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The economics of mitigating climate change: What can we know?

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ABSTRACT

The long-term economics of mitigating climate change over the long run has played a high profile role in the most important analyses of climate change in the last decade, namely the Stern Report and the IPCC's Fourth Assessment. However, the various kinds of uncertainties that affect these economic results raise serious questions about whether or not the net costs and benefits of mitigating climate change over periods as long as 50 to 100 years can be known to such a level of accuracy that they should be reported to policymakers and the public. This paper provides a detailed analysis of the derivation of these estimates of the long-term economic costs and benefits of mitigation. It particularly focuses on the role of technological change, especially for energy efficiency technologies, in making the net economic results of mitigating climate change unknowable over the long run.

Because of these serious technical problems, policymakers should not base climate change mitigation policy on the estimated net economic impacts computed by integrated assessment models. Rather, mitigation policies must be forcefully implemented anyway given the actual physical climate change crisis, in spite of the many uncertainties involved in trying to predict the net economics of doing so.

1. Introduction

Over the past 10 years, dozens of articles, reports, and papers have addressed the economics of mitigating climate change. As one might expect, both the quantitative results and the computational models that produced them have changed somewhat, though not dramatically, over time. During that decade, the negative impacts of climate change on the physical world have become more frequent, and most proposed climate mitigation targets have become more stringent. Today, the generally accepted temperature target, to which most governments agree, would limit the increase in temperature due to greenhouse gas emissions derived from human-related activities to 2 °C, relative to pre-industrial times, by 2100. As years pass, the time remaining to meet that target decreases. Furthermore, the costs of mitigating climate change will tend to increase if mitigation is delayed and if future energy technology costs and performance characteristics follow current forecasts, although forecasts of some of these important parameters have changed significantly over the last 10 years. Of course, the actual prices of the fossil fuels that climate change mitigation would displace have also changed in this time, even more than the long-run forecasts of future fuel prices, raising interesting questions about the current forecasts.

The best and most recent comprehensive reviews of the economics of mitigating climate change appeared in the Working Group III report of the Fourth Climate Assessment of the Intergovernmental Panel on Climate Change (IPCC) and the 6, sponsored by the British government [1,2]. Since both reports were published in 2007, the underlying research would have been undertaken prior to or during 2006, making both studies somewhat out-of-date already. However, because both are still cited as authoritative, we will focus

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on them here. The economic modeling efforts for analyzing climate change mitigation for the upcoming Fifth IPCC Climate Assessment, due in spring 2014, are basically now complete, though many of the new results have yet to be published. It is, therefore, particularly timely to re-assess the state of the art in estimating the net benefits or costs of mitigating climate change over the next 100 years and, moreover, to discuss the scientific rigor and the political relevance of these studies.

One of the key aspects of these prominent reviews was their discussions of the many uncertainties inherent in estimating the net benefits or costs of mitigating climate change by 2100. In addition, several inter-model comparison exercises for IAMs have been carried out since 2006 to try to understand better the basis for the different economic results for mitigation that different computer models and research teams have produced [3,4]. Barker [5] and Kuik et al. [6], as well as the Energy Modeling Forum #25 report, discussed much of the research into how to achieve fairly strict global climate mitigation scenarios, such as the 2 °C target [5–7]. But the most comprehensive statistical analysis of the net benefit/cost results for climate change mitigation of which we are aware appeared in Barker [8], on which both the Stern Review and the Working Group III report heavily relied [8,2,1]. Thus, it is important to review carefully the Barker [8] meta-analysis of the economic results for a very large number of mitigation scenarios. These results were also discussed at some length relative to the key issue of uncertainty in Pearce et al. [12].

At this point in the evolution of trying to estimate the net benefits or costs of mitigating human-induced climate change through 2100, we should ask how our understanding of these estimates has evolved since 2006, if it has, and what we now really know. This question is particularly important in considering the stricter mitigation scenarios that are consistent with limiting the temperature increase to less than 2 °C over this century because most governments have committed to achieving that goal, at least formally. However, most have not, in fact, done much to achieve it. This paper, therefore, will primarily address three questions:

1 Has there been much, or any, progress made in producing reasonably accurate net benefit or cost estimates for mitigating climate change over the next century since 2006, or even before 2006?
2 Is progress even theoretically possible, especially in light of likely changes in the cost and operating parameters of both supply and demand-side technologies?
3 What should we substitute for economic forecasts to lay a more profound basis for decision-making?

The analytical context for addressing these vexing questions is the large number of fundamental uncertainties inherent in attempting to make such projections. Many of these uncertainties reflect what are often called deep or radical uncertainties, which further research today cannot resolve for the long-term future [9,10]. As is the case in most complex systems, forecasts are highly uncertain in a scientific sense after a fairly short initial period, just as daily weather forecasts are unknowable for a month, or even less. However, most integrated assessment models used to analyze the economics of climate change have hundreds of input parameters, each of which is highly uncertain in the long run. Thus, this review of the past attempts to determine the economics of climate change mitigation over the long run leads directly to the hypothesis that the net benefits or costs are *unknowable* because of the many deep uncertainties involved [11,12]. When preparing decision-making, we must also take into consideration the fact that mitigation scenarios are not small perturbations on easily forecastable baseline scenarios, where linear "first order" differences would dominate. Rather, mitigation scenarios represent major transformations of the economy relative to baseline scenarios and, thus, represent large and highly non-linear changes that will strongly impact the development of new energy technologies on both the supply and demand sides, as well as other relevant technologies that offset greenhouse gas emissions worldwide. However, falsely claiming to know that a 100-year analysis of the economics of mitigating climate change shows "net costs" of X percent of gross domestic product (GDP), plus or minus some error bar, only serves to scare off politicians and other policymakers from doing much to mitigate climate change. Almost always, "net costs" are reported, not net economic benefits. Consequently, decisions for climate change are not popular, and politicians try to avoid this topic in election campaigns. Further, such a claim would serve no scientific purpose since we cannot know if it is true. Regardless, committing to embarking on a vigorous campaign to mitigate climate change is fundamentally a moral issue, not a long-run economic issue. Claiming that this imperative can be based on projections working with incremental changes undervalues the importance of radical changes. The global mitigation pathway pursued at any specific time can and should be adjusted every few years as we learn more about the short- to medium-term science, technology, and economics. Businesses use just such a procedure when applying the technique of scenario-planning.

