D.Hanemann
https://www.edockets.state.mn.us/EFiling/edockets/searchDocuments.do?method=showPoup&documentId={56E077B2-8B23-4157-8DED-1A36D01533C2}&documentTitle=20156-111060-02
REBUTTED BY: Happer, Lindzen, Spencer, Mendelsohn, Bezdek, Tol
(Note rebuttals of NAS Member economist Haneman by 3 climate scientists.
Happer, Mendelsohn, Tol denigrated expertise.
.
This seems a straightforward introduction to the relevant topics and mainstream views.
pp.46- Useful background history of the Interagency Working Group (IWG)
p.50 Figure 4: Standardized IAM Inputs
.
Attachments 1-4,6 and 5 are not included in the analysis, as they are mostly copies of other reports.
https://www.edockets.state.mn.us/EFiling/edockets/searchDocuments.do?method=showPoup&documentId={6EA2DA73-BEDA-48E5-A5FB-6BD80C250886}&documentTitle=20156-111060-03
EPRI:
https://www.edockets.state.mn.us/EFiling/edockets/searchDocuments.do?method=showPoup&documentId={3DDF82D6-6E5C-45C0-BBFC-5DBFBCC5B7EA}&documentTitle=20156-111060-04

INVESTIGATION INTO ENVIRONMENTAL AND SOCIOECONOMIC COSTS UNDER MINNESOTA STATUTE 216B.2422, SUBDIVISION 3.

OAH Docket No. 80-2500-31888

DIRECT TESTIMONY OF DR. MICHAEL HANEMANN

ON BEHALF OF

THE DIVISION OF ENERGY RESOURCES OF
THE MINNESOTA DEPARTMENT OF COMMERCE, IN CONSULTATION WITH THE MINNESOTA POLLUTION CONTROL AGENCY

JUNE 1, 2015

DIRECT 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, employer and business address

A. My name is William Michael Hanemann; I go by Michael Hanemann. I am a Professor of Economics and the Julie A. Wrigley Professor of Sustainability in the Department of Economics and the School of Sustainability at Arizona State University.

A complete summary of my educational and professional background is presented in DOC Ex. ___ at WMH-1 (Hanemann Direct)

Q. On whose behalf are you testifying?

A. I am testifying at the request of the Minnesota Department of Commerce, Division Office of Energy Resources (Department), in consultation with the Minnesota Pollution Control Agency (PCA), jointly referred to as the Agencies.

Q. Dr. Hanemann, please summarize your education and work experience as it relates to this proceeding.

A. I have a BA in Philosophy, Politics and Economics from Oxford University; an MSc in Economics from the London School of Economics; and an MA and a Ph.D in Economics from Harvard University. My Ph.D, and my subsequent teaching and research, have been in the field of economics known as environmental and resource economics. My Ph.D dissertation was on what is known as non-market valuation – the monetary valuation of the natural environment – and I have continued to conduct research on that topic ever since. Starting with my dissertation, I have contributed to the development of the two main empirical methods of measurement used in that field. I have also contributed to the economic theory of valuation of changes in human wellbeing – the conceptual foundations of benefit-cost analysis.

Since about 1980, I have been teaching and conducting research on the economics of water. In the US West and elsewhere, the effects on water supply and demand are a major pathway by which climate change may affect human wellbeing.

Together with my Berkeley colleague Professor Anthony Fisher, I have contributed to the economic theory of irreversibility, a topic relevant to some of the issues arising from climate change. Through our work in that area, I first became interested in the economics of climate change around 1992.

In 2002, I was asked by the California Energy Commission (CEC) to found and direct the California Climate Change Center at UC Berkeley. The center was funded by CEC between 2003 and 2006. From 2003 to 2010 I served on the steering committee that designed and managed the California Climate Scenarios project, a multi-investigator assessment of the potential impacts of climate change on California

When the Intergovernmental Panel on Climate Change (IPCC) began its Fifth Assessment exercise, I was selected as a lead author in Working Group III on the committee writing Chapter 3, the background chapter on the economics of climate change. While the chapter is the joint product of the committee members, I took the lead in drafting section 3.9, dealing with metrics of costs and benefits. During the course of the committee's work between 2011 and 2014 I read as much of the literature as I could find on the costs and benefits of reducing GHG emissions.

Q. Have you ever provided testimony in the State of Minnesota?

A. No, I have not.

II. PURPOSE OF TESTIMONY

Q. What is the purpose of your testimony?

A. My focus is to review and provide expert judgment on the estimate of the Social Cost of Carbon (SCC) developed by the U.S. Federal government's Interagency Working Group (IWG) for its report in 2013, an update of its earlier report in 2010.[1] I will be considering the economic concept that is being measured in the SCC and whether the estimate developed by the IWG is credible, reasonable for use in Minnesota, and the best estimate available at this time.

Q. What direction were you given in undertaking a review of the IWG's SCC?

A. I was asked to provide a review of the SCC as determined in the IWG assessment, and its underlying models; and to develop an opinion as to the applicability of the IWG's SCC for use by the Minnesota Public Utilities Commission (MPUC) pursuant to Minnesota Statutes, section 216B.2422, subd. 3 for the purpose of estimating the environmental costs associated with greenhouse gas (GHG) emissions to be used in resource planning by the Commission and by Minnesota utilities.

[1] The participants in the Interagency Working Group in 2010 were: The Council of Economic Advisers; the Council on Environmental Quality; the Department of Agriculture; the Department of Commerce; the Department of Energy; the Department of Transportation; the Environmental Protection Agency; the National Economic Council; the Office of Energy and Climate Change; the Office of Management and Budget; the Office of Science and Technology Policy; and the Department of the Treasury. The National Economic Council was added as a participant in 2013, but the Office of Energy and Climate Change was omitted; the rest of the membership was the same.

Q. How did you undertake your review of the IWG's SCC?

A. I reviewed various MPUC docket items as described below. I reviewed the IWG's 2010 report together with its technical appendix (Appendix 15A) and its 2013 report. I read the account of the 2010 IWG study by Greenstone, Kopits and Wolverton (2013) who actively participated in that study. I reviewed the documentation for the versions of the integrated assessment models (IAMs) used by the IWG in 2010 and 2013, as well as earlier and (where applicable) more recent versions. I also reviewed the documentation of other IAMs not used by the IWG.

The IWG's SCC is one of the areas on which I have taught and conducted research for many years. I have followed the literature on this topic over those years. In preparation for this review, I attempted to check as many items that were potentially relevant as I could.

Q. What documents did you review?

A. I reviewed the following:

- The Findings of Fact, Conclusions, Recommendations and Memorandum issued on March 25, 1996 by Administrative Law Judge Allan W. Klein regarding environmental costs associated with methods of generating electricity Docket No. E-999/CI-93-583;
- The MPUC Order Establishing Environmental Values dated January 3, 1997 Docket No. E-999/CI-93-583;
- The comments submitted by the Deputy Commissioner of the Minnesota Department of Commerce and the Assistant Commissioner of the

Minnesota Pollution Control Agency to the MPCU, dated June 10, 2014 in Docket No. E999/CI-00-1636; and

- The Notice and Order for Hearing issued by the MPUC, October 15, 2014

I reviewed several of the comments submitted to the Federal Office of Management and Budget following the IWG reports, and several of the comments submitted to the MPUC in Docket Nos. E999/CI-00-1636 and E999/CI-14-643.

I reviewed the 2010 and 2013 IWG reports, along with Greenstone, Kopits and Wolverton (2013). See DOC Ex. ___ at WMH-2 (Hanemann Direct), DOC Ex. ___ at WMH-3 (Hanemann Direct), and DOC Ex. ___ at WMH-4 (Hanemann Direct), respectively.

I reviewed the documentation for the versions of the integrated assessment models (IAMs) used by the IWG in 2010 and 2013, as well as earlier and (where applicable) more recent versions. I also reviewed the documentation of other IAMs not used by the IWG, and which I discuss later in my testimony.

I reviewed other articles by the developers of these models to see what light they might shed on the models. I reviewed the literature by other researchers who used those models or used the results of those models.

Following the publication of the 2013 IWG, the Electric Power Research Institute (EPRI) conducted a detailed analysis of the IAMs used by the IWG. I reviewed the resulting report, EPRI (2014). See DOC Ex. ___ at WMH-5 (Hanemann Direct).

Q. Why did you select these documents to review?

A. These documents provided me with a thorough background of the history of this issue at the MPUC, and additionally represented a robust foundation of material for description of the IWG reports and the IAMs used as a part of those reports.

Q. How will your testimony be organized?

A. First I provide a description of climate change and a discussion of the economic concept of an externality. Next I discuss the SCC: how it is estimated, its relationship to externalities, and its current use by the Federal Government and other entities.

Following my discussion on the SCC, I provide information on IAMs, which are used to estimate the SCC and discuss what they are, how they have been used in estimating the SCC, and the similarities and differences between the three IAMs considered by the IWG estimation of the SCC.

I then discuss how the IAMs were used by the IWG in its 2010 assessment of the SCC, why the SCC values change over time, and provide information regarding the update in the 2013 report and how the new 2013 SCC estimates compare with the estimates in the 2010 report.

Finally, I discuss why it is reasonable for the MPUC to use the SCC as determined by the IWG's 2013 report.

III. DESCRIPTION OF CLIMATE CHANGE AND EXTERNALITIES

Q. Can you provide a simple description of the concept of climate change?

A. Carbon dioxide and other greenhouse gasses (GHGs) are being released on earth. Some of the gas released is absorbed into the ocean; another portion remains in the atmosphere. This accumulation of gasses changes the energy balance in the atmosphere. The changes in the earth's energy budget lead to changes in the climate worldwide, including changes in temperature and precipitation, and to melting of sea ice and ice sheets, sea-level rise, ocean acidification and other phenomena.

Greenhouse gasses are released both by natural causes (for example, volcanic eruptions or releases of methane from a swamp) and by human actions (including the burning of fossil fuels, and deforestation and land degradation).

The resulting changes in climate have many consequences that affect the wellbeing of humans and natural ecosystems worldwide. In some cases, the effects are beneficial; often they are harmful.

Q. What is an economic externality and why does it matter?

A. An economic externality arises when a person takes an action that imposes costs or benefits not only on himself but also on other people. A distinction thus arises between the *private* costs and benefits of the action, which accrue to the actor, and the *external* costs and benefits, which accrue to others. This distinction defines an externality.

There is said to be a negative (harmful) externality when there is an external cost but no offsetting external benefit. There is said to be a positive (beneficial) externality when there is an external benefit but no offsetting external cost.

From society's perspective, the social cost and benefit of a person's action consist of the sum of the private costs and benefits and the external costs and benefits. If there is no externality, the private costs and benefits coincide with the social costs and benefits. If there is an externality, however, there is a divergence between the private and social costs of an action and/or between the private and social benefits.

The problem, when there is an externality, is that private actions are likely to lead to outcomes that are not in the best public interest. The presumption is that the actor pays attention to the private costs and benefits of his action but disregards the external costs and benefits.

With a negative externality, the presumption is that too much of a harmful activity takes place because the actor disregards the external costs. With a positive externality, the presumption is that too little of a beneficial activity takes place because the actor disregards the external benefit. This is why, with an externality, the outcome is not in the best public interest.

Air pollution from motor vehicles is an example of a negative externality. A driver bears the private cost of fueling his car with gasoline, but disregards the external costs of human health and other impacts caused by the particulate matter, nitrogen oxides (NOx), carbon monoxide (CO) and sulfur dioxide (SO2) emitted from the vehicle exhaust.

When an action causes a negative externality, this does not necessarily mean that it should not be undertaken at all because there is still some private benefit from that activity. The negative externality means that *less* of the action should be undertaken than when the external cost is disregarded.

Similarly, when an activity that creates a negative externality is regulated, as with emission standards for light duty vehicles, this does not mean there is no external cost associated with the emissions that do occur. Because of the regulation, there are typically fewer emissions than without the regulation, but those emissions still create some external cost.

