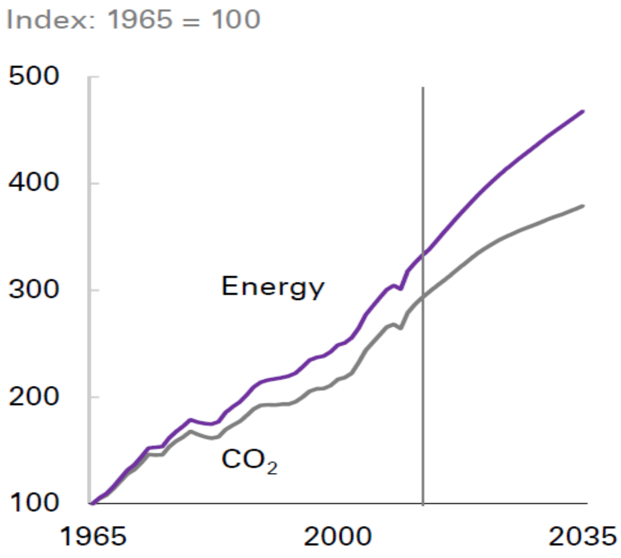
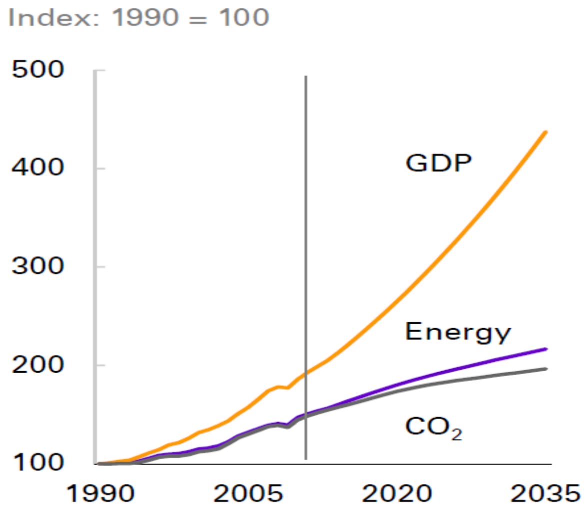
[1] This section cites the 2014 edition of BP's annual *Energy Outlook* even though more recent editions are available partly because it was the source cited in source material for this section (Bezdek, 2015) but also because subsequent editions incorporate assumptions about taxes and subsidies that recent political developments show are unlikely to be true. BP management apparently assumes international agreements such as the Paris Accord and national policies such as the U.S. Clean Power Plan will be implemented and massive subsidies to wind and solar power generation by China and Germany will continue, even though they already are being reduced. As described later in this section, even the 2014 edition used for this analysis assumes very optimistic rates of technological progress and decarbonization.

Figure 8.4.2.2.3
Energy consumption and CO_2 emissions, actual and projected, 1965–2035



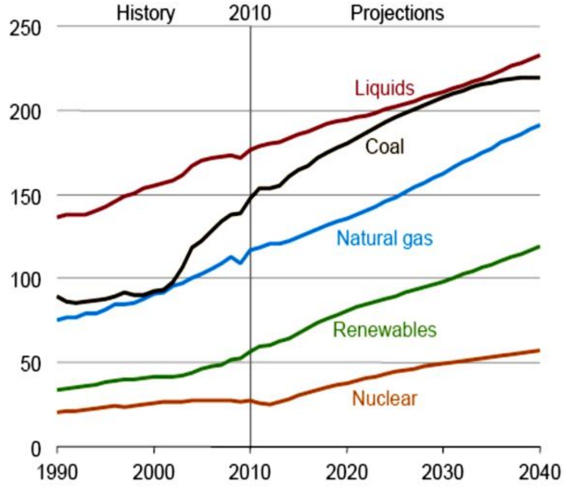
Source: BP, 2014, p. 20.

Figure 8.4.2.2.4
GDP, energy consumption, and CO_2 emissions, actual and projected, from 1990–2035



Source: BP, 2014, p. 88.

Figure 8.4.2.2.5
World energy consumption by fuel type, in quadrillion Btu, actual and projected, 1990–2040



Source: EIA, 2013, Figure 2, p. 2.

What does this tell us about the cost of reducing energy consumption as a way to reduce global GHG emissions in 2050 by 40% to 70% below 2010 levels and to "near zero $GtCO_2eq$ or below in 2100" (IPCC, 2014, p. 10, 12)? The relationship between world GDP and CO_2 emissions over the past century is illustrated in Figure 8.4.2.2.6. In 2010, expressed in 2007 dollars, a ton of CO_2 resulting from the use of fossil fuels "created" about $2,400 in world GDP.

Using BP and EIA's forecasts of GDP, energy use, and CO_2 emissions, Bezdek (2015) extended the relationship between world GDP and CO_2 emissions in the EIA reference case through 2050, with results shown in Figure 8.4.2.2.7. The relationship is forecast to be roughly linear, with an elasticity of 0.254 from 2020 to 2050. This is the CO_2-GDP elasticity rate, meaning reducing CO_2 emissions by 1% reduces GDP by 0.254%.

It merits emphasis that the EIA forecast already assumes world GDP will increase at a faster rate than primary energy consumption, and CO_2 emissions will increase at a lower rate than either GDP or energy consumption thanks to continued and even escalating government subsidies, favorable regulatory treatment, and tax breaks. Specifically, EIA projects:

- world GDP increases 3.6% annually,

- world primary energy consumption increases only 1.5% annually, and

- world CO_2 emissions increase only 1.3% annually.

This implies ambitious goals for technological advancements and public policies favorable to alternative energies are already incorporated into these forecasts, meaning even more programs aimed at speeding a transition to alternative fuels would be increasingly difficult and expensive. It also assumes, contrary to the analysis presented in Chapter 3 and earlier in this chapter, that alternative energies are able to produce enough dispatchable energy to replace fossil fuels at such an ambitious pace and beyond the 10% or 20% level beyond which the addition of intermittent energy begins to destabilize grids and impose large grid-management expenses. Different assumptions in the baseline projections would increase the cost estimates this model predicts, making this a very conservative model.

Figure 8.4.2.2.8 presents the independent variables and constants and calculates the impact on GDP and per-capita GDP of the IPCC's two reduction scenarios (of 40% and 70% below 2010 levels) and applying the European Union's goal of reducing emissions to 90% below 1990 levels to global emissions, rather than only to EU nations. Sources are presented in the note under the table. The impact on GDP can be summarized as follows:

- Reducing CO_2 emissions to 40% below 2010 levels by 2050 would reduce global GDP by 16%, to $245 trillion instead of the benchmark $292 trillion, a loss of $47 trillion.

- Reducing CO_2 emissions to 70% below 2010 levels by 2050 would reduce global GDP by 21%, to $231 trillion, a loss of $61 trillion.

- Reducing CO_2 emissions to 90% below 1990 levels would reduce global GDP by 24%, to $220 trillion, a loss of $72 trillion.

GDP losses can be converted into per-capita GDP numbers using the United Nations' 2017 population forecast for world population in 2050 of 9.8 billion (UN, 2017). The reference case forecast of world per-capita GDP in 2050 is about $29,800. As Figure 8.4.2.2.8 shows,

- Reducing CO_2 emissions to 40% below 2010 levels by 2050 would reduce average annual global per-capita GDP by 16%, to $24,959 instead of the benchmark $29,796, a loss of income of $4,837.

