BEFORE THE MINNESOTA OFFICE OF ADMINISTRATIVE HEARINGS
600 North Robert Street
St. Paul, MN 55101

FOR THE MINNESOTA PUBLIC UTILITIES COMMISSION
121 Seventh Place East, Suite 350
St Paul, MN 55101-2147

IN THE MATTER OF THE FURTHER INVESTIGATION INTO ENVIRONMENTAL AND SOCIOECONOMIC COSTS UNDER MINNESOTA STATUTE 216B.2422, SUBDIVISION 3

MPUC Docket No. E999/CI-14-643
OAH Docket No. 80-2500-31888

REBUTTAL TESTIMONY AND ATTACHMENT OF DR. MICHAEL HANEMANN

ON BEHALF OF

THE DIVISION OF ENERGY RESOURCES OF
THE MINNESOTA DEPARTMENT OF COMMERCE

AUGUST 12, 2015

REBUTTAL TESTIMONY OF DR. MICHAEL HANEMANN
IN THE MATTER OF THE FURTHER INVESTIGATION INTO ENVIRONMENTAL AND SOCIOECONOMIC COSTS UNDER MINNESOTA STATUTE 216B.2422, SUBDIVISION 3.

DOCKET NO. E-999/CI-14-643
OAH DOCKET NO. 80-2500-31888

TABLE OF CONTENTS

I. INTRODUCTION AND QUALIFICATIONS

Q. Please state your name.

A. My name is Dr. Michael Hanemann.

Q. Are you the same Michael Hanemann who previously filed Direct Testimony in this proceeding?

A. Yes, I am.

II. ORGANIZATION OF REBUTTAL TESTIMONY

Q. What is the purpose of your Rebuttal Testimony?

A. I respond to the Direct Testimonies of the following witnesses:

1. Peabody Energy Corporation's (Peabody) witness, Dr. Roger Bezdek,
2. Minnesota Large Industrial Group's (MLIG) witness, Dr. Ted Gayer,
3. Xcel Energy's (Xcel) witness, Mr. Nick Martin,
4. Peabody's witness, Professor Mendelsohn,
5. Clean Energy Organization's (CEO) witness, Professor Polasky, and
6. Great River Energy, Minnesota Power, Otter Tail Power, and the MLIG's witness, Dr. Anne Smith.

Q. What did you review to develop your Rebuttal Testimony?

A. I reviewed the direct testimonies and attachments submitted by Dr. Bezdek, Dr. Gayer, Mr. Martin, Professor Mendelsohn, Professor Polasky, and Dr. Smith, along with items they cited and in some cases items that their citations cited.

Q. How have you organized your Rebuttal Testimony?

A. Because a number of the witnesses covered similar topics, I have arranged my Rebuttal Testimony by topic. My Rebuttal Testimony addresses the following topics:

1. The supposition that CO_2 emissions are net beneficial
2. The relevant geographic scope of CO_2 emission impacts
3. The use of the federal social cost of carbon (SCC) for Integrated Resource Planning
4. The Interagency Working Group's (IWG) projection of future emissions
5. Whether SCC estimates should be based on the "first ton" or the "last ton" of CO_2 emissions
6. The relevance of "leakage"
7. The uncertainty regarding equilibrium climate sensitivity
8. Criticism of the Integrated Assessment Model (IAM) damage functions
9. The validity of criticisms of the IAM damage functions
10. Catastrophic outcomes
11. The use of the mean versus the median estimate of the SCC
12. The topic of discounting
13. Proposed range of SCC values

III. THE SUPPOSITION THAT CO2 EMISSIONS ARE NET BENEFICIAL

Q. In this proceeding, which witnesses asserted that CO_2 emissions are net beneficial, and on what basis?

A. Dr. Bezdek and Professor Mendelsohn in their direct testimonies both made this assertion. Dr. Bezdek made the assertion on the basis of (a) increased crop yields associated with elevated atmospheric concentrations of CO2 (including "carbon fertilization"); and (b) higher economic growth historically associated with the availability of cheap energy from fossil fuel sources in Peabody Ex.__ at 9 (Bezdek Direct). Professor Mendelsohn's assertion is based on (a) alone in Peabody Ex. ___ at 9 (Mendelsohn Direct).

Q. Have you yourself previously considered the issue of CO_2 fertilization?

A. Yes. I considered the issue of carbon fertilization when I started working on the impact of climate change on US agriculture. My interest was triggered around 1999 by the paper by Mendelsohn, Nordhaus and Shaw (1994),[1] and I started reviewing the literature on agricultural impacts, including carbon fertilization, in preparation for my 2005 paper[2] disproving both the econometric methodology and empirical conclusions of Mendelsohn, Nordhaus and Shaw (1994). I continued to review literature on carbon fertilization with regard to California agriculture while I was co-directing the California Scenarios Assessment Project, starting in 2003.

Q. What is your assessment of carbon fertilization?

A. For most but not all plants, photosynthesis increases when CO_2 rises. Whether this translates into increased crop growth, and increased yield of economically valuable plant products (*e.g.*, seed, fruits), and just how much, are less certain. The fertilization effect varies not only by plant but also with temperature, ozone, soil

---

[1]. Robert Mendelsohn, William Nordhaus and Daigee Shaw, "The Impact of Global Warming on Agriculture: A Ricardian Analysis," *American Economic Review* September 1994, 84 (4), 753-771.

[2]. Schlenker, Hanemann and Fisher, "Will U.S. Agriculture Really Benefit from Global Warming? Accounting for Irrigation in the Hedonic Approach," *American Economic Review* (March 2005) 395-406.

moisture, nutrient availability and microclimate. There are interactions with other factors that affect plant growth, including weeds, which could also respond to CO_2. The overall effect is complex and is likely to be quite variable.[3]

It is hard to tease out the effect on any large spatial scale through statistical analyses. At a given point in time, there is little cross-section variation in CO_2 levels. With time-series data, increasing levels of atmospheric CO_2 are confounded with other changes occurring over time that can also affect crop yield. Consequently, the existing evidence comes largely from small scale experiments, either through Free Air Concentration Enrichment (FACE) [4]experiments or non-FACE experiments involving greenhouses or controlled or open-top chambers. How well small-scale experimental results from FACE or chamber studies generalize on a field level and at large scale is not well known and is subject to much debate.

Q. Do the IAMs used in the SCC allow for carbon fertilization?

A. Yes. The developers of DICE and FUND acknowledge the existence of a CO_2 fertilization effect and account for it in some manner. It is not clear whether it is accounted for in PAGE.

Q. What was Dr. Bezdek's assessment of carbon fertilization?

A. For his assessment of the global impact of CO_2 fertilization in Peabody Ex. __ at RHB-2, pages 49-60 (Bezdek Direct), Dr. Bezdek relied on a 2013 report by Dr. Craig

[3]. See, for example, Seth G. Pritchard and Jeffrey S. Amthor, Crops and Environmental Change, Food Products Press, New York, 2005.

[4]. In a FACE experiment, horizontal or vertical pipes that emit CO_2 enriched air (and/or nitrogen-enriched air) encircle the experimental plot. Sensors control the concentration of CO_2, or nitrogen, in order to maintain it at the level desired for the experiment.

Idso.[5] That report uses a data base of plant-specific CO_2 growth response factors compiled from various small-scale experiments found in the literature. For each crop, the average value of the growth response factor in the data base is combined with projections of increased atmospheric concentrations of CO_2 and applied to the global production of that crop. This generates an estimate of the increase in gross revenue that Dr. Bezdek counted as a benefit from CO_2 in Peabody Ex.__ at RHB-2, page 5 (Bezdek Direct).

Q. Is gross revenue an accepted economic metric of wellbeing?

A. Gross revenue is not an accepted economic metric of wellbeing. The accepted metric is net revenue, which is roughly an order of magnitude smaller than gross revenue in the case of agricultural commodities.

Q. Does Dr. Bezdek's assessment that carbon fertilization dominates all other impacts of climate change on global agriculture comport with assessments in the generally-accepted literature?

A. No, it does not. The most authoritative contemporary source would be the Intergovernmental Panel on Climate Change's (IPCC's) Fifth Assessment Report. It states, with high confidence, that "[b]ased on many studies covering a wide range of regions and crops, negative impacts of climate change on crop yields have been more common than positive impacts."[6]

Idso of course has long been fossil-funded,
http://www.desmogblog.com/center-study-carbon-dioxide-and-global-change
http://www.desmogblog.com/2012/10/23/fakery-2-more-funny-finances-free-tax pp.77-81

[5]. Craig D. Idso, *The Positive Externalities of Carbon Dioxide*, Center for the Study of Carbon Dioxide and Global Change, 21 October, 2013.

[6]. IPCC, Working Group II, *Climate Change 2014: Impacts, Adaptation and Vulnerability Part A: Global and Sectoral Aspects*. p. 47.

William R. Cline, in his assessment of the impact of climate change on global agriculture, states as follows:

> The estimate for global productive capacity change including carbon fertilization is a decrease of about 3 percent. This reduction probably understates potential losses, however. If the carbon fertilization effect (already constrained to a 15 percent increase in these estimates, lower than in some earlier estimates) failed to materialize, the losses would be estimated at about 16 percent. The Ricardian models probably err in the direction of optimism by implicitly counting on availability of more water for irrigation under circumstances in which there could easily be less water. Neither the Ricardian nor the crop models deal explicitly with increased damage from pests or more frequent and more severe extreme weather events (floods and droughts).[7]

Also, I observe also that there is no indication that Dr. Idso's estimate of the monetary benefit to global food production has been published in a peer-reviewed journal.

Q. Were the documents that Dr. Bezdek relied upon a credible estimate of the impact of carbon fertilization on global agriculture?

A. No. Without some hard evidence of the external validity of the data used by Dr. Idso to demonstrate that Dr. Idso's estimate reliably applies under field conditions and on a global scale, and in the absence of a full peer review of his analysis, his analysis lacks credibility.

[7]. Cline, *Global Warming and Agriculture: Impact Estimates by Country*, Peterson Institute, Washington 2007 (pp. 95-96). The Ricardian model, to which Cline refers here, is the method proposed by Mendelsohn, Nordhaus and Shaw (1994).

Q. What did Dr. Bezdek assert regarding the effect of CO_2 emissions on economic growth?

A. Since the beginning of the Industrial Revolution, the global use of fossil fuels has increased enormously, as have the world population, per capita income, and human wellbeing. In Peabody Ex.__ at RHB-2, pages 70-75 (Bezdek Direct), Dr. Bezdek cited analyses that correlate the growth in world GDP with the growth in world energy consumption or carbon utilization over the period from about 1820 to about 2010.[8]

Q. Is correlation the same as causation?

A. No. Correlation is not causation. Neither of the regression analyses cited by Dr. Bezdek[9] includes any controls for other factors that may have changed in the world between 1800 and 2010, such as changes in human life span, education, scientific and technical knowledge, or the stock of physical capital.

Q. If a regression equation lacks controls for other possible explanatory factors, is it credible scientific evidence of causation?

A. No. For this reason, the regressions cited by Dr. Bezdek are mis-specified (which means they are missing key variables with significance to the predictive ability of the model), and they have no scientific validity.

---

8. The studies are: Gail Tverberg, "An Energy/GDP Forecast to 2050," http://ourfiniteworld.com/2012/03/12/world- energy-consumption-since 1820-incharts/ downloaded on July 26, 2015; and Robert Zubrin, "The Cost of Carbon Denial," National Review, July 31, 2013. Tverberg correlates GDP with energy consumption; Zubrin correlates it with carbon utilization.

9. See footnote above.

Q. Did Dr. Bezdek offer his own analysis?

A. Yes. For his own analysis in Peabody Ex.__ at 76 (Bezdek Direct), Dr. Bezdek focused on global CO_2 emissions and GDP. He calculated the ratio of world GDP to global CO_2 emissions in 2010, which amounts to $2,400 per ton of CO2 (in 2007 dollars). He took this value as a measure of the "indirect" benefit of CO2 emissions and compared it to the social cost of CO_2 emissions implied by the IWG's 2010 and 2013 SCC estimates. In Peabody Ex.__ at 78-79 (Bezdek Direct) he obtained benefit-cost ratios vastly greater than unity (*i.e.*, he found that benefits are far greater than costs).

Q. Does Dr. Bezdek's analysis imply that humankind receives a benefit from the use of energy or from the emission of CO_2 per se?

A. Dr. Bezdek's estimate implies that humankind obtains benefit from CO_2 emissions directly and not, say, from the use of energy.

Q. Is it plausible that generating CO_2 emissions per se benefits humankind?

A. No, it is not plausible.

Q. Did Dr. Bezdek allow for any spatial or temporal variation in what he sees as the beneficial effect of CO_2 emissions on economic growth?

A. No. He treated the benefit of CO_2 emissions as constant. His estimate implies than the emission of one ton of CO_2 raises global GDP (in 2007 dollars) by an average of $2,400 anywhere. He compared that value with the IWG's estimate of the SCC. With the SCC, because of the global mixing of CO_2 in the atmosphere, it is reasonable to assume that a unit of emissions causes the same increment of damage regardless of where in the world it was emitted. By comparing the SCC value to his value estimate of $2,400, Dr. Bezdek implicitly assumed that a unit of emissions causes the same increment of benefit regardless of the energy source being used and regardless of where, or how, the emission was generated.

Q. Does Dr. Bezdek's own estimate control for other explanatory factors?

A. His estimate does not control for any other factors that may affect global GDP such as stocks of physical, natural or human capital, scientific knowledge, prices, economic policies or cultural factors.

Q. How does the lack of controls affect Dr. Bezdek's estimate?

A. Because of the lack of controls, Dr. Bezdek's estimate is meaningless. It has no scientific validity.

Q. Suppose Dr. Bezdek's estimate had some scientific validity, would it then be relevant for the proceedings at hand?

A. No. Dr. Bezdek's estimate – if it were meaningful – would be picking up the effect on GDP of the cheap sources of energy that became available with the expanded use of fossil fuels. It is an effect mediated through reductions in the price of an input used for production. This is what is known in the economics literature as a (beneficial) pecuniary externality.

Q. Is there a difference between a pecuniary externality and the externality values for which the current proceeding is meant to address?

A. Yes. In DOC Ex. __ at 9-10 (Hanemann Direct), I summarized the development of the concept of an economic externality in. I noted that, while the concept was first put forth by Arthur Pigou in 1920 it took until the early 1950s before it was clarified and formalized mathematically. The result of the clarification generated through the mathematical formulation of the externality concept was to draw a distinction between two types of externality.

One type of externality, known as a real externality, prevents even competitive markets from producing an outcome in the best public interest and calls for governmental intervention whether through regulation or the imposition of a Pigouvian tax or subsidy. The other type of externality does not interfere with the social optimality of market outcomes in a competitive economy and does not call for governmental intervention whether through regulation or the imposition of a Pigouvian tax or subsidy. The second type of externality is a pecuniary externality.

Q. What is the definition of a pecuniary externality?

A. A pecuniary externality occurs when one actor affects the wellbeing of another through the working of the price system in a competitive market. To provide a hypothetical example, if I lived in a small town, my gargantuan appetite for donuts would drive up the price (reduce the supply available to others) of donuts for all residents in the town. Or, my discovery of new gold mine may dramatically boost the supply of gold and cause the world price of gold to decline. Those interactions are mediated through the functioning of the price system and constitute pecuniary externalities.

Q. Do pecuniary externalities trump real externalities?

A. No. The existence of a beneficial pecuniary externality does not trump or negate the implications of a harmful real externality. It has no bearing on the remedy called for by the harmful real externality, namely the existence of a Pigouvian tax that internalizes the social cost imposed on others through the real externality. In other words, the market cannot correct for a real externality without the imposition of a Pigouvian tax or subsidy or the imposition of regulation.

For this reason, even if Dr. Bezdek's estimate of $2400 per ton of CO^2 emissions (in 2007 dollars) were meaningful it would be irrelevant to the proceedings at hand.

Q. What opinion did Professor Mendelsohn offer with regard to carbon fertilization?

A. Professor Mendelsohn stated:

> . . .carbon fertilization has increased crop yields by a far larger amount across the entire world (Kimball 1983) suggesting a sizable net benefit. ... the carbon fertilization of trees has also led to an overall increase in ecosystem productivity and standing biomass (Gerber et al. 2004) which is an overall net benefit for ecosystems. [Peabody Ex.__ at 12 (Mendelsohn Direct)]

Q. Are the citations offered by Professor Mendelsohn to Kimball (1983) and Gerber *et al.*, (2004) in Peabody Ex.__ at 12 (Mendelsohn Direct) convincing evidence that the net impact of CO_2 emissions on human wellbeing is positive due to the magnitude of carbon fertilization effect?[10]

A. No. The phrase "net benefit" appears nowhere in Gerber et al. (2004). Gerber *et al*. is a paper about carbon sequestration in vegetation and how this might change with an increase in atmospheric CO_2. It contains no assessment of benefits to ecosystems.

Similarly, Kimball (1983) is a paper saying that, based on studies performed in greenhouses or growth chambers, CO_2 fertilization will increase yields, while recognizing that results in open fields could be different.

Given that climate change can also affect sea-level rise, inland flooding, water supply and demand, energy supply and demand, transportation systems, various aspects of human health such as vector- borne disease, diarrhea, and cardiovascular and respiratory illness, labor productivity, violence and social strife and unrest, migration, biodiversity and ecosystems, Professor Mendelsohn's apparent belief that he can infer the net global effect of warming based on his reading of the agricultural and forestry literatures is unfounded.

[10]. B.A. Kimball, Carbon Dioxide and Agricultural Yield: An Assemblage and Analysis of 430 Prior Observations," *Agronomy Journal*, Vol. 75, September – October 1983, pp. 779-788. Stefan Gerber *et al*., "Sensitivity of a Dynamic Global Vegetation Model to Climate and Atmospheric CO_2," *Global Change Biology* (2004) 10, 1223-1239.

IV. THE RELEVANT GEOGRAPHIC SCOPE OF CO_2 EMISSION IMPACTS

Q. What is the geographic scope that should be considered for impacts from climate change?

A. In DOC Ex.__ at 12 (Hanemann Direct), I noted that greenhouse gasses (GHGs) differ from criteria air pollutants in both the temporal and spatial scales of their impacts. With regard to spatial scale, GHGs emitted at a particular location on the earth mixes in the atmosphere with GHGs emitted from all other locations on earth. A molecule of emitted GHG contributes to damages from climate change experienced everywhere around the globe, regardless of where it is emitted. The impacts on human wellbeing play out on a global scale.

The question is: should this distinctive feature of GHGs be recognized when assessing their external social cost? The IWG said "Yes." It considered the global impact of GHGs when calculating the SCC.

Some commenters have argued "No," including Dr. Gayer and Dr. Smith.

Q. What did Dr. Gayer say about the geographic scope of impacts resulting from CO2 emissions?

A. Dr. Gayer stated:

> In the absence of even national reciprocity, the IWG's estimates [of SCC] should be adjusted to state level. Doing so would result in estimates that are approximately 0.4% of the global value in magnitude, suggesting extremely small damage estimates, with a high-end estimate of $0.37 per metric ton of CO2. [MLIG Ex.__ at 10 (Gayer Direct)].

He based his recommendation on the following consideration:

> The CO_2 policy under consideration by the Commission is a unilateral policy. It is not coordinated in either a national or global way with any other political entities. In other words, there is no explicit reciprocity by other states or nations. In considering a policy that accrues costs on Minnesotans but absent explicit reciprocity from the world for Minnesota's actions, it would be outside the typical practice of benefit-cost analysis for Minnesota to consider environmental benefits to the entire global population and to place equal weight on benefits to everyone in the global population as it does for Minnesotans."
>
> [MLIG Ex.__ at 9 (Gayer Direct)].

Q. What did Dr. Smith say about the geographic scope of impacts resulting from CO_2 emissions?

A. Dr. Smith stated:

> ...the IWG's SCC values are based on global damages, not Minnesota damages or U.S. damages. This is inappropriate in the case of an individual state's investment decisions when there are no reciprocal agreements with major emitting nations to also adopt that same SCC.
>
> [GRE,MP,OTP,MLIG Ex. ___ at 15 (Smith Direct)].

She elaborated on this position as follows:

> It might make sense for the Federal government to consider global damages when calculating the SCC, because the Federal government, unlike the individual states, has authority to negotiate international agreements to reduce global carbon emissions. For the Federal government, nationwide domestic policies may support its positions in those negotiations. Minnesota, however, lacks authority under the U.S. Constitution to enter into international treaties. Moreover, any unilateral changes Minnesota makes in its own emissions will have, at best, de minimis impacts on climate change, even putting aside issues of leakage that I discuss in my

> report. It is most appropriate, therefore, to consider the benefits to Minnesotans from Minnesota's actions to reduce CO_2.
>
> [GRE,MP,OTP,MLIG Ex. ___ at 27 (Smith Direct)].

Q. Should the geographic scope of impacts resulting from CO2 emissions be taking into account when determining the SCC value?

A. The geographical scale on which to consider impacts is a policy decision. While it has economic implications, economic theory per se cannot prescribe what spatial scope should be employed when considering the impacts of climate change. Dr. Smith appeared to agree that this choice is a policy decision. Referencing the assumptions with which she disagrees, one of which is the use of global impacts, she stated:

The list of five assumptions that I conclude should be made differently for Minnesota (if it is to use IAMs) are not objective issues that can be tested by scientific methods. Rather, they reflect the judgments of the analysts who use the IAMs on behalf of policy makers. [GRE,MP,OTP,MLIG Ex. ___ at 16 (Smith Direct)].