In light of this conclusion, we will ask what changes, if any, should be made in how this research is presented in the upcoming Fifth IPCC Climate Assessment, and we will discuss the policy implications that could result from misunderstanding this research. Many other types of results, not just net costs in the long-run, are often reported in the climate mitigation literature with much greater certainty than is scientifically justified. Such results include the mix of energy supplies optimal by 2050 or 2100 and the net costs of not including new nuclear plants or CCS facilities in the mix, among others. Our analysis concludes that we should stop trying to assess the long-run economics of mitigating climate change since that is unknowable. Instead, modeling work on the economics of mitigating climate change should focus on the details of *how* to mitigate climate change, beginning now, in a way that minimizes costs and maximizes the well-being of all people on our fragile planet over the short to medium term and, thus, how to create relevant normative scenarios. Such models will help to backcast from the desired normative scenario to the present and describe the pathways to this desired future.

2. Three key aspects of integrated assessment models

Since almost all the recent assessments of the economics of climate change have relied on "integrated assessment models" (IAMs), this paper will focus on enhancing our understanding of how those models typically calculate the net benefits and

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costs of mitigation over the next century. At the most general level, IAMs attempt to couple a representation of the world's economic systems to its energy- and land-use systems for about a dozen regions of the world in order to calculate how greenhouse gas emissions are likely to change as the magnitude and structure of the economy changes. The models then couple these projections of greenhouse gas emissions into the atmosphere, biomass, and oceans to simple climate change assessment models that yield likely temperature increases for any given future year.

Of course, other review articles have previously covered some of these topics, but relatively few *inter-model comparisons* at either the theoretical or the empirical level have appeared in the climate change literature. Barker [8] reviews the history of much of the inter-IAM comparison literature, and Edenhofer et al. [3] compare aspects of five "global energy–environment–economy models" [8,3]. In addition, Professor Stephen DeCanio's book *Economic Models of Climate Change* (2003) addresses a variety of issues, especially the economic theories that underlie the equations in the macro-economic modules [13]. Since this book does a fairly complete job of reviewing the theoretical validity of the macro-economic modules all IAMs contain, we will not address those issues pertaining to the second point above any further.[1] However, we will address the question of whether IAMs can adequately model the economics of future energy efficiency enhancements, since increasing the efficiency of energy end-use technologies (the demand side of the energy economy) over the long run is *a* crucial policy option for mitigating climate change, if not *the* crucial option.

Another theoretical aspect of computing the net economic benefits of mitigating climate change is the fact that all IAMs assume that some sort of idealized equilibrium for the economy (or at least for certain energy technology markets) will be achieved in each year for which results are computed. That assumption implies that any non-equilibrium state in the same year would be more costly to the economy since, by definition, it would not represent a "least-cost" (or maximum utility) state of affairs as defined by the model. Yet the real-world economy is never in a perfect equilibrium (or even close to it), especially in the base year from which all model calculations for the future begin. Thus, if all cost-effective investments in new energy-consuming or supply technologies had been made in the model's base year, they already would have significantly reduced the future net costs of mitigating climate change. The assumption inherent in most IAMs that the base year, as well as future years, had already achieved an economic optimum may, then, tends to overstate the net costs and underestimate the net benefits of achieving the necessary level of mitigation relative to where the energy economy actually stands today.[2] For example, many "bottom-up" studies of energy-efficiency investments claim that many such investments could be made at net negative costs today – i.e. net benefits – to reduce greenhouse gas emissions [7].

Moreover, this paper will not delve into the issue of the incremental ecological and other damages that are avoided by mitigating climate change to a specified level relative to a base or reference case set of damages. (The scholarly discussion of the trade-offs between different environmental impacts, known as Life Cycle Assessment, is not included either.) The topic of damages is important, but none of the previous damage functions incorporated into IAMs seem to have much basis in fact [14–16]. There seems to be little evidence to support their mathematical form or magnitude [17]. However, surprisingly, most IAMs discussed in Barker [8] and relied on by the 2007 IPCC report do not include any estimates of the likely future damage due to climate change at all [8,1]. Because no reasonable damage estimates have been incorporated into most IAM results, and because there is tremendous uncertainty inherent in even trying to make monetized estimates of damages that have yet to happen on a global scale, it is very hard to estimate, even roughly, the net benefits of mitigating climate change in the long run. Yet, as Dr. Stern has stressed recently, the damages caused by climate change could be very large [18].

This paper will consider three aspects of existing IAMs: 1) their overall structure and level of technological disaggregation, 2) the economic theory that determines each key equation within this structure, and 3) the input assumptions, both historic and future, for key parameters within these equations, including those that apply to new technologies. These topics will be treated solely from the perspective of how they affect the calculation of the net benefits and costs of mitigating climate change and the usefulness of these results to policymakers who are trying to significantly mitigate climate change.

3. To what should the costs of a mitigation scenario be compared?

To calculate the net benefits or costs of mitigating climate change, we must compare two scenarios. Most studies compare the net costs of a "reference" or "baseline" case to the net costs of a mitigation case, such as a scenario in which the global temperature increase is limited to 2 °C by 2100. The construction of the reference case usually only assumes that no new climate mitigation policies are implemented beyond those in place today. Conceptually, then, the reference case represents the costs to society that would *actually result* if the current level of climate change mitigation policies were maintained.

But there is a major problem with this approach. Integrated assessment modelers (and models) cannot forecast with reasonable accuracy what would actually happen to the trajectory of greenhouse gas emissions if no new mitigation policies were adopted worldwide over the next 50–100 years. In particular, failing implementation of new climate change mitigation policies, there might be a major economic crisis caused by climate change that causes the trajectory of GDP, or other economic indicators, to deviate substantially from the assumed projections. But integrated assessment modelers never model feedback between the amount of climate change and economic growth and would have an extremely difficult time doing so if they tried. The economy in a reference case could also begin to collapse because of the depletion of fossil fuel reserves, or because of a financial crisis. But even without considering climate change or resource depletion, no economist could possibly forecast the global economy for the next

[1] See also the critique in Barker [8], page 11, on the use of aggregated production functions used in climate-related IAMs [8].

[2] Some IAMs assume lag time for technology implementation to equilibrium levels.

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50–100 years with any reasonable accuracy for the purpose of policymaking. Because forecasting the future of the energy economy for the next 50–100 years is impossible (not just difficult), there is no valid baseline emissions scenario to which the costs of a mitigation scenario can be compared. It is not even clear that, in general, economic forecasts for only the next 10–20 years can be relied on for policy purposes.