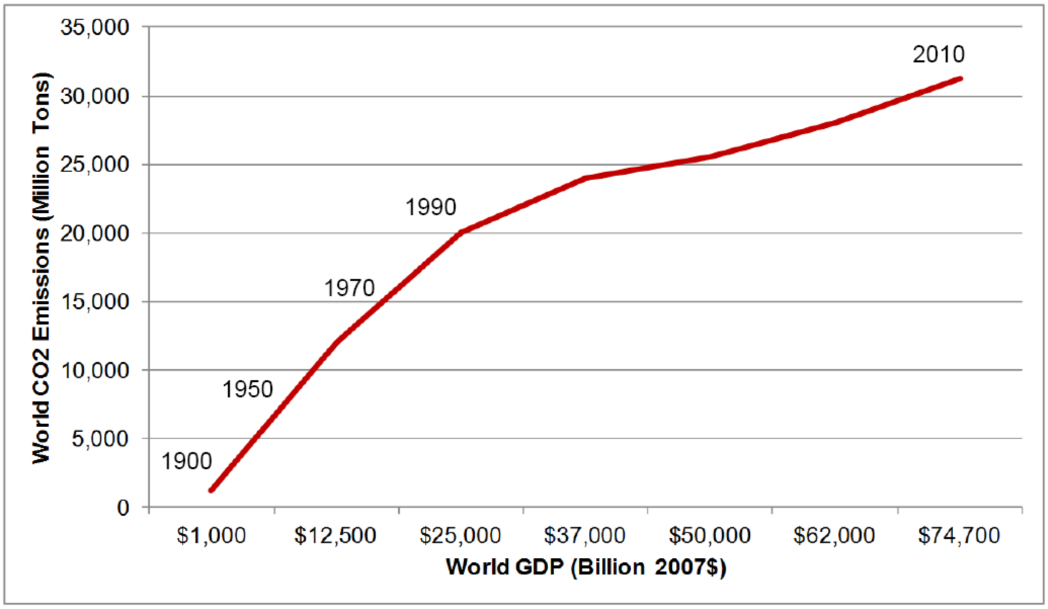
- Reducing CO_2 emissions to 70% below 2010 levels by 2050 would reduce global per-capita GDP by 21%, to $23,587, a loss of $6,209.

- Reducing CO_2 emissions to 90% below 1990 levels would reduce global per-capita GDP by 24%, to $22,531, a loss of $7,265.

These estimates assume alternatives to fossil fuels will be found that can supply enough energy, albeit at a higher cost, to meet the needs of a growing global population, albeit it once again at a lower level of prosperity than is currently being forecast. The analysis presented in Chapter 3 and again in the section preceding this one suggests this assumption is wrong. The need by intermittent energy sources such as wind and solar power for back-up power generation, which today can be provided in sufficient quantities only by fossil fuels, is unlikely to change enough to avert energy shortages, particularly in those countries that have chosen to abandon their coal, natural gas, and nuclear energy generation capacity.

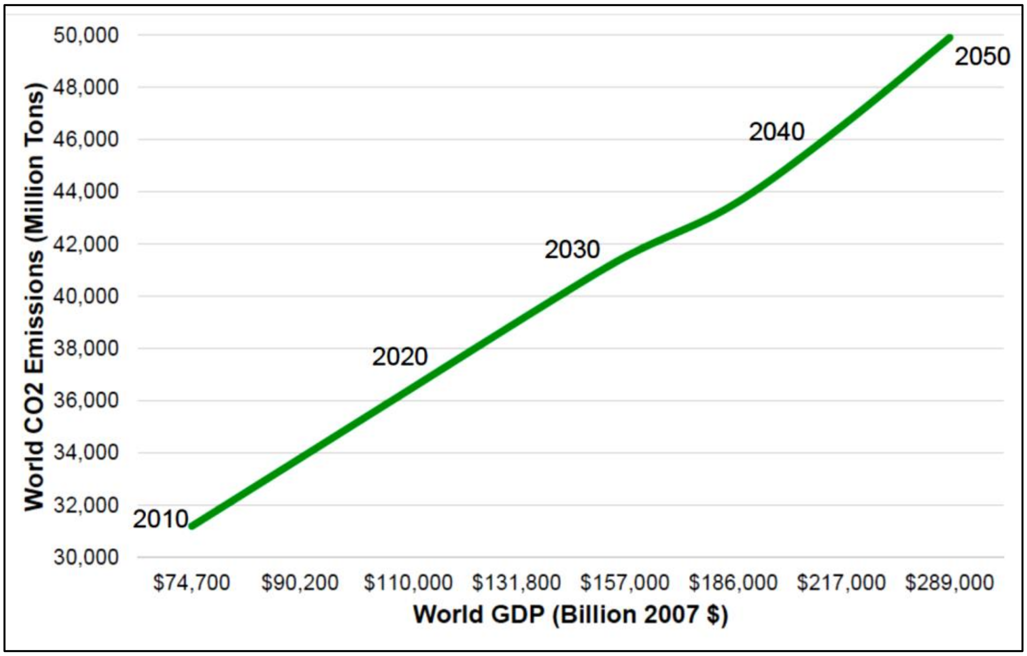
Recall from Chapter 3, Section 3.6.2, the calculation by Tverberg (2012), who sought to measure the lost GDP in 2050 resulting from the failure of renewable energies to offset the loss of 80% of the energy produced by fossil fuels, requiring a decrease in global energy consumption of 50%. She estimated the long-term elasticity of energy consumption (not fossil fuel use, the metric used in the preceding analysis) and GDP was 0.89. Among her findings: world per-capita energy consumption in 2050 would fall to what it was in 1905 and global per-capita GDP would decline by 42% from its 2010 level. Converting Tverberg's estimates into the outputs specified by the model developed in this section shows she forecast a reduction in GDP from our baseline projection of 81%; GDP in 2050 would be $54 trillion, a loss of $238 trillion; and per-capita income would be approximately $5,518. These figures appear in the bottom row of Figure 8.4.2.2.8.

Figure 8.4.2.2.6
Historical relationship between world GDP and CO_2 emissions, 1900–2010



Source: Bezdek, 2014.

Figure 8.4.2.2.7
Projected relationship between world GDP and CO_2 emissions, 2010–2050



Source: Bezdek, 2015.

Figure 8.4.2.2.8
Independent variables and constants for IPCC and EU 2050 mitigation targets

	Variables	**Beginning values**	**∆ from 2050 baseline**	**% less than 2050 baseline (BMT)**	**% reduction in 2050 GDP**	**2050 GDP (billion $)**	**Per-capita GDP**
UN	2050 population estimate (billion)	9.80	--	--	--	--	--
y_2	CO2 in 2020 (billion metric tons (BMT)	36.40	15	29.62%	--	--	--
y_1	CO2 in 2050 (BMT)	51.72	0	0.00%	--	--	--
x_2	GDP in 2020 (billion $)	$110,000	$182,000	62.33%	--	--	--
x_1	GDP in 2050 (billion $)	$292,000	0	0.00%	--	--	$29,796
Rise	$(y_2 - y_1) / y_2$	-42.09%	--	--	--	--	--
Run	$(x_2 - x_1) / y_2$	-165.45%	--	--	--	--	--
	Elasticity (rise / run)	0.254	--	--	--	--	--
	$/ton in 2050	$5,645.57	--	--	--	--	--
EIA	CO_2 emissions in 2010 (BMT)	31.20	20.52	39.68%	--	--	--
	$7/ton in 2010	$2,400	--	--	--	--	--
IPCC	CO_2 emissions 40% below 2010 CO_2 (BMT)	18.72	33.00	63.81%	16.23%	$244,599	$24,959
IPCC	CO_2 emissions 70% below 2010 CO_2 (BMT)	9.36	42.36	81.90%	20.84%	$231,156	$23,587
EIA	CO_2 emissions in 1990 (BMT)	21.50	30.22	58.43%	--	--	--
EU	CO_2 emissions 90% below 1990 CO_2 (BMT)	2.15	49.57	95.84%	24.38%	$220,800	$22,531
	50% reduction in global energy consumption	--	--	--	81.48%	$54,072	$5,518

2050 population estimate is from UN (2017); 2010 and 2020 CO_2 emission from EIA (2013); GDP forecast from World Bank (n.d.); 2050 CO_2 emission forecast from Bezdek (2015); IPCC emission reduction scenarios from Working Group III SPM pp. 10, 12 (IPCC 2014); EU emission reduction scenario is European Union nations only presented in EU (2012), projected to a global scenario. 50% reduction in global energy consumption scenario is from Tverberg (2012).

As catastrophic as these numbers appear to be, Tverberg believes her estimate is conservative, writing, “it assumes that financial systems will continue to operate as today, international trade will continue as in the past, and that there will not be major problems with overthrown governments or interruptions to electrical power. It also assumes that we will continue to transition to a service economy, and that there will be continued growth in energy efficiency.”