Dr. Smith appeared to imply that the choice of geographical scope and other such decisions made by the IWG were not policy decisions by the US government. Instead, they were policy decisions made by "analysts" working for the US government. That is a distinction without a difference.

Since I am testifying as an economist and the question of geographical scope is a policy decision rather than a matter of economics, I would defer to any precedent in Minnesota's previous decisions regarding the environmental cost of electricity that bear on the policy decision involved here.

Q. Has Minnesota indicated a policy judgment to adopt the global scope of impacts?

A. Yes, in both the current approach that the Minnesota Public Utilities Commission (PUC) uses to account for environmental externalities of CO_2 emissions, and in the recommendations from the Department of Commerce and the Minnesota Pollution Control Agency (jointly the Agencies) to the PUC state that environmental externalities for GHG should adopt a global scale of analysis.

V. THE USE OF SCC FOR INTEGRATED RESOURCE PLANNING

Q. Minnesota Statute, section 216B.2422, subd. 3 requires that "A utility shall use the values established by the commission in conjunction with other external factors, including socioeconomic costs, when evaluating and selecting resource options in all proceedings before the commission, including resource plan and certificate of need proceedings." The IWG's estimate of the SCC was developed for use in cost-benefit analysis. Is there a difference between cost benefit analyses and the uses required by Minnesota Statute that would preclude the use of the federal SCC as the PUC's CO_2 externality value?

A. Mr. Martin states that

> The SCC was developed for a specific and limited purpose. It was designed as a component of cost-benefit analysis of proposed Federal regulations, as part of the regulatory impact analysis required by the White House's Office of Management and Budget (OMB) under Executive Order 12866." He goes on to assert that "There is an important difference between using the SCC for its intended purpose and using the SCC in integrated resource planning and other Commission decisions.
>
> [Xcel Ex. ___ at 12 (Martin Direct)].

I disagree. Resource planning is a form of cost-effectiveness analysis. A cost-effectiveness analysis seeks to identify the least cost means of achieving a given target or goal. In turn, a cost-effectiveness analysis is a particular type of cost-benefit analysis where the alternatives all have the same benefit. In that case, maximizing the net benefit (the object of a cost-benefit analysis) is equivalent to minimizing the cost (the object of cost-effectiveness analysis).

VI. THE IWG's PROJECTION OF FUTURE EMISSIONS

Q. Please provide some background on the criticisms made in this proceeding of the IWG's emissions projections?

A. The degree of global warming between now and 2300 – the period considered by the IWG – depends on both past GHG emissions and future emissions occurring through 2300. Therefore, the IWG needed a standardized set of future emissions to feed into the three IAMs it was using in simulation mode. For an authoritative source, it drew on emission projections from the Energy Modeling Forum's (EMF) twenty-second model intercomparison exercise (EMF-22). However, that exercise projected emissions through 2100. The IWG made some assumptions to extend the projections through 2300. The emission projections used by the IWG drew criticisms from Mr. Martin and Dr. Smith.

Q. What did Mr. Martin say about the emission projections used by the IWG?

A. Mr. Martin sees these projections as a source of uncertainty in Xcel Ex. ___ at 30 (Martin Direct). In Xcel Ex. ___ at 33 (Martin Direct) he noted that the IWG's projection of emissions after 2100 was not peer-reviewed. He asserted that, even if the forecasts of population and GDP growth are correct, the forecast of emissions depends on assumptions regarding technology and the CO_2-intensity of energy that could prove inaccurate. In Xcel Ex. ___ at 34 (Martin Direct) Mr. Martin concluded that the IAMs into which the emission projections are fed do not modify them to account for endogenous technological change Mr. Martin stated that four of the five EMF-22 emission scenarios "are 'baseline' futures that assume no coordinated global GHG reduction effort or policy." While the IWG included a fifth emission projection that assumes a global climate agreement to stabilize atmospheric CO_2 concentrations at 550 parts per million (ppm) by the year 2100, it averaged that projection along with the other four projections, treating all five as equally likely. Mr. Martin illustrated in Xcel Ex. ___ at 33 (Martin Direct) the wide range of uncertainty in the IWG's projections of future emissions with a panel in his Figure 5, reproduced here as Figure 1A. The differences between Figures 1A, 1B, and 1C are discussed more fully below.

Figure 1A: IWG'S EMISSION SCENARIOS - PROJECTIONS THROUGH 2100
[Xcel Ex. ___ at 33 (Martin Direct)]

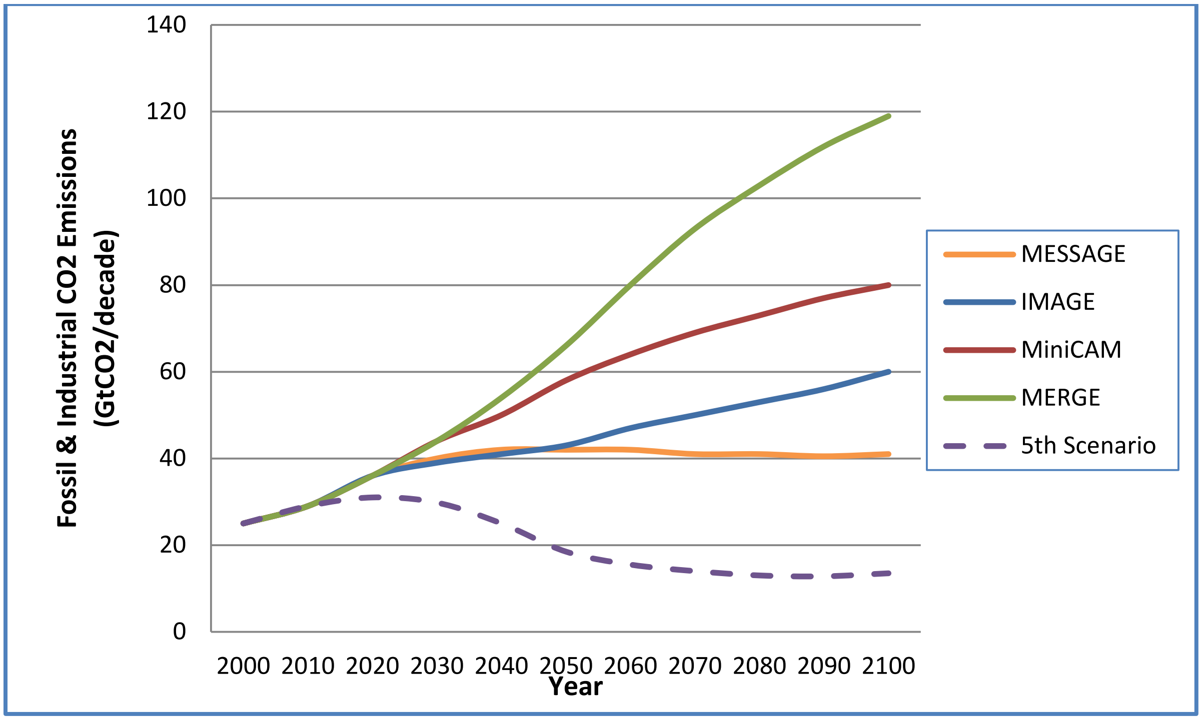


Figure 1B: IWG'S EMISSION SCENARIOS - PROJECTIONS THROUGH 2300
(IWG 2010, Figure A4)

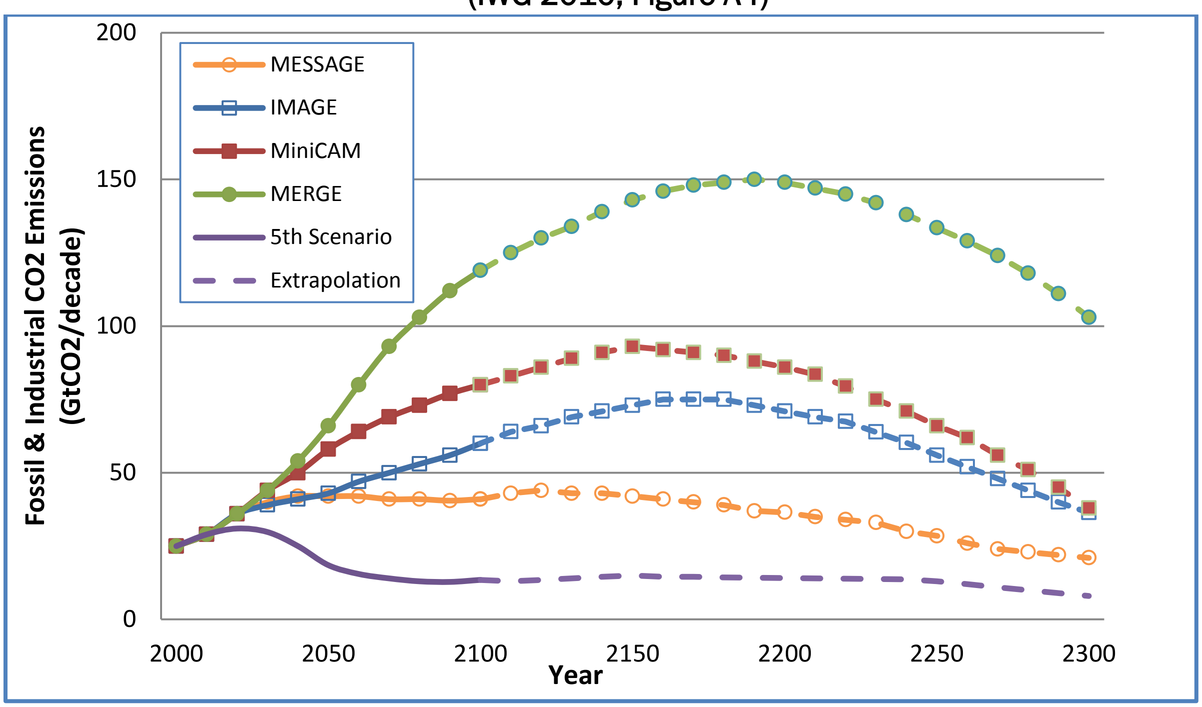
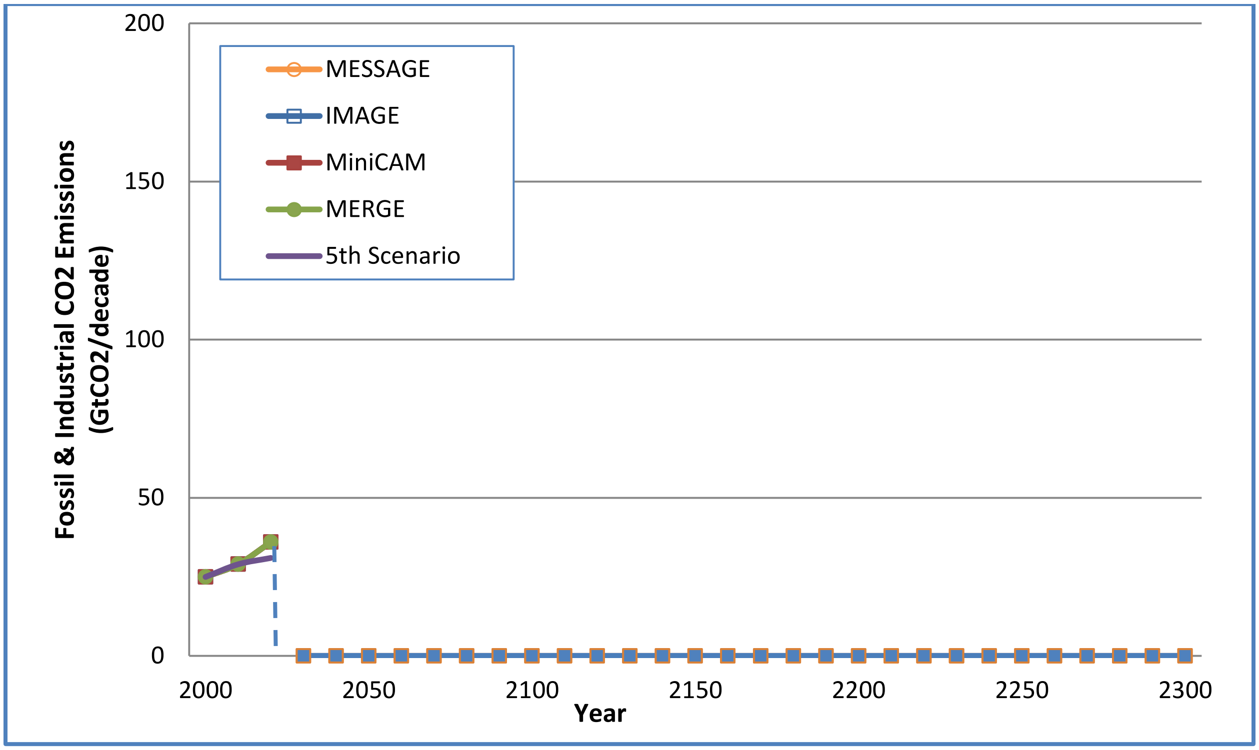


Figure 1C: PROJECTIONS THROUGH 2300 SHOWING DR. SMITH'S "FIRST TON" ANALYSIS



Q. What did Dr. Smith say about the emission projections used by the IWG?

A. In her Direct Testimony, Dr. Smith stated:

> Moreover, the IWG's 2300 model horizon assumes, unrealistically, that future generations will passively endure temperature changes as high as 10oC above pre-industrial levels, without taking any steps whatsoever to address the causes of such temperature changes. The fact that we are discussing the environmental impacts of GHG emissions now and that the Commission is taking steps to update its environmental costs shows just how unrealistic that assumption is.
>
> [GRE,MP,OTP,MLIG Ex. ___ at 22 (Smith Direct)]

Referring to high future global temperatures that "are certainly a cause for concern," she stated:

> Furthermore, the temperatures get that high not because of emissions over the next decade, but because of a continued accumulation of unabated global emissions growth long after the projected temperature changes start to reach unacceptably high levels. There is no provision in any of the IWG scenarios for societal response to the worst-case levels of ECS. That there is no learning or response in those scenarios is unrealistic even over 100 years and is just implausible for assessing societal damages in a period 200 to 300 years from now.
>
> [GRE,MP,OTP,MLIG Ex. ___ at AES-D2, page 30-31 (Smith Direct)]

And,

> Thus, the IAMs may provide useful computational efficiency, but the IWG has used them in a way that is out of line with any realistic view of how actual climate change, if it turns out to be consistent with pessimistic views, will be addressed by society. … The IWG's analysis forces the emissions projections that drive those very high temperatures outcomes to remain unchanged through the entire 300-year modeling horizon, no matter how high the scenarios shows temperature to have risen. This is equivalent to assuming that a wealthy and growing society will sit by and accept (for up to 300 years) any amount or rate of temperature change that they may find occurring without any technological reaction.
>
> [GRE,MP,OTP,MLIG Ex. ___ at AES-D2, page 30 (Smith Direct)]

Dr. Smith characterized the IWG's situation thus:

> An immediate difficulty that the IWG faced was that the EMF 22 projections had only been developed through the year 2100. Thus, even the best available modeling effort attempting to develop realistic rather than idealized scenarios specific to the inherently long-run concerns of climate policy chose to make projections through only 2100. As a result, the IWG made its own judgments on how to extend these socioeconomic projections from 2100 to 2300. Although the IWG explains how it chose to extrapolate the EMF projections,

> the judgments for those extrapolations are not evidentiary-based.
> [GRE,MP,OTP,MLIG Ex. ___ at AES-D2, page 67 (Smith Direct)]

She commented:

> Reasonable or not, these extrapolations of the IWG beyond 2100 are highly speculative and not supported by facts, available evidence, or peer-reviewed analyses.
>
> [GRE,MP,OTP,MLIG Ex. ___ at AES-D2, page 68 (Smith Direct)]

She noted that the recent study by the Electric Power Research Institute (EPRI, 2014) evaluates the IWG's emissions scenarios and concludes:

> As a group, the extensions lack a coherent, viable, and intuitive storyline (or set of storylines) that drive all of the extensions from 2100 to 2300.[11]
>
> [GRE,MP,OTP,MLIG Ex. ___ at 68 (Smith Direct)].

She also noted that, when the PUC's current estimates of environmental costs for CO_2 were developed in 1995 by Mr. Peter Ciborowski, he relied on projections of emissions that ended either by or before 2100.

She continued:

> These researchers' decisions to limit their analytic horizons (observed in both Mr. Ciborowski's references and also in the EMF 22 scenarios) are not because they fail to understand that damages from GHG emissions in the near term will last beyond 2100. Rather, modelers know that the uncertainty in any projections they can make expands as those projections go further in time, until at some point the projections are not useful or meaningful.
>
> [GRE,MP,OTP,MLIG Ex. ___ at AES-D2, page 69 (Smith Direct)]

[11]. EPRI (2014, p. 4-14) as quoted in GRE,MP,OTP,MLIG Ex. ___ at AES-D-2, page 68 (Smith Direct).

Q. What is your own opinion about the IWG's projection of emissions?

A. First, it might be useful to show the IWG's projections of emissions through 2300. They are exhibited in Figure 1B. If one just looked at Figure 1A, presented by Mr. Martin – the IWG projections through 2100 – one might imagine that the projected emissions just continue to grow in the two centuries following 2100. In fact, as Figure 1B demonstrates, that is not what the IWG assumed. It assumed that emissions level off and then decline.

Dr. Smith stated in GRE,MP,OTP,MLIG Ex. ___ at AES-D2, page 30 (Smith Direct) that there is "no provision in any of the IWG scenarios for societal response to the worst-case levels" of climate sensitivity. It is worth noting, however, that the IWG places a 20% weight on the emission projection keyed to climate stabilization at 550 ppm (the low trajectory in Figure 1B).

Q. What is the significance of the 550 ppm target?

A. In 2002, the United Nations Framework Convention on Climate Change (UNFCCC), an international organization established by treaty in 1992, formally adopted the goal of avoiding dangerous climate change. Dangerous climate change was widely considered to be warming in excess of 2°C. Thus, the European Union adopted the goal of avoiding more than 2°C warming.[12] The precise limit on atmospheric concentrations of CO_2 required to avoid this warming depends on the climate sensitivity. In the policy debates of the 1990s, the focus was on avoiding a CO_2 concentration in excess of 550 ppm -- roughly a doubling of the pre-industrial

[12]. See, for example, Michael Lazarus and Sivan Kartha, Linking Technology Developments with Emissions Commitments: Exploring Metrics for Effort and Outcome, Stockholm Environment Institute Working Paper WP-US-090, October 2009, p. 1.

concentration -- as the condition for avoiding more than 2°C warming. By about 2007, it was becoming clear that an atmospheric concentration of less than 550pm would be required to avoid warming beyond 2°C. It had also become clear that the current trajectory of emissions would lead to an overshooting of the 550pm level well before 2100, and possibly before mid-century. The question was becoming not whether we could avoid exceeding 550 ppm but rather whether, once 550 ppm was exceeded, we could decarbonize sufficiently so as to reduce the atmospheric concentration back down to 550 ppm.

Q. Why did EMF-22 focus on emissions only through 2100?

A. Dr. Smith attributed some significance to the fact that, whereas the EMF-22 terminated its projections in 2100, the IWG made projections through 2300. She implied in GRE,MP,OTP,MLIG Ex. ___ at AES-D-2, page 69 (Smith Direct) that this difference arose because the EMF modelers – unlike the IWG – "know that the uncertainty in any projections they can make expands as those projections go further in time, until at some point the projections are not useful or meaningful.". In fact, this is not the reason. The, reason is that EMF-22 had a different objective than the IWG. EMF-22 was not a cost-benefit analysis of climate mitigation policies. It did not consider damages from climate change. Instead, it focused on cost minimization in reducing emissions to meet targets being considered in current climate policy debates. Those climate targets were atmospheric concentrations of CO2 of 450 ppm, 550 ppm or 650 ppm in 2100. The whole focus of the EMF-22 was to look at abatement costs to meet a goal specifically in 2100. EMF-22 did not consider damages either before or after 2100. It therefore sheds no light on the relative merits of damage projections that terminate before or after 2100.

Q. Are the EMF-22 projections evidentiary based?

A. In GRE,MP,OTP,MLIG Ex ___ at 67 (Smith Direct) Dr. Smith castigated the IWG projections beyond 2100 for not being "evidentiary-based" and again in GRE,MP,OTP,MLIG Ex ___ at 68 (Smith Direct)] for not being supported by "facts, available evidence, or peer-reviewed analyses." By implication, she may be suggesting that the EMF-22 projections are supported by facts, available evidence, and peer-reviewed analyses.

That is not the case. There is no way to support a projection of anything to 2100 through "facts" or "available evidence" prior to 2100: that would be a meaningless criterion. By the sheer nature of projections into the far future, they cannot be evidentiary or fact based, they are based on reasonable assumptions.

It is worth noting that the MERGE and MESSAGE model were calibrated to 2000 data (*i.e.*, their parameter values were set using this data); IMAGE to 2006 data; and MiniCAM to 2008 data. Given the long lapse of time involved, I do not see how their projections of emission outcomes in 2100, say, can be considered so much less speculative than the IWG's projections for after 2100.