Q. Dr. Hanemann, please describe the general treatment of externalities.

A. The concepts of an externality and a divergence between private and social costs or benefits were described in 1920 by economist Arthur Pigou, the Professor of Economics at Cambridge University. Pigou showed the implication that followed from this divergence: an externality leads to what has since become known as a "market failure." In the case of a negative externality, the market failure is that too much of the activity causing the externality is undertaken and too many workers are engaged in that activity compared to what would be in the best public interest. Pigou also identified an economic remedy that would correct the market failure.

Pigou's remedy is related to the concept known as "the polluter pays" principle. This is the principle that a party responsible for causing pollution is also responsible for paying for the damage caused by that pollution, thus giving due consideration to the externality, also known as *internalizing* it.

Pigou's remedy is that an activity which creates a negative externality should be taxed in order to induce a reduction in the scale of that activity to a level that is in the best public interest. The tax – subsequently known as a Pigouvian tax – is set equal to the marginal external cost imposed by an additional increment in that activity.[2] This tax offsets the actor's disregard of the external cost which he imposes on others; through the tax, he himself bears that external cost. Through the tax, the polluter pays for the damage his action causes. In the case of an activity which

[2] In the current context, "marginal" means the same as "incremental."

creates a positive externality, Pigou's remedy is that a subsidy be offered to induce an expansion in the scale of that activity, set equal to the marginal external benefit generated by an additional increment in that activity; through the subsidy, the actor receives the external benefit that he generates. With both a negative externality and a positive externality, Pigou's remedy causes the actor to *internalize* the externality that was created.

Pigou was aware that governments can control externalities through various forms of regulation. He considered his remedy desirable because it uses market forces and creates an economic incentive for private actors to do the right thing for the overall social good – to moderate their activity to a level that is in the best public interest.

Pigou's analysis quickly attracted the attention of other economists in England and America. There followed a long discussion in the peer-reviewed literature covering various details and nuances of Pigou's analysis. By the early 1950s, his argument had been clarified and formalized mathematically. It became part of the standard canon of microeconomics, with special reference to the field of microeconomics known as public economics. An important focus of the field known as environmental economics, which emerged during the 1970s, was measurement of the external costs of negative externalities from pollution in order to implement Pigou's tax remedy.

Q. Does the emission of GHGs through human actions constitute an externality?

A. Yes, GHGs are externalities. With some types of pollution the negative externality comes about because, once emitted, the pollutants come into direct physical contact with those who are harmed by them – e.g., through ingesting mercury or lead, or inhaling fine particulates or carbon monoxide, etc. However, from an economic perspective, it is immaterial whether or not there is a direct physical contact between the emitted pollutant and the person harmed by its emission. What matters is the existence of harm to another person rather than the specific pathway of harm. It is the harm to others that creates an external cost. Therefore, from an economic perspective, GHGs are pollutants as much as mercury, lead, fine particulates or carbon monoxide.

However, there is a conceptual distinction between greenhouse gasses[3] and the pollutants listed above. Those pollutants constitute what is known as a *flow externality*. The harm comes, essentially, contemporaneously as the emissions are being released. If no emissions occur over the course of a year, say, then no harm occurs during that year. Greenhouse gasses are a *stock* externality: the harm comes from the *accumulated stock* of emissions, including past as well as present emissions. If no emissions occur over the course of a year, harm still occurs during that year due to the stock of pollutants which has accumulated from past emissions. With a stock pollutant, the harm continues for a span of time, until the stock of pollutants has dissipated.

In the case of some GHGs it can take centuries before past emissions are finally dissipated and cease to contribute to climate change and to cause harm.[4]

[3] Some GHGs are short-lived while others remain in the atmosphere for hundreds or thousands of years. The warming impacts of ozone or contrails last only days or months. Those of methane last for about 20 years. Those of CO2 persist for hundreds of years.

[4] Something similar can happen with some flow pollutants which accumulate, for example, in the tissues of the human body.

It is also important to note that GHGs differ from the pollutants listed above as flow externalities not only in the temporal nature of their damages but in the spatial nature of the damages. Greenhouse gasses emitted at a particular location on the earth are rapidly mixed in the atmosphere with GHGs emitted from other locations on earth. How GHG emissions work to influence climate, and the consequent impacts on human wellbeing, plays out on a global scale.[5] This contrasts with other pollutants such as mercury, lead, and fine particulates whose effects have a much more limited geographic effect than GHGs. A molecule of emitted GHG contributes to damages from climate change experienced everywhere around the globe, regardless of where it is emitted. This is not the same with other pollutants.

Q. Have governments adopted Pigou's approach based on creating an economic incentive to remedy an externality?

A. Yes, various levels of government in the US and abroad have used taxes and market incentives as a means of shifting people's behavior in ways deemed in the public interest.

An example at the federal level in the US is the excise tax on ozone-depleting chemicals introduced in 1989 to promote the policy goal of reducing the use of chlorofluorocarbons following the negotiation of the Montreal Protocol (Barthold, 1994).

The emissions trading scheme for SO2 emissions, initiated in 1995 under Title IV of the 1990 Clean Air Act Amendments is another example of a market-based

[5] Short-lived GHGs have only local effects on radiative forcing and climate change. Long-lived gasses such as methane and CO2 spread across the entire global atmosphere; their warming impact is global in scale.

system for regulating a pollutant externality. Trading of SO2 allowances had the (intended) effect of placing a price on emissions – an SO2 price. At a regional level, Southern California's RECLAIM market is a cap and trade system for NOx emissions.

Outside the US, a number of countries have levied environmental taxes, including carbon taxes in Denmark, Finland, Sweden, Ireland and France. The EU has had a cap and trade system for carbon dioxide (CO2) emissions since 2005 (World Bank, 2014).

In addition, something akin to a Pigouvian tax based on a measurement of external cost has been used for regulatory purposes. An example in the US is the use of environmental adders by some state Public Utilities Commissions (Including the MNPUC). The adder is a measure of the external cost imposed on society by residual downstream emissions from the generation of electricity after compliance with existing air pollution regulations. The monetized value of the damage is added to cost per kwh of electricity in order to permit a comparison of the costs of available options, for example in the context of integrated resource planning.[6]

Q. What is non-market valuation?

A. The economic valuation of the natural environment, and changes in environmental quality, is an application of *non-market valuation*. Non-market valuation seeks to measure, in monetary terms, the value that people place on things they care for. This includes things that cannot be purchased through a market. It subsumes, and generalizes, the economic valuation of things that *are* bought and sold in markets.

[6] NRC (2010, pp. 26-28)

The economic valuation of items obtained through a market has a pedigree in economics going back to the work of Alfred Marshall, Pigou's predecessor as Professor of Economics at Cambridge University.[7] His analysis required the use of a mathematical approximation, which came to be seen as troublesome. With new developments in the mathematical theory of consumer wellbeing[8] and consumer behavior around 1970, the issue was clarified, revealing a way to make Marshall's analysis precise. The extension from market to non-market valuation came about almost immediately (Maler, 1974). Maler's work was the direct basis for my own work on non-market valuation both in my Ph.D dissertation and subsequently.

Q. How does this apply to the impacts of climate change?

A. Climate change can affect people in different ways. Some people may benefit; others may be harmed. In some cases, it is their livelihood that is affected; in others, it is their health, access to food or clean water, the amenities of life, or the natural environment around them. While many non-monetary metrics can be used to characterize particular components of the impacts of climate change, they provide no unambiguous way to *aggregate* those metrics for the purpose of characterizing the overall change in human wellbeing. In principle, the economic theory of monetary valuation provides a way to perform this aggregation.

The changes that affect human wellbeing are classified as *market* and *non-market*. The market effects involve changes in market prices, changes in revenue and net income, changes in the quantity or quality of market commodities, or

[7] Marshall's analysis was first published in *Pure Theory of Domestic Values* (1879).
[8] I will use the terms "consumer wellbeing" and "consumer utility" synonymously.

changes in the availability of commodities. Non-market changes are changes in the quantity, quality or availability of things that matter to people, even though they are not obtained through the market. Examples of such non-market items that people value include health, quality of life, culture, environmental quality, natural ecosystems, wildlife, and aesthetics. A given change in a physical or biological system can generate both market and non-market damage to human wellbeing. For example, an episode of extreme heat in a rural area may cause heat stress for exposed farm labourers and dry up a wetland that serves as a refuge for migratory birds, while killing some crops and impairing the quality of others that survive. From an economic perspective, these damages would be conceptualized as (i) market impacts, including a loss of income for farmers and farm workers; an increase in prices of crops for consumers and/or a reduction in their quality; and (ii) non-market impacts including ecosystem harm and the impairment of human health (though some of these effects may be captured in the market wage of farm workers).

Q. What is the measure of economic value?

A. People often assume that the price of an item measures its economic value. This was also a view held by economists at various times between, say, 1900 and 1970. Since Marshall (1879) it had been known that this view is incorrect, but it took until the 1970s for that fact to become well accepted in economics.

The market price of an item measures what it would cost a person to obtain the item. What the item is worth to that person – for example, what he would be willing to pay, if necessary, to obtain it – is something different. The former reflects factors affecting supply; the latter reflects factors affecting demand. Supply and demand are two different concepts.

There do exist some circumstances where what an item is worth is equated to its price. In fact, this is a condition for optimizing the quantity purchased of an item, assuming the item is available for sale in a competitive market without quantity restrictions and in freely divisible quantities. Where those conditions hold, if the consumer is optimizing his purchase (choosing the quantity that he sees as maximizing his wellbeing) subject to a limit on how much money he can spend,[9] he should choose to purchase the quantity such that the value of the last unit purchased (its "marginal utility") just equals its price.

For example, if I freely and deliberately choose to buy 5 lbs of hamburger a week at a price of $4/lb, the presumption is that I stop my purchases at 5 lbs because the sixth pound is not worth $4 to me. If it was worth at least $4 to me, I would buy it. Similarly, if the *fifth* pound is worth *le*ss than $4 to me, I would not buy it: I would restrict my purchases to less than 5 pounds.

In the circumstances just described, the price of hamburger measures in monetary terms the marginal value to me of the last pound of hamburger purchased. But, it does not measure the value of *the other* units I purchased.[10] The presumption would be that those other units had a higher marginal value to me but that the marginal value declines as I acquire more units.

One implication is that, if hamburger were available at $4/lb only in packages of, say, 2, 4 or 6 lbs, I would buy a 4-pound package but not a 6-pound package. In

[9] This limit is known as the *budget constraint* or the *income constraint*.
[10] Those are known as *inframarginal* units.

that case, the marginal value of the last unit I purchase could be *higher than* its $4 price.

Another, related, implication is that my observed weekly expenditure on hamburger -- $20 – does not necessarily measure the value to me of the 5 pounds that I chose to buy. In fact, I might be willing to pay a total of, say, $30 to obtain my weekly "fix" of 5 pounds of hamburger.[11] I don't have to spend that much because the price is only $4/lb – but I would do so if it were necessary.

This leads to the nub of Marshall's analysis. Marshall defined the economic value of a package being consumed by a person as the most that he would be willing to pay rather than go without it. That is the economic measure of the (gross) value of the item to the person. In my case, the gross value to me of being able to consume 5 pounds of hamburger per week is $30. But that is not the same as what I actually pay.[12]

As a consumer, therefore, I benefit from being able to buy hamburger at $4/lb. I pay $20 for my 5 pounds but I would have been willing to pay up to $30 for this opportunity. This represents a net value to me – a "surplus of satisfaction" – amounting to $10. In 1879, Marshall called this net value the "consumer's rent." Later, in 1890, he adopted the term "consumer's surplus," which has been used ever since. [13]

---

[11] For example, I might be willing to pay $8 for the first pound of hamburger, $7 for the second pound, $6 for the third pound, $5 for fourth pound, $4 for the fifth pound, and only $3 for the sixth pound.

[12] By the logic of Marshall's argument, the actual expenditure on an item represents a *lower bound* on the value of being able to buy it: it understates the true value. Note that exactly the same analysis had been offered in 1844 by Jules Dupuit, a French engineer formulating principles for the cost-benefit analysis of state infrastructure projects. While Marshall offered exactly the same line of reasoning, I understand that no evidence exists that Marshall knew of Dupuit's work. Neither Marshall nor Dupuit used the example of hamburger. Marshall used the example of tea, while Dupuit used that of wine.