In conclusion, achieving the IPCC’s goal of reducing CO_2 emissions by between 40% and 70% from 2010 levels by 2050, the amount it believes would be necessary to keep global temperatures from increasing by more than 2°C above pre-industrial levels, would cost the world’s energy consumers at least $47 trillion to $61 trillion in lost goods and services (GDP) in the year 2050. Achieving the EU’s goal of reducing CO_2 emissions to 90% below 1990 levels by 2050 would cost at least $72 trillion that year. If renewables cannot completely replace the energy expected to be produced by fossil fuels in coming decades, the cost would skyrocket to $238 trillion. These are enormous numbers: the entire U.S. GDP in 2017 was only $19.4 trillion, and China's GDP was only $12.2 trillion. Would such a great loss of wealth be worthwhile? That is the topic of the next section.

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8.4.3 New Cost-Benefit Ratios

> *The evidence seems compelling that the costs of restricting use of fossil fuels greatly exceed the benefits, even accepting many of the IPCC's very questionable assumptions.*

According to the Working Group III contribution to the IPCC's Fifth Assessment Report, keeping average global surface temperature change to less than 2°C above its pre-industrial level by 2100 requires "lower global GHG emissions in 2050 than in 2010, 40% to 70% lower globally, and emissions levels near zero $GtCO_2eq$ or below in 2100" (IPCC, 2014a, pp. 10, 12). Without such reductions, "global mean surface temperature increases in 2100 from 3.7°C to 4.8°C compared to pre-industrial levels" (p. 8). Working Group III put the cost of reducing greenhouse gas emissions at 3.4% of GDP in 2050 (Table SPM.2, p. 15). Working Group II estimated the benefit of avoiding unmitigated climate change would be worth approximately 0.5% of GDP in 2050 (2050 (IPCC, 2014b, p. 663, and see Section 8.3.1 for discussion). The ratio of the two values suggests a cost-benefit ratio of 6.8:1 (3.4/0.5). This means reducing emissions would cost approximately seven times as much as the possible benefits of a slightly cooler world in 2050 and beyond. The IPCC itself makes a strong case *against* reducing emissions before 2050.

The IPCC's estimate of the benefit of avoiding ~ 2° C warming by 2050 can be compared to other estimates of the cost of reducing emissions to produce additional and more reliable cost-benefit ratios. Section 8.4.2.2 found a CO_2-GDP elasticity of 0.254, meaning for every 1% reduction in CO_{2eq} emissions between 2020 and 2050, GDP falls by 0.254%. This is the case even assuming rapid progress in technologies and a "de-coupling" of economic growth and per-capita energy consumption. Reducing emissions to 40% below 2010 levels would lower global GDP in 2050 by 16%; a 70% reduction would lower GDP by 21%; and a 90% below 1990 levels (the EU goal) would lower GDP by 24%. Tverberg found that if alternative energy sources were able to produce only 50% of the energy that would have been produced with the help of fossil fuels in 2050 – a reasonable scenario given the low density, intermittency, and high cost of fossil fuels – GDP would decline by a catastrophic 81%. Comparing these cost estimates to the possible benefit of avoiding a loss of 0.5% of annual global GDP in 2050, the IPCC's estimate of the benefits of mitigation, yields cost-benefit ratios of 32:1, 42:1, 48:1, and 162:1 respectively.

A third way to construct a cost-benefit ratio is to compare Bezdek's estimate of the GDP "created" by fossil fuels to the IPCC's and IWG's estimates of the "social cost of carbon" (SCC). According to Bezdek, in 2010 every ton of CO_2eq emitted "created" about \$2,400 in world GDP. The IPCC and IWG converge on an SCC of \$33 per ton of CO_2eq for 2010 assuming a 3% discount rate (IWG, 2013). Bezdek's estimate constitutes the opportunity cost of reducing emissions by one ton, while the IPCC's and IWG's estimate constitutes the possible social benefit of avoiding a 2°C warming by 2050. The ratio is 73:1 (2,400/33).

Bezdek estimates every ton of CO_2eq emitted in 2050 will "create" approximately \$5,645 in GDP. The IPCC doesn't offer an estimate of SCC for 2050, but the IWG does: \$71 at the 3% discount rate. (See Figure 8.1.3.2.) The ratio is 79:1 (5,645/71). In other words, the benefits of fossil fuels will exceed their social costs by a factor of 79 in 2050, *using the IWG's own SCC numbers.*

Replacing the IPCC's and IWG's inflated SCC estimates with the corrected estimates derived by Dayaratna *et al.* (2017) and reported in Section 8.3 would create even more lopsided cost-benefit ratios. An SCC near zero causes the cost-benefit ratio to become meaninglessly large and the net benefit of every ton of CO_2eq is approximately equal to \$2,400 in 2010 and \$5,645 in 2050.

Figure 8.4.3.1 summarizes the seven cost-benefit ratio analyses presented in this section.

Summarizing, the IPCC itself says the cost of reducing emissions enough to avoid more than a 2°C warming in 2050 will exceed the benefits by a ratio of approximately 6.8:1. The linear relationship between GDP and CO_2 emissions means attempting to avoid climate change by reducing the use of fossil fuels would cost between 32 and 48 times more than the IPCC's estimate of the possible benefit (measured as a percentage of GDP) of a cooler climate. If renewable energies are unable to entirely replace

Figure 8.4.3.1
Cost-benefit ratios of reducing CO_2eq emissions by 2050 sufficiently, according to IPCC, to prevent more than 2°C warming

	IPCC cost estimate (% of GDP)[a]	IPCC benefit estimate (% of GDP)[b]	NIPCC cost estimate (% of GDP)[c]	Bezdek cost estimate (SCC)[d]	IWG benefit estimate (SCC)[e]	Cost-benefit ratio
IPCC's cost-benefit ratio	3.4%	0.5%	--	--	--	6.8:1
NIPCC/IPCC cost-benefit ratio, 40% by 2050	--	0.5%	16%	--	--	32:1
NIPCC/IPCC cost-benefit ratio, 70% by 2050	--	0.5%	21%	--	--	42:1
NIPCC/IPCC cost-benefit ratio, 90% by 2050[f]	--	0.5%	24%	--	--	48:1
50% reduction in global energy consumption[g]	--	0.5%	81%	--	--	162:1
Bezdek/IWG SCC cost-benefit ratio 2010	--	--	--	\$2,400	\$33	73:1
Bezdek/IWG SCC cost-benefit ratio 2050	--	--	--	\$5,645	\$71	79:1

Sources: (a) IPCC, 2014b, cost of emission mitigation in 2050; (b) IPCC, 2014a, consumption loss avoided through emission mitigation, 1% is a single point estimate for model range of -1% – 1%, see Section 8.3.1 for discussion; (c) Lost GDP due to reduced energy consumption per Figure 8.4.2.2.8 (d) Bezdek, 2015, lost GDP divided by tons of CO_2eq mitigated; (e) IWG, 2013, estimate of SCC in 2010 and 2050 assuming 3% discount rate; (f) EU target using 1990 as baseline, extrapolated to reductions needed to achieve a national target; (g) Tverberg (2012).

fossil fuels, the cost could be 162 times more than the benefits. If we accept the IPCC's and IWG's estimates of the "social cost of carbon," the *benefits* of fossil fuels still exceed their social cost by ratios of 73:1 in 2010 and 79:1 in 2050.

In conclusion, the evidence seems compelling that the costs of restricting use of fossil fuels greatly exceed the benefits, even accepting many of the IPCC's very questionable assumptions.

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8.5 Regulations

Mitigation of global warming is attempted by many competing methods, including regulating or taxing profitable activities or commodities and subsidizing otherwise unprofitable activities or commodities. Cost-benefit analysis (CBA) can determine whether and by how much the benefits of a particular program exceed the costs incurred in implementing that program. Regulations can be ranked according to their cost-benefit ratios, revealing which programs produce the most benefits per dollar invested (Singer, 1979).

Since it is usually (and incorrectly) assumed there is an immediate need to act to save the planet from catastrophic global warming, real cost-benefit analyses of existing or proposed global warming mitigation strategies are seldom carried out. When they are, they generally rely on global climate models (GCMs) and integrated assessment models (IAMs), the flaws of which are described at length in Chapter 2, Section 2.5, and earlier in the current chapter.

Data and a methodology do exist, however, to produce fair, like-for-like, and transparent cost-effectiveness comparisons among competing mitigation strategies. A practicable metric was proposed by Christopher Monckton of Brenchley at international conferences in 2010, 2011, and 2012 and published in 2013 after peer review by the World Federation of Scientists and in 2016 as a chapter in *Evidence-based Climate Science* (Monckton, 2013, 2016). The remainder of this section presents a slightly revised and updated version of the 2016 publication.