Q. Will society act to avoid levels of emissions that generate high degrees of future warming?

A. Dr. Smith argued that "society" will not allow levels of emissions that generate high levels of warming in GRE,MP,OTP,MLIG Ex ___ at 72-73 (Smith Direct). I do not agree.

First, there is some degree of paradox in Dr. Smith arguing for Minnesota to adopt a relatively lax regulation of GHG emissions on the grounds that society will choose to avoid high levels of GHG emissions.

There are two reasons not to share Dr. Smith's optimism regarding future emissions. First, there is a time lag of decades before the effects of today's emissions are translated into future warming. "Society" may, therefore, be slow to act. Second, global emissions are not determined by "society" as stated by Dr. Smith. They are determined by the 196 members of the UNFCCC, who each have their own interests and concerns. Reduction of global CO2 emissions is an exercise in global collective action, and it is well known that collective action can be fraught with problems.

Dr. Smith's prediction that high levels of warming could not occur because we would not allow it strikes me as somewhat like making a prediction in the spring of 1914 that war could not break out because it was not in the interest of the great powers for that to happen. As we now know, those powers stumbled, or in Clark's (2013) memorable phrase, sleepwalked their way into war.[13] It is not so evident to me that we are not sleepwalking our way into global warming.

As time passes, we will know more about the likely trend of emissions during the coming decades. That information can – and should – be used to update future estimates of the SCC.

[13]. Christopher Clark, *The Sleepwalkers*, HarperCollins, 2013.

VI. WHETHER SCC ESTIMATES SHOULD BE BASED ON THE "FIRST TON" OR THE "LAST TON" OF CO2 EMISSIONS?

Q. How is an SCC estimate created?

A. The conventional manner by which an SCC estimate is created is as follows. To generate the SCC value for 2020, say, one introduces a small increment (one marginal ton of emissions) into CO2 emissions for 2020 – in effect, one adds a blip in 2020 to the trajectory of emissions shown in Figure 1B.[14] Given the one-time blip in emissions, one calculates (i) the annual atmospheric concentration of CO2 for each year following 2020, (ii) the annual degree of global warming for each year following 2020, and (iii) the annual damage associated with that annual warming for each year after 2020. The annual damages for each year after 2020 are compared with the annual damages over the same period in the baseline run, with no blip of emissions in 2020. The differences between the "with-blip" and "without-blip" damage trajectories measure the additional annual damages arising from the one-time emissions blip addition in 2020. To obtain the 2020 SCC, one discounts and sums those annual damage increments back to a present value in 2020. The blip approach just described is what Dr. Smith refers to as the "last ton" approach to calculating the SCC.

It was noted above that the warming in any future year – say, 2075 – depends on emissions that have already occurred before today as well as on emissions that will occur between today and 2075. Those emissions all mix and contribute to the atmospheric concentration of CO_2 in future years, and therefore to

[14].This would be done separately for each emission trajectory.

the warming that occurs in future years. They therefore affect both the baseline (no-blip) trajectory and of damages and the with-blip trajectory used to calculate the 2020 SCC.

To put it more directly, the estimate of the 2020 SCC depends on both past emissions and future emissions.

Q. What is the first ton approach proposed by Dr. Smith?

A. Dr. Smith proposed an alternative to the last ton approach, which she called the first ton approach in GRE,MP,OTP,MLIG Ex ___ at 33 (Smith Direct). Under this approach to calculating a SCC value for 2020, she assumed that no anthropogenic emissions occur after 2020. This became her baseline scenario. She then imposed an emission blip in 2020 on that baseline, and proceeded to compare the damages with and without the 2020 blip in the manner as described above.

In the case of DICE, her computer code to produce this first-ton calculation is described as follows:

> For DICE, industrial carbon as well as EMF non-CO_2 and other non-CO_2 forcings after 2020 were set to zero in the DICE input file, SCC_input_EMFScenarios.xlsx. This file was saved and then the model run after modifying it to read this new data file.
>
> [GRE,MP,OTP,MLIG Ex. ___ at AES-D2, page 110 (Smith Direct)].

For FUND, her code is described as follows:

> Damages in FUND are a function of the radiative forcing. The relative forcing is determined by emissions. To compute damages from the first tonne, all anthropogenic emissions occurring after 2020 needed to be eliminated.

[GRE,MP,OTP,MLIG Ex. ___ at AES-D2, page 110 (Smith Direct)].

With PAGE, an analogous procedure was implemented [GRE,MP,OTP,MLIG Ex. ___ at AES-D2, page 111 (Smith Direct)].

The logic of the first ton analysis is depicted in Figure 1C which shows the baseline trajectory of emissions over the period 2000 - 2300 which is being assumed by Dr. Smith in this analysis.

Q. Is the first ton approach a reasonable way to proceed?

A. The baseline for the first ton approach assumes that no emissions of CO2 occur anywhere in the world after 2020.

In my opinion, that is a ridiculous assumption. It is not a reasonable foundation on which to base an estimate of the SCC.

VII. THE RELEVANCE OF LEAKAGE FOR APPLYING A SCC.

Q. What is leakage as proposed by Dr. Smith?

A. In the context of regulation to limit GHG emissions, especially from electricity generation, leakage refers to the phenomenon that some of the reduction in the emissions produced by the regulation may be offset by increased emissions in other jurisdictions, not controlled by the regulator. For example, electric utilities in a regulated jurisdiction switch from high- to low-carbon fuels; but the high-carbon fuel not burned to generate electricity in the regulated jurisdiction ends up being burned by some other utility to generate electricity for consumption in another jurisdiction. Thus, emissions “leak” from the regulated jurisdiction to the unregulated jurisdiction.

Q. Should leakage be considered when applying a SCC value?

A. Dr. Smith asserts that leakage should be taken into account by PUC when applying the estimate of SCC:

> "If a Minnesota entity reduces its emissions by 100 tons but another entity elsewhere reacts by increasing its emissions by 75 tons (a phenomenon called 'leakage'), the actual change in global emissions is only 25 tons. In this case, the total environmental value of Minnesota's action would only be equal to the environmental value of the net reduction of 25 tons. That is, whatever value one might estimate for a SCC on a $/ton basis, that $/ton should only be multiplied by the net change in global tons, which may be lower than the number of tons that would be reduced directly as a result of a change in a Minnesota resource plan."
>
> [GRE,MP,OTP,MLIG Ex. ___ at AES-D2, page 100 (Smith Direct)]

To be clear, what Dr. Smith advocates is that, if the leakage factor is 75% and a regulated entity in Minnesota emits 100 tons of GHGs, PUC should apply its SCC value to only 25 tons of GHG emissions because the other 75 tons will leak away and will be emitted elsewhere in the United States.

Q. Do you agree that leakage should be considered when applying a SCC value?

A. I disagree. PUC regulates only utilities in Minnesota. It does not regulate utilities in other states or other countries. The level of GHG emissions in other states is not the responsibility of PUC. It has no responsibility for the aggregate level of emissions in the U.S. Consequently, what other states do -- or fail to do -- by way of their regulation of utilities is not regulated by PUC. It deals with the emissions of utilities that it regulates in Minnesota. If it attributes an environmental cost to those emissions --

whether of criteria pollutants or GHGs – there is no reason to modify its assessment of that cost based on what may or may not happen in other jurisdictions.

VIII. THE UNCERTAINTY REGARDING EQUILIBRIUM CLIMATE SENSITIVITY

Q. What is the equilibrium climate sensitivity?

A. The equilibrium climate sensitivity, usually abbreviated to "climate sensitivity," is a parameter that measures the increase in global average annual temperature, at the steady-state equilibrium, as compared to the pre-industrial temperature, when atmospheric concentration of CO2 is doubled.

Q. What does Mr. Martin state regarding the uncertainty in this parameter?

A. In his Direct Testimony, Mr. Martin cited Professor Pindyck (Pindyck 2015) on the uncertainty regarding the climate sensitivity.[15]

> We know very little about climate sensitivity, i.e., the temperature increase that would eventually result from a doubling of the atmospheric CO_2 concentration, but this is a key input to any IAM. The problem is that the physical mechanisms that determine climate sensitivity involve crucial feedback loops, and the parameter values that determine the strength (and even the sign) of those feedback loops are largely unknown, and are likely to remain unknown for the foreseeable future. As

[15]. For future reference, I will be citing the following papers by Professor Pindyck:
Robert S. Pindyck, The Use and Misuse of Models for Climate Policy (2015), NBER Working Paper 21097, April 2015.
Robert S. Pindyck, "Climate Change Policy: What Do Models Tell Us?" (2013a) *Journal of Economic Literature* 51(3), 860-872.
Robert S. Pindyck, "Pricing Carbon When We Don't Know the Right Price" (2013b) *Regulation* Summer 2013, 43-46.
Robert S. Pindyck, "The Climate Policy Dilemma" (2013c) *Review of Environmental Economics and Policy* 7(2) 219-237.
Robert S. Pindyck, "Uncertain Outcomes and Climate Change Policy," (2012) *Journal of Environmental Economics and Management,* Vol. 63, 289-303.

> Freeman, Wagner and Zeckhauser (2015) have shown, over the past decade our uncertainty over climate sensitivity has increased.' [Xcel Ex. ___ at 39 (Martin Direct).][16]

Mr. Martin correctly quoted Pindyck (2015) to the effect that our uncertainty over climate sensitivity has increased. But, he overlooked the implication that Freeman et al. draw from the increase in uncertainty. It is that implication which is the point of their paper.

Q. In what sense did the uncertainty regarding climate sensitivity increase?

A. The context is as follows. The First, Second and Third IPCC Assessment Reports gave the range of values for climate sensitivity as 1.5°C - 4.5°C. In 2007, the Fourth Assessment Report changed the range to 2°C - 4.5°C. In 2013, the Fifth Assessment Report changed the range back to 1.5°C - 4.5°C. In addition, whereas the Fourth Assessment Report gave a "best estimate" for climate sensitivity of 3°C, the Fifth Assessment Report provided no "best estimate." The first change extended the range of uncertainty, albeit in the low direction (less climate sensitivity, hence less warming). The second change implied a less highly "peaked" probability distribution of values.

Freeman *et al*.[17] used Pindyck's simplified IAM model from Pindyck (2012, 2013c) to analyze the impact of these changes on the estimate of society's

[16]. The quotation is from Pindyck (2015, pp. 1-2).

[17]. Mark C. Freeman, Gernot Wagner and Richard J. Zeckhauser, Climate Sensitivity Uncertainty: When is Good News Bad? NBER Working Paper 20900, January 2015.

willingness to pay (WTP) out of current consumption to avoid climate damages in the future, the metric used by Pindyck which is directly related to the SCC.[18]

Q. What is the economic implication of the increase in the uncertainty regarding climate sensitivity?

A. Freeman *et al*. observed that, while a decrease in the minimum possible climate sensitivity "is undoubtedly good news for the planet," it also implied a widening of the range of uncertainty. Using Pindyck's (2012, 2013c) mathematical model, Freeman et al. demonstrated that, because of the risk aversion and convexity (both of which I discuss further in this rebuttal) of the damage function in Pindyck's model, the widening of the uncertainty generally increases the WTP value of avoiding climate change. Essentially, as the uncertainty surrounding outcomes of climate change increases, one is willing to pay a higher premium to avoid exposure to that increasingly uncertain risk. They also demonstrated that reducing the peakedness of the climate sensitivity distribution increased the WTP value of avoiding climate change.

Thus, the implication of the increase in uncertainty referred to by Professor Pindyck is that it raises the SCC in his economic model of climate change.

[18]. The SCC measures society's WTP to lower damages by reducing emissions by one unit. Pindyck's WTP metric measures society's WTP to eliminate future climate change.

IX. CRITICISMS OF THE IAM DAMAGE FUNCTIONS

Q. What did Dr. Bezdek say regarding the IAM damage functions?

A. Dr. Bezdek quoted Pindyck (2013)[19], in Peabody Ex.__ , page 7 (Bezdek Direct) , that: "these [IAM] models have crucial flaws that make them 'close to useless' as tools for policy analysis". The statement is repeated verbatim on in Peabody Ex__ at 26-27 (Bezdek Direct). Dr. Bezdek repeats Pindyck's phrase "close to useless" in Peabody Ex.__ at RHB-2, pages 5, 7, 115, 116, and 117 (Bezdek Direct) and in Peabody Ex__ at RHB-3, pages 170 and 174 (Bezdek Direct). Exhibit 2 also contained two longer Pindyck quotes to a similar effect:

However, as Pindyck notes the IAM models are 'so deeply flawed as to be close to useless as tools for policy analysis. Worse yet, their use suggests a level of knowledge and precision that is simply illusory, and can be highly misleading.' [Peabody Ex__ at RHB-2, page 95 (Bezdek Direct)].

And,

Similarly, in his review of IAMs Pindyck also noted that the 'loss functions' are not based on any economic theory, but, rather, 'They are just arbitrary, made up to describe how GDP goes down when T [temperature] goes up.' [Peabody Ex.__ at RHB-2, page 106 (Bezdek Direct)].

Q. What did Dr. Smith say regarding the IAM damage functions?

A. Dr. Smith cited Pindyck (2013a) in the document "A Review of the Damage Functions Used in Estimating the Social Cost of Carbon" which is appended to her Direct Testimony, on the following three points:[20]

[19] Dr. Bezdek reference is to what I am calling Pindyck (2013a).
[20]. In these quotations, Dr. Smith's references to Pindyck (2013) are to what I am calling Pindyck (2013a).

(i) "As MIT Economics Professor Robert Pindyck notes, the lack of clear theoretical foundation or empirical bases for IAM damage functions means that the parameter values and functional forms for the damage functions used by the IWG are largely ad hoc and arbitrary (Pindyck 2013)."

[GRE,MP,OTP,MLIG Ex. ___ at 1, 3, 22 (Smith Direct)]

(ii) "As noted, Pindyck (2013) has written that IAM - based analyses such as those developed by the IWG create an 'illusory and misleading' appearance of knowledge and precision about the benefits of reducing CO2 emissions. With regard to the damage function specifically, Pindyck (2013) notes that '[W]e know almost nothing, so developers of IAMs can do little more than make up functional forms and corresponding parameter values. And that is pretty much what they have done.'"

[GRE,MP,OTP,MLIG Ex. ___ at 2, 5 (Smith Direct)]

(iii) "This would appear to be an example of the 'circularity' mentioned by Pindyck in which choices of damage functions are often justified by reference to each other." [GRE,MP,OTP,MLIG Ex. ___ at 23 (Smith Direct)] "In some cases, the studies used as "data" by the modelers are not independent of the modeler. Pindyck (2013) provides the following example of a potential lack of independence of models and "input" data. 'Nordhaus (2008) points out (page 51) that the 2007 IPCC report states that 'global mean losses could be 1-5% GDP for 4oC warming.' But where did the IPCC get those numbers? From its own survey of several IAMs. Yes, it's a bit circular.'"

[GRE,MP,OTP,MLIG Ex. ___ at 30 (Smith Direct)]

Q. What does Mr. Martin say regarding the IAM damage functions?

A. In his Direct Testimony, Mr. Martin cited Pindyck (2013a) as follows:

Pindyck argues that the designers of the IAMs, lacking empirical basis on which to base these key model

> functions, 'simply make up arbitrary functional forms and corresponding parameter values.'
>
> [Xcel Ex. ___ at 48 (Martin Direct)]

Q. Who is Professor Pindyck?

A. Professor Robert Pindyck, Professor of Economics at the Massachusetts Institute of Technology, is an eminent economic theorist who has written papers relating to climate change.

Q. Based on these quotations, one might think that Professor Pindyck rejects the use of the IWG estimates of SCC. Is that the case?

A. Quite the opposite, Professor Pindyck endorsed the SCC estimate developed at the time by the IWG.

Unlike Dr. Bezdek, Professor Pindyck (2013a,b) holds the view that fossil fuels generate a positive external cost:

Burning carbon has an external cost because it produces CO2 and other greenhouse gasses (GHGs) that accumulate in the atmosphere, and will eventually result in unwanted climate change.[21]

With regard to the SCC, Pindyck (2013a) states the following conclusion:

> My criticism of IAMs should not be taken to imply that, because we know so little, nothing should be done about climate change right now, and instead we should wait until we learn more. Quite the contrary. One can think of GHG abatement policy as a form of insurance: society would be paying for a guarantee that a low-probability catastrophe will not occur (or is less likely). As I have argued elsewhere, even though we don't have a good estimate of the SCC, it would make sense to take the

[21]. Pindyck (2013a, p. 860). A very similar statement appears in Pindyck (2013b, p. 43).

> Interagency Working Group's $21 (or updated $33) number as a rough and politically acceptable starting point and impose a carbon tax (or equivalent policy) of that amount.[22] This would help to establish that there is a social cost of carbon, and that social cost must be internalized in the prices that consumers and firms pay. (Yes, most economists already understand this, but politicians and the public are a different matter.) Later, as we learn more about the true size of the SCC, the carbon tax could be increased or decreased accordingly.[23]

Also in Pindyck (2013b), referenced in the text just quoted, Professor Pindyck writes:

> If we focus on "most likely" scenarios for which temperature increases are moderate and effects are small, the SCC is probably in the $10 to $40 range, justifying only a small tax on carbon emissions. But, the "most likely" scenarios are not the ones that should be of major concern. We should focus more on the unlikely but devastating scenarios, *i.e.*, the possibility of a climate catastrophe. Depending on the probability, potential effect, and timing, that might lead to an SCC as high as $200 per ton (although I have not actually tried to actually estimate the number.)

That leaves us with two policy priorities. First, we should take the $20 Interagency Working Group estimate as a rough and politically acceptable lower bound and impose a carbon tax (or equivalent policy) of that amount. Of course, climate change is a global problem and we should pressure other countries to adopt a similar abatement policy…

[22]. "See Pindyck (2013b). Litterman (2013) and National Research Council (2011) come to a similar conclusion." Professor Pindyck is referring here to: Bob Litterman, "What is the Right Price for Carbon Emissions?" *Regulation*, Summer 2013, 24-29; and National Research Council, *America's Climate Choices.* Washington, D.C.: National Academies Press, 2011.
[23]. Pindyck (2013a, p. 870).

> The second policy priority relates to climate change research. … What matters is the possibility of a catastrophic outcome, which does not simply means a very high increase in temperature and rising sea levels, but rather an economic effect of those physical changes that is catastrophic. We need to develop plausible estimates of probabilities of extreme climate outcomes and plausible estimates of the impacts of those outcomes.[24]

To summarize, these quotations demonstrate that Professor Pindyck certainly does not reject the use of the IWG's SCC estimate as characterized by other witnesses, and in fact believes that the true SCC may be considerably higher.

X. THE VALIDITY OF CRITICISMS OF THE IAM DAMAGE FUNCTIONS

Q. Is there in fact the degree of circularity in IAM damages that Professor Pindyck seems to imply?

A. As noted above, Dr. Smith quoted remarks by Professor Pindyck asserting a degree of circularity in the IAM damage functions in GRE,MP,OTP,MLIG Ex ___ at 24 (Smith Direct). While Professor Pindyck's remark holds for DICE, it does not hold for PAGE or FUND.

The damage functions in PAGE and FUND do not reveal evidence of being calibrated to damages in one another or to those in DICE. They are based on independent estimates of sectoral impacts for the sectors covered by those models.

In the versions of DICE through DICE 1999, the damage function was based explicitly on a consideration of sectoral impacts. In subsequent versions, starting with DICE 2007, the disaggregation into impacts on individual sectors seems to have

24. Pindyck (2013b, p. 46).

been abandoned and the focus was mainly on aggregate impacts across all sectors. In calibrating the damage function in these later versions of DICE, attention seems to have been paid to some summaries of estimates of aggregate damages appearing in the literature.

Q. Do you agree with the criticism that the damage functions lack an adequate foundation in economic theory?

A. I disagree with that criticism. The nature and magnitude of the impacts from climate change are empirical and quantitative questions. Economic theory typically provides qualitative predictions, based on assumptions. I find it odd to expect that economic theory would be informative about how much people will be affected by wildfire, say, or flooding, or drought, or crop failure, or increased incidence of malaria.

Thus, I regard the asserted lack of foundation in economic theory as being irrelevant, in practice, for the validity of damage functions.

Q. Do you accept the criticism, made by Dr. Smith, that the IAM damage functions are invalid because they are not dose-response functions?

A. I do not agree. Dose-response functions are typically formulated for narrowly defined outcomes, whether health outcomes or otherwise. They apply to particular outcomes – say, malaria rather than waterborne diseases in general – and they are calibrated to specific conditions. I am not aware that dose-response functions exist for the multiplicity of outcomes of impacts likely to be associated with climate change on the spatial and temporal scales required.

I addressed the issue being raised here in my Direct Testimony. To repeat what I said there:

> Q. Because DICE, PAGE, and FUND contain simplified representations of economic models, climate models, and impact models, does that mean they are inappropriate for use in policy making?
> A. The answer is No. A simplified representation of the three underlying component models is necessary in order to combine those components together and enable rapid iteration of the model for policymaking purposes. Without some simplification, the components could not be combined because of the extreme differences in their spatial and temporal scales. Furthermore, the computer infrastructure and time required to run complete Earth System models is prohibitive in a policy making setting.
>
> DOC Ex__, page42 (Hanemann Direct)

To summarize, it is not reasonable to expect the use of conventional dose-response functions on the spatial and temporal scales required for an IAM damage function. Dr. Smith's argument, therefore, lacks merit.