[13] Dupuit called it the "consumer's profit."

Marshall had no doubt of the validity of the concept of consumer's surplus (net willingness to pay) as the correct measure of (net) economic value. The troublesome question was how to measure it in practice. He proposed a method based on the consumer's demand function for the commodity. His proposed measure, intended as an approximation, was the area under the demand curve lying above the price paid.

As time passed, the nature of Marshall's approximation came to be seen as insufficiently reliable. The focus of valuation in economics switched to using market price as the measure of value, while ignoring the fact that this understated the value of infra-marginal units consumed and therefore understated the true total value.

This changed with the publication of a seminal paper by Hurwicz and Uzawa (1971) which demonstrated the tool needed to correct Marshall's approximation. This tool was employed by Willig (1976) to derive an exact measure of willingness to pay for change in the price of a market commodity.

Q. Is there an alternative to willingness to pay?

A. Willingness to pay (WTP) – the maximum a person would be willing to pay for something desirable rather than forego it – was long seen as the theoretically correct measure of economic value, although it was believed not susceptible of exact or reliable measurement. In 1941, a second, parallel measure of value was suggested: the minimum amount of compensation which a person would be willing to accept (WTA) to consent to forego something desirable. The English economist John Hicks, who in 1939 and 1941 had formalized the WTP measure using contemporary mathematical tools of economic theory, immediately formalized the WTA measure in parallel with WTP. WTP and WTA are now commonly referred to as the Hicksian welfare measures.[14]

By about 1946, the two measures of WTP and WTA were recognized as the core measures of economic value. However, there remained the problem of reliably calculating them. Marshall's consumer's surplus was identified as something intermediate between WTP and WTA, and an approximation to each of them, but it was an exact measure of neither. However, with the theoretical developments around 1970, everything fell into place. The path to exact measurement of WTP and WTA was discovered.

The modern understanding of economic value can be summarized as follows. Economists define economic value in terms of a trade-off. The economic value of an item to a person, measured in terms of money, is defined as the amount of money (income) the person would be willing to exchange for the item if such an exchange were possible. Thus, the economic value of an item is the *income equivalent* of the item – it is the quantum of income which the person would be willing to exchange for the item such that the exchange has the same effect on the person's wellbeing as the item itself.

As a matter of logic, there are exactly two ways to formulate such an exchange. One formulation is the most a person would be willing to give up in order to obtain the item (the WTP measure of income equivalence). The other formulation is the minimum compensation the individual would be willing to accept to consent to forego the item (the WTA measure of economic equivalence). The item in question

[14] The phrase "welfare measures" means that they are monetary measures of the change in individual wellbeing.

may be a marketed commodity, but it need not be: it can be *anything* that the person values. All economic measures of value can be shown to be either a WTP or a WTA measure.

These measures apply to both market and non-market changes in wellbeing. They apply to changes in wellbeing driven by changes in market prices, income, and the quantity or quality of market commodities. They also apply to changes in the quantity, quality or availability of non-market items that people value. Thus, they apply for measuring all aspects of climate change impacts.

The WTP and WTA values are not generally the same.[15] They are generally expected to be different. Where they do differ, the WTP measure is generally expected to be smaller than the WTA measure (Willig, 1976; Hanemann, 1991).

Which measure should be used is a policy judgment. This judgment can be related to the question of property rights. Assume the item is a benefit. If the person in question has a right to that benefit, then logically its value to him should be measured by his WTA for the item – the compensation that he would require to surrender it. Conversely, if the person does not have a right to that benefit, then logically its value to him should be measured by his WTP for the item – the most that he would be willing to pay for it. Similarly, if the item is a harm and the person has a right to be free of that harm, then logically the value of the harm should be measured by his WTA – the compensation that he would require to consent to the harm. If the item is a harm but the person has no right to be free of that harm, then logically the value of the harm should be measured by his WTP – his willingness to pay to avoid the harm.

[15] They are guaranteed to be the same only when the change involves purely a change in income.

In fact, the climate economics literature has adopted the WTP measure of value, often expressed as a percentage of per capita income. My impression is that this is being done because of the somewhat greater simplicity in measuring WTP than WTA, but without any explicit judgment of what property right should apply. To the extent that WTA is deemed to be the correct welfare measure, using the WTP measure would understate the damage from climate change.

To repeat, In the case of climate harm, the WTP measure of damage is not necessarily the amount of income that a person loses as a result of climate change: it is the amount of his income that the person is estimated to be willing to give up to avoid the harm. This measure covers not only the income loss that might be incurred but also anything else that contributes to a reduction of the person's wellbeing.

IV. DEFINITION AND ESTIMATION OF THE SOCIAL COST OF CARBON

Q. What is the Social Cost of Carbon, and how does it relate to a negative externality?

A. The Social Cost of Carbon (SCC) measures the additional external cost associated with an incremental unit of greenhouse gasses emitted now. The costs continue far into the future. What is measured, therefore, is the *discounted present value* of the stream of additional external costs occurring as a consequence of emitting an incremental unit now.

To the extent that the changes in climate associated with greenhouse gas emissions are beneficial, the external cost is negative (i.e., a benefit). However, the empirical evidence and theoretical understanding indicate that, in aggregate, the net effect is harmful. Hence, the SCC is positive.

The SCC is thus a measure of the marginal external cost associated with the emission of an additional unit of greenhouse gasses now. This marginal external cost would be internalized if there were a Pigouvian tax equal to the marginal external cost on that unit of emissions. Hence there is a close connection between the SCC and the Pigouvian tax that would correct the market failure arising from the externality.

The use of "carbon" in the SCC reflects three things: (1) the dominance of carbon dioxide among the current greenhouse gasses; (2) the translation of non-CO2 GHGs into CO2-equivalent units, and (3) the use of "carbon" as shorthand for carbon dioxide and its equivalents.

Q. How is the Social Cost of Carbon estimated?

A. To estimate the marginal external cost associated with an additional unit of GHG emissions one needs to estimate, in general terms, (1) how that emission changes the existing accumulation of GHGs in the atmosphere via the carbon cycle;[16] (2) how that, in turn, changes the amount of energy stored in earth's system (the change in radiative forcing); [17] (3) how the change in radiative forcing leads to changes in the climate worldwide, (4) how those changes in climate affect things that matter to humans, such as water supply and drought, crop production, disease and human

[16] In addition to the atmosphere, CO2 is absorbed by, released from, and stored in the oceans, rocks, soil, and plants and trees. The term *carbon cycle* refers to the set of various processes, both biotic and abiotic, that transport CO2 into and out of these various reservoirs of CO2, and thus determine the concentration of CO2 in the atmosphere.

[17] The earth's climate is a vast heat machine, receiving, transporting, storing and releasing heat (thermal energy). The amount of energy stored determines the temperature of the planet. Natural and anthropogenic processes that alter the earth's energy budget are drivers of climate change. The *radiative forcing* is a measure of the change in the rate of heat energy transfer caused by a particular driver, such as a change in the concentration of a GHG. Positive radiative forcing leads to surface warming, while negative radiative forcing leads to surface cooling.

health, outbreaks of wildfire, coastal flooding, and ecosystem functioning etc.; and (5) how humans value the changes in those things.

The calculation of these items is conducted within the framework of what is known as an Integrated Assessment Model (IAM) – this is a computable, numerical model that accounts for items (1), (2), (3), (4) and (5).

The sequence of events being analyzed plays out over a period of time. How an increment in today's emissions affects future atmospheric concentrations of GHGs, and how that affects future climate, depend in part on what will be emitted later. Those emissions are all accounted for in the IAM.

Emissions are generated by worldwide economic activity, which also is accounted for in the IAM.

V. INTEGRATED ASSESSMENT MODELS

Q. What is an Integrated Assessment Model?

A. IAMs are mathematical computer models that are based upon explicit assumptions about the behavior of a modeled system. They attempt to incorporate information from physical and social sciences that consider economic, political, and demographic variables in addition to the climate system to provide a coherent synthesis of different information that is available for use by decision makers.

In the present context, an IAM combines a reduced form representation of the carbon cycle and the climate system together with a reduced form representation of the economy, economic growth and the generation of GHG emissions and a reduced form representation of the impacts of climate change and how those impacts are valued (the external cost generated).

The strength of an IAM is that it combines the three components in one integrated model – the representation of how economic activity generates emissions, the representation of how the emissions lead to climate change, and the representation of the economic cost of the resulting impacts.

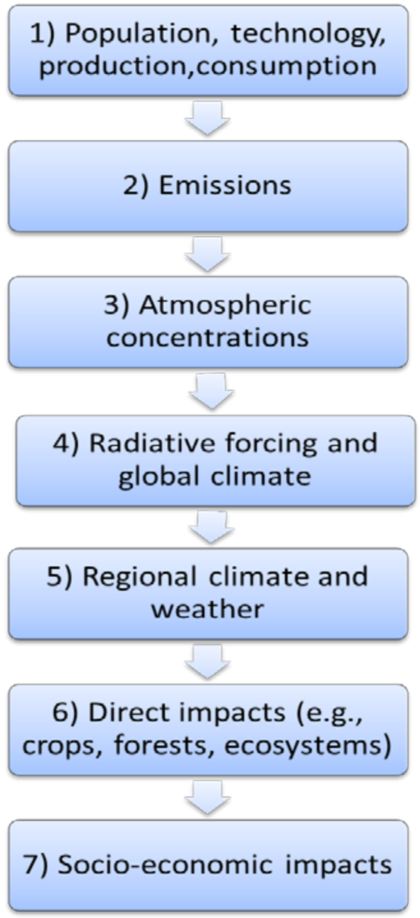
Q. What is meant by "reduced form?"

A. The term is being used here to connote a simplified version of a larger model. The larger model ("the structural model") has equations characterizing physical or behavioral relationship ("structural equations") which, in the reduced form model, are simplified into a smaller number of equations that summarize the outcome of interactions among the structural equations after variables have been solved out of them.

Q. How are IAMs constructed?

A. The following is a schematic depiction of the elements of an IAM:

Figure 1. Elements of an IAM



Boxes 1-2 correspond to the representation of how economic activity generates emissions, and how much those emissions are abated and at what cost. Boxes 3-5 correspond to the representation of how the resulting emissions lead to climate change.[18] Boxes 6-7 correspond to the representation of the resulting impacts of the change in climate and their economic valuation.

The climate variables tracked in boxes 4 and 5 are the change in global annual average temperature.

The numerical computations corresponding to boxes 1-7 are conducted period by period – a determination of economic activity in the period, a determination

[18] Box 3 is a representation of the carbon cycle.

of emissions generated in that period, a calculation of the change in atmospheric emissions stored in the atmospheres the period, the change in radiative forcing; the change in climate (increase in global average annual temperature); and the physical and economic impact resulting from the increase in global average annual temperature in that period.[19] This is done for each period starting in a base year (e.g., 2010) and continuing at least through 2100.

The IAM output is a set of time paths (trajectories) for variables such as average annual Gross Domestic Product (GDP) during each time period, average annual GHG emissions and abatement, average annual atmospheric GHG concentration, average annual change in global temperature, the average annual economic value of the impacts caused by the change in temperature, and the average annual carbon tax (social cost of carbon). The trajectories are typically reported through about 2100.

Q. How is the economic valuation expressed?

A. The economic valuation of the impacts of climate change is expressed using the *willingness to pay* measure of economic value. This measures the maximum amount that the public existing at that point in time would be willing to pay annually to avoid the harm at that time.

This annual willingness to pay is expressed as an equivalent percentage of annual GDP at the time. As explained further below, it is intended to cover not only market impacts of climate change but also non-market impacts, and not only changes in income but also changes in market prices and, more generally, any

[19] Depending on the model, as described further below the periods are generally years or decades.

changes that are considered to affect public wellbeing as accounted for by the model.

For the purpose of this valuation, boxes 6 and 7 are combined into a single function (or set of functions) characterizing the economic value associated with particular groups of impacts at a point in time as a function of the increase in global average annual temperature occurring at that time. This function is known as the *damage function*.