It is not surprising then, that when different models compare the net costs or benefits of mitigating climate change, the models and modeling teams end up using a very wide range of greenhouse gas emissions trajectories as their reference case [1, Fig. 3.8 (page 187)]. This reflects, in part, the tremendous uncertainty of making 50–100 year economic and greenhouse gas emissions forecasts. The uncertainties reflect both the uncertainty in the underlying economic (GDP) forecasts as well as the uncertainties associated with how the assumed internal operating parameters and costs of dozens of energy supply and demand technologies will change over the long run in this scenario. Thus, one cannot simply compare the net costs of mitigating climate change across different model results without explicitly accounting for the differing emissions trajectories of the reference cases. For example, if two models develop a mitigation scenario for the same level of temperature increase in 2100, but one model needs to reduce average emissions by 50% more than the other relative to their reference cases during the 2005–2100 period, then one would expect the net costs of mitigating this higher level of reference case emissions to be more than 50% higher in order to achieve the same final mitigation scenario. (The net costs would probably be more than 50% higher because the net marginal costs of mitigation tend to increase the greater the mitigation requirement.) In conclusion, right from the beginning, if the research community cannot even develop a reasonably accurate reference case with very limited uncertainty over the next 100 years, then the net long-run costs of mitigating climate change cannot be calculated, since they are derived by identifying the usually small differences in costs between the reference case and mitigation case scenarios.[3] Yet, doing so is impossible for all the reasons stated above.

4. The Stern Review and its meta-analysis of IAM net cost results

Section 10.2 of the 2007 Stern Review covers the results from other models regarding the costs of emission-saving measures. The review lists many requirements of an adequate IAM methodology for computing the net costs and benefits of mitigation [2]. It says that a broad assessment of net costs "requires a thorough modeling of consumer and producer behavior, as well as the cost and choice of low-GHG [greenhouse gas] technologies" (page 268). It goes on to say, "To estimate how costs can be kept as low as possible, models should cover a broad range of sectors and gases, as mitigation can take many forms, including [reducing] land-use and industrial-process emissions. Most models, however, are restricted to estimating the cost of altered fossil-fuel combustion applied mostly to carbon, as this reduces model complexity. Although fossil-fuel combustion accounts for three-quarters of developed economies' carbon emissions, this simplifying assumption will tend to over-estimate costs, as many low-cost mitigation opportunities in other sectors are left out (for example, energy efficiency, non-CO_2 emissions mitigation in general, and reduced emissions from deforestation) …." (page 269). The Stern Review then lists the key model comparison studies carried out in, or recently before, 2006 and comments that "the wide range of model results reflects the design of the models and their choice of assumptions, which itself reflects the uncertainties and differing approaches inherent in projecting the future" (page 269).

To get a better sense of the kinds of uncertainties the Stern Review fails to address, we will first critique the meta-analysis of IAM-generated cost projections carried out by Barker [8] that the Stern Review itself commissioned [8]. This meta-analysis seems to have provided the primary basis for the Stern Review's conclusion that the net costs/benefits of mitigating climate change (on a present-value basis) by 2050 probably lie in the range of a cumulative loss of GDP of 1%, plus or minus 3%, by 2050. This appears to be quite a wide range compared to the central value, and it allows for the possibility that growth in GDP could be at least as high as 2% more in the mitigation scenario than in the reference case, or 4% lower. On the other hand, since even +2% in cumulative GDP growth over 40–45 years is only about +0.05% *per year*, on average, we see that the entire range of results cited by both Barker [8] and Stern is, in fact, extremely small relative to average historical global GDP growth rates, which were in the 2–3% per year range. Anyone who is aware of typical inaccuracies in making economic forecasts, even over the short run, would assume that the *cumulative* uncertainty in such estimates in the long run would be vastly greater than the average annual value of 0.05% in the results cited in the Stern Report [2].[4]

Fortunately, and usefully, the Barker review reports separate inter-model comparison results for net costs grouped by the level of CO_2 reductions in the atmosphere achieved in the future. It demonstrates the intuitive result, noted above, that the likely net costs of mitigation are much lower when smaller reductions in CO_2 emissions are needed. These results, as segregated by the mitigation level achieved, are, however, presumably averaged over the very wide range of baseline or reference scenarios that appear in Table 5 [8, page 20]. For example, Table 5 shows that the cumulative net cost in terms of reduction of GWP (global GDP) for the strictest mitigation scenario of 450 ppm of CO_2 in the atmosphere averages 3.1%. However, since this result for the mitigation scenario presumably is averaged pairwise over a wide range of baseline scenarios, we cannot tell what the net cost might be per percentage point of reduction of CO_2 from a specified baseline. It is surprising that the Barker study does not report the results in this way, given that one of the independent variables in the regression analysis performed is "CO_2 change from baseline

[3] Small differences between any two types of forecasts, such as forecasts of net costs for two different scenarios, are subject to greater error than either of the separate forecasts from which the differences are derived, especially when the sign of the difference is not even known.

[4] The precise Barker [8] results from Table 4 for all 1335 scenarios and model runs included a net cumulative GDP loss of 0.9%, plus or minus one standard deviation of 2.0% (page 19) [8]. Clearly, one might wonder why the spread in the cumulative cost results over 40–45 years is so small when expressed on an annual basis.

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(percent)," as listed in both Tables 4 and 5. Thus, the 3.1% reduction in GWP goes along with an average reduction of CO_2 by 47.9%, but it would have been more precise and interesting to see how the net benefits and costs varied by the percentage reduction in CO_2 based on each reference case/mitigation case pair. One can only assume that reporting the results this way would have greatly reduced the standard deviation of 6% listed for the net costs of this sub-category of mitigation scenarios.

Of course, the reason it would probably be more instructive if the net cost results were reported in terms of percentage of CO_2 reduction is that, to first approximation, the total net costs of mitigation equal the amount of CO_2 mitigated (in tonnes, not percent) times the average cost per tonne to reduce CO_2 emissions. Thus, while "percent CO_2 reduction" is not equivalent to tonnes, it is probably better to include it as a denominator for the results, rather than just reviewing results in terms of the final absolute CO_2 level achieved in the atmosphere without any attention paid to the starting or reference levels in the atmosphere. But in general, the cost per tonne of emission reductions will likely vary with the absolute level of baseline emissions, as well as with the mitigation level achieved, so including an independent variable for both the absolute baseline emissions level and the tonnes of CO_2 reduction from that level would probably improve the statistical properties of the Barker regression equation. This approach would be mathematically identical to including both the absolute baseline emissions level and the absolute mitigation scenario emissions level as independent variables. Either way, it is especially clear from the huge variation in baseline CO_2 emissions depicted in Barker Fig. 1 that any meta-analysis of the economic impacts of mitigation should account for both the baseline and mitigation levels of CO_2 emissions as directly as possible.