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8.5.1 Common Variables

Nine independent variables and constants common to all mitigation-cost assessments appear in Figure 8.5.1.1. Their derivations are presented in the sections below.

The observed rate of global warming from 1979 to 2017, taken as the least-squares linear-regression trend on the mean of the HadCRUT4 terrestrial surface and UAH satellite lower-troposphere datasets

(Morice *et al.*, 2012, updated; UAH, 2018), is equivalent to 1.5 K per century, little more than one-quarter of the 5.7 K per century upper-bound warming rate imagined by Stern. (See Figure 8.5.1.2.) This implies the notion of a 10% probability that global warming will destroy the Earth by 2100 may be dismissed as mere rhetoric. Application of such low discount rates on the grounds of "intergenerational equity" unduly favors investment in mitigation as against doing nothing now and adapting later. As President Vaclav Klaus of the Czech Republic explained in a lecture at Cambridge, "By assuming a very low (near-zero) discount rate, the proponents of the global-warming doctrine neglect the issues of time and of alternative opportunities. Using a low discount rate in global warming models means harming current generations vis-à-vis future generations. Undermining current economic development harms future generations as well" (Klaus 2011).

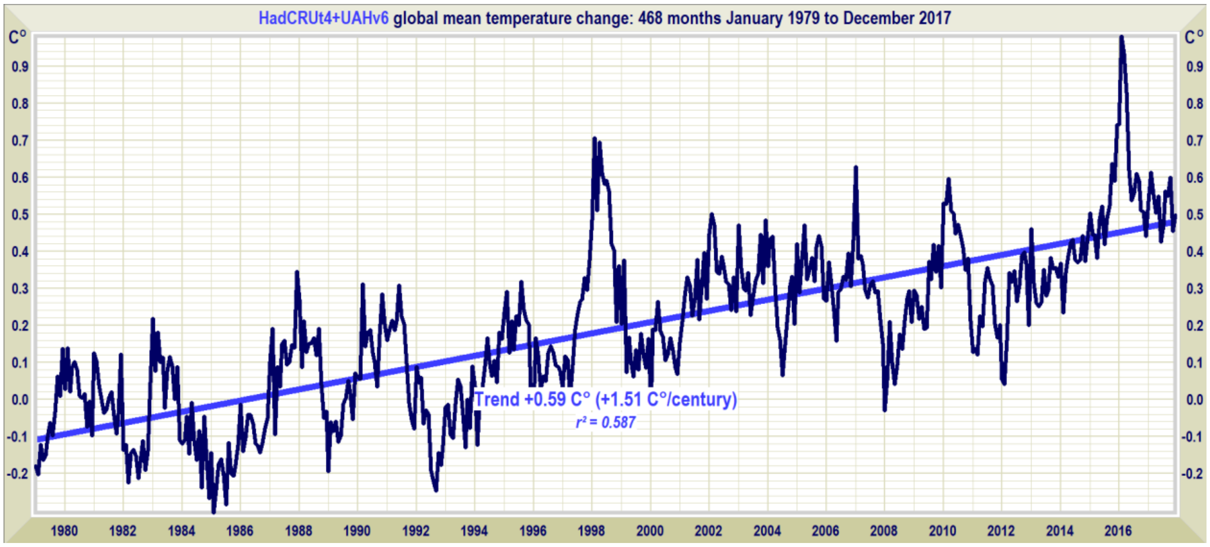
The U.S. Environmental Protection Agency (EPA) adopts as its starting point a somewhat more reasonable 3% intertemporal discount rate, still less than half the U.S. Office of Management and Budget (OMB) recommended discount rate of 7% for intertemporal appraisal of public-sector investments. However, the EPA also adopts a device for which there is little rational justification: It arbitrarily assumes the value of every human life on the planet increases by 2.75% per year. This allows the EPA to conduct its intertemporal appraisals on the basis of a 0.25% discount rate. At the time of writing, EPA is inviting expert comment on its investment appraisal method.

Figure 8.5.1.1
Independent variables and constants for all mitigation strategies

y	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
Annual real global GDP ($ trillion) assuming 3% p.a. growth											
g_m	**44.7**	**60.0**	**80.6**	**108**	**146**	**196**	**263**	**354**	**475**	**638**	**858**
Cumulative real global GDP ($ trillion) assuming 3% p.a. growth											
$g_{m_{\text{cum}}}$	**44.7**	**409**	**658**	**828**	**944**	**1023**	**1077**	**1114**	**1140**	**1157**	**1169**
Discounted cost of inaction (% GDP) to year y											
Z_m	**3.0**	**2.05**	**1.40**	**0.96**	**0.65**	**0.45**	**0.31**	**0.21**	**0.14**	**0.10**	**0.07**
Transient sensitivity parameter ($\text{K W}^{-1}\text{ m}^2$) including feedback											
λ_{tra_y}	**0.30**	**0.31**	**0.32**	**0.33**	**0.34**	**0.35**	**0.36**	**0.37**	**0.38**	**0.39**	**0.40**
Predicted business-as-usual CO_2 concentration (ppmv) in year y											
C_y	**368**	**392**	**418**	**446**	**476**	**508**	**541**	**577**	**616**	**656**	**700**
Global population (billions)											
w	**7.0**	**7.5**	**8.0**	**8.6**	**9.2**	**9.9**	**10.6**	**11.4**	**12.2**	**13.1**	**14.0**

Constant	Value	Description
ΔT_{Cha}	$\mathbf{3.35\ K}$	Charney sensitivity to doubled CO_2 (CMIP5)
d	**7%**	OMB required discount rate
q	$\mathbf{0.734}$	Fraction of anthropogenic forcing arising from CO_2
k	**5**	Coefficient in the CO_2 forcing function
ΔQ_C	$\mathbf{3.464\ W\ m^{-2}}$	Radiative forcing from doubled CO_2
λ_P	$\mathbf{0.3\ K\ W^{-1}\ m^{2}}$	Planck (zero-feedback) sensitivity parameter

Figure 8.5.1.2
Global surface temperature anomalies and trend, 1979–2017 (mean of HadCRUT4 & UAH)



On the grounds of intergenerational equity one should not harm future generations by adopting the device of a sub-market discount rate such as that of Stern, still less that of the EPA. Instead, one should adopt, as Murphy (2008) and Nordhaus (2008) conclude, the minimum reasonable discount rate of 5% or better, the OMB's 7% rate, just as one would adopt it for any commercial investment appraisal.

8.5.1.2 Global GDP g and its growth rate

Since the cost of mitigating future anthropogenic warming is very large, it is generally expressed as a fraction of global gross domestic product (GDP), the total annual output of all of humanity's endeavors, enterprises, and industries. Global GDP g is taken as \$60 trillion in 2010 (World Bank, 2011), growing at 3% year^{-1} (3% per year). See Figure 8.5.1.1 for twenty-first-century values.

8.5.1.3 The cost Z of climate inaction

A predicted cost of climate inaction Z over a term t of years $1 \le a \le t$ is generally expressed as a percentage of GDP. Eq. 8.5.1 converts such a cost Z_s derived on the basis of a suspect or submarket discount rate d_s to the equivalent mitigation cost Z_m derived on the basis of a mainstream or midmarket discount rate d_m. Here, the annual percentage GDP growth rate r will be assumed to be 3%.

$$Z_m = Z_s \frac{\sum_{a=1}^{t} \left(\frac{1 + r/100}{1 + d_m/100}\right)^a}{\sum_{a=1}^{t} \left(\frac{1 + r/100}{1 + d_s/100}\right)^a} \qquad \text{(Eq. 8.5.1)}$$

For instance, Stern's mid-range inaction cost Z_s, amounting to 3% of GDP across the entire twenty-first century derived on the basis of his 1.4% submarket discount rate and the assumption of 3 K global warming by 2100, falls by nine-tenths to just 0.3% of GDP when rebased on the U.S. OMB's 7% discount rate using Eq. 8.5.1.

Furthermore, Stern made no allowance for the fact that no welfare loss arises from global warming of less than 2 K above pre-industrial temperature, equivalent to 1.1 K above the temperature in 2000. On Stern's mid-range assumption of 3 K twenty-first-century warming, and assuming a uniform twenty-first-century warming rate, no welfare loss would arise until 2038, so that at the U.S. OMB's 7% discount rate the cumulative welfare loss arising from total climate inaction would fall to less than 0.1% of GDP.