Q. How did Professor Mendelsohn's modify the DICE damage function?

A. Professor Nordhaus' damage function in DICE implies that, for any degree of warming above preindustrial temperature, there is some amount of damage (measured as a reduction in GDP), however small. Professor Mendelsohn disagrees with Professor Nordhaus and feels it appropriate to modify this.

He implemented two alternative modifications. In each there is no damage – no effect, negative or positive – from warming below a threshold level. In one case, he set that threshold at 1.5°C above preindustrial global temperature. In the other case, he set it at 2°C above pre-industrial global temperature.

Q. Who is Professor Nordhaus?

A. Professor William Nordhaus, Sterling Professor of Economics at Yale University, is an eminent economist who is regarded as the father of climate change economics. He created the first version of an economic growth model that contained a constraint on CO_2 emissions in 1977, and he created the first IAM model with climate damages – the DICE model -- in 1991. He is a member of the US National Academy of Sciences.

Q. Why did Professor Mendelsohn feel the need to change the damage function in DICE?

A. He asserted that the empirical evidence justifies the change.

Q. What is the empirical evidence upon which Professor Mendelsohn relies?

A. He relied on the following evidence:

> Global temperature today is about 0.8°C warmer than the pre-industrial temperature. According to DICE 2013, there should already be a global damage from climate change in 2015 equal to $173 billion annually. Clearly damage this great would be conspicuous. In practice, however, it is very difficult to detect this global damage today, even with careful scientific measurements.
>
> [Peabody Ex__ at ROM-2, page 11 (Mendelsohn Direct)]

According to Professor Mendelsohn's spreadsheet which was subsequently supplied to me, 25 annual global GDP in 2015 amounts to about $75 trillion. Thus, annual damage of $173 billion amounts to about 0.23% of global GDP. The spreadsheet is provided as an attachment to this rebuttal testimony as DOC Ex.___ WMH-R-1.

[25]. DOC Ex. ___ WMH-R-1, Basic DICE Runs.xlsx.

Q. Is this powerful evidence?

A. Not at all. I am not sure why Professor Mendelsohn thinks that an amount which today is so small as to be within the range of noise should be conspicuous, and why failure to detect it should discredit Professor Nordhaus' damage function.

Professor Mendelsohn's argument that Nordhaus' damage function must be wrong because nobody yet notices any effects of the warming that has occurred since pre-industrial times is indeed a specious argument.

The damage function formula in DICE is chosen by Professor Nordhaus. If he wished to use a different formula, he would. Professor Mendelsohn is free to disagree with Professor Nordhaus' choice of formula. But, if he wants others to accept his modification, he needs to present solid evidence why he is right and Professor Nordhaus is wrong. This he has singularly failed to do.

Q. Does Professor Mendelsohn actually concede that there have been detectable changes since pre-industrial times?

A. Yes. He stated:

> there are detectable physical effects associated with the 0.8°C warming since pre-industrial times" and "warmer temperatures are encouraging ecosystems to move poleward (IPCC 2013b) which is a change that may lead to damage in some places. For example, plants have flowered earlier, birds have arrived sooner after winter, and birds have over wintered in more northern locations in the northern hemisphere.
>
> [Peabody Ex__ at ROM-2, page 11 (Mendelsohn Direct)]

Q. Apart from using a different damage function, does Professor Mendelsohn make any other changes to the IWG analysis?

A. He used only DICE, not PAGE or FUND. Whereas the 2013 IWG Report used DICE 2010, he uses DICE 2013.

In addition, he used DICE in its native optimization format and he sets aside the standardized inputs on population, income and emissions that the IWG fed into PAGE and FUND along with the non-optimization (simulation) version of DICE. He also conducted a deterministic analysis (*i.e.*, an analysis with no randomness), rather than using probabilistic versions of the climate sensitivity and other model parameters.

Q. Does it make a difference whether one uses DICE as an optimization or in a simulation format?

A. Yes, it makes a great difference. I explained the difference between a simulation model and an optimization model in DOC Ex.__ at 37-38 (Hanemann Direct). In the optimization version of DICE, global emissions of CO_2 are modeled as though they were determined by a single decision maker who controls emissions made around the world. This assumption simplifies the mathematical analysis and is common in the theoretical literature in economics.

However, this assumption is hopelessly unrealistic. The United Nations Framework Convention on Climate Change (UNFCCC) has 196 members – all the United Nations member states plus Cook Island, Niue, and the European Union. To represent UNFCCC actions as though all members spoke with one voice is not a reasonable way to characterize how the world will proceed in dealing with climate change.

The simplifications embedded in the optimization version of DICE are not innocuous. They imply that abatement occurs more speedily than in the real world, that warming builds up less than is likely in the real world, and that the damages are smaller than is likely in the real world. The simplifications, therefore, generate a lower estimate of the social cost of carbon than is likely to occur in the real world. This is one factor causing a difference between the IWG's estimate of the SCC and that of Professor Mendelsohn.

Q. Did other commenters also rely on the idealized but unrealistic assumption of a single, infinitely-lived maker who controls global emissions?

A. Yes. Dr. Gayer and Dr. Smith also relied on the idealized but unrealistic assumption of global emissions being determined by a single, infinitely lived, optimizing decision maker.

Dr. Gayer relied on this assumption for the discussion of the efficient provision of environmental quality on page 3 of Gayer and Viscusi, "Determining the Proper Scope of Climate Change Benefits," appended to his Direct Testimony.

Dr. Smith relied on this assumption for her discussion of the optimal level of emissions in GRE,MP,OTP,MLIG Ex. ___ at AES-D2, page 55-56 (Smith Direct).

Since the assumption is highly unrealistic, it casts doubt on their arguments.

Q. How does Professor Mendelsohn's revised damage function affect the estimate of the SCC?

A. This is indicated in Table 1, based on a spreadsheet of output results provided to me and included as an attachment to this rebuttal testimony.26 Professor Mendelsohn ran DICE 2013 in four modes: optimization using DICE's default damage function; optimization using his alternative damage functions modified so that there is no effect of global warming until it reaches 1.5°C or 20C; and a non-optimizing version where global emissions follow a business-as-usual (BAU) trajectory.

Those are the four rows in the Table 1 below. The columns show the projected year in which the highest atmospheric concentration of CO_2 occurs and the level in that year; the year in which the greatest warming occurs and the amount of warming in that year; and the degree of warming projected for 2200 and 2300. Making the damage function less damaging has two effects. It lowers the SCC; and it reduces the incentive to reduce emissions, so that atmospheric CO_2 reaches higher levels and there is more warming before – under optimization – abatement efforts kick in. Professor Mendelsohn's analysis using DICE's default damage function generates a SCC of $18.60 in 2015.[27] Professor Mendelsohn's changes to that damage function lower the SCC by two-thirds or more. This is a very large alteration to the specifications of DICE based on very little evidence to back it up.

[26]. DOC Ex. ___ WMH-R-1, Basic DICE Runs.xlsx.

[27]. Professor Mendelsohn states: "In this report, we utilize DICE2013 which is the most recent version of DICE and is the version used in The Climate Casino (Nordhaus 2013)" [Peabody Ex__ at ROM-2, page 10 (Mendelsohn Direct)]. However, it is worth noting that the value Nordhaus actually gives in that book for the social cost of carbon is "about $25" (Nordhaus, *Climate Casino*, Yale University Press, p. 229). Nordhaus refers directly to the IWG's (2010) estimate of the SCC, and he endorses it. He writes: "There are currently many estimates of the social cost of carbon. A U.S. government report provided the best estimate of about $25 per ton of CO_2 for 2015." (*Climate Casino*, p. 228).

Table 1. DICE MODEL WITH ALTERNATIVE DAMAGE FUNCTIONS

DICE WITH ALTERNATIVE DAMAGE FUNCTIONS							
	Peak CO_2 (ppm)		Peak Warming (C)		Warming (C) in 2200	Warming (C) in 2300	Social Cost of Carbon 2015 ($)
DICE DAMAGE FUNCTION	Year Attained	Level	Year Attained	Level			
OPTIMIZATION							
Nordhaus	2100	602	2130	3.38	2.5	0.3	$18.60
Mendelsohn – 1.5 C	2120	700	2150	4.07	3.49	2.1	$6.90
Mendelsohn –2 C	2125	740	2160	4.32	3.96	2.39	$4.45
BUSINESS AS USUAL							
Nordhaus	2225	1275	2290	6.85	6.44	6.85	$19.04

Table 1 also serves to illustrate the effects of the assumption of optimization by a single decision maker who controls global emissions. In the absence of such a decision maker, climate outcomes would be more adverse – worse than under the three optimization scenarios, although probably not quite as bad as the BAU scenario. The BAU scenario itself is very concerning: by 2100, the atmospheric concentration of CO2 would be three times the pre-industrial level of 280 ppm, and by 2150 four times that level. Warming would exceed 6°C by 2175.

Q. Is it correct to say that there is no empirical basis in which to base an IAM damage function?

A. In Xcel Ex. ___ at 48 (Martin Direct) Mr. Martin stated that the designers of IAMs lacked an empirical basis on which to base these key model functions (i.e., the damage function). That statement is incorrect. A more accurate statement would be that the designers drew for their damage functions on an empirical literature mainly from the 1990s. As EPRI (2014) notes:

> "[T]he models draw directly and indirectly on older literature, some dating back to the 1990s. Scientific impacts knowledge has progressed since, as summarized in synthesis products like IPCC (2007, 2014). However this knowledge is not reflected in the current SCC model damage formulations."[28]

In the case of DICE, a detailed accounting of individual sectoral impacts based on the citation of specific impact studies ends with DICE (2000). In the case of FUND, EPRI (2014, Table 6-2) identifies 32 studies which form the information base for FUND's damage functions, only 4 of which appeared after 2002. EPRI (2014, Table 6-2) identifies 8 studies that form the information base for the damage functions in PAGE, seven of which date from the period 2006-2009. In total, fewer than 50 studies form the information base on which these IAMs draw. That represents a small fraction of the information now available in the economic literature on climate change impacts, and a minuscule fraction of what is available in the larger impact literature.

With regard to the economic literature, the IPCC Fifth Assessment Report observed: "A Web of Knowledge search on the terms ("climate change" or "global warming") and "damage and "economic impacts" returns 39 papers for pre-2000, 136 papers for 2000-2009 and 209 papers for 2010 through September 2013."[29] By this reckoning, in September 2013 there were at least 374 English language economic impact studies that could feed into the information base for an IAM damage function.

[28]. EPRI (2014, p. 6-7).
[29]. IPCC WGIII (2014, p. 244).

In the larger impact literature, through 2010, there were 4,822 studies in English containing the words "climate change" and "cost," and over 75,000 studies containing "climate change."[30]

The literature, while still highly incomplete, is not quite as non-existent as suggested.

Q. What is your own assessment of the IAM damage functions in response to the positions of other witnesses?

A. The damage functions in DICE, FUND and PAGE fairly accurately reflected the economic literature on climate impacts as of about 2001. However, the empirical literature has exploded since then, and the IAM developers have failed to keep up with it. My assessment of the newer literature is that these studies generally indicate more severe damages than the earlier literature and thus, if anything, the damage estimates in the IWG SCC are too low.

Q. What causes the newer literature on the impacts of climate change to indicate more severe damages than the earlier literature?

A. In general, there is a much larger volume of studies than existed fifteen years ago. An important feature of the newer studies is that they are becoming more granular with regard to the spatial and temporal scales at which impacts are assessed

The more severe damage estimates in newer literature comes about partly because of increased granularity of the General Circulation Models (GCMs) used to

[30]. IPCC WGII (2014, Figure 1-1).

make projections of climate change on a global scale, and partly because the GCM analyses are increasingly being supplemented by what is known as spatial downscaling. The downscaling translates the GCM projections from the relative coarse native spatial grid scale of the GCMs to a finer spatial scale.

Because of what is known as the convexity of the damage functions, developing a more granular analysis, whether through spatial or temporal disaggregation, is typically likely to generate higher estimates of damages.

This is an important reason why the new literature, being more granular, tends to come up with higher estimates of damages.

Q. Can you explain what is meant by convexity of the damage function?

A. Convexity is a mathematical property that relates to the behavior of the marginal damage as the degree of warming increases.

The concept of marginal damage is closely related to the concept of the social cost of carbon.

The damage function in the IAMs expresses the damage occurring during a period as a function of the degree of warming occurring at that time. The marginal damage measures the increment in damages during a period associated with a unit increment in warming – it is the extra damage per degree increase in warming.

Of interest here is how the marginal damage varies as the temperature becomes warmer. If the marginal damage does not change when it is warmer or cooler, the damage function is linear in temperature.

If the marginal damage is larger when it is warmer – *i.e.*, the marginal damage increases with temperature – the damage function is said to be convex. The more sharply the marginal damage increases as temperature increases, the more convex the damage function.

Figure 2a shows a linear damage function. Figure 2b shows a convex damage function.

Figure 2a. Linear Damage Function

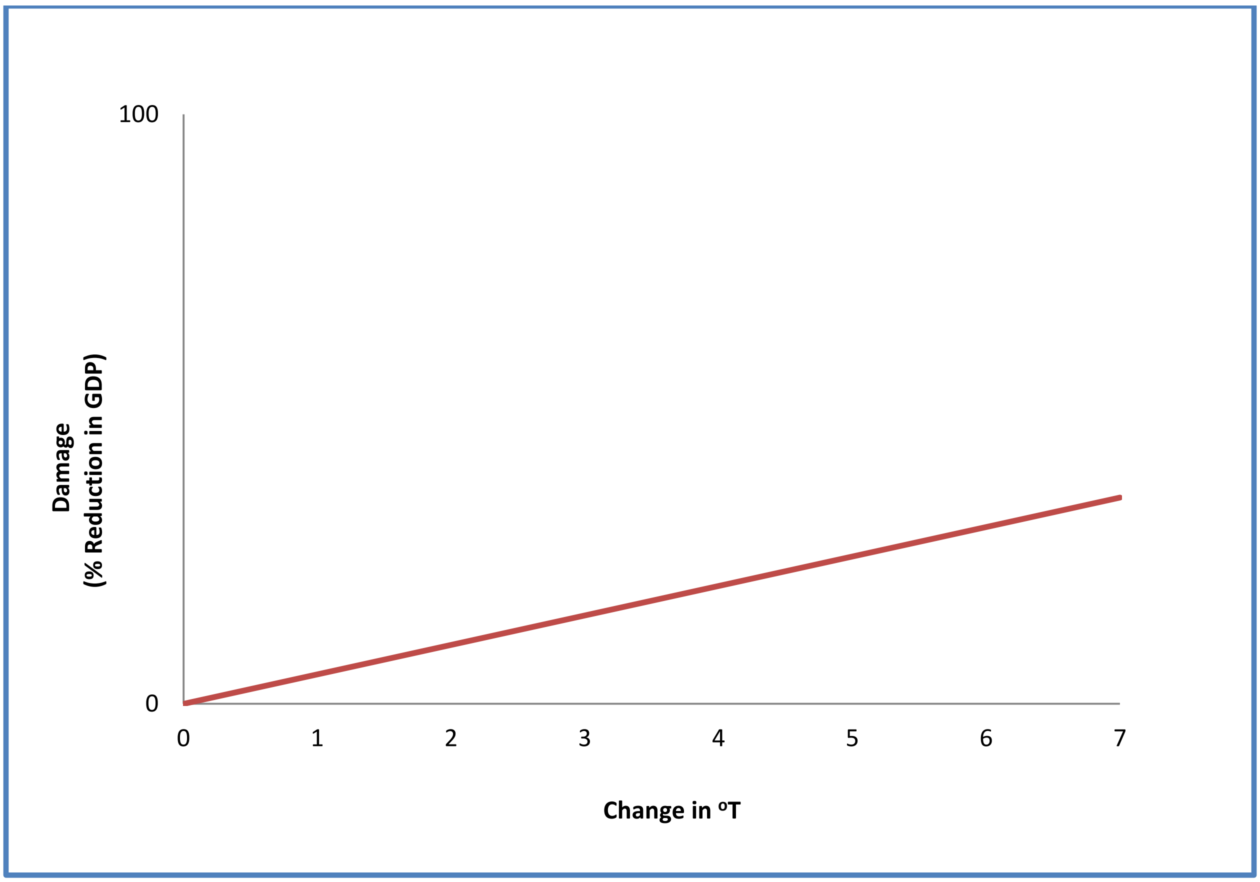
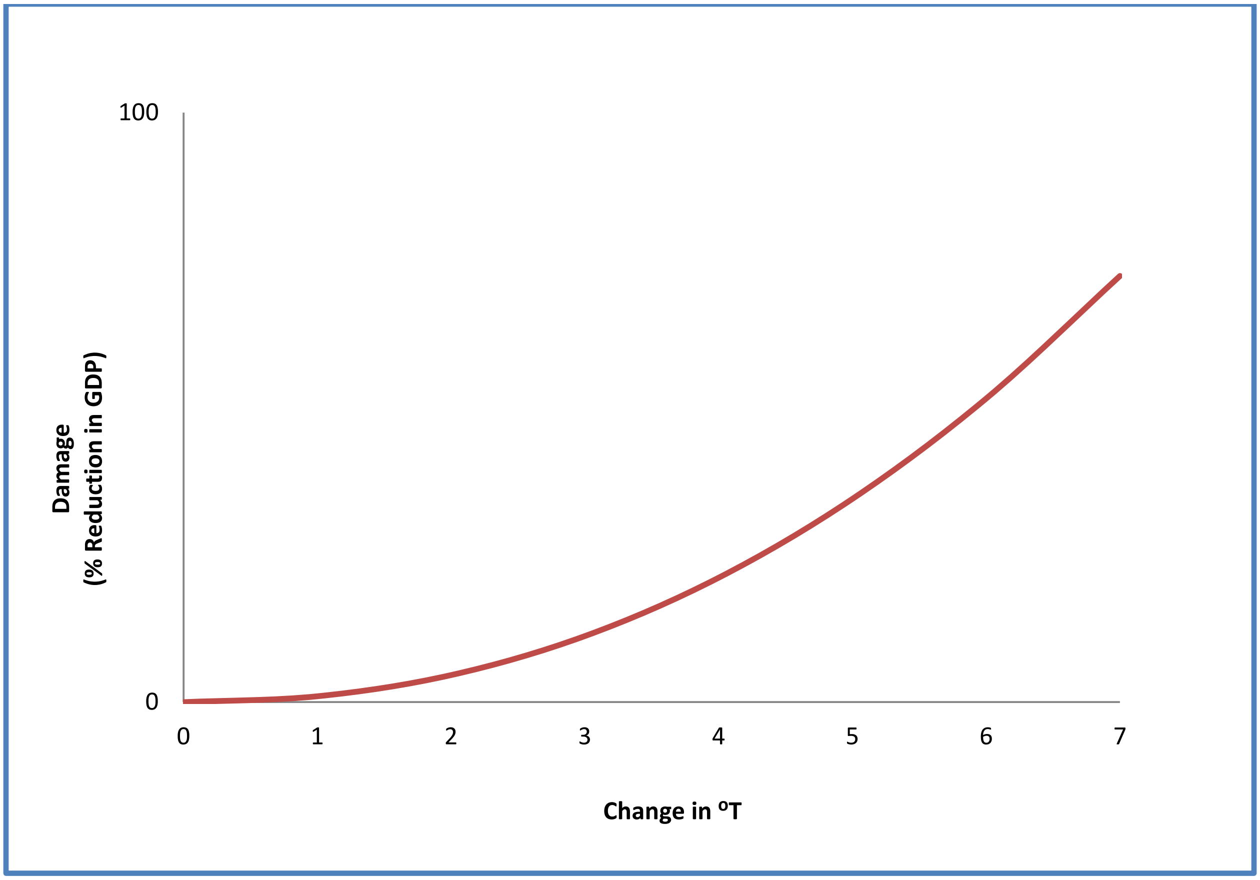


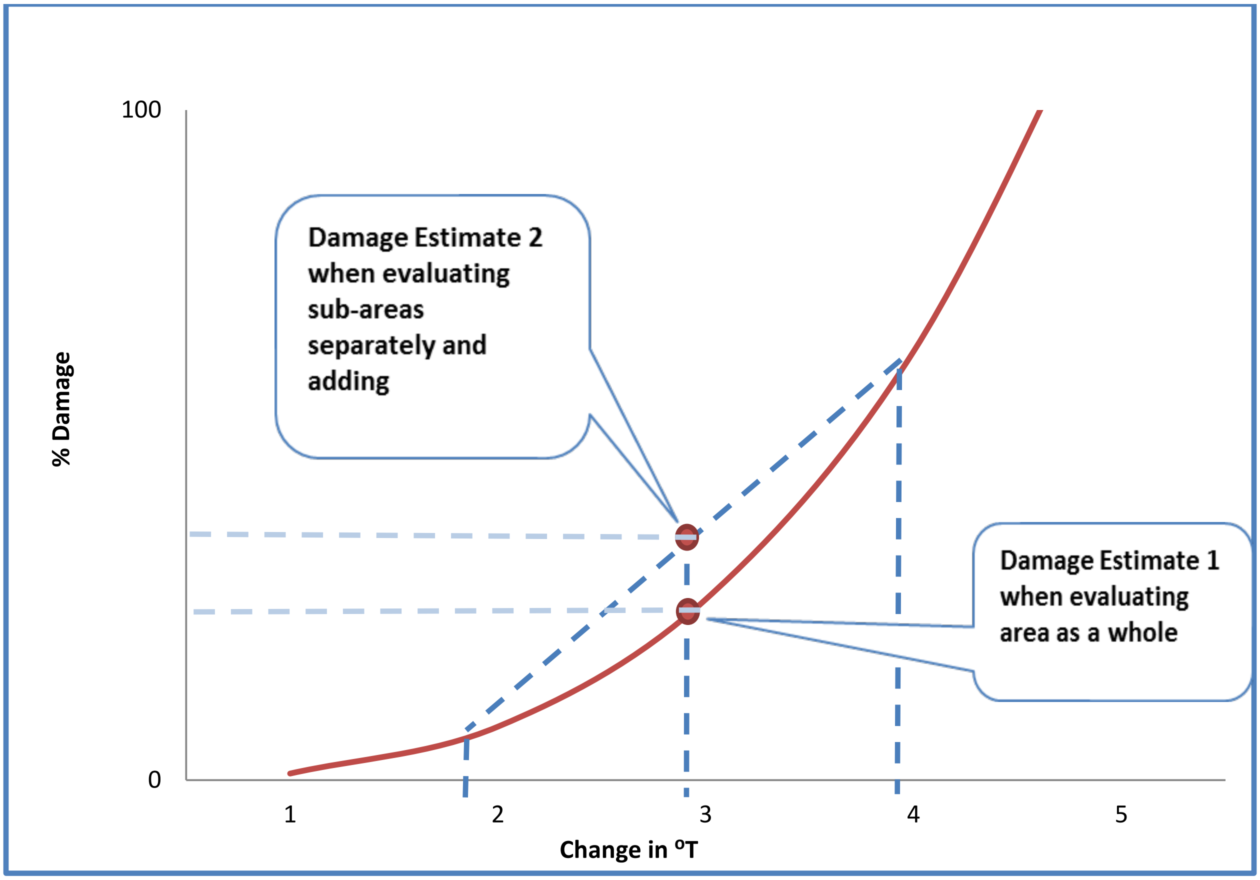
Figure 2b: Convex Damage Function



Q. Why does disaggregation yield higher damage estimates when the damage function is convex?

A. This is illustrated in Figure 3. Suppose that there is a projection of a 3°C warming for a given area. That degree of warming is fed into a damage function and it generates an estimate of damage, depicted as Estimate 1 in shown in Figure 3.