The next question is the role that the average cost of mitigating a single tonne of CO_2 plays in Barker's meta-analysis of total net costs. If one model or modeling team assumed very different marginal mitigation costs per tonne of CO_2 than another team, then the total net costs of mitigation between these two models would vary significantly for this reason alone. The marginal mitigation costs per tonne of CO_2 could vary significantly from one scenario to another if different modeling teams assumed very different capital investment costs per unit of low-carbon energy generation capacity, e.g., wind generators or nuclear power plants, and different discount rates. But the capital investment costs of low-carbon generation capacity are a component of the *gross* costs of mitigation, not the *net* costs. To derive net mitigation costs, one must subtract from the gross costs of mitigation the benefit of not providing the same amount of energy from a higher-carbon energy source in the reference case, namely, from a source that the new low-carbon source would displace. For example, additional investment in enhanced energy-efficiency technologies might have a gross cost of $100 per tonne of CO_2 emissions reductions, but that technology might displace coal-based electric generation with a gross cost of $150 per tonne. Thus, in this case, there would be a net *savings* of mitigation of $50 per tonne of CO_2 mitigation, a clear economic benefit. To calculate the net costs or benefits of mitigation, two sets of gross costs from the different scenarios must be taken into account: the costs of the lower-carbon emitting technology from the mitigation case and the costs of the displaced higher-carbon emitting technology from the reference case that can be substituted. Modeling teams need, of course, to make assumptions about both sets of costs separately, for the reference and for mitigation cases for 50–90 years into the future.

The next logical question becomes whether the Barker meta-analysis adjusted statistically for differences in the net costs for a single unit of CO_2 reduction to help account for the total differences in net costs for the "same" scenarios as reported by various modeling teams. To answer this, we reviewed Section 4.2 of Barker's paper titled "Reasons for Differences in the Model Results" [8, pages 25–27]. Section 4.2.3 specifically claims to address model "assumptions" and states, "[T]he wide range of predicted values may depend critically on the structural assumptions of the models, including the baseline scenarios, sectoral and regional detail, substitution possibilities, international capital mobility, economies of scale, environmental damages and benefits, and the discount rate." While this is correct, it is curious that Barker's list of important assumptions does not include what we would call "non-structural assumptions," including the numerical values of key input assumptions needed in all IAMs, e.g., the capital costs and operating parameters of new low-carbon electricity generators and other technologies.[5] In fact, one can see from reviewing Barker's Appendix A that the multi-variate regression analysis included independent structural variables for "number of regions," "number of sectors," "number of fuel sectors/types," and the presence of a "backstop technology." But the Barker analysis appears to have completely omitted any consideration of the potentially more important gross *cost* parameters associated with the fossil fuels and assumed backstop technologies as independent variables.[6]

Any statistical meta-analysis that attempts to explain the net cost differences obtained by different modeling teams for different scenarios must include these gross cost parameters because the total net cost differences depend directly on the gross costs of each energy technology modeled. In contrast, the *number* of energy technologies modeled may not have much impact on the net costs, particularly if the technologies have very similar gross costs, or if some widely available technologies dominate the technological change during the course of a scenario. In reviewing the definitions of the independent variables used in the Barker meta-analysis, we find that Table A1 lists 15 independent variables, but *none* of these variables have any type of direct gross cost factored into its quantification. Ironically, we can conclude that Barker's meta-analysis [8] relies on a regression equation that tries to explain net cost (net GWP) differences using almost purely *structural* descriptions of the models relied on to generate those costs, while not including as independent variables the actual gross technology cost assumptions that are clearly more directly relevant from a theoretical perspective. Specifically, if all the cost input assumptions run for a single reference case and mitigation case by a given IAM were precisely doubled, then the net cost difference for the GWP obtained by comparing these scenarios would approximately

5 Note that here Barker [8] explicitly supports our earlier point, namely, that the net costs of mitigation will depend to some degree on the emissions level of the reference case utilized by each modeling team as well as that of the mitigation scenario [8].

6 The cost of a "backstop technology" equals the long-term cost of a liquid fuel substitute for a current liquid fuel such as gasoline.

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double, as well.[7] Thus, the gross cost input assumptions for new technologies in each type of scenario are of *primary* importance for statistically "explaining" net cost differences between the scenarios in a meta-analysis, not necessarily the structural differences in the models.

Is there any other reason why the omission of any cost-based independent variable is a major problem for the Barker analysis and the Stern Review, as well as for our further understanding of the net costs of mitigating climate change? Yes. The meta-analysis, which depends on results derived from a multi-variate regression analysis of hundreds of IAM results, cannot possibly be even close to accurate if it omits other types of variables (cost-based, in this case) that are *theoretically essential* to calculating the result being analyzed. When performing a regression analysis, all independent variables that are theoretically essential for deriving the result, whether highly significant or not, must be included for the analysis to be valid.[8] Thus, the basic results of the Barker meta-analysis of net costs for mitigating climate change, as cited in Tables 4 and 5, including those relied on by the Stern Review, must be taken to be invalid [14]. One thing that we can conclude with certainty about the Barker [8] meta-analysis is that the inclusion of additional theoretically relevant independent variables would significantly reduce both the scatter or standard errors of the equations and the results for the standard deviation in terms of percent difference in GWP due to mitigation. However, what would happen to the predicted values for the dependent variable "percent change GWP" due to mitigation for any particular set of input assumptions is unknown.

This critique of the Barker meta-analysis leads to the question of which IAM results are likely to be more accurate than the others and which sets of numerical values for the many input assumptions these models require are the most likely to occur in the future. But is this really a useful question? Can we, and should we, pretend to be able to forecast the future economic costs of each technology, in each scenario, with any reasonable accuracy? Or, even more challenging, can we accurately forecast small cost differences between two very different possible future scenarios involving very different mixes of technologies? If we cannot, can we get a reasonable approximation of the likely net costs or benefits of mitigating climate change, or not?