8.5.1.4 Charney sensitivity ΔT_{Cha}

The standard metric for projecting anthropogenic global warming is Charney sensitivity ΔT_{Cha}; i.e., climate sensitivity to a doubling of atmospheric CO_2 concentration. Charney (1979) held that his eponymous sensitivity was $3.0\ [1.5, 4.5]$ K, the value adopted by IPCC (1990) and, with little change, in all subsequent Assessment Reports. In the third-generation (CMIP3) and fifth-generation (CMIP5) models of the Climate Model Intercomparison Project, Charney sensitivity was thought to be $3.35\ [2.1, 4.7]$ K (Andrews *et al.*, 2012). Predicted global warming from all anthropogenic sources over the twenty-first century tends to be approximately equal to Charney sensitivity. Here, the CMIP3/5 mid-range estimate 3.35 K will be assumed *arguendo* to be normative.

8.5.1.5 The CO_2 fraction q

IPCC (2013, Fig. SPM.5) finds that, of the $2.29\ \mathrm{W\,m^{-2}}$ net anthropogenic forcing to 2011, $1.68\ \mathrm{W\,m^{-2}}$ is attributable to CO_2. Accordingly, the CO_2 fraction $q = 1.68/2.29 = 0.734$.

8.5.1.6 The CO_2 radiative forcing ΔQ_C

Andrews *et al.* (2012), reviewing an ensemble of two dozen CMIP5 models, provides data on the basis of which one may conclude that the radiative forcing ΔQ_C in response to doubled CO_2 concentration is $3.464\ \mathrm{W\,m^{-2}}$. On the interval of interest, the CO_2 forcing function is approximately logarithmic. Thus, $\Delta Q_C = k \ln(C_1/C_0)$, where C_0 is the unperturbed concentration (Myhre *et al.*, 1998; IPCC, 2001, Section 6.1). Thus, $k = 3.464/\ln 2 = 5$.

8.5.1.7 The Planck sensitivity parameter λ_P

The Planck sensitivity parameter λ_P, the quantity by which a radiative forcing ΔQ_E in Watts per square meter is multiplied to yield a temperature change ΔT_S before accounting for temperature feedback, is the first derivative $\Delta T_S/\Delta Q_E = T_S/(4Q_E)$ of the fundamental equation of radiative transfer. Surface temperature $T_S = 288.4$ K (ISCCP, 2018). Given total solar irradiance $S_0 = 1364.625\ \mathrm{W\,m^{-2}}$ (Mekaoui *et al.*, 2010) and albedo $\alpha = 0.293$ (Loeb *et al.*, 2009), radiative flux density $Q_E = S_0(1 - \alpha)/4 = 241.2\ \mathrm{W\,m^{-2}}$ at the mean emission altitude. Therefore, λ_P is today equal to $0.30\ \mathrm{K\,W^{-1}\,m^2}$ (Schlesinger, 1985).

8.5.1.8 The transient-sensitivity parameter λ_{tra}

IPCC (2007, Table SPM.3) gives predicted transient anthropogenic forcings ΔQ_{tra} and warmings ΔT_{tra} from 1900 to 2100 for six scenarios. On all six scenarios, the bicentennial transient-sensitivity parameter λ_{bi}, which exceeds λ_P to the extent that some temperature feedbacks have acted, is $0.5\ \mathrm{K\,W^{-1}\,m^2}$ (see IPCC 2001, p. 354, citing Ramanathan, 1985).

An appropriate twenty-first-century centennial value λ_{tra} is the mean of λ_P and λ_{bi}; i.e., $0.4\ \mathrm{K\,W^{-1}\,m^2}$, in agreement with Garnaut (2008), who wrote of keeping greenhouse-gas increases to 450 ppmv CO_2 equivalent above the 280 ppmv prevalent in 1750 with the aim of holding twenty-first-century global warming to 2 K, implying $\lambda_{\text{tra}} = 0.4\ \mathrm{K\,W^{-1}\,m^2}$. Values of ΔT_{tra} implicit in this value of λ_{tra} are shown in Figure 8.5.1.1.

8.5.1.9 Global population w

Global population w is here taken as 7 billion (bn) in 2000, rising exponentially to 14 bn in 2100.

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8.5.2 Case-specific variables

Only three case-specific inputs are required and are described below.

8.5.2.1 The discounted cost X_m

The cost X_m of a given mitigation strategy is discounted to present value at the chosen market intertemporal discount rate d_m.

8.5.2.2 The business-as-usual CO_2 concentration C_y

The currently predicted business-as-usual CO_2 concentration C_y in the target final year y_2 of any existing or proposed mitigation strategy is given in Figure 8.5.1.1, allowing ready derivation of an appropriate value for any year of the twenty-first century. CO_2 concentration in the twenty-first century is extrapolated from trends in Tans (2011) and Conway & Tans (2011) according to the mid-range estimates in IPCC (2007, 2013), by which CO_2 increases exponentially from 368 ppmv in 2000 to 700 ppmv in 2100.

This value is the benchmark against which any foreseeable reduction in CO_2 concentration achieved by the mitigation strategy is measured. It will be seen from the case studies that such reductions are in practice negligible.

8.5.2.3 The fraction p of global business-as-usual CO_2 emissions the strategy will abate

The fraction p of projected global business-as-usual CO_2 emissions until year y_2 that will be abated under the (usually generous) assumption that the strategy will work as advertised is an essential quantity that is seldom derived in any integrated assessment model.

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8.5.3 Outputs

A robust cost-benefit model comprising a system of simple equations informed by the independent variables described in Sections 8.5.1 and 8.5.2 may readily be applied to any given mitigation strategy. The model can produce three outputs.

8.5.3.1 The unit mitigation cost M

Unit mitigation cost M is here defined as the cost of abating 1 K global warming on the assumption that all measures to abate anthropogenic warming to year y have a cost-effectiveness identical to the strategy under consideration.

8.5.3.2 Global abatement cost H per capita and J as % GDP.

On the same assumption, the strategy's global abatement cost is the total cost of abating all predicted global warming ΔT_{C21} (see Figure 8.5.1.1) over the term t from year y_1 to year y_2. This global abatement cost may be expressed in three ways: as a global cash cost X_d, as a cost H per head of global population, and as a percentage J of global GDP over the term t.

8.5.3.3 The benefit/cost or action/inaction ratio A

Finally, the benefit/cost or action/inaction ratio A of the chosen mitigation strategy is the ratio of the GDP cost J of implementation to the GDP cost Z_d of inaction now and adaptation later.

8.5.4 Cost-benefit Model

The purpose of the model is to give policymakers unfamiliar with climatology a simple but focused and robust method of answering two questions: how the cost of an existing or proposed mitigation strategy compares with those of competing strategies, and whether that cost exceeds the cost of not mitigating global warming at all.

The model comprises the following sequence of equations designed to be readily programmable. The model is so simple that it can be run on a pocket calculator. Yet, because it is rooted in mainstream climate science, it will give a more focused and reliable indication of the costs and benefits of individual mitigation strategies than any integrated assessment model.

Where p, on $[0, 1]$, is the fraction of future global emissions that a mitigation strategy is projected to abate by a target calendar year y_2, and C_{y2} is the IPCC's projected unmitigated CO_2 concentration in year y_2, model Eq. M1 gives C_{mit}, the somewhat lesser concentration in ppmv that is expected to obtain in year y_2 if the strategy is successfully followed.

$$C_{\text{mit}} = C_{\text{y2}} - p(C_{\text{y2}} - C_{\text{y1}}) \qquad \text{M1}$$

The CO$_2$ forcing equation is model Eq. M2, where C_0 is the unperturbed concentration.

$$\Delta Q_C = k\ln(C_1/C_0) = 5\ln(C_1/C_0). \qquad \text{M2}$$

Accordingly, the CO$_2$ forcing ΔQ_{aba} abated by the chosen strategy is given by Eq. M3.

$$\Delta Q_{\text{aba}} = 5\ln(C_{y2}/C_{\text{mit}}). \qquad \text{M3}$$

Then the global warming abated by the mitigation strategy to the final year y_2 is given by Eq. M4.

$$\begin{aligned}\Delta T_{\text{aba}} &= \lambda_{\text{tra}_{y2}}\, k\,[\ln(C_{y2}/C_{y1}) - \ln(C_{\text{mit}}/C_{y1})] \qquad \text{M4}\\ &= 5\,\lambda_{\text{tra}_{y2}}\,\ln(C_{\text{y2}}/C_{\text{mit}}).\end{aligned}$$