Q. What is the formula for a damage function?

A. Since the IAM is a mathematical model, the damage function, like the other components of the IAM, is represented through an algebraic equation. As with other equations in the IAM, the precise formula of the equation differs across different IAMs. Here, as an example, I present a formula often used to represent the damage function.[20]

Suppose k is a region of the model, such as a country (the spatial resolution differs across IAMs). Let t be a particular time period covered by the model. Let Y_{kt} denote the GDP that would have occurred in region k in period t if there were no effects from global warming. Let ΔT_{kt} denote the increase in average annual temperature in region k in period t as compared to, say, the pre-industrial period. The projection of ΔT_{kt} is what emerges from the IAM component corresponding to box 5.

The economic value of the market and non-market impacts in region k and period t associated with ΔT_{kt} is denoted D_{kt}. The damage function expresses D_{kt} as a

[20] The formula presented below applies to DICE and PAGE, but not FUND.

function of ΔT_{kt} and Y_{kt}. In two of the IAMs discussed below, DICE and PAGE, the damage function takes the algebraic form of a *power* function:

$$D_{kt} = a_k[\Delta T_{kt}/\Delta T^*]^b Y_{kt} \qquad (1)$$

where a_k and b are coefficients whose numerical value is specified by the modeler.[21]

This formula expresses the damage in the given region and period as a fraction of the GDP that would have occurred in that region absent any warming.

The term ΔT^* appearing in the equation is a *benchmark* degree of change in global average temperature, used to calibrate the value of the coefficient $a_k t$. This benchmark is typically taken as the equilibrium degree of warming due to the increase in radiative forcing associated with a sustained *doubling* of atmospheric CO2 relative to the pre-industrial level. The benchmark warming, in turn, is calculated from the formula

$$\Delta T^* = \lambda \, \Delta RF \qquad (2)$$

where ΔRF denotes the increase in radiative forcing associated with a sustained doubling of atmospheric CO2, and λ is a parameter known as *the climate sensitivity*. The climate sensitivity, a key parameter resulting from climate models, reflects both the direct warming from the increase in radiative forcing and also warming resulting indirectly from feedback processes triggered by that warming.[22]

The formula in (1) has the property that, when $\Delta T = 0$, $D_{kt} = 0$: no damage occurs when there is no warming.

A second property of the formula in (1) is that, when $\Delta T = \Delta T^*$, $D_{kt} = a_k Y_{kt}$. Thus, the coefficient a_k measures the economic value of the damages in region k –

[21] I use "coefficient" and "parameter" interchangeably to denote constants in an algebraic formula.
[22] An example of such a feedback is the following. Warmer surface temperatures at high latitudes cause a melting of the permafrost. The melting of the permafrost causes methane to be released to the atmosphere, which increases the radiative forcing and triggers more warming.

expressed as a fraction of the region's GDP -- associated with the benchmark warming resulting from a doubling in atmospheric CO2.

Since 1989, there have been studies in the literature which estimate the economic value of damages associated with this benchmark warming.[23] Based on some of those studies, the IAM modeler forms an estimate of these damages, and uses his estimate to set the value of a_k.

The remaining coefficient in (1) is b. This controls how much less damage occurs with warming below the benchmark level, and how much more damage occurs with warming above that level. The value of b is a judgment by the modeler. In DICE, the value is set to b = 2.[24] In PAGE, *b* is a random variable between 1.5 and 3.[25]

Q. Is this the only type of Integrated Assessment Model?

A. The term "Integrated Assessment Model" is also used in the literature to refer to models that cover boxes 1 through 5 but omit boxes 6 and 7. Those models trace the link from economic activity to changes in climate, but not the link from changes in climate to impacts and external costs. They do not contain a damage function. Therefore, no estimate of the social cost of carbon can be obtained from this other type of IAM.

As explained below, the IWG made use of both types of IAM. It deployed three IAMs that cover the full suite of steps, from Box 1 through Box 7; those are the

[23] In the earlier literature, ΔT*was often estimated at 2.5°C. More recently, it is generally estimated at 3°C.
[24] When something is a function of a variable to the power two (i.e., squared), it is said to be a *quadratic* function of that variable.
[25] That is to say, its value is chosen by taking draws from a probability distribution bounded by the values 1.5 and 3.

models known by the acronyms DICE, FUND, and PAGE.[26] However, for the analysis corresponding to boxes 1 and 2, the IWG adopted results generated by four models of the second type.[27]

While the strength of IAMs like DICE, FUND and PAGE is that they combine economic models, climate models and impact models within one integrated framework, their constraint is that they provide a simplified representation of each of those model types. Their climate model is a simplified representation of General Circulation Models. Their model of economic activity and the generation of emissions is a simplified version of what is found in models like IMAGE and other economic models. Their representation of impacts is a simplified version of what is found in more detailed models of individual types of impact.

Q. For how long have economists been calculating the Pigouvian tax or the social cost of carbon for GHG emissions?

A. Economists have been estimating the damages associated with global warming since 1992, when the first papers and books on this topic were published. The models used by the IWG, DICE, PAGE and FUND, first appeared in 1993, 1994, and 1995, respectively, and were each used at that time to calculate a Pigouvian tax or a SCC for emissions of CO2.

---

[26] These models are explained further below.

[27] These are models known by the acronyms IMAGE, MERGE, MESSAGE and MINICAM. They are four of ten models which contributed to a model inter-comparison exercise, the twenty-second such exercise conducted by Stanford University's Energy Modeling Forum. That particular exercise, known as EMF-22, focused on GHG abatement ("mitigation") policies required to meet certain climate targets, assessing the costs and energy implications of meeting those targets. The IWG did not deploy the models involved (IMAGE, MERGE, etc). Instead, the IWG adopted a subset of the published results from that inter-comparison exercise (Clarke et al., 2009).

Around the same time, other models with a simplified structure compared to DICE, PAGE or FUND were published which were also used to calculate the optimal emissions of CO_2 or the Pigouvian tax on CO_2, including the CETA Model (Peck and Teisberg (1992), the MERGE Model (Manne and Richels, 1995), and the analysis by Cline (1992).

Q. Please describe the IAMs used by the IWG in estimating the SCC.

A. The three IAMs used by the IWG are the three main such models in the literature. They were developed in the 1990s for the purposes of determining the benefits and costs of GHG mitigation and measuring the social cost of carbon.

Q. What is the pedigree of DICE?

A. DICE – the Dynamic Integrated Climate-Economy model – is the oldest of the three models. It was developed by Professor William Nordhaus of Yale University. It grew out of his work on the economically optimal allocation of scarce fossil fuel resources published in the 1970s. In Nordhaus (1977) and Nordhaus (1982) he extended his work to incorporate a constraint on CO_2 emissions, but without a representation of climate change and its impact. The first version of the complete DICE model, using a simplified solution concept, was published in Nordhaus (1991a, b). The version using the full method of numerical solution appeared in Nordhaus (1992, 1993a,b, 1994).

This was extensively revised in the version known as DICE 1999 (Nordhaus and Boyer 1999, 2000; Nordhaus 2001). The revision included changes in modeling the generation of GHGs through economic production, changes in the representation of the climate system, and revision of the relationship characterizing economic damages as a function of the increase in global average annual temperature (the "damage function") based on more recent studies of potential climate change impacts.

DICE 2007 was the next revision and update of DICE (Nordhaus 2007, 2008, 2009, 2011). This revision included changes in the structure of the damage functions, with explicit inclusion of damages from sea level rise. This was the version used by IWG 2010. DICE was revised in 2010 (Nordhaus 2010) to incorporate more fully information from the IPCC's Fourth Assessment Report, parts of which became available after DICE 2007 had been finalized. The most recent update is DICE 2013 (Nordhaus and Sztorc). This contains numerous changes compared to the 2007 and 2010 versions of DICE. The damage function was greatly simplified, the carbon cycle and climate models were recalibrated to recent earth system models; projections of future population, output and emissions were updated; and the time step was changed from 10 to 5 years.

Q. What is the pedigree of PAGE?

A. PAGE - the Policy Analysis of the Greenhouse Effect model – was developed in 1991 by Dr. Chris Hope at Cambridge University for use by EU decision makers in assessing the marginal economic impacts of carbon emissions (Hope, 1994). It used data on impacts developed in 1992 for the EU. An update and extension of the model, PAGE 1995, appeared in 1995 (Hope 1995; Hope and Maul, 1996; Plambeck and Hope, 1996; Plambeck et al., 1997). PAGE 2002 was the next update (Hope 2006a,b; Wahba and Hope 2006; Alberth and Hope, 2007). This version was the basis for the extensive analysis of climate change policy and economics conducted by Lord Stern for the UK Government, known as the Stern Review (Stern 2006). PAGE 2002 was also the version used by the IWG in its 2010 study. PAGE 2009 appeared around the time that the IWG analysis was being completed (Hope 2011 a,b,c; 2013). This revision includes modification of the damage function and changes to the representation of the carbon cycle and the climate system. PAGE 2009 is the version used by the UWG for its 2013 report.

Q. What is the pedigree of FUND?

A. FUND – the Climate Framework for Uncertainty, Negotiation and Distribution model – was developed by Professor Richard Tol in Holland in the early 1990s, originally to study international capital transfers in climate policy (Tol, 1995, 1996. 1997, 1998, 1999 a,b,c,d, 2000 a,b,c, 2001 a,b,c,d,e.). The version used by the IWG for its 2010 study was FUND 3.5 (Anthoff and Toll, 2012). The version used for the 2013 study was FUND 3.8 (Anthoff and Toll, 2014).

Q. Have these models been cited by the IPCC Assessment Reports?

A. The Intergovernmental Panel on Climate Change (IPCC) is an intergovernmental scientific body under the auspices of the United Nations, established in 1988 at the request of member governments. It was originally formed under the auspices of the World Meteorological Organization (WMO) and the United Nations Environment Program (UNEP), and was later formally recognized by the United Nations General Assembly. Countries which are members of the IPCC are also members of the WMO and UNEP. The IPCC is tasked with producing reports that support the United Nations

Framework Convention on Climate Change (UNFCCC), which is the main international treaty on climate change.

IPCC reports are internationally regarded as authoritative on the topics covered. The IPCC has published five comprehensive assessment reports reviewing the latest climate science. Each assessment report is in three volumes, produced by Working Group I (The Physical Science), Working Group II (Impacts), and Working Group III (Mitigation). The First Assessment Report was published in 1990, the Second in 1995, the Third in 2001, the Fourth in 2007, and the Fifth in 2014. The findings of DICE, PAGE and FUND are cited by Working Groups II and III in the Second, Fourth and Fifth Assessment Reports.

Q. To what extent are these models similar, and to what extent different?

A. DICE, PAGE and FUND were developed independently by three different modelers. They shared similar objectives, but they went about fulfilling those objectives somewhat differently. The models share a family resemblance, but their details vary. The similarities and differences are summarized in Figure 2.

In the following paragraphs, I walk through the various elements involved in the models commenting on their similarities and difference.

First, the spatial resolution of the models is different FUND divides the world into 16 regions. Economic activity, emissions, and impacts are modeled separately for each region. PAGE divides the world into 8 regions, with economic activity, emissions, and impacts modeled separately for each region. DICE models the world as a global entity.

Second, FUND operates on an annual time step. DICE operates on a decadal time step. PAGE operates on a decadal time step from 2000 to 2060 and a 20-year time step between 2060 and 2100.

Third, all three models take the trajectory of population over time as exogenous to the model (i.e., determined outside the model).

Fourth, with regard the growth of income over time, PAGE and FUND take this as exogenous (i.e., determined outside the model). In DICE, by contrast, the per capita income is endogenous (i.e., determined inside the model). This is because PAGE and FUND are *simulation* models, whereas DICE is formulated and solved as an *optimization* model.