Finally, there are other serious problems with how Barker [8] performs the meta-analysis of IAM results that further undermine the validity of their results. One is how Barker accounts for the presence, or absence, of a "constant cost backstop technology" in each IAM. First, it is not clear if one or more types of backstop technologies are being referenced. Second, what is being backstopped? Liquid fuels, such as oil? Electricity generation? The paper does not specify. Nor does the paper specify the cost or price of the backstop energy technology to which it refers and why it assumes the cost to be constant. The answers to these questions about the determination of the backstop dummy variable for use in the regression analysis for each model in Barker's database would probably significantly illuminate the multi-variate regression results. For example, the price of the backstop technology might have a strong influence on the overall macroeconomic impact on GWP. If one backstop technology was a CO_2-rich, non-conventional oil product, the higher its price, the lower the net cost of mitigation would be, since more low-carbon technologies would be cheaper. Furthermore, the idea of a model assuming the existence of a *constant* cost backstop technology is, itself, fairly strange. For most energy resources, the higher the demand for the resource, the higher its marginal cost of supply becomes; therefore, the cost of a backstop technology should not be constant. Thus, any well-structured IAM should allow energy and technology prices to rise and fall appropriately, as demand rises and falls.

This example of the kinds of questions raised by the independent variables selected by Barker [8], and especially by the cost- and price-related questions, illustrates the kinds of questions and issues that arise relative to the use of many of the other independent variables chosen for the regression equation relied on in this meta-analysis. We conclude that the Barker meta-analysis is an inadequate basis for the Stern Review to have concluded anything about the magnitude of the likely net costs of mitigating climate change over the long run. This is especially true given the overly narrow range of input technology cost assumptions used in most IAMs — in fact, often each modeling team only uses a single set of cost assumptions for each technology over the next 100 years. Therefore, the Barker meta-analysis is based on an artificially limited range of data points because each IAM relies on an overly limited range of input assumptions. But all a meta-analysis like this one, even if well-structured, can accomplish is to tell us something, on average, about the *group of models* used to run the designated scenarios, and not the likely cost results for actually mitigating climate change.

5. The IPCC's Fourth Climate Change Assessment — 2007

For our purposes, the most relevant chapter in the IPCC's Fourth Assessment is Chapter 3 of the Working Group III report, "Issues related to mitigation in the long term context" [1]. There, the authors point out that "the costs of stabilization crucially depend on the choice of the baseline, related technological change and resulting baseline emissions; stabilization target and level; and the portfolio of [mitigation] technologies considered. … Additional factors include assumptions with regard to the use of flexible [policy] instruments and with respect to revenue recycling [of carbon taxes]" (page 172). As a basis for analysis, the chapter uses the results of the Energy Modeling Forum (EMF-21) scenarios and the Innovation Modeling Comparison Project (IMCP) network scenarios [7]. However, the authors note that "these new modeling comparison activities are *not* [emphasis added] based on fully harmonized baseline scenario assumptions, but rather on 'modeler's choice' scenarios" and that "further uncertainties have been introduced due to different assumptions and modeling approaches" (page 174). It is important to note that Barker's meta-analysis of economic results included most, if not all, of these scenarios as well [8, pages 18–20]. Chapter 3 also states that another difficulty in making analytically sound

[7] The net cost might not exactly double because of subtle effects of non-linearities in the model structure relevant to computing incremental cost differences.

[8] The issue as to whether relatively "insignificant" but theoretically important independent variables should be retained in the final equation as reported is not relevant to the point we are making here.

comparisons between the economic results of different IAMs is that the “information and documentation of the scenarios in the literature varies considerably” (page 174), which is a nice way of saying that important parameter values and model methodologies for running many scenarios were never well-documented in the literature.[9]

Since our focus here is on the economic costs and benefits of mitigating climate change, it is important to first point out that, as the IPCC states, “there are different metrics for reporting costs of emissions reductions, although most models report them in macro-economic indicators, particularly GDP losses” (page 172). That the results of different model runs are reported in terms of different metrics adds to the lack of clarity about how to interpret the net costs or benefits of mitigating climate change in the literature, if not to the uncertainty in the reported numbers themselves. Changes in GDP in going from a baseline to a mitigation scenario, in particular, do not only reflect the costs and benefits of mitigating climate change, but also reflect many complex related changes within the economy, e.g., rebound effects for energy demand. Yet, the IPCC cites the net costs of mitigation over the long run as one of the most important results of Chapter 3. The reported results range from very small net benefits to the statement that “GDP losses in the lowest stabilization scenarios in the literature (445–535 ppmv CO_2-equivalent) are generally below 5.5% by 2050” (1, page 172).

Besides the uncertainty and confusion created by different models using different metrics to report their net cost results, another significant source of uncertainty is whether or not models include estimates of the economic damage avoided by mitigating climate change. In fact, as noted above, most IAMs do not include estimates of net damages, a major omission if one wants to give policymakers a clear and comprehensive view of the economic trade-offs of mitigating climate change. Chapter 3 states, “Due to considerable uncertainties and difficulties in quantifying non-market damages, it is difficult to estimate SCC [social cost of carbon] with confidence. Results depend on a large number of normative and empirical assumptions that are not known with any certainty” (page 173). This is very likely the main reason why most IAMs do not include estimates of avoided damages when quantifying the net costs of mitigating climate change, but one might make the same equally valid statement about almost all the long-term input assumptions these models make, as we have also stated above. Finally, Chapter 3 of the IPCC report points out that another source of uncertainty and inaccuracy in all the economic results is that for the IAMs on which it relies, “the risk of climate feedbacks is generally not included in the … analysis” (page 173). Despite the fact that climate change will impact the reference or baseline case more strongly than any mitigation case, the IPCC does not take into account at all this differential impact on the world economy in the future. However, these differential impacts on metrics such as the GDP could be very substantial and could even be larger than the impacts on GDP of attempting to simply mitigate climate change.

How, then, in light of all these acknowledged profound uncertainties, did the IPCC derive the net costs of mitigation that they report for comparison purposes, for different levels of mitigation? And why does the IPCC believe it is reasonable to report such uncertain results given the serious misinterpretations of these results that could occur? (Pearce et al. [12] also address these key questions.) Section 3.2 describes how the *baseline* scenarios were developed. Given that different modeling teams with different baseline scenarios assumed very wide ranges of the key drivers of CO_2 emissions, such as population and GDP growth, the results for baseline CO_2 emissions had an enormous spread by 2100, from nearly 0 tonnes per year to more than 200 G-tonnes per year. (Current levels of CO_2 emissions are “only” about 30 G-tonnes per year. See Fig. 3.8 on page 187 for the full spread.) Interestingly, the average results for improvements in energy efficiency in the baseline scenarios were about 1% per year, ranging from about 0.5% to 1.9% per year depending on the model. As the report itself notes, “this range implies a difference in total energy consumption in 2100 of more than 300% — indicating the importance of the uncertainty associated with this ratio” (page 183).