Figure 3: How Convexity Influences the Damage Estimate



Alternatively, divide the area into two subareas. For simplicity, suppose they are equal in size, but one sub-area faces a warming of 2°C while the other a faces a warming of 4°C. Use the damage function to calculate the damages for each sub-area separately, and add them. That generates the estimate of damage depicted as Estimate 2 in Figure 3.

With convexity, the total in Estimate 2 is somewhat larger than Estimate 1, the estimate obtained by evaluating the area as a whole. In the sub-area with 2°C warming the normalized damage will be less than the area-wide average, while it will be larger in the sub-area with 4°C. But, with convexity, the latter exceeds the area-wide average by more than the former falls short.

Estimate 1 corresponds to what is obtained when the damage function is applied to very broad areas, as in the IAMs. Estimate 2 corresponds to what is obtained with spatial disaggregation.

A similar effect occurs with temporal averaging, for example when using the warming of annual temperature rather than the warming of seasonal temperatures taken separately. Due to the convexity of the damage function, disaggregating temperature change by seasons, or even more finely, would raise the estimate of aggregate damage.

Q. Are there examples that help to contextualize these effects?

A. The following example from California illustrates those two effects. Hayhoe *et al*. (2004)[31] conducted an analysis of the potential impacts of climate change in California under two emissions scenarios. I will mention the results for the low emissions scenario (known as the B1 scenario).[32] As simulated by the UK Hadley climate model (HadCM3), under this emission scenario there is a 2°C increase in global average temperature by 2100, compared to the global average in 1990-1999. But, the temperature increase is distributed unevenly around the globe. The increase is smaller over the ocean and in lower latitudes, and larger on land and at higher latitudes. By 2100 in California and much of the US West under this scenario, there is a 3.3°C increase in statewide average annual temperature.

[31]. Katherine Hayhoe *et al*. "Emissions Pathways, Climate Change, and Impacts on California," *Proceedings of the National Academy of Sciences of the United States of America (PNAS)* August 2004; 101 (34). California is one of the states that has most energetically promoted downscaling of climate change projections. It has funded studies of the downscaled impacts of climate change for the past fifteen years, generating a larger volume of literature than for any other US state.

[32]. Equivalent results were obtained with the high emissions scenario.

The increase is different at different times of the year. Statewide average winter temperature (December – February) in California rises by 2.3°C, while statewide average summer temperature (June – August) rises by 4.6°C. Moreover, there is spatial variation between the temperature increases along the coast versus inland. In the Central Valley, the main farming area in California, the increase in summer temperature reaches 5°C.[33]

It makes a substantial difference to the estimated impact on California agriculture whether one represents the climate change as an increase of 2°C (global average annual temperature), 3.3°C (California statewide average annual temperature), or 5°C (Central Valley summer-time average). While the effect on yield of 2°C temperature increase combined with carbon fertilization may or may not be large, the effect of a 5°C increase during the growing season is likely to be very negative.

Q. How do the IAM damage functions characterize global warming?

A. The IAM damage functions involve a highly aggregated characterization of global warming. DICE uses the change in global average annual temperature. PAGE and FUND use the change in regional average annual temperature averaged over very broad regions of the globe.

DICE, for example, would evaluate the scenario just described as a warming of 2oC (corresponding to the increase in global average annual temperature) and would assess damages as though that was the change occurring on the ground. In fact, as

---

[33]. For further details, see Hayhoe et al. (2004).

noted above, this understates the severity of the warming that is likely to be experienced by many people in California at the times of year when it matters most.

Although their scale is regional rather than global, PAGE and FUND are likely to understate the severity of warming actually experienced by many people for the same reason – their high degree of spatial aggregation masks the granularity of what actually occurs on the ground.

Q. Is this the only way in which the IAM damage functions understate the effects of climate change?

A. No. The IAMs exclude all aspects of changes in climate apart from average annual temperature. In particular, they do not account for precipitation, which is an important factor for flooding, water-borne disease, impacts on vegetation and ecosystems, and other types of impacts. To the extent that those impacts do not covary *(i.e.*, tend to move in the same direction) with average annual temperature, they are not accounted for by the IAM damage functions.

While changes in average temperature are included in the IAMs, extreme temperature events are not accounted for in the IAM damage functions.

Q. Could warming affect the rate of growth of GDP, and if it did, what difference would that make?

A. A criticism made by Pindyck (2013a) of the IAM damage functions is that they represent the degree of warming in a given time period as impacting only the contemporaneous level of GDP in that period. Dr. Bezdek mentions this criticism in his Exhibit 2 and quotes Pindyck (2013) as follows:

First, some effects of warming will be permanent; *e.g.*, destruction of ecosystems and deaths from weather extremes. A growth rate effect allows warming to have a permanent impact. Second, the resources needed to counter the impact of warming will reduce those available for R&D and capital investment, reducing growth. Third, there is some empirical support for a growth rate effect. Using data on temperatures and precipitation over 50 years for a panel of 136 countries, Dell, Jones and Olken have shown that higher temperatures reduce GDP growth rates but not levels. Likewise, using data for 157 countries during 1950 to 2007, Bansal and Ochoa show that increases in temperature have a negative impact on economic growth.34 Peabody Ex.__ at RHB-2, page 107 (Bezdek Direct)

Dr. Bezdek refers back to the same Pindyck quotation in his Exhibit 3. This appears in a subsection of the table with the heading "Damage Functions Used in IAMs Consistently Overestimate the Damage from Warming." Dr. Bezdek's text in reference to the Pindyck citation there reads as follows:

> IAM damage functions tend to place too much value ("willingness to pay") on abatement because they track absolute levels of GDP rather than growth rate.
>
> [Peabody Ex.__ at RHB-3, page 168-169 (Bezdek Direct)]

In fact, this sentence is not something that Pindyck says – it is what Dr. Bezdek says. And, it is absolutely wrong.

Here is what Dell Jones and Olken (2014) find regarding growth effects versus level effects:

> Growth effects, which compound over time, have potentially first-order consequences for the scale of economic damages over the longer run, greatly

[34]. Pindyck (2013a, pp. 867-8).

> exceeding the level effects on income, and are thus an important area for further modeling and research.[35]
>
> The point is that reducing the rate of growth of GDP rather than its level in a given year is more damaging over time. To the extent that the IAM damage functions represent warming in a period as affecting the level of GDP in that period, rather than the growth rate (or, say, the capital stock) this leads them to understate the damages from warming.[36]

Q. Did Dr. Smith acknowledge the existence of any factors that could lead the IWG estimate of SCC to be an underestimate?

A. Not to my knowledge.

Q. Did Dr. Smith acknowledge that the IWG in fact warns that the IAM damage functions omit some important damages?

A. The Interagency Working Group acknowledges various limitations of the analysis. For example, the 2010 IWG Report stated:

Current IAMs do not assign value to all of the important physical, ecological and economic impacts of climate change recognized in the climate change literature … because of lack of precise information on the nature of the damages and because the science incorporated into these models understandably lags behind the most recent research. Our ability to quantify and monetize impacts will undoubtedly improve with time. But it is also likely that even in future applications, a number of potentially significant damage categories will remain non-monetized. (Ocean

---

35. Melissa Dell, Benjamin F. Jones and Benjamin A. Olken, "What Do We Learn from the Weather? The New Climate-Economy Literature" *Journal of Economic Literature* 52(3) (2014, p. 753).

36. Jensen and Traeger (2014) investigate another pathway by which uncertainty about economic growth could affect the SCC within an optimal growth model like DICE (Svenn Jensen and Christian P. Traeger, "Optimal Climate Change Mitigation Under Long-Term Growth Uncertainty: Stochastic Integrated Assessment and Analytic Findings," *European Economic Review*, 69 (2014), 104-125). They find that it could substantially raise the estimate of SCC.

acidification is one example of a potentially large damage from CO2 emissions not quantified by any of the three models. Species and wildlife loss is another example that is exceedingly difficult to monetize.) (op. cit., p. 29)

Also, the IWG's Response to Comments stated:

> Based on the current scientific understanding of climate change and its impacts, and on the limitations of the IAMs in quantifying and monetizing the full array of potential catastrophic and non-catastrophic damages, the IWG concluded that the distribution of SCC estimates may be biased downwards. Since then, the peer-reviewed literature has continued to support this conclusion.[37]

In this context, "biased downwards" means that the SCC underestimates damages. Dr. Smith did not acknowledge this observation by the IWG.

Q. Did Dr. Smith acknowledge the IWG's observation that its SCC estimate fails to account for the possibility of climate tipping points which would raise the SCC estimate?

A. Not to my knowledge.

The 2010 IWG Report noted that the SCC estimate may not capture the economic effects of all possible adverse consequences of climate change, including "potentially discontinuous 'tipping point' behavior in Earth systems." (op. cit., p. 31)

A climate tipping point is loosely defined as a threshold beyond which abrupt, and irreversible and damaging climate outcomes may occur. Examples include boreal forest dieback; Amazon rainforest dieback; loss of Arctic and Antarctic sea ice and melting of the Greenland and Antarctic ice sheets; disruption of the Indian and West

[37]. Interagency Working Group, *Response to Comments: Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866* (July 2015, p. 27).

African monsoon; disruption of the Atlantic thermohaline circulation; and loss of permafrost leading to methane release.[38]

The 2010 IWG Report notes: "Many of these tipping points are estimated to have thresholds between about 3oC and 5oC." (op. cit., p. 31)

The IPCC Fifth Assessment Report notes that the risk associated with crossing these tipping points increases with rising global temperature, but the precise location of the tipping point is uncertain.

The damage function in DICE 1999 contained a component intended to measure the risk premium to avoid a global tipping point such as disruption of the thermohaline circulation, but that is not an individual component of the damage functions in DICE 2007, 2010 or 2013. PAGE contains a specific element representing discontinuity impacts (i.e., abrupt change or catastrophe). FUND does not have a specific component representing catastrophic climate change.

Even if tipping points are reflected in the IAM damage functions, there is no allowance for uncertainty about the location of the tipping points.

The question of how such uncertainty could affect the decision to mitigate GHG emissions and the SCC value has been examined by Lemoine and Traeger (2014) and by Cai et al. (2015).[39] Their mathematical analysis validates a heuristic assessment given originally by Litterman (2013).[40]

Litterman makes an analogy with riding a bicycle downhill, especially in a bicycle race. Suppose, looking ahead, you see what might be a dangerous curve.

[38]. Lenton *et. al*. "Tipping Elements in the Earth's Climate System," *Proceedings of the National Academy of Sciences*, Vol. 105, no. 6, February 12, 2008, 1786-1793. (2008).
[39]. Derek Lemoine and Christian Traeger, "Watch Your Step: Optimal Policy in a Tipping Climate," *American Economic Journal: Economic Policy* 2014 6(1) 1-31. Yongyang Cai et al. "Environmental Tipping Points Significantly Affect the Cost-Benefit Assessment of Climate Policies," *Proceedings of the National Academy of Sciences* Vol. 112, no. 15, April 14, 2015, 4606-4611.
[40]. Bob Litterman, "What is the Right Price for Carbon Emissions?" *Regulation*, Summer 2013, 24-29.

What a good cyclist does is to apply the brakes until he gets a better sense of how bad the curve is. Once he determines that the curve won't be a problem, or once he gets through it, then he can pick up the pace. Lemoine and Traeger (2014) and Cai *et al.* (2015) develop the mathematical analogy in the context of a stochastic optimal growth model. The equivalent of braking when facing an uncertain hazard ahead is to boost mitigation efforts when confronting an uncertain threshold for a tipping point. Once the tipping point danger is resolved, the pace of mitigation may fall back (unless another uncertain threshold for a tipping point lies ahead). There is a parallel impact on the SCC estimate. The existence of an uncertain threshold for a tipping point lying ahead is shown to raises the current SCC value. Once the tipping point danger is resolved, the SCC value drops down. This overturns the conventional pattern in which the SCC starts out low and rises over time: with tipping point uncertainty, the SCC would start out high.

Dr. Smith did not acknowledge that tipping points could raise the IWG estimate of the SCC.

Q. Did Dr. Smith acknowledge the IWG's observation that regulation of GHGs should possibly include a degree of risk aversion?

A. To my knowledge, she did not.

Q. What is risk aversion?

A. It is an economic concept that can be explained as follows.

Suppose a decision maker were offered a gift of $100. Suppose, alternatively, he were offered a gamble, with a 50% chance of his receiving nothing together with a

50% chance of his receiving $200. The expected value (mean value) of the gamble is $100. If the individual were indifferent between receiving the gamble or receiving its expected value for sure, he would be said to be risk-neutral. If he preferred receiving the gamble to the gift of $100, he is said to be risk-loving. If preferred receiving $100 for sure to receiving the gamble, he is said to be risk-averse.

Which would be preferred is an empirical question – it is an individual judgment. As a generalization, the empirical evidence suggests that, most of the time, people are more likely to be risk averse than to be risk neutral or risk loving.

Suppose a person is risk averse, and prefers receiving $100 for sure. Then, the gamble must be worth something less than $100 to him. What the gamble is worth is said to be the certainty equivalent of the gamble. The certainty equivalent is defined as the amount of money for sure that is seen by the decision maker as being equivalent to the gamble in terms of its impact on his wellbeing. Suppose, in this case, the individual thinks the gamble is worth only $80 – i.e. he would be indifferent being receiving the gamble and receiving $80 for sure. The difference between the expected value of a gamble and the certainty equivalent is called the risk premium: it is the amount by which the risk adverse individual discounts the expected value of the gamble because of his dislike of risk (i.e., because of his risk aversion). In the present example, the risk premium amounts to $20.

The concept of a risk premium applies to risks with non-monetary outcomes as well as those with purely financial outcomes. For example a risk averse water user facing an unreliable water supply would be willing to pay a risk premium to improve the reliability of his supply.

It applies also to losses as well as to gains. A risk averse person would pay a premium to avoid the risk of a loss. This is how insurance works. There is a 1% chance, say, that your $20,000 car might be damaged or stolen during the course of a year, but you choose to buy insurance that would make you whole if those events occurred. The expected value of your loss is $200 per year (= 0.01*20000). The insurance company charges you both that amount plus a small additional amount to cover its cost of doing business – say, it charges you $230.

If you would not pay more anything than $200 for your annual insurance premium, you are risk neutral. If you would only pay an amount less than $200, you are risk loving. If you would be willing to pay some amount more than $200 for insurance (but not necessarily too much more), you are risk averse. In the latter case, the amount by which what you are willing to pay for insurance against a loss exceeds your expected loss is your risk premium. It is what you are willing to pay to avoid the risk of being harmed by having your car damaged or stolen.

The IWG noted the issue of risk aversion in its 2010 Report. It pointed out: "Even if individuals are not risk averse for such scenarios, it is possible that regulatory policy should include a degree of risk aversion." (op. cit., p.30)

Q. Would the sum of the considerations discussed above cause the IWG estimates of the SCC to be biased downwards?

A. Yes, in my opinion it would.

Q. What is your own assessment of the IAM damages?

A. The damage functions in DICE, FUND and PAGE do not well reflect the current empirical literature on climate change impacts. In addition, the theoretical literature has developed mathematical modifications of the damage function formula that can account for the considerations just discussed above and has demonstrated their application to DICE. My assessment of these newer literatures is that they generally indicate more severe damages than the earlier literature.

However, at present the damage functions in DICE, FUND and PAGE are the only damage functions currently available for use in a model inter-comparison exercise.[41] The decision by the IWG to use those models was reasonable at the time and is still reasonable today.

But, it is important to recognize that these damage functions are likely to understate the actual social cost of carbon.

Q. Does your opinion that the damage function in the IAMs likely understates the actual SCC change your recommendation that the PUC adopt the IWG's SCC?

A. No, it does not.

XI. CATASTROPHIC OUTCOMES

Q. Does Dr. Smith believe that we need to consider possibly catastrophic outcomes?

A. The answer is apparently No.

[41]. The ENVISAGE IAM may also be available. However, I do not believe that its damage function would be any less immune to the criticisms made of the DICE, PAGE and FUND damage functions that have been summarized above.

In GRE,MP,OTP,MLIG Ex. ___ at AES-2, page 72 (Smith Direct) Dr. Smith believes that the analysis of climate impacts should be terminated at 2100 or 2140 precisely because, beyond that time frame, there could be large increases in global temperature under some scenarios and simulations. In effect, she is arguing to exclude potentially catastrophic outcomes from consideration.

Q. Do policymakers and regulators need to consider possibly catastrophic outcomes resulting from climate change?

A. In my view, the answer is yes.

The justification for this answer is well expressed by Pindyck (2013a), as follows:

> Why do we need to worry about large temperature increases and their impact? Because even if a large temperature outcome has low probability, if the economic impact of that change is very large, it can push up the SCC considerably. As discussed in Pindyck (2013c), the problem is that the possibility of a catastrophic outcome is an essential driver of the SCC.[42]

Q. Why does Dr. Smith want to exclude catastrophic outcomes from consideration?

A. One reason why Dr. Smith recommended disregarding the possibility of large degrees of warming is that she believes that the world's population will not stand by and allow themselves to be exposed to high temperatures.[43]

This is like arguing to the Nuclear Regulatory Commission that it should disregard the possibility of low risk but catastrophic accidents because the operator of a nuclear power plant would never allow such accidents to happen.

[42]. Pindyck (2013a, p. 869).
[43]. Ibid.

Her second reason was that the existing IAM damage functions are not calibrated to large degrees of warming and therefore are unreliable.

Professor Pindyck, who is quoted in her testimony, makes a similar point that the IAM damage functions are not calibrated to large degrees of warming, but he then draws a very different conclusion from it. He states:

> It is difficult to see how our knowledge of the economic impact of rising temperatures is likely to improve in the coming years. More than temperature change itself, economic impact may be in the realm of the "unknowable." If so, it would make little sense to try to use an IAM-based analysis to evaluate a stringent abatement policy. The case for stringent abatement would have to be based on the (small) likelihood of a catastrophic outcome in which climate change is sufficiently extreme to cause a very substantial drop in welfare.[44]

Instead of confining the analysis to the time period before catastrophic outcomes occur, Professor Pindyck recommends that we explicitly consider them:

> First, consider a plausible range of catastrophic outcomes (under, for example, BAU), as measured by percentage declines in the stock of productive capital (thereby reducing future GDP). Next, what are plausible probabilities? Here, "plausible" would mean acceptable to a range of economists and climate scientists. Given these plausible outcomes and probabilities, one can calculate the present value of the benefits from averting those outcomes, or reducing the probabilities of their occurrence.45

[44]. Pindyck (2013a, p. 869).
[45]. Pindyck (2013a, p. 870).

Q. In your opinion, is Dr. Smith's attempt to exclude catastrophic climatic outcomes from consideration when computing the SCC consistent with Professor Pindyck's position in his literature?

A. Absolutely not. As noted above, Professor Pindyck sees "the possibility of a catastrophic outcome as an essential driver of the SCC."[46]

Q. Are the existing IAM damage functions likely to overstate or understate the damage associated with catastrophically large degrees of warming?

A. As I outlined earlier in this rebuttal regarding effects of climate tipping points, they are likely to understate the damage associated with catastrophically large degrees of warming.