The unit mitigation cost M is given by Eq. M5, and the predicted global warming ΔT_{y2} over the term is given by Eq. M6,

$$M = X_m/\Delta T_{\text{aba}}; \qquad \text{M5}$$

$$\Delta T_{y2} = 5\,\lambda_{\text{tra}_{y2}}\ln(C_{y2}/C_{y1}). \qquad \text{M6}$$

The global abatement costs G in cash, H per capita and J as a percentage of global GDP of abating all predicted global warming ΔT_{y2} over the term t of the strategy are given by Eqs. M7–M9, where w is global population, G is the real cumulative discounted cost of abating ΔT_{y2}, and Z_m is the real cumulative discounted cost of inaction over the same term.

$$G = M\,\Delta T_{y2}. \qquad \text{M7}$$

$$H = G/w. \qquad \text{M8}$$

$$J = 100\,G/Z_m. \qquad \text{M9}$$

Finally, the benefit-cost or action-inaction ratio A is given by Eq. M10, where A is the ratio of the cumulative discounted GDP cost J of the strategy over the term to the cumulative discounted cost of inaction as a percentage of GDP over the term.

$$A = J/Z_m. \qquad \text{M10}$$

8.5.5 Model Applied

8.5.5.1 2009 U.S. Cap-and-Trade Bill

In the United States in 2009, Democrats tried and failed to pass a “cap-and-trade” bill (HR 2454, SB 311) its sponsors said would cost \$180 bn per year for 40 years, or \$7.2 tn in all, which is here discounted by 7% yr^{-1} to \$2.6 tn at present value. The stated aim of the bill was to abate 83% of U.S. CO$_2$ emissions by 2050. Since the U.S. emitted 17% of global CO$_2$ at the time (derived from Olivier and Peters, 2010, Table A1), the fraction of global CO$_2$ emissions abated would have been 0.14. The business-as-usual CO$_2$ concentration in 2050 would be 508 ppmv without the bill and 492 ppmv (from Eq. M1) with it, whereupon radiative forcing abated would have been 0.16 W m^{-2} (Eq. M3) and global warming abated over the 40-year term would have been less than 0.06 K (Eq. M4).

Accordingly, the unit cost of abating 1 K global warming by measures of cost-ineffectiveness equivalent to the bill would have been equal to the ratio of the discounted cost to the warming averted; i.e., \$46 tn K^{-1} per Kelvin (Eq. M5). Therefore, the cash cost of abating all of the predicted 0.44 K global warming (Eq. M6) from 2011 to 2050 would have been more than \$20 tn; or more than \$2000 per head of global population, man, woman, and child; or 3.3% of cumulative discounted global GDP over the term. The action/inaction ratio would then be the ratio of the 3.3% GDP cost of action to the 0.45% GDP cost of inaction to 2050, i.e. 7.4: 1. Implementing the cap-and-trade bill, or measures of equivalent unit mitigation cost, would have been almost seven and a half times costlier than the cost of doing nothing now and adapting to global warming later – always supposing that the cost of any such adaptation were to exceed the benefit of warmer weather and more CO$_2$ fertilization worldwide.

Additional case studies are briefly summarized in Sections 8.5.5.2–8.5.5.9. Section 8.5.6 draws lessons from the results delivered by the cost-benefit model.

8.5.5.2 The UK’s Climate Change Act

In 2008, the British parliament approved the Climate Change Act of 2008. The cost stated in the government’s case was \$39.4 bn yr^{-1} for 40 years, which, discounted at 7% yr^{-1} to present value, would be \$526 bn. The aim was to cut national emissions by 80% over the term.

Since UK emissions are only 1.5% of global emissions, the fraction of global emissions abated will be 0.012. CO_2 concentration by 2050 would have been 508 ppmv without the bill and will be 506 ppmv with it. Anthropogenic forcing abated over the term will be $0.013\ \mathrm{W\,m^{-2}}$, and warming abated will be 0.005 K. Unit mitigation cost will thus be \$526 bn / 0.005, or $\$112\ \mathrm{tn\,K^{-1}}$. The cash cost of abating all of the predicted 0.44 K warming over the term will be \$49.5 tn; the cost per head of global population will be \$5000, or 8% of GDP over the term. The action-inaction ratio is 18: 1.

8.5.5.3 *The European Union's carbon trading scheme*

EU carbon trading costs $\$92\ \mathrm{bn\,yr^{-1}}$ (World Bank 2009, p. 1), here multiplied by 2.5 (implicit in Lomborg, 2007) to allow for numerous non-trading mitigation measures. Total cost is \$2.3 tn over the 10-year term to 2020, or \$1.6 tn at present value. The declared aim of the EU scheme was to abate 20% of member states' emissions, which were 13% of global emissions (from Boden *et al.*, 2010a, 2010b). Thus, the fraction of global emissions abated will be 0.026. CO_2 emissions in 2020 will be 419 ppmv without the EU scheme and 418 ppmv with it. Radiative forcing abated is thus just $0.007\ \mathrm{W\,m^{-2}}$, and warming abated is 0.002 K.

Accordingly, the unit mitigation cost of the EU's carbon trading scheme is $\$690\ \mathrm{tn\,K^{-1}}$, and the cash cost of abating the < 0.1 K warming predicted to occur over the 10-year term is \$64 tn; or \$8000 per head of global population; or 26% of global GDP. Acting on global warming by measures of equivalent unit mitigation cost would be 18 times costlier than doing nothing now and adapting later.

8.5.5.4 *California's cap-and-trade Act*

Under AB32 (2006), which came fully into effect in 2012, some $\$182\ \mathrm{bn\,yr^{-1}}$ (Varshney and Tootelian, 2009) will be spent in the 10 years to 2021 on cap and trade and related measures. The gross cost is thus \$1.8 tn, discounted to \$1.3 tn. California's stated aim was to reduce its emissions, which represent 8% of U.S. emissions, by 25%. U.S. emissions at the beginning of the scheme were 17% of global emissions: thus, the fraction of global emissions abated will be 0.0033. CO_2 concentration will fall from a business-as-usual 421 ppmv to just under 421 ppmv by 2021. Anthropogenic forcing abated will be $0.001\ \mathrm{W\,m^{-2}}$, and warming abated will be less than one-thousandth of a Kelvin.

Accordingly, unit mitigation cost of California's cap-and-trade program will approach \$4 quadrillion per °K of global warming avoided; cost per head will be \$43,000, or almost 150% of global GDP over the term. It will be well more than 100 times costlier to mitigate global warming by measures such as this than to take no measures at all and adapt to such warming as may occur.

8.5.5.5 *The Thanet wind array*

Subsidy to one of the world's largest wind turbine installations, off the English coast, is guaranteed at \$100 million annually for its 20-year lifetime; i.e. \$1.06 bn at present value. Rated output of the 100 turbines is 300 MW, but such installations yield only 24% of rated capacity (Young, 2011, p. 1), so total output, at 72 MW, is only 1/600 of mean 43.2 GW UK electricity demand (Department for Energy and Climate Change, 2011). Electricity accounts for one-third of U.K. emissions, which represent 1.5% of global emissions. Therefore, the fraction of global emissions abated over the 20-year period will be 8.333×10^{-6}. Business-as-usual CO_2 concentration in 2030 would be 446.296 ppmv without the array, falling to 446.2955 ppmv with it. Forcing abated is $0.000005\ \mathrm{W\,m^{-2}}$, so that warming abated is less than 0.000002 K.

Accordingly, the unit mitigation cost of the Thanet wind array is $\$670\ \mathrm{tn\,K^{-1}}$. To abate the predicted 0.2 K warming over the 20-year term, the cost in cash would be \$135 tn; per head \$16,000; and almost one-third of global GDP over the term. It would be 34 times costlier to act on global warming than to do nothing today and adapt later.