Section 3.3 describes how the *mitigation* scenarios were produced. Mitigation or abatement measures for reducing greenhouse gas emissions include structural changes in the energy system, fuel switching, greater use of low- or no-carbon energy supplies such as nuclear generation of electricity and carbon sequestration technologies, enhanced energy efficiency, and changes in land use (pages 200–201). Fig. 3.20 provides an interesting perspective on the relationship between the cumulative CO_2 emissions of the baseline cases, compared to the same quantity for the mitigation scenarios for the pairs of IAM runs analyzed in the IPCC report (page 201). (A “pair” of scenarios is a mitigation scenario and the baseline scenario from which it is derived.) The high degree of scatter observed for the data points in this plot means that for any given total amount of CO_2 emissions in a baseline scenario, there is a very wide range of emissions reductions and, therefore, of absolute levels of emissions of the corresponding mitigation scenarios analyzed by the IAM teams. This demonstrates that for the same baseline level of emissions over the 100 years from 2000 to 2100, different IAMs and/or different sets of input assumptions lead to very different results for CO_2 emissions from the corresponding mitigation scenario in the different pairs of scenarios. Thus, the high degree of scatter in Fig. 3.20 would also lead to a high degree of scatter and uncertainty in the incremental costs of mitigation, if these costs were also plotted in a similar fashion.

Similarly, at a more detailed level of analysis, Fig. 3.21 provides a view of the changing relationship over time of the relative impact of enhanced energy efficiency when compared to the reduction of the carbon content of energy supplies (page 202). Again, for any given radiative forcing level (which is approximately the same as the expected temperature increase), a very wide range of relative effects exists. Thus, for some models and sets of input assumptions, enhanced energy efficiency plays a much larger role in reducing CO_2 emissions in any given future year than the use of low-carbon energy supplies. Since the average and marginal costs of energy efficiency and low carbon-supply

[9] We have even found it to be difficult or impossible to find many key input assumptions for the IAMs relied on in the research team websites. As Barker [8] says, “many of the one-sector growth models are calibrated on long-term growth paths, but few report any formal fitting to historical data” [8, page 9].

technologies differ from each other in each model run, this variation in their relative importance will also lead to significant variation and uncertainty in the net costs and benefits of mitigating climate change for the exact *same* level of radiative forcing. These results for four of the well-known IAMs are further broken down by type of technology in Fig. 3.23 (page 203). Here, we can see that even at this very detailed level, each model shows very different results for the amount of CO_2 reductions for the mitigation scenarios relative to the baseline scenarios analyzed for every major CO_2 abatement technology separately. As the IPCC report states, "the differences between the models also emphasize the impact of different assumptions and the associated uncertainty" on the net CO_2 emissions (page 202).

Section 3.3.5.3 of the Fourth IPCC Assessment report specifically addresses the issue of the "stabilization" or mitigation *cost* results that derive from the many pairs of baseline/mitigation scenarios analyzed. Again, the report stresses that the economic results are given in three different metrics depending on the IAM used: GDP losses, the net present value of abatement costs, and carbon prices. These cost results are presented separately for each output metric, as they should be, in Fig. 3.25 (page 205). This figure shows the relationship between the net costs, as measured by each of the three different metrics, and the stabilization targets or "categories." (A stabilization "category" represents a fairly narrow range of expected temperature increases over the long run.) Again, we find a wide range of economic results for any given stabilization category, especially for the lower categories that represent stronger levels of mitigation. For example, for the strictest mitigation categories I and II, the net long-run economic results for each of the three metrics can vary by factors of 5–10, or more. Thus, the IPCC analysis indicates that depending on the IAM used and the set of cost and price assumptions input to each IAM for any single scenario, *the net costs or benefits of mitigating climate change are projected to vary widely, even when the results are segregated both by the type of economic metric reported and the likely impact on the climate of the mitigation scenario*.

Finally, the IPCC report provides a summary of the quantitative economic results for mitigation categories I and II. It finds that "[the cumulative global] GDP losses of the lowest stabilization categories (I & II) are generally below 5.5% by 2050, however the number of studies are relatively limited and in these scenarios stabilization is achieved predominantly from low baselines. The absolute GDP loss numbers for 2050 reported above correspond on average to a reduction of the *annual* GDP growth rate of less than … 0.12 percentage points for the categories … I & II…" (page 206). (Note again, that the *cumulative* 5.5% reduction in GDP by 2050 is claimed by the IPCC to translate into an *annual average* reduction of only about 0.12% in each year from 2000 to 2050.) This statement implies that out of an annual average GDP growth rate of, perhaps, 2.0 or 2.5% projected throughout the 21st century, the change in GDP due to climate change mitigation could be measured, on average, as precisely as 0.12 percentage points per year for 50 years.

Yet given all the uncertainties and variability in the economic results of the IAMs, especially for category I and II results, the claimed high degree of accuracy in GDP loss projections is highly implausible. After all, economists cannot usually forecast the GDP of a *single* country for *one year* into the future with such a high accuracy, never mind for the entire world for 50 years, or more. We must conclude from the results cited by the IPCC itself that projecting GDP losses due to mitigating climate change to be below 5.5% cumulatively by 2050 is quite unknowable to any reasonable degree of accuracy especially in light of the huge uncertainties that exist for each input parameter that this argument does not even take into account.