Figure 2: IAM Comparisons

	Dice	Fund	Page
Spatial Resolution	1 Region The World	8 Regions USA, EU, Other OECD, FSU & ROE, China & CP Asia, India &SE Asia, Africa & ME, Latin America	16 Regions USA, WEU, CAN, JPK, ANZ, CEE, FSU, MDE, CAM, SAM< SAS, SEA, CHI, NAF, SSA, SIS
Population Growth	Determined **outside** of the model	Determined **outside** of the model	Determined **outside** of the model
Income Growth	Determined **within** the model	Determined **outside** of the model	Determined **outside** of the model
CO2 Emissions: Land use change Fossil fuel usage		Land use emission determined **outside** of the model Fossil fuel usage determined **within** the model	Both determined **outside** of the model
Non-CO2 Emissions: Land use change Fossil fuel usage	Emission determined **outside** of the model	Some emission determined **outside** of the model Some emissions determined **within** the model	Other than SO2 emission determined **outside** of the model SO2 emissions determined **within** the model
Time Steps	10 year steps	Yearly	10 year steps (2000-2006) 20 year steps (2060-2100
Representation of Carbon Cycle			
Impacts of Warming	Sea level rise, Non-sea level	Sea level rise; Agriculture; forests; heating; cooling; water resources; tropical storms; extra-tropical storms; migration; biodiversity; cardiovascular, respiratory, vector-borne disease; diarrhea.	Economic (market), Non-economics (non-market), Sea Level, Catastrophic
Damage Function Sea-level Non sea-level Catastrophic	Quadratic of mean sea-level rise Quadratic of temperature No separate estimate	Elaborate formula Separate formula for each category Probabilistic	Power function of sea-level rise Power function of temperature Probabilistic when warming over 3°C

Source: Table based on Table 4.1 and 4.3 in EPRI 2014

Q. What is the difference between a simulation model and an optimization model?

A. A simulation model proceeds through time period by period. In each period, inputs to the calculations for that period consist of variables determined inside the model from previous periods' computations plus inputs exogenous to the model (i.e., determined outside the model). After the completion of computations for that period, some of the results are stored for use as inputs to future periods' computations. There is a separate set of computations for each period in sequence.

In an optimization model, while each period is evaluated, there is a linkage between the determination of variables made for one period and those made for other periods, reflecting the optimization being conducted.[28] In the case of DICE, the optimization takes the form of a standard *economic growth model* modified to account for a stock externality (namely, GHGs).

The essence of the optimization in an economic growth model is that investment, consumption and output across all periods considered should be chosen so as to maximize the discounted present value of wellbeing aggregated over the entire span of periods considered. The maximization across all periods determines the optimal values of the variables for each individual period.

The time span being considered in DICE – several centuries – contains many generations of people living on earth. A common approach in the economic literature to dealing with this situation, and one adopted by DICE, is to represent it as though there was a single individual, representative of the entire population, who is alive over the entire span of time considered. The representative individual controls each period's economic variables (e.g., output, investment, consumption, and the

[28] "Optimization" denotes the maximization or minimization of some objective or criterion.

generation of emissions). In each period, the representative individual's wellbeing benefits from consumption in that period but is harmed by the damage from warming in that period. The output available from production in a period, adjusted downwards for the damage from warming in that period, can be used in one of three ways. It can be consumed in that period, which increases current wellbeing (utility); it can be invested in productive capital, which raises the output available in future periods but contributes nothing to current wellbeing; or it can be applied to the reduction of GHGs (mitigation) from the production of output in the current period, which contributes nothing to current wellbeing but reduces future warming. The allocation of each period's output to consumption, investment and mitigation is determined so as to maximize the total discounted present value of the representative individual's wellbeing (utility) over the span of time considered.

Being simulation models, PAGE and FUND do not embody this type of optimization.

Q. How do these models account for GHG emissions and the carbon cycle?

A. All three models account for CO2 emissions from land use change as well as from the use of fossil fuel in electricity generation and industrial production. The IAM accounting of GHG emissions are summarized in Figure 3 below.

Figure 3: IAM GHG Emissions

	Dice	Fund	Page
Population	Determined **outside** of the model	Determined **outside** of the model	Determined **outside** of the model
Income	Determined **within** the model	Determined **outside** of the model	Determined **outside** of the model
Fossil & Industrial CO_2	Determined **within** the model	Determined **within** the model	Determined **outside** of the model
Land CO_2	Determined **within** the model	Determined **outside** of the model	Determined **outside** of the model
Non-CO_2 Kyoto gases	Included via other radiative forcing	*	*
SO_2	Included via other radiative forcing	*	**
Other radiative forcing	Determined **outside** of the model	None	Determined **outside** of the model
* = Emissions determined outside the model, forcing determined within the model			
** = Emissions and forcing determined outside the model			
Source: Table based on Table 4.1 in EPRI 2014			

PAGE uses a time trajectory for both these emissions determined outside the model. In FUND, CO2 emissions from land use change are determined outside the model, while industrial CO2 emissions are determined inside the model and are derived from economic output and assumptions regarding energy intensity and emission intensity. In DICE, CO2 emissions from both land use change and industrial production are determined inside the model.

Non-CO2 gases are takes as given externally in DICE. FUND models some non-CO2 gases within the model. PAGE models SO2 within the model but takes other non-CO2 gases as given externally.

To model the accumulation of these GHGs in the atmosphere, these models employ a simpler approach than the highly detailed and computationally intensive cell-based approach of the modern Earth System Models. Instead, they use what are known as *box models*. In these models, the entire atmosphere is modeled as one single reservoir ("box"); and the entirety of the oceans is modeled as one or two reservoirs, producing what is known as a two- or three-box model.[29] . The key is then to assign values for the model parameters governing the flow of carbon between the reservoirs such that the end result mimics what is found in more sophisticated Earth System Models, which simulate the carbon cycle with explicit consideration of many factors influencing carbon flow such as the dynamics, chemistry, and biology of the oceans and land vegetation.

DICE uses a 3-box model to represent the flow of CO2 in the Earth system.[30] The carbon cycle representation in DICE was revised between DICE 2007 and DICE 2010: the mathematical formulation stayed the same, but the numerical values assigned to flow-moderating parameters were altered to better match the carbon cycle in the more recent versions of the detailed Earth System Models.

FUND takes an approach that is of the same general type as DICE but with different details. FUND uses a box model approach but with the boxes not explicitly tied to specific physical reservoirs (e.g. upper ocean, deep ocean). Instead, there are five 5 processes that represent the removal of CO2 from the atmosphere after emission. Each of the processes has a unique rate of removal associated with it, the summation of all these processes represent the total removal CO2 by the land/ocean. As with DICE, the numerical values of the parameters are chosen to

[29] In a three-box model, one of the ocean boxes is a "quickly mixing reservoir" representative of the upper ocean and biosphere, while the other box represents the deep ocean. Box models were used by climate modelers in the 1960s and 1970s before more powerful computing resources became available.
[30] Other greenhouse gases are included in DICE but are not modeled explicitly as with CO_2. Instead, the impact of other greenhouse gases is included by directly changing the warming in the atmosphere rather than through emissions and resulting atmospheric concentration levels.

arrive at results consistent with those of recent versions of the detailed Earth System Models.

PAGE uses a single box to represent the removal of CO_2 emissions from the atmosphere to the land and the ocean. As with DICE and FUND, this is designed to capture a number of processes in a compact mathematical form.

Q. How do the models account for the effects of warming?

A. Starting with DICE 2007 onwards, DICE has had two categories of impact (two global damage functions): one for the effects of sea level rise, and the other for aggregate non-sea level rise impacts. PAGE 2002 (used by the IWG in its 2010 report) had three categories of impact (three regional damage functions for each of the 8 regions): economic (i.e., market) impacts; non-economic (i.e., non–market) impacts; and discontinuity (e.g., abrupt change or catastrophe) impacts. PAGE 2009 (used by the IWG in its 2013 report) adds a fourth category of impact for sea level rise. FUND has 14 categories of impact (14 regional damage functions for each of the 16 regions): sea level rise; agriculture; forests; heating; cooling; water resources; tropical storms; extra-tropical storms; migration; biodiversity; cardiovascular, respiratory and vector borne disease; and diarrhea.

In the case of sea level rise, the damage is modeled as a function of the rise in global mean sea level, which, in each model, is projected as a function of temperature and lagged temperature. In DICE the global damage is expressed as a quadratic function of the rise in mean sea level. In PAGE and FUND with their regional spatial resolutions, factors such as regional coastal length or topography are used in the calibration of the regional sea level rise damage function. In PAGE, the function is a power function of projected global sea level rise. In FUND, a more elaborate formula is employed.

Similarly, the non-sea level rise damage function is a quadratic function of temperature in DICE and a power function in PAGE.[31] In FUND, there is a different formulation of the damage function for each category of impact.

The economic impact of a climate catastrophe is not modeled separately in DICE or FUND. In PAGE it is represented by a damage function which kicks in with a positive probability when the increase in global average annual temperature exceeds 3°C. [32]

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.

Earth System Models are computable numerical models which represent the physical processes occurring in the atmosphere, in the ocean and on the land

[31] See the discussion following equation (1) above.
[32] The use of a probability distribution for the numerical value of certain parameters in FUND and PAGE is intended to account for scientific uncertainty regarding the value of those parameters.

surface in order to simulate the response of the global climate system to a sequence of emissions covering actual emissions during the twentieth century plus projected emissions through the next one or two centuries. These models divide up the atmosphere and the oceans into a three-dimensional grid. They often represent the vegetation on land incorporating plant growth and soil processes. Atmospheric grid cells may have sides of 150-200 km in length, resulting in about half a million grid cells, together with 20-40 vertical layers for each cell.

The model computes how each cell exchanges heat, moisture, humidity, salinity, etc. with its neighboring cells, with the calculations repeated for each time period, where the period is perhaps 10-20 minutes. A one year's simulation would require the calculations to be repeated for each cell about 30,000 times. To perform the simulation for all cells over two or three centuries requires the use of supercomputers and, even then, it can take months of computing time.

By contrast, economic models that project GHG emissions operate on an annual time scale and a national spatial scale. In some modes, the emissions models are optimized subject to the constraint of a given degree of future warming, which requires iterations with the climate response embodied in them. It is simply not feasible to run the climate model and the economic emissions model in tandem: the climate model has to be greatly simplified in order to combine it with the emissions model.

While there is global mixing of emissions, meaning that mitigation policy focuses essentially on aggregate global emissions, the impacts of climate change can vary on a very local spatial scale. In the work on impacts in California for the California Energy Commission over the past decade, a spatial scale of 12 km by km was used. The time scale used was monthly, but we found that for many impacts (e.g., crop production or human health) a daily time scale would be desirable. In some cases, such as electricity demand or stream flooding, an hourly time scale would be preferable to account for extreme weather events that are likely to dominate the calculation of economic damage.

With mitigation modeled on an annual and national scale, and impacts playing out on a local and, say, daily time scale, some simplified representation of impacts is essential in order to put them on the same footing as mitigation in an integrated assessment modeling exercise.

In short, the use of simplified representations of climate change and impacts in the IAMs does not render them inappropriate for use is estimating the SCC. To the contrary, because of the constraints of computing capacity it is essential in order to be able to combine all three elements – emissions, climate change and impacts – in a unified assessment.

VI. FEDERAL INTERAGENCY WORKGROUP (IWG)

Q. How did the Federal Workgroup come about?

A. Prior to 2008, the U.S. federal government did not consistently value reductions in carbon dioxide emissions in proposed federal rules (Greenstone et al. 2011). In 2008, as the result of a lawsuit brought against the Federal Transportation Administration, United States Court of Appeals for the Ninth Circuit ruled that executive branch agencies must include the climate benefits of a significant regulatory action in federal benefit-cost analyses (BCA) to comply with Executive Order 12866. As a result of that ruling, in 2008 and 2009, the U.S. Department of

Transportation (USDOT), U.S. Environmental Protection Agency (USEPA) and U.S. Department of Energy (USDOE), began applying estimates of the SCC. The individual agencies developed separate estimates of the SCC based on their interpretation of the academic literature. Initial applications of the SCC in regulatory impact analysis ranged from $0 to $159 per metric ton of CO2 emitted (GAO, 2014). See DOC Ex. ___ at WMH-6 (Hanemann Direct)

In 2009, in part due to the inconsistent application of estimates of the SCC, the federal government convened an interagency workgroup to review and develop estimates of the SCC. The IWG was convened by the Council of Economic Advisers and the Office of Management and Budget, with participation by the Council on Environmental Quality, the National Economic Council, the Office of Energy and Climate Change, the Office of Science and Technology Policy, the Environmental Protection Agency, and the Departments of Agriculture, Commerce, Energy, Transportation, and the Treasury.