8.5.5.6 *Australia's carbon trading scheme*

Australia's 2011 Clean Energy Act cost $\$10.1\ \mathrm{bn\,yr^{-1}}$, plus $\$1.6\ \mathrm{bn\,yr^{-1}}$ for administration (Wong 2010, p. 5), plus $\$1.2\ \mathrm{bn\,yr^{-1}}$ for renewables and other costs, a total of $\$13\ \mathrm{bn\,yr^{-1}}$, rising at $5\%\ \mathrm{yr^{-1}}$, giving a total discounted cost of \$117 bn at present value. The stated aim of the legislation was to reduce Australia's CO_2 emissions by 5% over the term. Australia's emissions represent 1.2% of global emissions (derived from Boden and Marland, 2010; Boden *et al.*, 2010). Thus the fraction of global emissions abated is 0.0006. CO_2 concentration would fall from a business-as-usual 418.5 ppmv without the Australian scheme to 418.49 ppmv with it, so that warming of 0.00005 K would be abated.

The unit mitigation cost of Australia's carbon trading scheme would be \$2.2 quadrillion per Kelvin. To abate the 0.1 K warming predicted for the period (the warming did not occur) would be \$201 tn. The cost per head would exceed \$25,000, or 81% of global GDP throughout the term. The cost of acting on climate change by measures such as Australia's scheme would approach 60 times that of inaction.

8.5.5.7 Gesture politics 1: a wind turbine on an elementary school roof in England

On March 31, 2010, Sandwell Council in England answered a freedom-of-information request (McCauley, 2011) by disclosing that it had spent £5875 (\$7730) on buying and installing a small wind turbine capable of generating 209 KWh in a year – enough to power a single 100 W reading-lamp for less than three months. The fraction of UK emissions abated by the wind turbine is 33% of 209 KWh / 365 days / 24 hr / 43.2 GW, or 0.00000002%, and, since UK emissions are only 1.5% of global emissions, the fraction of global emissions abated is less than 0.000000000003. Forcing abated is $< 0.000000000002\ \mathrm{W\,m^{-2}}$. Warming abated is 0.0000000000005 K.

The unit mitigation cost of a wind turbine on an elementary school roof in England is \$14.5 quadrillion per Kelvin. To abate all of the 0.2 K global warming predicted to occur over the 20-year life of the wind turbine, the cost is \$3 quadrillion, or \$340 tn per head, or 700% of GDP. Action costs more than 730 times inaction.

8.5.5.8 Gesture politics 2: Maryland's 90% cut in CO_2 emissions

In the United States, the state of Maryland's government decided that from 2011 to 2050 it would reduce its CO_2 emissions by 90% at a discounted cost of \$7.3 tn, about three times the discounted cost of the rejected national cap-and-tax scheme over the same period. The reduction would have amounted to 1.5% of national emissions, which are 17% of global emissions. Therefore, the fraction of global emissions abated is 0.0025. The predicted business-as-usual CO_2 concentration of 507.55 ppmv would fall to 507.25 ppmv. Radiative forcing abated is less than $0.003\ \mathrm{W\,m^{-2}}$, and warming abated is 0.001 K.

The unit mitigation cost is \$7.3 quadrillion. The cost of abating the predicted 0.44 K global warming over the period is \$3 quadrillion, or \$320,000 per head of global population, or well more than 500% of global GDP over the period. Attempted mitigation by measures as costly as Maryland's scheme would be 1150 times costlier than inaction today and adaptation later.

8.5.5.9 Gesture politics 3: The London bicycle-hire scheme

Perhaps the costliest measure ever adopted in the name of abating global warming was the London bicycle-hire scheme, which cost \$130 bn upfront, together with large annual maintenance costs that are not included here, for just 5000 bicycles – a cost of \$26,000 per bicycle. Transport represents 15.2% of UK emissions (from Office for National Statistics, 2010, Table C). Cycling represents 3.1 bn of the 316.3 bn vehicle miles traveled on UK roads annually (Department for Transport, 2011). There are 23 million bicycles in use in Britain (Cyclists' Touring Club, 2011).

Global emissions will be cut by 1.5% of 15.2% of $3.1/316.3 \times 5000/23{,}000{,}000$. Thus the fraction of global emissions abated will be 4.886×10^{-9}. If the lifetime of bicycles and docking stations is 20 years, business-as-usual CO_2 concentration of 446.296 ppmv will fall to 446.2989 ppmv through the scheme. Forcing abated is $0.000000003\ \mathrm{W\,m^{-2}}$; warming abated is $0.000000001\ K$; unit mitigation cost exceeds \$141 quadrillion per Kelvin abated; and the cash global abatement cost of \$28.5 quadrillion is \$3.3 million per head, or almost 7000% of global GDP to 2030. Action costs more than 7000 times inaction.

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8.5.6 Results Discussed

For the sake of simplicity and accessibility, the focus of the method is deliberately narrow. Potential benefits external to CO_2 mitigation, changes in global warming potentials, variability in the global GDP growth rate, or relatively higher mitigation costs in regions with lower emission intensities are ignored, for little error arises. GDP growth rates and climate-inaction costs are assumed uniform, though in practice little climate-related damage would arise unless global temperature rose by at least 1 K above today's temperatures. Given the small amount of warming abated by CO_2-reduction strategies, as well as the breadth of the intervals of published estimates of inaction and mitigation costs, modeling non-uniform GDP growth rates and climate-inaction costs may in any event prove irrelevant.

Government predictions of abatement costs (cases 1 and 2) are of the same order as those in Stern (2006) and Garnaut (2008) and the reviewed literature. However, the costs of specific measures (cases 3 through 6) prove significantly higher than official predictions. Gesture policies (cases 7 through 9) are absurdly costly and are studied here because there are so many of them. These results indicate there is no rational economic case for global warming mitigation. The arguments for mitigation are, therefore, solely political.

Mitigation is so much costlier than adaptation that real and substantial damage is being done to Western economic interests. Though the cost-benefit model concentrates exclusively on the direct costs and benefits of specific mitigation strategies, it should be understood that there are very heavy costs (but very few and very small benefits) not included in this analysis. All industries suffer by the doubling and tripling of electricity and gasoline prices allegedly in the name of abating global warming. Given that the raw material costs of coal, oil, and gas have halved in recent decades, electricity prices should have fallen commensurately. Instead, almost entirely owing to global warming mitigation policy, they have risen, and are now perhaps five times what they would be in a free market. Likewise, no account has been taken of such real and substantial indirect costs as the need for spinning-reserve backup for wind turbines and solar panels.

Further, no account has been taken of the considerable economic damage done by excessive electricity prices. Certain energy-intensive industries, such as aluminum smelting, will soon be extinct in the West. Britain's last aluminum smelter was closed some years ago owing to the government-mandated, global-warming-policy-driven cost of power, even though the facility was powered by its own hydroelectric generating station. Aluminum smelters in Australia are also under direct threat.

The results from the cost-benefit model show very clearly why mitigation of global warming is economically unjustifiable. The impact of any individual mitigation strategy on CO_2 emissions is so minuscule as to be in most cases undetectable, yet the cost of any such strategy is very large. Accordingly, CO_2 mitigation strategies inexpensive enough to be affordable will be ineffective, while strategies costly enough to be effective will be unaffordable.

The results from the model would lead us to expect that, notwithstanding the squandering of trillions in taxpayers' and energy-users' funds by national governments and, increasingly, by global warming profiteers, mitigation strategies have had so little effect that the global mix of primary energy sources for power generation is unlikely to have changed much. Sure enough, coal, the primary target of the war on fossil fuels, had a 38% global market share in 1997 and has a 38% market share today, not least because, while the West cripples its economies by closing coal-fired power stations, China alone opens at least as many new power stations per month as the West closes. (See Figure 8.5.6.1.) China's CO_2 emissions per capita are now as high as in Western countries: yet China, unlike the West, is counted as a "developing country" and is, therefore, exempted from any obligations under the Paris Climate Accord.