If one compares the basic results for the net long-run costs of mitigation between the 2007 IPCC report and the Stern Report, the similarity in these results is not surprising, since the set of IAM runs analyzed in the Stern and IPCC reports substantially overlap. However, it is not at all clear why the IPCC Chapter 3 co-authors appear to believe that the results as presented in Fig. 3.25 represented a reasonably *complete* range of results, given the many uncertainties involved in making such estimates that they do not even model. The range over which most economic results happen to cluster based on the input assumptions chosen by various IAM research teams does not necessarily reflect the most likely range of values for the results. Problematically, the IPCC never attempted to present or analyze the actual ranges for different input assumptions the IAMs actually utilized to determine if a reasonably robust range for each parameter (of hundreds) had been relied on. Without analyzing the uncertainty in each type of individual input assumption, one cannot reasonably conclude that the results of the model runs do or do not represent a full range of uncertainty with respect to the possible economic costs and benefits of mitigating climate change, even if one assumes that the models were accurate within these ranges of input assumptions. However, based on our own limited review of many of the input assumptions on which different IAMs relied, the results did *not* come close to representing a reasonable range for each type of important input assumption. Thus, simply relying on the range of economic results the modeling teams just happened to choose to produce is not a scientific and systematic methodology for developing evidence relevant to the economics of mitigating climate change.

Perhaps, however, some may deem our fundamental criticism of 100-year IAM-based economic forecasts for mitigation, namely, that they could not possibly be known to any reasonable standard of accuracy to be reported, unfair. Some may contend that even if the GDP of the baseline scenario cannot be accurately forecast in the long run, the *increment* to GDP due solely to mitigating climate change still could be predicted to a higher degree of accuracy because the net cost of mitigation is fairly constant when averaged over different baseline scenarios having different underlying GDP growth rates. Unfortunately, Fig. 3.20, as discussed, appears to undermine that possible defense, since it shows that for baselines with similar cumulative CO_2 emissions (which often correlate to similar GDP levels over the long run), the cumulative emissions reductions due to mitigation often vary enormously. Thus, the incremental costs of mitigation are also likely to vary widely for the same baseline emissions trajectory depending on the model utilized, since the incremental costs amount to roughly the amount of CO_2 reduction required times the average cost of mitigating a unit of CO_2 emission, both of which vary greatly. This means that the IPCC reported results for the CO_2 impacts for baseline/mitigation scenario pairs completely undermines the idea that incremental GDP costs would be fairly constant for all baselines and, therefore, could be accurately predicted. Furthermore, the net costs of mitigation as reported by the IPCC do not take into account a vast array of additional uncertainties described above.

6. Conclusions about methodologies for estimating the mitigation costs of climate change from more recent literature

Beginning a discussion of the literature on the economics of climate change mitigation, Barker [5] states that "studies which investigate the costs of deep mitigation, e.g. more stringent stabilization targets such as 450 ppm CO_2-eq or lower, are very scarce as these targets are generally considered to be infeasible" [5, page 4]. This might have been considered true until 2007, but in the last six years many more feasible, yet stringent, mitigation scenarios have become available [3,4]. Technically speaking, if a model cannot achieve a particularly stringent mitigation level, the net costs of achieving it are infinite. But that result seems a priori impossible in the current situation, since it is not physically impossible to achieve stringent mitigation targets beginning now. Thus, the so-called "infeasibility" of a scenario, as sometimes cited in the literature, serves as a warning that the economic model being used is too restrictive and has significant flaws or faulty assumptions. Barker [5] goes on to discuss a few specific model results that would successfully achieve a 450 ppm CO_2-eq target, or better, by 2100. However, one of the key considerations motivating this paper is the concern that either some IAMs are structured in ways that preclude limiting a temperature increase to 2 °C or lower or that many, if not all, are structured in ways that are not able to yield reasonably accurate net cost or benefit results for mitigating climate change to the 2° target, even in the short to medium term.

Needless to say, if a justifiable consensus that the net costs to the world economy of achieving the 2 °C target were strongly positive existed, it would send a very negative message to policy-makers and political actors who lean towards resisting any significant actions to mitigate climate change anyway. This is the basic political problem, besides maintaining scientific honesty, that the IAM research community must consider before reporting highly uncertain net cost results So, again, where does the state of knowledge stand? Is it even possible to conceive of creating an integrated assessment model that could provide a reasonably definitive answer to the question of whether positive net costs, or net benefits, are likely to result from mitigating climate change over the long run? Can the research community even be expected to know under what assumptions net costs would result and under what other assumptions net benefits would result, given all the other uncertainties and unknowable factors that arise when creating IAMs and modeling the world economy under conditions of vast technological change that would occur over such a long time period?

It is important to recognize that Barker's [5] findings, no more than those of the Barker [8] findings, do not contribute any support to the idea that we can estimate, with a fair degree of accuracy, the net costs of mitigating climate change to any particular level, and specifically to the 2 °C target [5]. The 2007 paper begins with the observation that "it is important at the outset to emphasize that the uncertainty about the cost estimates increases for lower stabilization targets, namely [those] targets at 450 ppm CO_2-eq and below" [5, page 3]. It continues, "The inherent uncertainty of costs becomes more pronounced because there are few underlying studies that address the economics of land use and new technologies … that are required for the task [of mitigation]." "These new technologies are inherently speculative … and with very limited experience of costs" (page 3). In the 2006 report, regarding the types of macroeconomic modules within IAMs, Barker also commented that "one of the most serious weaknesses is the assumption in all the models, except E3MG, that the world economy is at full employment in the base year and in most models throughout the projection [period]" [8, page 13]. As Barker notes, the assumption of full employment is untrue, and we would add it is not ever likely to be true for any major region of the world for very long, if ever.

Thus, we cannot know whether IAMs can produce even roughly approximate results based on how they model investments in new energy-related supply or demand technologies in each key sector of the economy. This is particularly true when investors and consumers in each sector have a wide range of choices in new demand-side equipment which operate at different levels of efficiency. In fact, we can find no literature comparing investment decisions for energy-consuming equipment implicit in IAMs with real-world trends in the past. Part of the problem with even attempting such an analysis is that at the global level, almost all, if not all, IAMs treat the major sectors of the economy in such an aggregate fashion that it is never clear which new end-use technologies are accounting for the investments calculated by the models. Many IAMs have only one equation each for representing energy use in the residential building, commercial building, industrial, and transportation sectors though some models incorporate a limited degree of disaggregation. Because of the use of a single equation for a sector, changes in the technologies used in the future in that sector (however defined) cannot be identified explicitly. For example, with a single equation for passenger travel in vehicles, one cannot tell the difference between a trend towards the use of more efficient gasoline engines in cars and switching from gasoline engines to electric vehicles.

7. Energy efficiency and the EMF #25 study

The uncertainty in how investments are made in new energy-consuming technologies applies equally to major investments in entire new office buildings, new factories, or new cars. The carbon emissions for any single new investment could easily vary by factors of 20%, 40%, or even more, with respect to older alternatives, especially in the transportation sector. Consequently, the greenhouse gas emissions consequences of investments in new energy-consuming technologies in even a base case or *reference* case would be highly uncertain, unless each new technology, in each year, could be precisely specified. The emissions consequences of investments in new energy-consuming equipment and facilities, given changing consumption patterns, in a *mitigation* scenario would be even more uncertain.