Q. How might that affect the resulting estimate of SCC?

A. It would lead the IWG's estimates to understate the true value of the SCC.

XII. USE OF THE MEAN VERSUS THE MEDIAN ESTIMATE OF THE SCC

Q. How did Mr. Martin characterize the probability distributions of SCC values developed by the IWG and their means?

A. Mr. Martin correctly pointed out that the mean is a good measure of central tendency for data which are normally distributed in Xcel Ex. ___ at 26 (Martin Direct). He also correctly noted in Xcel Ex. ___ at 26 (Martin Direct) that the SCC values developed by the IWG are not normally distributed – they are skewed with a long right tail.

---

[46] Pindyck (2013a, p. 869).

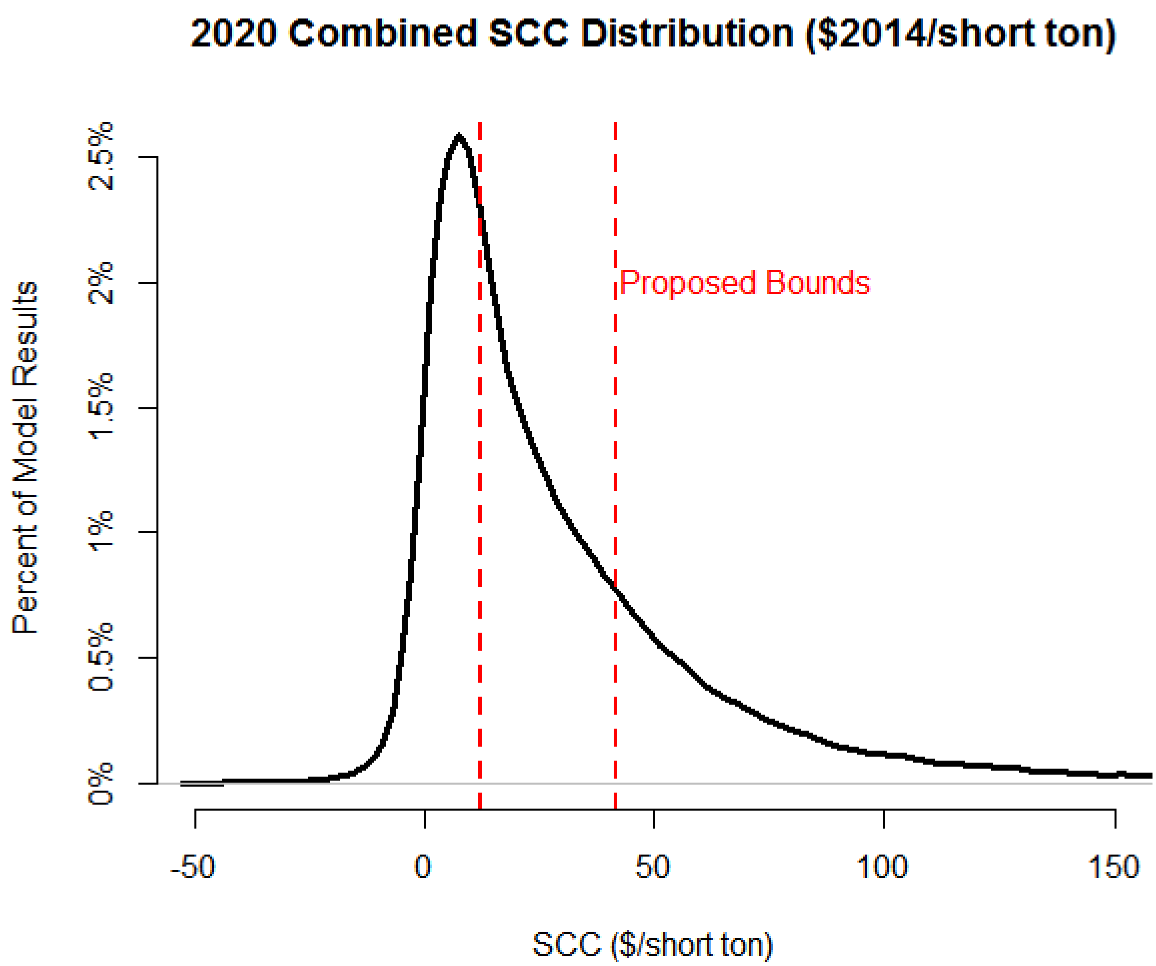
He then stated in Xcel Ex. ___ at 27 (Martin Direct) that, with a skewed distribution, the mean is greatly influenced by "outliers".

Q. Do you agree with his characterization?

A. No. In my view, "outlier" is the wrong term for what is going on in Figure 9 in Xcel Ex. ___ at 65 (Martin Direct), reproduced below. In statistics, an outlier is an observation that is distant from other observations.[47] What we have here, however, is a continuum of observations with increasingly large values. In this case, it is not that there are outlier values of the SCC. It is that the distribution of SCC values is skewed with a long right tail.

A non-normal distribution (in this case positively skewed), will intrinsically include data points that are much larger than others in the same population. That is the nature of skewed population, as shown below in Figure 9 in Xcel Ex. ___ at 65 (Martin Direct).

[47] The Merriam-Webster gives the following definition: "a statistical observation that is markedly different in value from the others of the sample."



One can see from this figure that the much larger damage estimates that Mr. Martin is characterizing as outliers as part of the SCC damage calculation are within the accepted distribution of a population of SCC estimates exhibiting positive skewness.

Mr. Martin proposed to eliminate the larger damage values, via his use of the median rather than the mean, that lie well within the distribution exhibited by the SCC damage estimates. To exclude those data points produces an SCC estimate that is not fully representative of all the possible damage outcomes modeled by the IWG.

Q. Mr. Martin advocated for the use of the median rather than the mean value of the distribution. Do you agree with that recommendation?

A. I disagree for the same reason as that given by the IWG:

> The choice of the mean or the median as a measure of central tendency depends on the context. In skewed distributions, such as for the SCC estimates, the median will often give a more "typical" outcome, while the mean will give full weight to the tails of the distribution. In some cases, the typical outcome is of most interest. For example, in describing household incomes the median is most often used because the focus is on understanding the income of the typical household, and using the mean might distort this picture by giving undue weight to a small number of very wealthy households. In the climate change context, however, sound decision-making requires consideration of not only the typical or most likely outcomes, but also less likely outcomes that could have very large (or small, or even negative) damages (the tails of the distribution). Use of the median to represent the SCC in a regulatory impact analysis would not necessarily lead to the most efficient policy choice that uses resources wisely to mitigate potential climate impacts (e.g., maximize the expected net benefits). In this case, the IWG believes that the mean is the appropriate measure of central tendency.[48]

I take away three points from what the IWG says.

First, the choice of a measure of central tendency with which to represent a probability distribution depends on the decision context and the purpose for which the measure of central tendency will be used. It depends on the criteria by which the decisions are being made.

[48]. Interagency Working Group, *Response to Comments: Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866* (July 2015, p. 26).

Second, that judgment is a policy judgment. The IWG has clearly made this policy judgment.

Third, what is at involved here is essentially a matter of risk management – regulating GHG emissions so as to avoid the risk of possibly very harmful climatic outcomes in the right tail of the warming and SCC probability distributions.

Using the median effectively chops off the tails of the distribution. It removes them from consideration. That is contrary to the objective of a risk management policy.

Q. Mr. Martin's range of values excludes the 95-percentile of the SCC distribution. Do you agree with his decision to exclude the 95-percentile from consideration?

A. I disagree with his decision in Xcel Ex. ___ at 29 (Martin Direct) to exclude the 95-percentile of the SCC distribution from consideration. I believe there is a case for considering the 95-percentile of the SCC distribution.

This is done in other regulatory contexts involving low risk but potentially catastrophic outcomes. It is common in that setting to focus attention on events that can occur with as little as a 5% probability and to examine the probability density function through at least the 95-percentile (the point where there is a 95% probability that a lower value outcome occurs).

An analogy is offered by Mr. Nick Robins of the United Nations Environmental Program. Mr. Robins is quoted in a new report on the value at risk from climate change by the Economist Intelligence Unit as follows:[49]

[49]. Economist Intelligence Unit, *The Cost of Inaction: Recognizing the Value at Risk from Climate Change*, London (2015, p. 14).

We wouldn't get on a plane if there was a 5% chance of the plane crashing, but we're treating the climate with that same level of risk in a very offhand, complacent way.

This concern with tail risks (risks associated with the low probability, high damage events represented in the skewed tail of the distribution) is consistent with, and validates, the IWG's analysis in reporting the 95-percentile value of the SCC distribution for the 3% discount rate.

XIII. DISCOUNTING

Q. Dr. Bezdek states that the discount rate is arbitrary.50 Do you agree with that assertion?

A. I disagree. There is a well-developed economic theory of the discount rate. Technically, when we talk of using a 5% discount rate, say, to compute the SCC we are referring to what is known as the consumption rate of discount. That, in turn, is derived from something known as the utility rate of discount. Below, I explain those concepts to show how the discount rate is not arbitrary.

[50] On page 7 of his Direct Testimony he states: "Certain inputs (e.g. the discount rate) are arbitrary, but have huge effects on the models' SCC estimates." [Peabody Ex.__ at 7 (Bezdek Direct)].

Q. Dr. Smith rejected the use of a 2.5% discount rate. She stated: "I conclude the IWG's use of a 2.5% discount rate does not conform to criteria to base Minnesota's estimates of environmental cost values on evidentiary foundations."[51] Do you agree with that conclusion?

A. I disagree. As explained below, I believe that a consumption rate of discount of 2.5% is certainly compatible with calculations based on reasonable economic assumptions.

Q. What is the utility rate of discount, and why is it relevant?

A. The utility rate of discount is the rate at which individuals are willing to trade off an amount of wellbeing – utility - now in exchange for an increase of wellbeing of the same magnitude in the future. The decision at hand can be viewed through the following metaphor. An individual faces future danger. However, he can take action now that would avert the future harm. Should he do so? Taking action now entails a cost. Paying the cost reduces the money he has to buy other things that he would enjoy now. Paying the cost and foregoing those items, therefore, would reduce his wellbeing now. On the other hand, the future harm will reduce his wellbeing then. The dilemma: should he reduce his wellbeing today to avoid a reduction in his future wellbeing?

The answer requires a comparison between changes in his wellbeing at two points in time – now, and the future. Two sets of factors influence the comparison: (i) the magnitude of the change in well-being, and (ii) how the person feels about future versus present wellbeing. The latter factor is measured by what is called the person's

[51] Smith Direct Testimony, p. 24. GRE,MP,OTP,MLIG Ex. ___ at 24 (Smith Direct).

rate of time preference.[52] It is also known as the utility rate of discount. That rate reflects how the person is willing to trade-off wellbeing (utility) at one point in time for another point in time.

If the person values a unit of his future wellbeing as equally important as a unit of present wellbeing, he has a zero rate of time preference ($\delta = 0$). He would apply a zero discount rate to his future wellbeing

If he values a unit of his future wellbeing as less important than a unit of present wellbeing he has a positive rate of time preference ($\delta > 0$). He would apply a positive discount rate to his future wellbeing. The greater the disparity in the value of the future and present units of wellbeing, the larger the rate of time preference.

If he values a unit of his future wellbeing as more important than a unit of present wellbeing he has a negative rate of time preference ($\delta < 0$). He would apply a negative discount rate to his future wellbeing. In that case, the greater the disparity in the value of the future and present units of wellbeing, the lower the rate of time preference.

The rate of time preference is a subjective decision by the decision maker. And, it determines his willingness to make an investment that entails a cost now but improves his future welfare.

In a highly simplified form, this symbolizes the choice being faced with regard to regulating the emission of GHGs.

---

[52]. It is represented by the parameter δ in the text from Pindyck (2013a) quoted below. In the context of a growth model framed around decision-making by a single individual representative of society, such as DICE, the parameter δ is referred to as the *social* rate of time preference.

Q. What is the consumption rate of discount, and how does it relate to this discussion?

A. So far, the tradeoff has been framed in terms of utility or wellbeing – giving up some wellbeing now in exchange for more wellbeing later.

The same tradeoff can also be framed in monetary terms: giving up some income, or consumption, now in exchange for more income, or consumption, later. That tradeoff depends on how the person values a unit of consumption now versus a unit of consumption later. The factor involved in this trade-off is known as the consumption rate of discount.

It is the consumption rate of discount that should be used when calculating the SCC.

Q. What is Ramsey discounting and why is it important to this discussion?

A. The relationship between the consumption rate of discount and the utility rate of discount was first explicated by the British economist Frank Ramsey in 1928. He first developed the economic growth model on which the DICE model draws. He proved that the consumption rate of discount is the appropriate discount factor to use when an optimizing individual is contemplating the transfer of consumption (income) from one point in time to another. And he demonstrated that the consumption rate of discount depends on two factors: (i) the utility rate of discount, and (ii) the extent to which the person's income (or consumption) will be different in future compared to today.

If the person expects his income (or consumption) to be the same in the future as to day, his consumption rate of discount exactly equals his utility rate of discount (his δ).

If he expects his income to be larger in the future than today, that introduces a correction factor which needs to be added to δ. The correction factor arises because (a) his income will be larger, and (b) as his income rises the marginal utility that he obtains from an additional unit of income decreases. I will refer to the correction factor that combines (a) and (b) as the marginal utility factor.

Conversely, if he expects his income to be smaller in the future than today, that introduces a correction factor which needs to be subtracted from δ. In this case, the marginal utility factor lowers the consumption rate of discount to a value less than δ.

In Professor Nordhaus' analysis with DICE used in the optimization mode, the marginal utility factor plays a large role. He assumes a value of 1.5% for δ, while the marginal utility factor amounts to 4%, yielding a consumption rate of discount totalling 5.5%.[53]

By contrast, in the Stern Review,[54] Professor Stern assumes a value of 0.1% for δ, while the marginal utility factor amounts to 1.3%, yielding a consumption rate of discount totaling 1.4%.

The consumption rate of discount is what is used for estimating the SCC. Hence, these differences in estimates of the consumption rate of discount produce substantial differences in estimates of the SCC.

---

[53]. William Nordhaus, *A Question of Balance* Yale University Press (2008, p. 61).

[54]. Nicholas Stern, *The Economics of Climate Change*, Cambridge University Press, 2007. At the time, Professor Stern, a distinguished British economist, was serving as Chief Economist for the UK Government, and he was commissioned to conduct an independent assessment of the economic impacts of climate change. He used PAGE for his analysis. His assessment was considerably more negative than that Nordhaus' assessment with DICE.

Q. What assumptions underlie Ramsey discounting?

A. Several assumptions underlie Ramsey discounting as applied in the IAMs. These include:

- The assumption that climate policy can be viewed through the metaphor of a single, infinitely-lived individual arranging his consumption over the course of his (infinite) lifetime.
- -The assumption that the individual has constant preferences and constant expectations regarding what gives him wellbeing throughout the course of his lifetime. And
- The assumption that everything the individual cares about can be boiled down to one item – the amount of money that he has – and all impacts of climate change can be reduced to the equivalent of a change in the money that he has.

If any of these assumptions is judged unreasonable, it would change the formula for the consumption rate of discount.

Q. Are these reasonable assumptions?

A. In my view, No.

The notion of a single, infinitely lived decision maker determining the world's GHG emissions from now to beyond 2300 is a fiction which provide a mathematically convenient framework for conducting the IAM analysis. But, it is a fiction. It does not capture many important elements of the climate problem that we face. In particular, it sweeps aside the ethical issues associated with inter-generational and intra-generational equity.

If one took seriously an obligation to preserve the planet for future generations, Ramsey discounting falls away.

For the moment, accept the notion of mankind over the next 300 years being represented through the metaphor of a single, infinitely-lived individual. The notion that human preferences remain unchanged over three centuries, and that what people expect out of life stays unchanged over three centuries, is wildly implausible.

However, it is this assumption which underlies the argument made by Dr. Smith in GRE,MP,OTP,MLIG Ex. ___ at AES-2, page 88 (Smith Direct) that "future generations will be far wealthier and have far higher consumption than is the case in the present". She makes the argument in the context of arguing for a high discount rate. The mathematical basis for the argument regarding the increase in future wealth comes directly from the decreasing marginal utility effect, and assumes that future generations will have exactly the same expectations out of life as we do today – their incomes will be many times higher, in real terms, than our income today but their expectations will be completely unchanged by the passage of time and the rise in their standard of living.

If the assumption is incorrect – if people's expectations do change over time – that undercuts the decreasing marginal utility effect. Depending on how much people's preferences and expectations change, it would reduce or eliminate the decreasing marginal utility effect, thereby lowering the consumption rate of discount.[55]

[55]. For an economic growth model that allows for people's expectation to change over time, see Harl E. Ryder and Geoffrey M. Heal, "Optimal Growth with Intertemporally Dependent Preferences," *Review of Economic Studies*, 40 (January 1973), pp. 1-31.

Finally, if people care separately for both things that money can buy and also for other, non-market things, such as preserving the natural environment, and if they do not see those two types of items are perfect substitutes for one another, this adds an additional, third term, to the Ramsey formula for the consumption rate of discount. If one makes the assumption – which I consider plausible – that people care for unimpaired natural environment but this is increasingly threatened and declines in scale with economic growth and with climate change, the mathematical effect is to reduce the value of the consumption rate of discount.

For these reasons, I regard Professor Nordhaus' estimate of 4% for the marginal utility factor, as far too high.

Q. Is the value δ = 0.1 outlandish?

A. Professor Pindyck opens his discussion of discounting as follows:

> We can begin by asking what is the "correct" value for the rate of time preference, δ? This parameter is crucial because the effects of climate change occur over very long time horizons (50 to 200) years, so a value of δ above 2 per cent would make it hard to justify even a very moderate abatement policy. Financial data reflecting investor behavior and macroeconomic data reflecting consumer and firm behavior suggest that δ is in the range of 2 to 5 percent. While a rate in this range might reflect the preferences of investors and consumers, should it also reflect intergenerational preferences and thus apply to time horizons greater than fifty years? Some economists (*e.g.*, Stern 2008 and Heal 2009) have argued that on ethical grounds δ should be zero for such horizons, i.e., that it is unethical to discount the welfare of future generations relative to our own welfare. But why is it unethical? Putting aside their personal views, economists have little to say about that question. I would argue that the rate of time preference is a policy parameter, i.e., it reflects the choices of policy makers, who might or might not believe (or care) that their policy decisions reflect the values of voters. As a

> policy parameter, the rate of time preference might be positive, zero, or even negative.

I agree with Professor Pindyck that, in the present context, the choice of the rate of time preference is an ethical judgment. It has economic implications, but economic theory per se cannot prescribe what numerical value to employ. Setting a value is a policy judgment.

Therefore, I do not consider Stern's value of δ to be outlandish.

Q. Could a consumption rate of discount of 2.5% be compatible with calculations based on reasonable economic assumptions?

A. Yes. I believe that making realistic assumptions about people's preferences over time could plausibly generate values of the marginal utility factor in the range from 1.3 (Stern's value) to 2, and I believe that a pure rate of time preference of, say, δ = 0.5 is ethically highly defensible.

Furthermore, a realistic model of people's preferences would admit the possibility that they engage in hyperbolic discounting – as opposed to geometric discounting – which would further lower the consumption rate of discount.

Q. What is geometric discounting?

A. Geometric discounting is the technical name given to the conventional type of discounting, the type of discounting employed by the IAMs and the type we have been discussing so far. With geometric discounting, a constant rate of discount is employed to discount from one period to the next.

Suppose an outcome X could occur one period from now, or two periods from now, or three periods from now. Assume the constant rate of discount is α. With geometric discounting, the mathematical formula for discounted present value of X is as follows. If the outcome, X, occurs one period from now, its discounted present value is X/(1+α). If it occurs two periods from now, the discounted present value is X/(1+α)2. If it occurs three periods from now, the discounted present value is X/(1+α)3. More generally, if the outcome X occurs T years from now, with geometric discounting the formula for the discount factor (i.e., the factor by which X is multiplied) is [1/(1+ α)T].

Q. What is hyperbolic discounting?

A. Hyperbolic discounting is the name given to an alternative form of discounting, one in which the rate employed to discount from one period to the next declines as the two periods being considered lie further in the future.

Geometric discounting treats the difference between X occurring next year or the year after as the same as that between X occurring 101 years from now versus 102 years from now – in both cases there is a delay of one year. Hyperbolic treats X occurring 101 years from now versus 102 years from now as being different than the comparison of X occurring next year versus two years from now. Hyperbolic discounting focuses on the relative time difference, not the absolute time difference. Waiting 102 years instead of 101 years is a 1% delay in the timing of the outcome; waiting two years instead of one year is a 100% delay. With hyperbolic discounting, the former delay receives less weight than the latter because it is a delay of only 1%.

The value of X when it is delayed for year is discounted less heavily if the delay occurs after 101 years than after one year.

With hyperbolic discounting, the distant future is discounted less heavily than with geometric discounting. If hyperbolic discounting were applied when calculating the SCC, as opposed to the geometric discounting used in the IAMs, it would substantially raise the SCC value.

There is now considerable empirical evidence that when people make real choices regarding future outcomes, they generally employ something like hyperbolic discounting rather than geometric discounting to weigh future outcomes. Both the UK Government and the French Governments have adopted hyperbolic discounting for policy evaluation.