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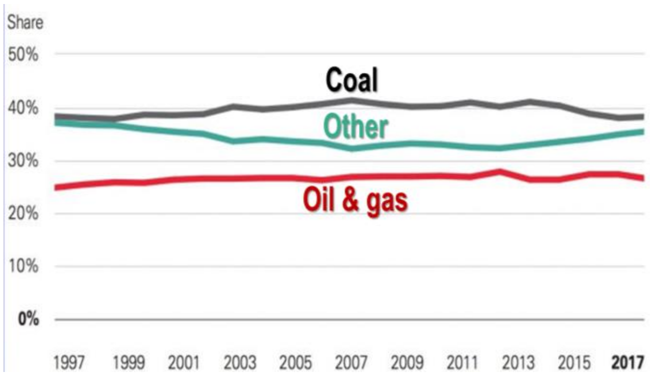
Figure 8.5.6.1
Fuel sources as percentages of global power generation, 1997-2017



Source: BP, 2018, p. 6

8.6 Conclusion

> *The benefits of fossil fuels far outweigh their costs. Various scenarios of reducing greenhouse gas emissions have costs that exceed benefits by ratios ranging from 6.8:1 to 162:1.*

Cost-benefit analysis (CBA) offers a methodology for weighing, in an even-handed and precise manner, the costs imposed by the use of fossil fuels on humanity and the environment, on the one hand, and the benefits produced by their use on the other. If the costs, including all the damages associated with toxic emissions and anthropogenic climate change, exceed the benefits, then efforts to force a transition from fossil fuels to alternatives such as wind turbines and solar photovoltaic (PV) cells are justified and ought to continue. If, on the other hand, the benefits of fossil fuels are found to exceed the costs, even after proper discounting of costs and risks far in the future, then the right path forward would be *energy freedom* rather than more restrictions on the use of fossil fuels.

A focus of this chapter was on the use of integrated assessment models (IAMs) in the climate change debate. While relied on by governments around the world to "put a price on carbon," they are unreliable, suffering from "cascading uncertainty" whereby uncertainties in each stage of the analysis propagate forward (Frank, 2016) and "cascading bias," whereby high-end estimates are multiplied together resulting in risk estimates that are orders of magnitude greater than what empirical data suggest (Belzer, 2012).

This chapter closely examined the IAMs used by the IPCC and found major methodological problems at every step. The IPCC's emission scenarios are little more than guesses and speculative "storylines." The IPCC falsely assumes the carbon cycle is sufficiently understood and measured with sufficient accuracy as to make possible precise predictions of future levels of carbon dioxide (CO_2) in the atmosphere. And the IPCC relies on an estimate of climate sensitivity – the amount of warming likely to occur from a doubling of the concentration of atmospheric carbon dioxide – that is out-of-date and probably too high, resulting in inflated estimates of future temperature change (Michaels, 2017).

The IPCC has done a masterful job compiling research on the impacts of climate change, but it does not distinguish between those that might be due to the human presence and those caused by such natural events as changes in solar radiation, volcanic activity, or ocean currents (IPCC, 2014a, pp. 4–5). It makes no attempt to aggregate the many studies it cites, and since they utilize different methodologies and definitions of terms, cover different periods of time, and often focus on small geographic areas, such an effort would prove impossible. The IPCC is left saying "the impact of climate change will be small relative to the impacts of other drivers" " (IPCC, 2014b, p. 662), and when measured in terms of lost gross national product (GDP), its estimate of -0.2 to -2.0% (IPCC, 2014a, p. 663) should put climate change near the bottom of the agenda for governments around the world.

The "social cost of carbon" (SCC) derived from IAMs is little more than an accounting fiction created to justify regulation of fossil fuels (Pindyck, 2013). Model-generated numbers are without any physical meaning, being so far removed from any empirical data that, using the analogy provided by Risbey *et al*. (1996), there are hardly any "bricks" in this edifice, only "glue," being the subjective judgements of the modelers. Changing only three assumptions in two leading IAMs – the DICE and FUND models – reduces the SCC by an order of magnitude for the first and changes the sign from positive to negative for the second (Dayaratna *et al.,* 2017). With reasonable assumptions, IAMs show the benefits of future climate change probably exceed its cost, even though such models have many other assumptions and biases that tend to exaggerate the negative effects of greenhouse gas emissions.

The literature review conducted in earlier chapters of this book and summarized in Figure 8.4.1.1 identified 25 impacts of fossil fuels on human well-being. Sixteen are net benefits, only one (oil spills) is a net cost, and the rest are either unknown or likely to have no net impact. This finding presents a serious challenge to any calls to restrict access to fossil fuels. While the decisions about how to classify each impact may be somewhat subjective, they are no more so than those made by the IPCC when it composed its own similar table, which appears in the Summary for Policymakers for the Working Group II contribution to the Fifth Assessment Report (IPCC, 2014a, pp. 21–25).

Cost-benefit analyses conducted for this chapter and summarized in Figure 8.4.3.1 show the IPCC's own cost and benefit estimates put the cost of restricting the use of fossil fuels at approximately 6.8 *times* greater than the benefits. Replacing the IPCC's unrealistically low cost estimate with ones originally produced by Bezdek (2014, 2015) and updated for this chapter show reducing the use of fossil fuels costs between 32 and 48 times as much as the IPCC's estimate of the benefits of a slightly cooler world. If renewable energy sources are unable to entirely replace fossil fuels, the cost could soar to 162 times the possible benefit. The ratio of Bezdek's cost estimate per ton of CO_{2eq} and the SCC produced by the Interagency Working Group in 2015 is 73:1 for fossil fuel used in 2010 and 79:1 for fossil fuels used in 2050: the cost of stopping climate change by restricting the use of fossil fuels would be 73 to 79 times greater than the benefits, and this assumes there are benefits.

Why is the case for fossil fuels so strong? Because wind and solar power cannot generate enough dispatchable energy (available 24/7) to replace fossil fuels. Energy consumption would have to fall to attain the IPCC's stated goal to lower global greenhouse emissions 40% to 70% by 2050 and to "near zero $GtCO_2eq$ or below in 2100" (IPCC, 2014c, pp. 10, 12). Less use of fossil fuels means slower economic growth and lower per-capita income for billions of people around the world, even assuming rapidly advancing technologies and a "decoupling" of economic growth from energy consumption. Reducing greenhouse gas emissions to 90% below 1990 levels by 2050, the goal of the European Union, would lower world GDP in 2050 by 24%, a loss of some $72 trillion, the equivalent of losing eight times the entire GDP of the United States.

The major losses of per-capita income that would be caused by achieving either the IPCC's or the EU's goals for reducing greenhouse gas emissions would be most harmful to the poor living in developed countries and many people living in developing countries. Recall from Chapter 3, Section 3.2.3, the comparison of life in Ethiopia and the Netherlands, two countries with similar natural endowments but dramatically different in per-capita energy consumption and per-capita incomes. People living in Ethiopia are 10.5 times more likely to have HIV/AIDS, 17 times more likely to die in infancy, die 24 years sooner, and spend 99% less money on health care (ifitweremyhome.com, n.d.). Implementing the IPCC's plan would slow or prevent the arrival of life-saving energy and technologies to millions of people living in similar conditions around the world.

Chapter 5 described how replacing fossil fuels with wind turbines and solar PV cells would cause devastating damage to the environment by vastly increasing the amount of surface area required to grow food and generate energy. Figure 5.2.2.1 showed how using oil to produce 2,000 MW of power requires about nine square miles, solar panels require 129 square miles, wind turbines require 683 square miles, and ethanol an incredible 2,450 square miles (Kiefer, 2013). Wildlife would be pushed to extinction nearly everywhere in the world were alternative energies relied on for most of our energy needs.

Finally, Chapter 7 documented the close associations between prosperity and peace, prosperity and democracy, and democracy and peace. By slowing economic growth around the world, a dramatic reduction in the use of fossil fuels could undermine some of the world's democracies and make wars over food and other scarce resources a reality again. The dramatic fall in battle-related deaths in state-based conflicts since 1946, shown in Figure 7.1.1, could be reversed as wars broke out around the world. Recall LeBlanc and Register (2003, p. 229) saying the history of humanity was "constant battles" until the prosperity, technology, and freedom made possible by the Industrial Revolution made peace possible. They thought "the opportunity for humans to live in long term balance with nature is within our grasp if we do it right." That vision would be lost as humanity is plunged back into never-ending warfare by attempts to restrict access to fossil fuels.

The cost-benefit analyses conducted in this chapter confirm that the benefits of using fossil fuels far outweigh their costs. More than that, continued reliance on fossil fuels is essential if we are to feed a growing world population and still preserve space for nature. The process that allowed humanity to discover and put to use the tremendous energy trapped inside fossil fuels – relying on markets to find efficient win-win responses to climate change and balance the interests and needs of today with those of tomorrow – should be permitted to continue to dictate the pace of a transition to alternatives to fossil fuels, not irrational fears of a climate catastrophe or hopes of technological miracles.

The global war on energy freedom, which commenced in earnest in the 1980s and reached a fever pitch in the second decade of the twenty-first century, was never founded on sound science or economics. The world's policymakers ought to acknowledge this truth and end that war.

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