The IWG convened on a regular basis between 2009-2010 to consider public comments, explore the technical literature in relevant fields, and discuss key inputs and assumptions in order to generate SCC estimates (IWG 2010). See DOC Ex. ____ at WMH-2 (Hanemann Direct). Their stated objective was to “develop a range of SCC values using a defensible set of input assumptions that are grounded in the existing literature. In this way, key uncertainties and model differences can more transparently and consistently inform the range of IWG’s SCC estimates used in the rulemaking process” (IWG 2010).

Q. How did the IWG proceed in estimating a SCC for its 2010 report?

A. The IWG did not undertake a new climate modeling effort nor did it try to develop a new IAM. Instead, it used the current versions of the three best known and most widely cited IAMs in the literature: DICE 2007; FUND 3.5; and PAGE 2002.

Q. What did it do with the IAMs?

A. The essence of what the IWG did was to run the models side by side, and then average the results.

Before running the models, the IWG standardized the model inputs so the models had a common set of drivers. Thus, it standardized the projections of future population, income and emissions.

Before running the models, the IWG also standardized the non-CO2 radiative forcing and the climate sensitivity parameter used in the models. The latter corresponds to λ in equation (2) above, and characterizes how a doubling of the atmospheric concentration of CO2 translates into an increase in global average annual temperature. The IWG also made the value of the climate sensitivity a random variable with the same probability distribution for all three models.[33] This was done to acknowledge the scientific uncertainty that exists regarding this parameter which is the key to summarizing the response of the global climate system to increased radiative forcing from the accumulation of GHGs in the atmosphere.

Once the annual damages had been calculated, the IWG standardized the discount rate used to add up the annual damages and convert them to a present discounted value, using three alternative discount rates.

[33] I use the terms "random" stochastic" and probabilistic" interchangeably.

Q. Why did the IWG choose to standardize inputs to these models?

A. In running the models side by side it wanted to put them on a common footing to the extent possible. This is the standard practice in model inter-comparison exercises for other models.

In performing the standardization, the IWG harmonized the socio-economic drivers of emissions, the non-CO2 radiative forcing, the climate sensitivity parameter and the discount rate, but it preserved how, given the emissions, each model individually (i) projected the change in atmospheric concentration of GHGs, and (ii) evaluated the economic cost of the damage caused by the warming generated by that change in atmospheric GHG concentration.

Q. Did the standardization of inputs cause a change in model structure for any of the IAMs?

A. It necessitated a change in the structure of DICE, but not in PAGE or FUND. This is because, while PAGE and FUND are simulation models, DICE is an optimization model. The standardization made by the IWG converted DICE into a simulation model, so that it was on a common footing with the other two models. Without making the change, differences between optimization and simulation would have confounded the model comparison.

Q. What was involved in standardizing the inputs?

A. In all three models, income (production) is a determinant of GHG emissions. While income is determined outside PAGE and FUND, it is determined within DICE as part of the optimization performed by that model. Therefore, income was made external to DICE in the same manner as PAGE and FUND. The IWG used the same income projections for all three models.

The three models use slightly different population projections, in each case taken as external to the model. The IWG used a common population projection for all three models.

The three models treat non-CO2 Kyoto gasses slightly differently. This was standardized so as to place PAGE on the same footing as DICE.

These changes are summarized in Figure 4 below.

Figure 4: Standardized IAM Inputs

	Dice	DICE - IWG	Fund	Fund - IWG	Page	Page - IWG
Population	Determined **outside** the model	Determined **outside** the model	Determined **outside** the model	NC	Determined **outside** the model	NC
Income	Determined **inside** the model	Determined **outside** the model	Determined **outside** the model	NC	Determined **outside** the model	NC
Fossil & Industrial CO_2	Determined **inside** the model	Determined **outside** the model	Determined **inside** the model	NC	Determined **outside** the model	NC
Land CO_2	Determined **inside** the model	NC	Determined **outside** the model	NC	Determined **outside** the model	NC
Non-CO_2 Kyoto gasses (CH_4, N_2O, Fluorinated-gases)	Included via other radiative forcing	NC	Emissions determined **outside** the models, forcing determined **inside** the model	NC	Emissions determined **outside** the models, forcing determined **inside** the model	Included via other radiative forcing
SO_2	Included via other radiative forcing	NC	Emissions determined **outside** the models, forcing determined **inside** the model	NC	Emissions and forcing determined **inside** the model	NC
Other Radiative Forcing	Determined **inside** the model	NC	None	NC	Determined **outside** the model	NC
NC = No Change						

Source: Table based on Table 4.1 in EPRI 2014

In order to obtain a common set of projections of income, population, industrial and land CO2 emissions, non-CO2 emissions, and non-CO2 radiative forcings, the IWG turned to results presented at the Energy Modeling Forum's (EMF) 22nd model inter-comparison study (Clarke et al., 2009).[34] This model inter-

[34] Based at Stanford University, the EMF organizes structured forums for discussing important modeling issues regarding the economics of energy and climate change. It was established in 1976 and is considered the premiere forum for objective discussion within the energy/economic modeling community.

comparison exercise "engaged ten of the world's leading IAMs[35] to focus on the combined implications of three factors integral to international climate negotiations: (1) the long-term climate-related target, expressed in this study in terms of the CO2-equivalent concentration associated with the GHGs regulated under the Kyoto Protocol, (2) whether or not this target can be temporarily exceeded prior to 2100 ("overshoot") allowing for greater near-term flexibility, and (3) the nature of international participation in emissions mitigation" (op. cit., p. S64). The EMF-22 is a highly authoritative source for the required inputs. The IWG used five of the model projections presented at the EMF forum. The items taken from EMF 22 and used by the IWG as standardized inputs to DICE, PAGE and FUND are listed in Figure 5, patterned after Table 4.2 in EPRI (2014). See DOC Ex. ____ at WMH-5 (Hanemann Direct).

[35] In terms of my definition, these are IAMs of the second type – they lack a damage function.

Figure 5: Energy Modeling Forum inputs

	Dice	Fund	Page
GDP	Global levels	Regional per capita income growth	Regional growth rates
Population	Global levels	Regional population growth	Regional growth rates
Fossil & Industrial CO_2	Global emissions	Derived regional emissions based on regional per capita income and population growth and FUND emission coefficients	Regional emissions
Land CO_2	Global emissions	Derived regional emissions based on regional per capita income and population growth and FUND emission coefficients	Regional emissions
Non-CO_2 Emissions:	CH_4, N_20, & fluorinated gas forcing*	CH_4, N_2O,& SF_6 emissions	CH_4, N_2O, & fluorinated gas forcing*
Other Non-CO_2 **	Aerosols and residual forcing	Global SO_2 emissions	Regional SO_2 emissions & other forcing

* Derived from EMF – 22 reported total Koto radiative forcing and computed CO2 radiative forcing

** Model specific inclusion and implementation of non-Kyoto emissions and forcing. Non-Kyoto missions and forcing not reported in EMF-22

DICE, PAGE and FUND were each run five times using the five common sets of EMF inputs.

Q. What was involved in making the climate sensitivity uncertain?

A. The value of the climate sensitivity was made the same across all three models in each model run. To accommodate the scientific uncertainty regarding this key parameter, the IWG incorporated it in the three IAMs not as a single fixed value but as a random variable. The IWG used the Roe and Baker (2007) probability distribution for the value of the climate sensitivity. This distribution is often used in the scientific literature. It was selected by the IWG after consulting with several lead authors of the relevant chapter in the 2007 IPCC Fourth Assessment Report, and after considering three other alternative distributions. The Roe and Baker distribution was chosen because it was the only one to be based on a theoretical understanding of the climate system's response to increased GHG concentrations, and it better matches the IPCC's expressed judgment regarding the distribution of climate sensitivity values.

To implement this choice of probability distribution, the IWG used a numerical simulation procedure, randomly drawing 10,000 possible values of the climate sensitivity in a manner that conformed to the Roe and Baker distribution. Each value drawn was then applied to all three IAM models in common.

While DICE itself has no random parameters, PAGE and FUND both do contain some random components with particular probability distributions for certain model parameters – 10 random parameters in the case of PAGE, and 11 random parameters in the case of FUND. The IWG preserved the existing random components in PAGE and FUND, while adding the random component associated with the climate sensitivity parameter. Thus, in the case of PAGE and FUND, the IWG ran 10,000 replications of those models which also included draws from the probability distributions of the random parameters native to them.

Q. How did the IWG discount the damages that go into the SCC?

A. With five socioeconomic/emissions scenarios and 10,000 replications of the random parameters, for each model there were 50,000 sets of output, containing estimates of the annual damages over the period 2010 through 2100 due to warming induced by an emissions scenario.

The IWG then faced the question of how to aggregate the damages over that span of time. These damages are conventionally expressed as a discounted present value, with each year's damages discounted back to 2010 and summed.

Because one is dealing with an unusually long span of time, the discount rate used for this purpose has a huge impact on the result. The present value in 2010 of $100 of damage occurring in 2100 is just $10.83 using an annual discount rate of 2.5%. Using an annual discount rate of 5%, it is $1.24. A lower discount rate yields a larger discounted present value, while a higher discount rate yields a smaller discounted present value.[36] The choice of discount rate fundamentally controls the weight being placed on outcomes that befall future generations, either giving them some consideration in today's assessment or essentially removing them from consideration.

[36] For example, a discount rate of 1.4% yields a present value of $28.61 while using a discount rate of 5.5% yields a present value of $0.81.

The IWG chose to use three alternative values for the annual discount rate: 2.5%, 3% and 5%. This was a policy judgment by the IWG, which judged that those three rates "reflect reasonable judgments under both descriptive and prescriptive approaches" to determining an appropriate rate of discount (IWG, 2010, p.23). See DOC Ex. ____ at WMH-2 (Hanemann Direct).

With each value of the discount rate, and each starting year, the IWG calculated the discounted present value of damages, from that year forward, associated with the given emissions scenario and the given draw of values for the random parameters. For each starting year, each IAM, and each value of the discount rate, the 50,000 (= 5*10,000) estimates of the discounted present value of damages constitute 50,000 draws from the underlying probability distribution governing the present value of damages, from that year forward. For the purpose of describing what come next, I will refer to these as "baseline discounted present values"

Q. How was the SCC then calculated?

A. To calculate the SCC associated with a unit increment of emissions in any given year, the IWG introduced an additional unit pulse of emissions in that particular year (and only that year), and then repeated the calculations listed above.

To illustrate the procedure, suppose the SCC was being calculated for 2020. From the procedure given above, for each IAM and each discount rate there would be 50,000 baseline discounted present values of damages occurring from 2020 forward and discounted back to 2020. Then, with the model results following the one-time, one-unit pulse of emissions in 2020, there would be another 50,000 `discounted present values of damages occurring from 2020 forwards and discounted back to 2020. Subtracting the baseline discounted present value of damages from 2020 forward from the newly computed present value of damages with the 2020 one-time increment provides an estimate of the social cost of carbon in 2020. This measures the increment in the discounted present value of damages from 2020 forwards as the result of a marginal increase in emissions in 2020, using the particular baseline socioeconomic/emissions scenario and the particular draw of values for the random parameters. For each choice of discount rate and each IAM, there are 50,000 estimates of the value of the SCC in 2020. Pooling the results of the three IAMS yields 150,000 estimates of the value of the SCC in 2020 for each discount rate.

The IWG calculated the resulting estimates of the SCC for 2020 as the average value across the 150,000 replications of the three models combined, for each separate value of the discount rate (2.5%, 3% and 5%). In addition, for the 3% discount rate, it presented the upper 95th-percentile of the 150,000 replications (the SCC value that was exceeded in only 5% of the replications).