Q. Why does Dr. Smith reject the idea of hyperbolic discounting?

A. Dr. Smith refers in passing to the notion of a discount rate that declines with the passage of time – in effect, hyperbolic discounting – only to reject it in GRE,MP,OTP,MLIG Ex. ___ at AES-2, page 82, 88 (Smith Direct). Following an argument given by Farrow and Viscusi (2011),[56] she rejects it on the grounds that it would lead to what is known as time inconsistency.

Q. What is time inconsistency?

A. The context in which time inconsistency arises is that of a single decision maker making decisions over a span of time. He recognizes the interdependence between future and present decisions. A decision made now can have consequences for the

[56]. S. Farrow and W.K. Viscusi, 2011. "Towards Principles and Standards for the Benefit-Cost Analysis of Safety," *Journal of Benefit-Cost Analysis* 2(3).

choices he will face in the future and, therefore, for his future decisions. And the future decisions can have consequences for what he should choose today. The individual is rational and makes decisions in a forward-looking manner, recognizing the inter-temporal dependence among his decisions. He determines today not only his present choices but also his future choices based on his expectation today of future circumstances.

Time inconsistency arises when, at some future time, he fails to make the choice that he determined now he would make at that time. For example, he makes a particular choice today based on a decision that, 40 years from now, he will choose X over Y. But, when the occasion arrives 40 years from now, at that time he actually chooses Y over X. His future behavior is inconsistent with what today he had planned it to be. This time inconsistency is said to undermine the whole notion of optimality and rational planning.

Moreover, it is known that hyperbolic discounting can lead to this type of time inconsistency.

Q. Is time inconsistency a compelling reason to reject hyperbolic discounting in the context of the calculation of the SCC?

A. In my opinion, no. The notion of time inconsistency is based on the assumption of a single decision maker with unchanging tastes and unchanging expectations for life. That is not an appropriate lens through which to conceptualize the issue of global climate policy. It is therefore not a valid basis for rejecting the use of hyperbolic discounting in an IAM.

Time inconsistencies occur all the time in the real world. The US government, under President Obama, makes decisions in 2015 that the US government under President Bush, looking forward a decade from 2005, had intended to be rejected. That is time inconsistency in US government decision making.

To reject hyperbolic discounting on the grounds that it could lead the US government to make time inconsistent choices a century or more from now is, in my view, a far from compelling argument.

Q. Dr. Smith asserted that an SCC calculated based solely on estimates of the consumption rate of discount is too low.[57] Do you agree?

A. I disagree.

Rather than the consumption rate of discount, Dr. Smith argued for using something closer to the market rate of interest ("the opportunity cost of capital") when calculating the SCC.[58]

The market rate of interest and the consumption rate of capital are two different concepts. They are different in the same way that the worth of an item to a person is a different concept than the price the person has to pay to acquire the item – a difference that I explained in In DOC Ex__ at 15-17 (Hanemann Direct).

The consumption rate of discount measures how much consumption (income) a decision maker would be willing to give up today in exchange for an extra unit of consumption (income) a year from now. The market rate of interest is the price that

[57] GRE,MP,OTP,MLIG Ex. ___ at 24 (Smith Direct) "An upper bound based solely on estimates of the consumption rate of interest (or the social rate of time preference) is too low"

[58] GRE,MP,OTP,MLIG Ex. ___ at 24-26 (Smith Direct)

measures how much it would cost that decision maker in terms of today's consumption (income) in order to acquire an extra unit of consumption (income) a year from now. As I noted in that part of my Direct Testimony, what an item is worth to a person is conceptually different than what it costs – the former reflects factors affecting demand, while the latter reflects factors affecting supply.

I also noted that there exist some circumstances where what an item is worth is equated to its price. That outcome occurs in a competitive market where the decision making is optimizing the quantity of the item in question. This condition applies also to equality of the market rate of interest and the consumption rate of discount – the two are equated when the decision maker is making an optimal intertemporal choice in a competitive market.

The assumption of optimality is the crux of the analysis when DICE is being run in its native optimization format. In that case, it depicts what would happen to global GHG emissions if they were controlled by a single, infinitely-lived decision maker optimizing his wellbeing over many centuries. Such an individual would choose levels of consumption and investment in each period so as to ensure that the marginal return on investment just equaled the marginal value of consumption or, equivalently, that the market rate of interest just equaled the consumption rate of discount.

But, this result is of no practical relevance for climate policy, or for the SCC, in the real world. In the real world, there is not a single, infinitely-lived decision maker controlling the trajectories of global consumption, investment and GHG emissions, and those trajectories are not being determined optimally.[59] In the absence of this

[59]. Two other assumptions required for optimality are that there is no market failure and there is perfect foresight in all capital markets indefinitely into the future.

optimality, there is no presumption that the observed market rate of interest measures the consumption rate of discount. The market rate of interest, therefore, is an incorrect basis for calculating the SCC.

Q. Was the IWG wrong on economic grounds to focus on the SCC results corresponding to a 3% consumption rate of discount?

A. The IWG was making a policy judgement when it decided (a) to use discount rates of 2.5%, 3% and 5% in developing results for the SCC, and (b) to select the 3% value of the SCC as the central estimate.

I respect its judgment.

Q. Dr. Smith stated: "Federal guidance … actually requires use of a 7% rate when a regulation will affect private sector spending because 7% approximates the opportunity cost of displaced private sector investment."[60] Should the IWG have used a discount rate of 7%.

A. The IWG, whose policy judgment this is, and whose policy judgment I respect, addresses that assertion as follows:[61]

> While most regulatory impact analysis is conducted over a time frame in the range of 20 to 50 years, OMB guidance in Circular A-4 recognizes that special ethical considerations arise when comparing benefits and costs across generations. Although most people demonstrate time preference in their own consumption behavior, it may not be appropriate for society to demonstrate a similar preference when deciding between the well-being of current and future generations. Future citizens who are affected by such choices cannot take part in making them, and today's society must act with some

[60] GRE,MP,OTP,MLIG Ex. ___ at 24 (Smith Direct).
[61]. Interagency Working Group, *Response to Comments: Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866* (July 2015, pp. 21-22).

> consideration of their interest. Even in an intergenerational context, however, it would still be correct to discount future costs and benefits generally (though perhaps at a lower rate than for intragenerational analysis), due to the expectation that future generations will be wealthier and thus will value a marginal dollar of benefits or costs less than the current generation. Therefore, it is appropriate to discount future benefits and costs relative to current benefits and costs, even if the welfare of future generations is not being discounted. Estimates of the discount rate appropriate in this case, from the 1990s, ranged from 1 to 3 percent. After reviewing those considerations, Circular A-4 states that if a rule will have important intergenerational benefits or costs, agencies should consider a further sensitivity analysis using a lower but positive discount rate in addition to calculating net benefits using discount rates of 3 and 7 percent.

The IWG examined the economics literature and concluded that the consumption rate of interest is the correct concept to use in evaluating the net social costs of a marginal change in CO2 emissions, as the impacts of climate change are measured in consumption-equivalent units in the three IAMs used to estimate the SCC. This is consistent with OMB guidance in Circular A-4, which states that when a regulation is expected to primarily affect private consumption, for instance, via higher prices for goods and services–it is appropriate to use the consumption rate of interest to reflect how private individuals trade-off current and future consumption.

As explained in the 2010 TSD, after a thorough review of the discounting literature, the IWG chose to use three discount rates to span a plausible range of constant discount rates: 2.5, 3, and 5 percent per year. The central value, 3 percent, is consistent with estimates provided in the economics literature and OMB's Circular A-4 guidance for the consumption rate of interest. The upper value of 5 percent represents the possibility that climate damages are positively correlated with market returns, which would suggest a rate higher than the risk-free rate of 3 percent.

Additionally, this discount rate may be justified by the high interest rates that many consumers use to smooth consumption across periods. The low value, 2.5 percent, is included to incorporate the concern that interest rates are highly uncertain over time. It represents the average rate after adjusting for uncertainty using a mean-reverting and random walk approach as described in Newell and Pizer (2003), starting at a discount rate of 3 percent. Further, a rate below the riskless rate would be justified if climate investments are negatively correlated with the overall market rate of return. Use of this lower value also responds to the ethical concerns discussed above regarding intergenerational discounting.

XIV. SUGGESTED RANGE OF SCC VALUES

Q. Are the IWG's estimates of \$36 (in 2007 dollars per metric ton of CO_2) for the 2015 SCC and \$42 for the 2020 SCC reasonable, and are they best available point estimates?[62]

A. Yes.

Q. If you had to recommend a range of values for the 2015 SCC and 2020 SCC, what range would you recommend?

A. I would recommend the range of estimates presented by the IWG corresponding to the alternative discount rates it considered – 2.5%, 3% and 5%.[63]

The range for the 2015 SCC is from \$11 (5%) to \$56 (2.5%).

The range for the 2020 SCC is from \$12 (5%) to \$62 (2.5%).

---

[62] These values are given in Interagency Working Group, *Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866*. Revised July 2015, page 3.

[63] Ibid.

Q. Is there additional information you wish to note about the IWG's SCC estimate?

A. First, as stated above, I believe the IAM damage functions used by the IWG are likely to understate the SCC.

Second, I believe that 5% is likely to be too high as an estimate of the social consumption rate of discount because the marginal utility factor which it reflects is likely to be overstated for the reasons I gave above (page 39, line 1286 – page 40, line 1308).

Third, if one viewed the SCC through the lens of risk management, the IWG's 95-percentile value of the 2015 SCC (($105) and the 2020 SCC ($123) would be a relevant consideration.[64]

Q. Does this additional information you mention change your recommended ranges that you have stated?

A. No, it does not. My recommendations remain unchanged.

Q. In your direct testimony you supported adoption of the IWG SCC by the PUC. Have you changed your opinion based on the information you have seen since then?

A. I have not changed my opinion. I believe that the IWG SCC is currently the best estimate of the environmental externalities associated with CO_2 emissions and it is reasonable for PUC to adopt it.

Q. Does this conclude your Rebuttal Testimony?

A. Yes it does.

---

[64] Ibid.

Period	1	2	3	4	5	6	7	8
Year	2010	2015	2020	2025	2030	2035	2040	2045
Industrial Emissions (GTCO2 per year)	33.55300011	37.96539	42.5601	47.27613	52.05866	56.85798	61.62868	66.329
Atmospheric concentration of carbon (ppm)	389.8591549	406.6273	424.5765	443.8503	464.5256	486.6266	510.1353	535.0002
Atmospheric Temperature (deg C above preindustrial)	0.8	0.930514	1.069637	1.216889	1.371819	1.533939	1.702691	1.877435
Output (Before Damages and Abatement, trillion USD pa)	63.58198682	75.63195	89.11	104.0074	120.3114	138.0033	157.0577	177.4404
Output (Net of Damages and Abatement, trillion USD pa)	63.47333792	75.4571	88.83778	103.5962	119.7068	137.1363	155.842	175.7705
Climate Damages (fraction of gross output)	0.0017088	0.002312	0.003055	0.003954	0.005025	0.006282	0.007741	0.009411
Consumption Per Capita (thousand USD per year)	6.933420191	7.818094	8.797829	9.870983	11.03699	12.29574	13.64721	15.09112
Carbon Price (per t CO2)	0	0	0	0	0	0	0	0
Emissions Control Rate (total)	0	0	0	0	0	0	0	0
Social cost of carbon	15.91443858	19.03715	22.60978	26.63665	31.12141	36.06667	41.47385	47.34314
Interest Rate (Real Rate of Return)	0.050970481	0.050354	0.04945	0.048403	0.047293	0.046164	0.045039	0.04393

9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
2050	2055	2060	2065	2070	2075	2080	2085	2090	2095	2100	2105	2110	2115	2120	2125	2130
70.92027	75.36655	79.63427	83.69204	87.5105	91.06218	94.32151	97.26476	99.87012	102.1178	103.9899	105.4707	106.5496	107.2185	107.4724	107.3103	106.7359
561.1431	588.4646	616.8483	646.1648	676.2736	707.0264	738.2684	769.84	801.5785	833.319	864.8956	896.1427	926.8957	956.994	986.2818	1014.609	1041.835
2.057459	2.241992	2.430221	2.621313	2.814429	3.008745	3.203459	3.397805	3.591059	3.782544	3.971631	4.155262	4.333244	4.505388	4.671514	4.831457	4.985066
199.1072	222.0026	246.0584	271.1924	297.3074	324.2897	352.0086	380.3155	409.0431	438.005	466.9961	495.7915	524.1613	551.8613	578.6372	604.2307	628.3859
196.8568	219.0232	242.1783	266.217	291.0196	316.4515	342.3636	368.5922	394.9591	421.2726	447.328	472.9352	497.8827	521.952	544.9214	566.5715	586.6914
0.011302	0.013421	0.015769	0.018346	0.021149	0.02417	0.0274	0.030825	0.034432	0.038201	0.042116	0.046101	0.050135	0.054197	0.058268	0.062326	0.066352
16.62678	18.2529	19.96747	21.76764	23.64963	25.6086	27.63854	29.73213	31.88059	34.07356	36.29897	38.54388	40.79298	43.02867	45.23115	47.37864	49.44785
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
53.67347	60.46257	67.70694	75.4018	83.54084	92.11598	101.1168	110.5298	120.3378	130.5185	141.0441	151.8852	162.999	174.3265	185.7914	197.2982	208.7329
0.042841	0.041774	0.040729	0.039704	0.038697	0.037704	0.036722	0.035746	0.034772	0.033795	0.032818	0.031831	0.030828	0.029801	0.028746	0.027661	0.026546

26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42
2135	2140	2145	2150	2155	2160	2165	2170	2175	2180	2185	2190	2195	2200	2205	2210	2215
105.7577	104.3898	102.6521	100.5702	98.1752	95.50296	92.59309	89.48759	86.2294	82.86085	79.42226	75.95084	72.4799	69.03834	65.65058	62.33664	59.11245
1067.827	1092.464	1115.642	1137.269	1157.276	1175.611	1192.246	1207.173	1220.408	1231.987	1241.964	1250.41	1257.409	1263.056	1267.452	1270.7	1272.907
5.132209	5.272772	5.406664	5.533816	5.654186	5.767756	5.874539	5.974576	6.067939	6.154731	6.235085	6.309164	6.377159	6.439282	6.49577	6.546875	6.592865
650.8576	671.4197	689.8747	706.0621	719.8664	731.2221	740.1158	746.5851	750.7139	752.6251	752.4713	750.425	746.6693	741.3898	734.7681	726.9776	718.18
605.085	621.5791	636.0303	648.3318	658.419	666.2728	671.9199	675.4302	676.9119	676.5035	674.365	670.6692	665.593	659.3107	651.9886	643.782	634.8324
0.070327	0.074232	0.078049	0.081764	0.085359	0.088823	0.092142	0.095307	0.098309	0.101141	0.1038	0.106281	0.108584	0.11071	0.112661	0.11444	0.116054
51.41461	53.25474	54.94519	56.46517	57.79736	58.92895	59.85232	60.56534	61.07117	61.37768	61.49654	61.44212	61.23052	60.87851	60.40286	59.81969	59.14416
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
219.9639	230.8462	241.2273	250.9547	259.8846	267.8914	274.8744	280.7639	285.523	289.1465	291.6576	293.1025	293.5439	293.055	291.7146	289.6025	286.7966
0.025404	0.02424	0.023064	0.021887	0.020723	0.019587	0.018492	0.017451	0.016475	0.01557	0.014739	0.013985	0.013304	0.012694	0.012148	0.011663	0.01123

43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59
2220	2225	2230	2235	2240	2245	2250	2255	2260	2265	2270	2275	2280	2285	2290	2295	2300
55.99022	52.97893	50.08476	47.31154	44.66115	42.13385	39.72867	37.44358	35.27581	33.22197	31.27825	29.44054	27.70454	26.06583	24.51996	23.06249	21.68905
1274.176	1274.61	1274.305	1273.352	1271.836	1269.838	1267.428	1264.672	1261.63	1258.354	1254.892	1251.285	1247.57	1243.778	1239.938	1236.072	1232.202
6.634016	6.670612	6.702939	6.731282	6.755924	6.777143	6.795206	6.810375	6.822898	6.833013	6.840943	6.846902	6.851087	6.853684	6.854866	6.85479	6.853605
708.524	698.1446	687.1629	675.6873	663.8136	651.6262	639.1994	626.5982	613.8791	601.0915	588.278	575.4756	562.7163	550.0276	537.433	524.9527	512.6039
625.2674	615.2	604.7299	593.9439	582.9176	571.7158	560.3946	549.0016	537.5778	526.1579	514.7715	503.4435	492.1951	481.0443	470.006	459.093	448.3157
0.117507	0.118807	0.119961	0.120978	0.121866	0.122632	0.123287	0.123838	0.124294	0.124662	0.124952	0.12517	0.125323	0.125418	0.125461	0.125458	0.125415
58.39017	57.57033	56.69592	55.77689	54.82202	53.83895	52.83434	51.81394	50.78271	49.74491	48.7042	47.66372	46.62614	45.59373	44.56846	43.55195	42.54561
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
283.3704	279.3922	274.9242	270.022	264.735	259.1064	253.1736	246.9685	240.518	233.8441	226.9645	219.8929	212.6389	205.2085	197.6039	189.8241	181.8642
0.010846	0.010505	0.010201	0.00993	0.009688	0.009471	0.009276	0.0091	0.00894	0.008796	0.008663	0.008542	0.008431	0.008327	0.008231	0.008142	0.008058

Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Year	2010	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060	2065	2070	2075	2080
Industrial Emissions (GTCO2 ı	33.553	31.69366	34.55799	37.2119	39.58855	41.6284	43.27898	44.49467	45.23653	45.4721	45.1752	44.32579	42.90979	40.91891	38.35046
Atmospheric concentration of	389.8592	406.6273	420.5606	435.0638	450.0544	465.4014	480.9364	496.4635	511.7669	526.6182	540.7815	554.0187	566.0934	576.7748	585.8403
Atmospheric Temperature (de	0.8	0.930514	1.064466	1.201535	1.341309	1.483263	1.626749	1.771007	1.915189	2.058374	2.199595	2.337856	2.472148	2.601466	2.724811
Output (Before Damages and	63.58199	75.89774	89.65038	104.877	121.5943	139.8168	159.5571	180.8254	203.6295	227.9752	253.8656	281.3018	310.2824	340.8038	372.8601
Output (Net of Damages and	63.47285	75.66945	89.29988	104.3565	120.8433	138.7609	158.1061	178.8725	201.0506	224.6284	249.5921	275.9265	303.616	332.645	362.9989
Climate Damages (fraction of	0.001709	0.002312	0.003025	0.003855	0.004804	0.005874	0.007066	0.008374	0.009793	0.011313	0.012918	0.014593	0.016318	0.01807	0.019824
Consumption Per Capita (thou	6.878295	7.772042	8.754903	9.827028	10.98912	12.2421	13.58688	15.02426	16.5548	18.17885	19.89651	21.70768	23.61207	25.60931	27.69898
Carbon Price (per t CO2)	1.001094	18.6043	22.201	26.2663	30.81631	35.86616	41.42963	47.51887	54.14408	61.31319	69.03155	77.30157	86.12244	95.48966	105.3947
Emissions Control Rate (total)	0.039	0.200563	0.22439	0.249851	0.276908	0.305532	0.335705	0.367412	0.400639	0.435375	0.471606	0.509317	0.548489	0.589098	0.631115
Social cost of carbon	15.45948	18.6043	22.201	26.2663	30.81631	35.86616	41.42963	47.51887	54.14408	61.31319	69.03155	77.30157	86.12244	95.48966	105.3947
Interest Rate (Real Rate of Re	0.051603	0.050664	0.04958	0.048438	0.047285	0.046147	0.045036	0.04396	0.042923	0.041927	0.040971	0.040057	0.039184	0.038353	0.037565

16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
2085	2090	2095	2100	2105	2110	2115	2120	2125	2130	2135	2140	2145	2150	2155	2160	2165
35.20726	31.49743	27.23421	22.43582	17.12372	11.32713	5.083833	0	0	0	0	0	0	0	-29.1954	-29.4018	-29.5825
593.0785	598.2914	601.2962	601.9274	600.0377	595.499	588.2051	578.0752	566.0565	555.5174	546.2704	538.1519	531.0189	524.7463	519.2252	495.6659	474.1926
2.8412	2.949663	3.049244	3.138992	3.215478	3.278069	3.326065	3.35868	3.376001	3.381284	3.377231	3.366071	3.349634	3.329409	3.3066	3.26203	3.199776
406.4429	441.5408	478.1384	516.2147	555.7391	596.6746	638.9565	682.4698	727.1963	773.5386	821.4197	870.8018	921.7006	974.221	1028.627	1081.682	1136.185
394.6647	427.631	461.8879	497.426	534.2569	572.3733	611.7492	652.6297	695.8439	740.7768	787.3437	835.4966	885.2378	936.6556	984.2589	1036.871	1091.313
0.021553	0.02323	0.024825	0.026308	0.027606	0.028691	0.029537	0.03012	0.030431	0.030526	0.030453	0.030252	0.029958	0.029597	0.029193	0.028411	0.027337
29.88076	32.15454	34.5206	36.97998	39.53559	42.19206	44.95737	47.84563	50.86941	54.01587	57.27291	60.62689	64.05946	67.54252	71.09861	74.80795	78.65356
115.8246	126.7614	138.182	150.0579	162.359	175.0422	188.0478	197.0879	192.1607	187.3567	182.6728	178.106	173.6533	169.312	229.2021	223.472	217.8852
0.674505	0.719223	0.765219	0.812433	0.860807	0.910253	0.960645	1	1	1	1	1	1	1	1.2	1.2	1.2
115.8246	126.7614	138.182	150.0579	162.359	175.0422	188.0478	201.2962	214.6754	228.0844	241.4448	254.7023	267.8311	280.8392	294.1896	306.6712	318.0669
0.036818	0.036116	0.035461	0.034862	0.034323	0.033859	0.033494	0.0332	0.03282	0.032381	0.031891	0.031341	0.030705	0.030216	0.030081	0.029863	0.02959