The SCC values were calculated in this manner not only for 2020 but also for 2010, 2020, 2030, 2040, and 2050 (IWG 2013, p. 12). See DOC Ex. ____ at WMH-3 (Hanemann Direct). The SCC values for years in between were calculated with a straight line projection between the years for which the SCC had been calculated.[37]

[37] That is to say, it used a straight line interpolation between the SCC values for 2010 and 2015; between the values for 2015 and 2020; etc.

Q. Why does the SCC increase over time?

A. The IWG's estimate of the SCC increases over time because, over time, there is a greater accumulation of CO2 in the atmosphere, and higher future levels of population, global output, and emissions, and thus a higher total willingness to pay to avoid climate change damages. As stated in the 2010 TSD (p. 28): "*The SCC increases over time because future emissions are expected to produce larger incremental damages as physical and economic systems become more stressed in response to greater climatic change*."

VII. THE IWG'S 2013 UPDATE

Q. What changed in the IWG's 2013 report relative to its 2010 report?

A. In 2009, while the IWG was conducting the analysis for its 2010 report, an updated version of PAGE was released, PAGE 2009, replacing PAGE 2002, the version used by the IWG for its 2010 report. The update was intended to take account of the latest scientific information primarily in the IPCC's Fourth Assessment Report.

In 2010, when the IWG report was released, an updated versions of DICE was released, DICE 2010, replacing DICE 2007, the version used by the IWG for its 2010 report. The update, similarly, incorporated information from the Fourth Assessment Report which was partially available when DICE 2007 was being finalized.

Around this time, updated versions of FUND also became available. The version used by the IWG for its 2010 report is FUND 3.5. The version used in the 2013 report is FUND 3.8.[38]

[38] The technical documentation for version 3.5 posted on the FUND web site is dated May 17, 2010. The posted documentation for version 3.8 is dated August 7, 2014. I assume that those versions were made available to IWG some time prior to those posting dates.

Compared to the 2010 IWG, the changes in the 2013 report reflect updates to the individual models by their developers rather than any changes in the IWG's approach or methodology.

Q. What were changes in the versions of the IAMs used in 2013?

A. According to an analysis subsequently conducted by the Electric Power Research Institute, the electricity industry's research arm, "For DICE, the carbon cycle was revised with weaker ocean update. For FUND, the transient temperature response was unchanged and indirect radiative forcing from methane was added. For PAGE, the carbon cycle/ocean carbon uptake was revised, as was scaling to regional temperatures. For DICE and FUND, the climate modeling revisions, all else equal, resulted in higher SCC estimates. For PAGE, it is unclear."[39] The following table, taken from the EPRI report, summarizes the changes made in the three IAMs used by the IWG in 2013.

[39] EPRI (2014, p. 5-7).

Figure 6: Changes to IAMs and their Implications

Model	Modification	SCC Implication	Type
DICE	Carbon cycle parameters – weaker ocean uptake	+	Revision
	Sea level dynamics and valuation – explicit modeling	-	Change
FUND	Space heating	+	Fix
	Sea level rise and land loss	?	Fix
	Transient temperature response	+	Change
	Methane – account for additional radiative forcing effects	+	New
PAGE	Sea level rise	?	Change
	Revised damage function to account for saturation – modified GDP loss function	?	Fix
	Regional scaling factors	?	Revision
	Probability of discontinuity	+	Revision
	Adaptation	+	Revision
	Change in land/ocean carbon update	?	Revision
	Regional temperature change	?	Revision
A plus sign implies an increase in the model's SCC relative to that model's 2010 values.			
Revision types: Revision = updated; Change = formulation change; Fix = issue fixed; New = new feature.			
Source: Based on Table 2.4 in EPRI (2014)			

Q. Did the IWG alter its methodology in the 2013 report?

A. No. Aside from differences due to updating of the IAM versions by the model developers, the methodology applied by the IWG to the IAMs remained the same as in the 2010 report. (i) The overall experimental design was unchanged. (ii) The comparison of the three IAMs was not changed. (iii) The five socioeconomic/emission projections were unchanged. (iv) The methodology for extending the socioeconomic/emissions assumptions after 2100 was unchanged. (v) The probability distribution used for the climate sensitivity parameter was unchanged. (vi) The types of uncertainties considered and their specifications, both standardized and model-specific, were unchanged (except as those were affected by the updates made by the model developer. (vii) The treatment of discounting was unchanged.

Q. What is the most recent IWG estimate of the SCC?

The most recent estimate of the SCC is the IWG's 2013 estimate in its 2013 Report (Table A1). The IWG presents annual SCC estimates through 2050 for the three discount rates and the 95th percentile of the 3% discount rate. These estimates are presented in 2007 dollars. The IWG recommends adjusting these numbers to current year dollars using the GDP deflator index.

Figure 7: Annual SCC Values: 2010-2050 (2007$/metric ton CO2)

Discount Rate	5.0%	3.0%	2.5%	3.0%
Year	Avg	Avg	Avg	95th
2010	11	32	51	89
2011	11	33	52	93
2012	11	34	54	97
2013	11	35	55	101
2014	11	36	56	105
2015	11	37	57	109
2016	12	38	59	112
2017	12	39	60	116
2018	12	40	61	120
2019	12	42	62	124
2020	12	43	64	128
2021	12	43	65	131
2022	13	44	66	134
2023	13	45	67	137
2024	14	46	68	140
2025	14	47	69	143
2026	15	48	70	146
2027	15	49	71	149
2028	15	50	72	152
2029	16	51	73	155
2030	16	52	75	159
2031	17	52	76	162
2032	17	53	77	165
2033	18	54	78	168
2034	18	55	79	172
2035	19	56	80	175
2036	19	57	81	178
2037	20	58	83	181
2038	20	59	84	185
2039	21	60	85	188
2040	21	61	86	191
2041	22	62	87	194
2042	22	63	88	197
2043	23	64	89	200
2044	23	65	90	203
2045	24	66	92	206
2046	24	67	93	209
2047	25	68	94	211
2048	25	69	95	214
2049	26	70	96	217
2050	26	71	97	220

Q. What caused the difference in the SCC estimates between the 2010 report and the 2013 report?

A. The difference is due to updates by the modelers of the three IAMs used by the IWG. There was no change in the methodology used by the IWG. In Figure 6, I show the changes in the IAMs and the implication of those changes on the social cost of carbon.

Q. Could the IWG's 2013 estimate of the SCC be updated in the future?

A. Yes. The existing IWG's SCC estimates can be updated annually using the GDP deflator index as recommended by the IWG. Furthermore, as newer versions of the IAMs become available what was done by the IWG could be repeated.[40] As the federal government updated their estimates of the SCC, those estimates would be available for use by the State of Minnesota in determining the environmental externalities associated with CO2 emissions.

VIII. USE OF THE FEDERAL SCC ESTIMATE

Q. How does the Federal government use the SCC?

A. Federal agencies use the social cost of carbon (SCC) in regulatory impact analyses (RIA) to evaluate the benefits and costs of proposed rulemakings in a manner that accounts for the impact of GHG emissions. Some of these rulemakings have directly targeted CO2 emissions, such as the car and truck standards, whereas others have set standards for conventional or toxic pollutants that indirectly affect CO2 emissions, such as the Mercury and Air Toxics Standard (MATS).

[40] See page 33 of 2010 IWG TSD.

Apart from RIA applications, the federal government has used the IWG's SCC in other analyses. For example, the US DOT requires grant applicants for their Transportation Investment Generating Economic Recovery (TIGER) program to use the IWG's SCC in documenting the benefits of proposed projects. The U.S. DOT Federal Railroad Administration requires applicants for high-speed rail grants to value reduced CO2 emissions using the IWG's SCC. In a planning process somewhat analogous to Integrated Resource Planning efforts, the Federal Aviation Administration Environmental Design and Portfolio Management Tools incorporate estimates of reduced CO2 from alternative airport configurations, flight operations approaching and leaving airports, flight routing and trajectories, and fuel composition emissions using the IWG's SCC.

Q. Have other states or agencies adopted using the IWG's SCC estimates, and if so which ones?

A. Yes. The IWG's SCC estimates have also been used in analysis and discussions outside of the United States. For example, Canada used a social cost of carbon based on the IWG's SCC in their regulatory impact analysis for the 2013 Heavy-duty Vehicle and Engine Greenhouse Gas Emission Regulations[41] In addition, on April 22, 2014, Montgomery County, Maryland, revised it County Code 18A on environmental sustainability to require the SCC to be incorporated into return on investment for energy efficiency and sustainability decisions.

[41] http://canadagazette.gc.ca/rp-pr/p2/2013/2013-03-13/html/sor-dors24-eng.html

Q. How do other entities use estimates of the SCC.

A. The use of an estimate of the SCC is currently a component of numerous Integrated Resource Plans across the nation. For example, Puget Sound Energy, Portland General Electric, Tennessee Valley Authority, and NV Energy are among the many utilities incorporating the IWG's SCC estimates in their recent planning documents.

Through their annual disclosure process, in 2013, the Carbon Disclosure Project (CDP) found that 29 companies said they use an internal price of carbon for planning purposes.[42] As stated by CDP:

> *"ExxonMobil is assuming a cost of $60 per metric ton by 2030. BP currently uses $40 per metric ton. Royal Dutch Shell uses a price of $40 per ton. Xcel Energy cites use of $20 per ton. Devon Energy established a carbon price of $15 per ton of CO2 to account for the cost or benefits associated with any change in GHG emissions resulting from proposed projects. Ameren uses $30 per ton in future planning (2025) in its power generation and distributed energy businesses and includes that price in its mandatory Integrated Resource Plan for 2011-2014"*

The IWG's SCC estimates have also been used in analysis and discussions outside of the United States. For example, Canada used a social cost of carbon based on the IWG's SCC in their regulatory impact analysis for the 2013 Heavy-duty Vehicle and Engine Greenhouse Gas Emission Regulations.[43]

https://energy.stanford.edu/events/clearing-air-ensuring-long-term-value-shell-addressing-climate-change-and-pricing-carbon-0 16:52
01/12/16 Angus Gillespie, VP CO2 for Shell

[42] These companies include Microsoft, General Electric, Walt Disney, ConAgra Foods, Wells Fargo, DuPont, Duke Energy, Dow Chemical, Bank of America, Google, Delta Air Lines, Walmart, and PG&E, Royal Dutch Shell, Xcel Energy, Devon Energy, BP, and Exxon Mobil Corporation.

[43] http://canadagazette.gc.ca/rp-pr/p2/2013/2013-03-13/html/sor-dors24-eng.html

IX. ENVIRONMENTAL EXTERNALITIES IN THE STATE OF MN

Q. What is the requirement of the State of Minnesota to use estimates of environmental externalities?

A. On August 1, 1993, the Laws of Minnesota 1993, Chapter 356, Section 3 became effective. This law, codified as Minn. Stat. § 216B.2422, subd. 3 requires that the Commission "to the extent practicable, quantify and establish a range of environmental costs associated with each method of electricity generation."

Q. How does the State of Minnesota use estimates of environmental externalities?

A. Minnesota State law requires each electricity utility to use the environmental externality values in conjunction with other factors when evaluating resource options in all proceedings before the Commission. The most common application of environmental externalities is in electric utility Integrated Resource Planning (IRP). However, the State has also applied the estimates of environmental externalities to other analyses such as in large energy facility certificates of need and in the determination of the "value of solar." In this later instance, the state used the IWG's SCC as one component in the methodology used to determine the appropriate rate that should be paid to distributed solar generation.

X. ASSESSMENT OF THE IWG METHODOLOGY

Q. Was what the IWG did to estimate the SCC unusual?

A. The IWG ran three well-known models side by side, which had never been done before.

The reason this had never been done before is that two of the models were – and still are – not readily available for use by anyone other than the model-builders and their collaborators.

DICE is readily available. The model code and full instructions for running it have been posted on the web since the time of DICE 1993. As a result, many academic papers have been published over the past 10-15 years by other researchers who use DICE, make changes to it, and/or run probabilistic simulations in the same sort of manner as the IWG. The same is not true for PAGE and FUND.

The IWG was the first entity that had independent access to all three models. Since then, as far as I know, the Electric Power Research Institute (EPRI), the electricity industry's research arm, is the only other entity that has had independent access to all three models.

Q. Is it surprising that DICE, PAGE and FUND are different in how they represent the carbon cycle, the climate system, and the damages associated with an increase in the global average annual temperature?

A. In my opinion, it is not surprising that the three models are different in this regard. The models originated around the same time, in the 1990s, in similar circumstances. They were developed by economists with a similar purpose in mind. But they were developed by three separate researchers, and they embody each researcher's ideas as to how one should build a model. To my knowledge, the modelers have never collaborated or participated in a model inter-comparison exercise. Indeed, prior to the IWG's study, there has not been any model inter-comparison exercise like that performed quite regularly by the EMF on what I am calling IAMs of the second type.[44] The IWG study stands out, therefore, and represents an important development in this literature.

Q. Was it appropriate for the IWG to use these three models – DICE, PAGE and FUND?

A. In my opinion it was appropriate for the IWG to use these three models. They are well known and have been widely cited in the economic literature on climate change and mitigation policy for the last two decades. In fact, to most people familiar with this literature, it would have been surprising had the IWG *not* used DICE, PAGE and FUND.

Q. Was it appropriate for the IWG to standardize the inputs that are drivers of climate change?

A. In my opinion, it was appropriate for the IWG to standardize the socioeconomic/emission inputs used in DICE, PAGE and FUND as drivers of climate change in order to put them on a common footing to the extent possible. This made them more comparable. Standardizing the external model inputs is the conventional practice in model inter-comparison exercises.

Q. Was it appropriate for the IWG to use the EMF 22 exercise as the source of data for these standardized inputs?

A. In my opinion, it was appropriate for the IWG to draw the standardized values of the socioeconomic/emissions inputs from the EMF-22 model inter-comparison exercise,

[44] That is to say, models which span boxes 1-5 in the Figure presented in my response #25, but omit boxes 6 and 7.

which had just been completed prior to the IWG ‘s study. The EMF model inter-comparison exercises are seen as authoritative in the economic literature on climate change and mitigation policy.

Q. Was it appropriate for the IWG to change the structure of DICE into a simulation model?

A. In my opinion, it was appropriate for the IWG to change the structure of DICE to make it a simulation model rather than an optimization model. This change was required in order to standardize the income and emission inputs into DICE and to render it more directly comparable with the other two IAMs used by the IWG. It was also required in order to standardize the discount rate across the three models.

Q. Was it appropriate for the IWG to standardize the non-CO2 radiative forcing?

A. In my opinion, it was appropriate for the IWG to standardize the non-CO2 radiative forcing across the three models. Non-CO2 emissions constitute a relatively small part of total GHGs. By harmonizing their treatment, this made the models more readily comparable.

Q. Was it appropriate for the IWG to standardize the climate sensitivity and make it a random variable?

A. In my opinion, it was appropriate for the IWG both to standardize the climate sensitivity parameter and to make it a random variable with the same probability distribution across all three models.

Making the climate sensitivity parameter a random parameter has been done before in the literature and is not unusual or novel.

Q. Was it appropriate for the IWG to use the Roe and Baker distribution for the climate sensitivity?

A. In my opinion, it was appropriate for the IWG to use the Roe and Baker distribution as the common probability distribution of the climate sensitivity. This probability distribution is based on a theoretical understanding of the climate system's response to increased radiative forcing and it is widely cited in the literature.

Q. Was it appropriate for the IWG to standardize the discount rate used for aggregating annual damages into a discounted present value?

A. In my opinion, it was appropriate for the IWG to employ a common discount rate across all three models when aggregating the annual damages projected by the models into a discounted present value. Without doing this, it would have been pointless to make a comparison of SCC estimates across the models.

Q. Was it appropriate for the IWG to use 2.5%, 3% and 5% as the common values of the discount rate?

A. The three values chosen by the IWG and the 3% value chosen by the IWG for the central estimate are policy judgments by the IWG. In my opinion, it was appropriate for the IWG to use these numerical values. They are consistent with the values used in the existing literature on the economics of climate change and of GHG mitigation.

Another major study, the Stern (2006) Review, conducted for the UK Government, used a discount rate of 1.4%. For DICE, Nordhaus uses 5.5%. I am not at this time aware of values higher than 5.5% or lower than 1.4% being used in the existing literature on the economics of climate change.

Q. Were there other modifications for the purposes of model comparisons that the IWG could have made to these models for its 2010 report?

A. One thing that the IWG did not do was to recode the three models in a common programming language. It used each of the three models in its native code, while standardizing elements of the model structure and harmonizing the model inputs. Subsequently, EPRI, the electricity industry's research arm, recoded all three models in a common programming language (EPRI, 2014). My understanding is that this was a rather arduous and time-consuming task. I doubt that the IWG would have had the time to do this when conducting its studies in 2010 and 2013.

Recoding the models in a common programming language has now made it possible to compare the individual model components – corresponding to the boxes in the Figure in my response #24 – in more detail than has ever been done before. The analysis by EPRI (2014) highlights differences that exist in the modeling approaches. As EPRI (2014) notes, the recoding of the models in a common programming language would make it possible to "mix and match" model components across the three models. The recoding of the models in a common programming language makes it possible to compute estimates of the SCC across the three models.

https://www.edockets.state.mn.us/EFiling/edockets/searchDocuments.do?method=showPoup&documentId={E3792AC3-A5AB-4208-931C-B8EB7D85A64F}&documentTitle=20156-111429-03
http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=3002004657 links to full report
pp.114 offers comparisons
"A number of insights leap out. First, net benefits in terms of increased agricultural productivity due to CO2 fertilization and reduced heating demand (i.e., avoided energy) are prominent in FUND, and dominate FUND's aggregate results discussed previously. **Until warming reaches about 2.5°C after mid-century, benefits from low levels of warming in agriculture and heating outweigh the damages in other sectors."**

Q. Were there any other IAM models that the IWG could have used?

A: No, not of the type necessary. Earlier in this testimony, I explained the distinction between two types of integrated assessment models. One type of IAM contains a damage function component that translates increases in global average temperature to impacts on human wellbeing, expressed in monetary terms as an equivalent reduction in GNP. The second type – which is more common in the literature – tracks the chain of causation from economic activity to emission of GHGs to their accumulation in the atmosphere to increased radiative forcing and to changes in global average temperature, but does not then trace the link from changes in climate (global temperature) to economic activity and human wellbeing.

As already noted, the second type of model does not produce an estimate of the external cost, i.e., the social cost of carbon. In a policy analysis, the second type of model is typically used to determine the optimal pattern of abatement activities (mitigation) that would be required to meet a pre-set degree of global warming – for example, the pattern that minimizes the cost of abatement while meeting the given target degree of warming. This type of model typically has an extensive representation of the different sources of energy used in the economy and how they are used. This is elaborated in great detail compared to the highly simplified representation in the first type of IAM such as DICE, PAGE and FUND.

At the time the IWG was producing its 2010 report, to my knowledge, only one IAM of the second type had a representation of damages, the MERGE model (Manne and Richels,1995, 2005). That version of MERGE allowed for market and non-market damages from an increase in global temperature.

Q. Could MERGE be considered a legitimate alternative to DICE, PAGE, and FUND in this type of analysis?

A. Very little analysis appears to have gone into the formulation of market and non-market damage functions in MERGE. Thus, I do not believe MERGE can provide an adequate or reasonable representation of damages.

Q. Are there any other alternatives to DICE, PAGE, and FUND?

A. With regard to models of the first type like DICE, PAGE and FUND, there were a handful of possible alternatives available to the IWG.

Two are spinoffs of DICE.

ENTICE (Popp, 2004) and ENTICE-BR (Popp, 2006) are modifications of DICE 2000 that add endogenous links between energy innovation and climate policy. ENTICE-BR adds a backstop energy technology. Since those were out of date relative to the version of DICE used by the IWG, I do not think they would have been reasonable to use.

AD-DICE (de Bruin et al., 2009) also modifies DICE 2000 by explicitly including adaptation as a separate activity. This, too, was out of date relative to the version of DICE used by the IWG and would not have been reasonable to use.

A different model is WITCH (World Induced Technical Change Hybrid Model) developed by an Italian team of researchers at the FEEM research center in Venice (Bosetti et al., 2006; Bosello et al., 2010; de Cian et al., 2012). This is a hybrid model because it is an adaptation of an existing IAM of the second type that had been developed at FEEM. For WITCH 2006, the researchers added to the existing model, which had a disaggregated representation of the global energy system, an accounting of CO_2 emissions together with the simplified representation in DICE 2000 of the carbon cycle, the change in radiative forcings, the change in global average temperature, and the aggregate damages resulting therefrom. In effect, this changed boxes 1 and 2 of DICE 2000, but left the rest the same. For WITCH 2008, the researchers added non-CO_2 emissions, using the radiative forcing from MERGE. Running WITCH side-by-side with DICE, PAGE or FUND would have raised some issues of comparability because the modeling of economic activity was far more disaggregated in WITCH. As noted above, the IWG placed the projection of emissions on a common footing across the IAMs it used by taking emission scenarios from MERGE and other models. This would have supplanted the portion of WITCH that was different from DICE 2000. Therefore, little would have been served by running WITCH alongside DICE 2007 and the other two models. Thus, it was reasonable for the IWG not to have used WITCH.

The other model of which I am aware is ENVISAGE (Environmental Impact and Sustainability Applied General Equilibrium Model). This was developed by economists at the World Bank. (van der Mensbrugghe 2008, 2010a, b; van der Mensbrugghe and Roson, 2010, 2012; Galeotti and Roson, 2012). It, too, is a hybrid model growing out of an existing and highly elaborate computable model of the economies of countries around the world. In ENVISAGE 2008, as with WITCH, the climate module of DICE 2000 was grafted on to that existing model to form an IAM. In ENVISAGE 2010, the climate module of MERGE was used instead. For damages, the researchers developed damage functions for sea level rise, agricultural productivity, water availability, labor productivity, tourism, human health and energy demand. I do not know if this version of ENVISAGE would have been available to the IWG at the time it was working on its 2010 report. Had it been available, it would have raised issues of comparability with DICE, PAGE and FUND because of the disparity of detail in the representation of economic activity and the emission of GHGs.

XI. OPINION ON THE USE OF THE IWG 2013 ESTIMATE OF THE SCC BY THE MPUC

Q. In your opinion, was it reasonable to use the three IAMs employed by the IWG?

A. Yes, it was reasonable to use DICE, PAGE and FUND. They have received by far the most attention in the literature. They are widely known and respected. Their estimates of the SCC are commonly cited, including in the IPCC's Fourth Assessment Report.

Q. Was it reasonable to average the results obtained from the three models?

A. Averaging implies weighting those models equally. This was a policy decision made by the IWG.

I am not aware of any suggestions in the existing economic literature on this topic that would provide a basis for doing something different. What was done was reasonable.

Q. Was it reasonable to use the three discount rates employed by the IWG?

A. Yes, the range of values used for the discount rate – 2.5%, 3% and 5% – reasonably spans the values found in the existing peer-reviewed literature on the economics of climate change which range from 1.4% to 5.5%.

Q. Would it be reasonable to use the IWG's 2010 estimate of the SCC instead of its 2013 estimate?

A. In my opinion, the answer is no. the 2010 estimate of the SCC differs from the 2013 only because it uses what are outdated versions of DICE, PAGE and FUND. The updated versions of the IAMs used for the IWG's 2013 study took account of more recent scientific information, including information from the IPCC Fourth Assessment report. It would be unreasonable to base a current estimate of the SCC on earlier versions of the IAMs, just as it would be unreasonable to base a scientific assessment of climate change on an old IPCC Assessment Report rather than the current Assessment Report.

Q. Is the 2013 IWG estimate of the SCC the best available measure to determine the environmental cost of CO2?

A. Yes. To my knowledge, at the present time, this is the best available estimate of the environmental cost of an additional ton of CO2 emission.

Q. Is the IWG 2013 estimate of the SCC reasonable for use by MPUC?

A. Yes. For the reasons I have specified throughout my testimony I consider the use of the SCC by the MPUC reasonable.