33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49
2170	2175	2180	2185	2190	2195	2200	2205	2210	2215	2220	2225	2230	2235	2240	2245	2250
-29.7345	-29.8562	-29.9465	-30.005	-30.0317	-30.027	-29.9914	-29.9256	-29.8307	-29.7078	-29.5579	-29.3826	-29.183	-28.9605	-28.7167	-28.4529	-28.1705
454.5528	436.5289	419.9325	404.6006	390.3922	377.1846	364.8715	353.3606	342.5715	332.4341	322.8873	313.8777	305.3585	297.2886	289.6319	282.3564	275.4339
3.123278	3.035427	2.93865	2.83497	2.726072	2.613353	2.497963	2.380848	2.26278	2.144384	2.026165	1.908527	1.791789	1.676204	1.561964	1.44922	1.338081
1191.986	1248.956	1306.98	1365.951	1425.767	1486.333	1547.554	1609.341	1671.609	1734.274	1797.256	1860.481	1923.874	1987.368	2050.897	2114.397	2177.811
1147.404	1204.979	1263.885	1323.979	1385.123	1447.186	1510.043	1573.574	1637.667	1702.213	1767.11	1832.262	1897.579	1962.973	2028.366	2093.681	2158.847
0.026045	0.024601	0.023057	0.021459	0.019842	0.018235	0.01666	0.015135	0.013671	0.012278	0.010961	0.009725	0.008572	0.007502	0.006514	0.005608	0.004781
82.62123	86.6985	90.874	95.13713	99.47788	103.8867	108.3545	112.8725	117.4325	122.0266	126.6472	131.2873	135.94	140.599	145.2583	149.9121	154.5552
212.4381	207.1271	201.949	196.9002	191.9777	187.1783	182.4988	177.9364	173.4879	169.1508	164.922	160.7989	156.779	152.8595	149.038	145.312	141.6792
1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
328.183	336.8461	343.9012	349.212	352.6621	354.1558	353.6206	351.0094	346.3024	339.5102	330.6762	319.88	307.2401	292.9168	277.1148	260.0854	242.1271
0.029278	0.02894	0.028585	0.028218	0.027845	0.02747	0.027096	0.026725	0.026359	0.025999	0.025647	0.025303	0.024968	0.024642	0.024325	0.024018	0.023721

50	51	52	53	54	55	56	57	58	59
2255	2260	2265	2270	2275	2280	2285	2290	2295	2300
-27.871	-27.5557	-27.2261	-26.8834	-26.5288	-26.1635	-25.7886	-22.6634	-17.5258	-13.8377
268.8392	262.5502	256.5467	250.8108	245.3263	240.0788	235.055	230.2429	227.3874	227.6076
1.228628	1.12092	1.014992	0.910868	0.808559	0.708067	0.609389	0.512514	0.421648	0.343285
2241.08	2304.153	2366.976	2429.501	2491.677	2553.454	2614.774	2675.572	2735.925	2795.86
2223.798	2288.47	2352.804	2416.743	2480.231	2543.212	2605.623	2667.709	2729.387	2790.287
0.00403	0.003355	0.002751	0.002215	0.001746	0.001339	0.000992	0.000701	0.000475	0.000315
159.1825	163.7893	168.3716	172.9254	177.4475	181.9354	186.3878	190.8048	195.1808	199.5059
138.1373	134.6838	131.3167	128.0338	124.833	121.7121	118.6693	111.9838	102.8809	95.96314
1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.178417	1.140123	1.112412
223.5851	204.8475	186.3379	168.5019	151.7851	136.6	123.2753	111.9838	102.881	95.9632
0.023433	0.023154	0.022886	0.022627	0.022379	0.022142	0.021918	0.021697	0.021472	0.021252

Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Year	2010	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060	2065	2070	2075
Industrial Emissions (GTCO2 per year	33.553	35.09511	38.64193	42.01698	45.14893	47.98403	50.49362	52.63365	54.36595	55.6592	56.48879	56.83658	56.69068	56.04534
Atmospheric concentration of carbon	389.8592	406.6273	422.7386	439.6652	457.335	475.6243	494.3755	513.4184	532.5623	551.6025	570.3265	588.5189	605.9664	622.4611
Atmospheric Temperature (deg C abc	0.8	0.930514	1.067277	1.209691	1.357101	1.508756	1.663815	1.821372	1.980473	2.140129	2.299343	2.457121	2.612492	2.764521
Output (Before Damages and Abaten	63.58199	75.96538	89.79868	105.1097	121.9205	140.2517	160.1225	181.5472	204.534	229.0882	255.2126	282.907	312.1684	342.9906
Output (Net of Damages and Abatem	63.5815	75.95409	89.77987	105.0791	121.8723	140.1778	160.0015	181.3394	204.1863	228.5334	254.3682	281.6754	310.4368	340.6324
Climate Damages (fraction of gross o	0	0	0	0	0	2.05E-07	7.17E-05	0.000276	6.16E-04	1.09E-03	1.71E-03	0.002446	0.003304	0.004269
Consumption Per Capita (thousand U	6.880101	7.789826	8.790247	9.883063	11.07034	12.35422	13.73642	15.21807	16.80009	18.4831	20.2674	22.15297	24.13951	26.22643
Carbon Price (per t CO2)	1.001094	6.895567	8.796447	11.10376	13.84742	17.02792	20.59929	24.56757	28.93576	33.70375	38.86817	44.42229	50.35574	56.65441
Emissions Control Rate (total)	0.039	0.115553	0.134163	0.154861	0.177553	0.201986	0.227704	0.254674	0.282864	0.31224	0.342763	0.374394	0.407086	0.440789
Social cost of carbon	5.356997	6.895567	8.796447	11.10376	13.84742	17.02792	20.59929	24.56757	28.93576	33.70375	38.86817	44.42229	50.35574	56.65441
Interest Rate (Real Rate of Return)	0.05222	0.051195	0.050085	0.048948	0.047818	0.046702	0.045603	0.044533	0.043495	0.042492	0.041525	0.040596	0.039703	0.038847

15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
2080	2085	2090	2095	2100	2105	2110	2115	2120	2125	2130	2135	2140	2145	2150	2155	2160
54.90065	53.26232	51.14134	48.55346	45.51853	42.05881	38.20152	33.97815	29.42449	24.58064	19.4911	14.20484	8.775434	3.261224	0	-7.78125	-13.1723
637.8041	651.8081	664.3001	675.1227	684.1362	691.2194	696.2691	699.2019	699.9551	698.4878	694.7817	688.842	680.6988	670.4076	658.051	645.1961	628.9303
2.912314	3.055033	3.19189	3.322155	3.445156	3.55779	3.659819	3.751008	3.831118	3.899918	3.957177	4.00267	4.036178	4.057489	4.066401	4.063959	4.048519
375.3647	409.2787	444.7179	481.6643	520.0971	559.992	601.3273	644.0783	688.2175	733.7146	780.5364	828.6464	878.0047	928.5666	980.2806	1033.314	1087.233
372.2407	405.2394	439.6062	475.3189	512.3557	550.7107	590.3731	631.3332	673.5831	717.1162	761.9273	808.0125	855.3678	903.9883	954.2559	1005.185	1057.591
0.005326	0.006456	0.007643	0.008865	0.010102	0.011306	0.012455	0.013529	0.014509	0.015378	0.016121	0.016723	0.017174	0.017464	0.017586	0.017552	0.017342
28.41295	30.69809	33.0808	35.55998	38.13455	40.80398	43.56771	46.42526	49.37623	52.42037	55.55762	58.78816	62.11246	65.5314	69.04637	72.64706	76.34417
63.30028	70.27137	77.54191	85.08272	92.86209	100.8488	109.0066	117.2941	125.664	134.0627	142.43	150.6983	158.7921	166.6277	169.312	181.1799	187.6943
0.475446	0.510996	0.547369	0.584494	0.622298	0.660714	0.699665	0.739058	0.778784	0.81872	0.858719	0.898617	0.938222	0.977317	1	1.053063	1.089145
63.30028	70.27137	77.54191	85.08272	92.86209	100.8488	109.0066	117.2941	125.664	134.0627	142.43	150.6983	158.7921	166.6277	174.1121	181.1799	187.6943
0.038027	0.037244	0.036496	0.035785	0.035112	0.034475	0.033873	0.033302	0.032763	0.032254	0.031774	0.031321	0.030895	0.030497	0.030074	0.029717	0.029378

32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48
2165	2170	2175	2180	2185	2190	2195	2200	2205	2210	2215	2220	2225	2230	2235	2240	2245
-18.3694	-23.2874	-27.8331	-30.0717	-30.1135	-30.1268	-30.1111	-30.0662	-29.9927	-29.8911	-29.7623	-29.6073	-29.4274	-29.2238	-28.9976	-28.7503	-28.483
611.0232	591.6732	571.1131	549.6128	528.6566	509.5272	492.0113	475.9233	461.1023	447.4082	434.719	422.9284	411.9434	401.683	392.0762	383.0607	374.5821
4.01999	3.978321	3.923526	3.855713	3.776333	3.688015	3.592951	3.492963	3.389558	3.283974	3.177223	3.070125	2.963339	2.857389	2.752686	2.64955	2.548222
1142.177	1198.081	1254.869	1312.445	1370.89	1430.281	1490.494	1551.417	1612.947	1674.99	1737.456	1800.26	1863.322	1926.565	1989.915	2053.297	2116.639
1111.264	1166.185	1222.319	1279.985	1339.218	1399.605	1460.984	1523.206	1586.135	1649.645	1713.618	1777.947	1842.529	1907.27	1972.079	2036.871	2101.561
0.016955	0.016399	0.015682	0.014817	0.013835	0.012782	0.011696	0.010605	0.009533	0.008497	0.007511	0.006582	0.005717	0.004919	0.00419	0.003528	0.002934
80.13848	84.03133	88.02499	92.12346	96.32175	100.6057	104.963	109.3826	113.8544	118.3691	122.9181	127.4935	132.088	136.6948	141.308	145.9223	150.5333
193.5355	198.5734	202.6651	201.949	196.9002	191.9777	187.1783	182.4988	177.9364	173.4879	169.1508	164.922	160.7989	156.779	152.8595	149.038	145.312
1.12354	1.155839	1.185569	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
193.5355	198.5734	202.6651	205.6515	207.4186	207.9346	207.1959	205.2258	202.0742	197.817	192.5558	186.4164	179.5476	172.1178	164.3103	156.3149	148.3165
0.029059	0.028759	0.028484	0.028203	0.02789	0.027557	0.027213	0.026863	0.026511	0.026161	0.025815	0.025474	0.025141	0.024817	0.024502	0.024199	0.023908

49	50	51	52	53	54	55	56	57	58	59
2250	2255	2260	2265	2270	2275	2280	2285	2290	2295	2300
-27.3977	-24.3782	-21.5387	-18.9959	-16.8202	-15.0376	-13.6372	-12.5818	-11.8184	-11.288	-10.9325
366.5923	359.5612	354.6337	351.5042	349.8264	349.2454	349.4255	350.0705	350.9363	351.835	352.6329
2.44888	2.352428	2.261482	2.177965	2.103077	2.037338	1.980687	1.932612	1.892288	1.858714	1.830813
2179.862	2242.935	2305.901	2368.669	2431.16	2493.302	2555.036	2616.312	2677.089	2737.332	2797.009
2166.173	2230.803	2295.158	2359.131	2422.638	2485.624	2548.051	2609.894	2671.137	2731.767	2791.771
0.002404	0.00194	0.001548	0.001227	0.000971	0.000771	0.000617	0.0005	0.000411	0.000344	0.000292
155.1381	159.7327	164.3076	168.8554	173.3702	177.8482	182.2866	186.6835	191.038	195.3491	199.6164
140.4766	132.9579	125.9666	119.63	114.0006	109.0689	104.7806	101.0542	97.79673	94.91512	92.32399
1.19433	1.174792	1.15621	1.139442	1.125049	1.113294	1.104182	1.097519	1.092988	1.090204	1.088775
140.4766	132.9579	125.9666	119.63	114.0006	109.0689	104.7805	101.0542	97.79671	94.91509	92.32396
0.023627	0.023346	0.023068	0.022797	0.022534	0.022282	0.02204	0.02181	0.02159	0.021381	0.021181

Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Year	2010	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060	2065	2070	2075
Industrial Emissions (GTCO2 per year	33.553	36.09295	39.924	43.6249	47.11453	50.31775	53.16901	55.61792	57.63778	59.2379	60.39353	61.08494	61.29897	61.02871
Atmospheric concentration of carbon	389.8592	406.6273	423.3776	441.0689	459.6469	478.9981	498.9611	519.3387	539.9121	560.4585	580.7749	600.6551	619.8927	638.2858
Atmospheric Temperature (deg C abo	0.8	0.930514	1.068098	1.212137	1.361961	1.516809	1.67581	1.837996	2.002325	2.167719	2.333115	2.497478	2.659813	2.819173
Output (Before Damages and Abaterr	63.58199	75.98117	89.83183	105.1606	121.9895	140.338	160.2232	181.6604	204.6633	229.2452	255.4127	283.1631	312.4918	343.3914
Output (Net of Damages and Abatem	63.5815	75.97546	89.82216	105.1446	121.9636	140.297	160.1598	181.5648	204.523	229.0285	255.0607	282.6023	311.6336	342.1328
Climate Damages (fraction of gross o	0	0	0	0	0	0	0	0	1.44E-08	7.51E-05	2.96E-04	0.000661	0.001162	0.001792
Consumption Per Capita (thousand U	6.876809	7.788031	8.7898	9.884074	11.07315	12.35942	13.74518	15.23251	16.82323	18.51827	20.31764	22.22113	24.22828	26.33838
Carbon Price (per t CO2)	1.001094	4.449924	5.733143	7.329022	9.289129	11.66323	14.49215	17.79614	21.55662	25.68972	30.1916	35.05526	40.27042	45.82342
Emissions Control Rate (total)	0.039	0.090595	0.105766	0.122944	0.142233	0.163689	0.187295	0.212905	0.240186	0.26852	0.297883	0.32824	0.359553	0.391776
Social cost of carbon	3.430163	4.449924	5.733143	7.329022	9.289129	11.66323	14.49215	17.79614	21.55662	25.68972	30.1916	35.05526	40.27042	45.82342
Interest Rate (Real Rate of Return)	0.052296	0.05125	0.050131	0.048995	0.047869	0.046767	0.045698	0.044663	0.043654	0.042666	0.041706	0.040776	0.03988	0.039018

15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
2080	2085	2090	2095	2100	2105	2110	2115	2120	2125	2130	2135	2140	2145	2150	2155	2160
60.27313	59.03681	57.32945	55.16541	52.56295	49.54269	46.12986	42.3537	38.24731	33.84764	29.19543	24.33513	19.31487	14.18636	9.004771	3.828572	-1.28074
655.6402	671.7725	686.5124	699.7048	711.2112	720.9104	728.6987	734.491	738.2219	739.8463	739.3402	736.7015	731.9506	725.131	716.3101	705.5792	693.0546
2.974669	3.125474	3.270823	3.410016	3.542417	3.664971	3.777491	3.8798	3.971729	4.05312	4.123825	4.183711	4.232656	4.270557	4.297326	4.3129	4.317243
375.8517	409.8596	445.3991	482.4512	520.9937	561.001	602.4491	645.3111	689.5576	735.1566	782.0737	830.2719	879.7121	930.353	982.1509	1035.06	1089.033
374.0763	407.4393	442.196	478.3206	515.787	554.5813	594.686	636.0845	678.7615	722.7025	767.8947	814.3261	861.9859	910.8636	960.9494	1012.233	1064.704
0.002536	0.003382	0.004312	0.005308	0.006352	0.007402	0.008436	0.009435	0.01038	0.011255	0.012043	0.012732	0.013309	0.013765	0.014091	0.014283	0.014337
28.55048	30.86346	33.27602	35.78681	38.39442	41.09783	43.89601	46.7879	49.77252	52.84894	56.01635	59.27399	62.62123	66.05751	69.58232	73.19518	76.89557
51.69714	57.871	64.32114	71.02086	77.94151	85.05495	92.32909	99.72766	107.2098	114.73	122.2372	129.6755	136.9827	144.0916	150.9286	157.4153	163.4678
0.424861	0.458748	0.493377	0.528681	0.564595	0.601061	0.638009	0.675357	0.713012	0.750866	0.788794	0.826655	0.86429	0.90152	0.938143	0.973936	1.008653
51.69714	57.871	64.32114	71.02086	77.94151	85.05495	92.32909	99.72766	107.2098	114.73	122.2372	129.6755	136.9827	144.0916	150.9286	157.4153	163.4678
0.038191	0.037398	0.036639	0.035915	0.035227	0.034575	0.033955	0.033366	0.032808	0.032278	0.031776	0.031299	0.030847	0.030418	0.03001	0.029621	0.029251

32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48
2165	2170	2175	2180	2185	2190	2195	2200	2205	2210	2215	2220	2225	2230	2235	2240	2245
-6.25903	-11.04	-15.5561	-19.7389	-23.5209	-26.8359	-29.6204	-30.0904	-30.0089	-29.9014	-29.7683	-29.6102	-29.4281	-29.2229	-28.9956	-28.7474	-27.4375
678.8773	663.2135	646.2541	628.2141	609.3319	589.8674	570.0999	550.3258	531.9595	515.165	499.7626	485.5959	472.5285	460.4416	449.2313	438.8068	429.0887
4.31035	4.292265	4.263082	4.222965	4.172165	4.111035	4.040059	3.959874	3.87243	3.779689	3.683273	3.584515	3.484505	3.384125	3.284084	3.184945	3.087147
1144.019	1199.968	1256.825	1314.535	1373.04	1432.277	1492.178	1552.665	1613.819	1675.569	1737.807	1800.436	1863.364	1926.505	1989.775	2053.091	2116.369
1118.348	1173.151	1229.092	1286.146	1344.281	1403.453	1463.603	1524.974	1587.27	1650.283	1713.87	1777.903	1842.26	1906.833	1971.517	2036.213	2100.973
0.014252	0.014029	0.013675	0.013194	0.012598	0.011899	0.011112	0.010256	0.009361	0.008457	0.007565	0.006704	0.005884	0.005115	0.004402	0.003749	0.003156
80.68288	84.55634	88.51492	92.5573	96.68181	100.8864	105.1691	109.5277	113.9513	118.428	122.9474	127.4999	132.0772	136.6715	141.2763	145.886	150.4965
168.9985	173.9168	178.1309	181.5502	184.0874	185.6619	186.202	182.4988	177.9364	173.4879	169.1508	164.922	160.7989	156.779	152.8595	149.038	143.7212
1.042026	1.073763	1.103554	1.13107	1.15597	1.177905	1.196519	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.192684
168.9985	173.9168	178.1309	181.5502	184.0874	185.6619	186.2021	185.6467	184.016	181.3709	177.796	173.3968	168.2972	162.6349	156.556	150.2067	143.7212
0.028897	0.028557	0.02823	0.027914	0.027608	0.027311	0.027024	0.026722	0.026406	0.026084	0.025759	0.025435	0.025115	0.024801	0.024495	0.0242	0.02391

49	50	51	52	53	54	55	56	57	58	59
2250	2255	2260	2265	2270	2275	2280	2285	2290	2295	2300
-25.241	-23.0234	-20.8845	-18.903	-17.1335	-15.6057	-14.3277	-13.2897	-12.4692	-11.8362	-11.3569
420.6746	414.0007	408.9156	405.2237	402.7017	401.1158	400.2375	399.856	399.7873	399.8789	400.0118
2.991893	2.900891	2.815521	2.736792	2.665328	2.601384	2.544885	2.495489	2.452654	2.415705	2.383896
2179.594	2242.741	2305.734	2368.499	2430.972	2493.092	2554.809	2616.075	2676.851	2737.1	2796.789
2165.721	2230.28	2294.55	2358.446	2421.902	2484.867	2547.302	2609.178	2670.471	2731.161	2791.229
0.002627	0.002167	0.001776	0.001449	0.001182	0.000966	0.000793	0.000656	0.000547	0.000461	0.000393
155.1014	159.6924	164.2625	168.8059	173.3179	177.7948	182.234	186.6333	190.9912	195.3065	199.5783
137.2592	130.9883	125.0397	119.5031	114.4276	109.8267	105.6849	101.9668	98.62437	95.60406	92.85185
1.179055	1.165091	1.151476	1.13877	1.127388	1.117585	1.109466	1.103015	1.098117	1.094593	1.092229
137.2592	130.9883	125.0397	119.5031	114.4276	109.8267	105.6849	101.9668	98.62437	95.60406	92.85184
0.023623	0.02334	0.023063	0.022794	0.022535	0.022285	0.022046	0.021817	0.021598	0.021389	0.021189