Most IAMs are very simplistic in their treatments of technological change by assuming nearly exact continuity of past energy efficiency trends when projecting a reference case for the future, often assuming an average decrease in energy use of about 1.2% per dollar of GDP per year when averaged over all sectors of the economy.[10] Building off that underlying historical trend, one critical question is how prominent IAMs account for energy efficiency improvements (and the investment decisions leading to such improvements) in climate change mitigation scenarios relative to the underlying reference case. This is an important issue because enhanced energy efficiency is usually the first policy priority in real-world planning to mitigate climate change. Therefore, the net costs or benefits of investments in enhanced energy-efficient equipment for building shells, factories, etc., may prove to be either the largest or second-largest contributor to the net costs and benefits of overall climate change mitigation as measured by the GWP, or other metrics. (The costs or benefits of changing the fossil fuel-based sources of energy to renewable energy sources are the other major contributor to changes in GWP.)

The recent literature on the economics of climate change contains almost no papers or reports that review the details of how IAMs treat investments in enhanced energy efficiency and the impact on energy consumption of changing lifestyles. This is also true for the IPCC's Fourth Climate Assessment, as well as for the Stern Review, which, as noted, primarily relied on the Barker [8] analysis that the Review commissioned. And, surprisingly, even though the Barker [8] analysis claimed to focus on induced technological change as a new contribution to the literature, it barely mentioned enhanced energy efficiency as a type of such induced technological change and did not analyze it in appropriate detail.

However, one major exception to this void in the literature stands out: “Energy Efficiency and Climate Change Mitigation,” a major study done by the Energy Modeling Forum (EMF) project #25 [7]. In fact, this project likely began in 2009 because of such widespread neglect of the topic of enhanced energy efficiency. (Note that this was fully two years after the publication of the most recent IPCC assessment.) The EMF project #25 led to both a March 2011 report and a much longer set of articles published as Volume 32 of *The Energy Journal* in October 2011 [7,19]. More than 50 energy and climate modelers and analysts, covering members of most of the climate change-related IAM modeling teams throughout the world, participated in this project.

Although this project focused solely on the United States, it relied on the same basic methodologies used to model the economics of climate change worldwide. EMF #25 analyzed the results from 10 different IAMs run for the United States. Here, we will focus on the analysis presented in the March 2011 report [7]. The “highlights” section of that report noted that some IAMs used for the study had an explicit treatment of some options (new technologies) for energy efficiency, while others relied more on “market responses and economic equilibrium” (page ix). In addition, the highlights noted, “Other structural model features, parameter values and assumptions about key conditioning factors appear to be primary contributors to differences in model outcomes” (page ix). Finally, one of the study's main conclusions was that “improvements are required to make the models more useful for policymaking” on energy efficiency (page ix).

As noted, enhanced energy efficiency is a very important form of induced technological change for climate change mitigation because it is often very cost-effective for investors, i.e., it has positive net economic benefits prior to consideration of any economy-wide rebound effects. This reflects the fact that the energy system is not currently close to a state of economic equilibrium, in part because the world has substantially under-invested in enhanced energy efficiency in the past. Thus, the more they are available, and the cheaper new energy-efficient technologies become, the more likely the net costs of mitigating climate change as a whole will be negative, i.e., there will be net benefits. New lifestyle patterns can accentuate these effects.

However, many of the IAMs that have been run for past IPCC climate assessments and many included in the Barker [8] database do not model energy efficiency well, either in terms of its direct impacts on the energy system or in terms of the way new investments in energy efficiency impact the GWP. In the extreme case, some climate-related IAMs do not even allow for an increased level of energy efficiency in the mitigation scenarios relative to the baseline or reference scenarios, except implicit changes due to energy price elasticity impacts. In these mitigation model runs, it is not clear if there are increased investments in energy efficiency that impact GWP or GDP calculations, and the models' overly rigid structures preclude mitigating climate change by enhancing energy efficiency from the start.

In model runs where the amount of energy efficiency is allowed to increase in the mitigation scenarios relative to the reference scenarios, the maximum level of increased energy efficiency often seems to be capped at about 0.5% per year, or less, in energy units per dollar of real GDP. This means that the entire economy cannot improve its energy efficiency by more than about 0.5% per year, usually starting from an approximate baseline a 1.2% per year increase in efficiency per dollar of GDP, which reflects the actual trend over the last several decades. The maximum rate of energy efficiency improvement averaged throughout the economy is, then, only about 1.7% per year, or less, in many climate mitigation scenarios. In contrast, even the fairly cautious International Energy Agency has supported policies to increase the level of energy efficiency improvements to about 2.5% per year from 2009 to 2035 in the “450 Scenario” in their 2011 annual report, and many environmental organizations argue that similar rates of improvement are possible and necessary [20,21]. Even higher rates of improvement are possible from an engineering perspective.

Evidentiary support for our earlier observation that most IAMs over-constrain the amount of enhanced energy efficiency allowed to occur in mitigation scenarios comes directly from the EMF #25 study. Again, some of the 10 models on which it relied were general equilibrium models with very limited technology detail for end-use sectors. Some other models had more end-use technological detail, but instead of assuming that consumers always purchased the lowest-cost and most energy-efficient options, those models often constrained adoption rates for new, more efficient technologies to be consistent with “people's actual behavior,” however so determined (page 1). For the EMF #25 study,

[10] This is not surprising in light of the fact that the coefficients in most models are fit by statistical means to historic data.

some model input assumptions were made consistent between models for any given scenario, e.g., oil prices and the U.S. GDP growth path. But other input assumptions varied "sharply" such as "non-petroleum fuel prices and the costs and availability of electricity generation sources," causing the results to vary significantly from one model to another (page 3). The study does not explain why it chose not to harmonize these input assumptions as well. Having many key cost assumptions vary between models for the "same" scenario makes comparing the results of the model runs, as the study tried to do, potentially meaningless, since it is not clear what can be learned about the models themselves unless the results are somehow "corrected" or adjusted for the differences in input assumptions, of which there are hundreds.

Fig. 2 in the EMF #25 report shows the average impact on all the model results due to a modest $80 per tonne of CO_2 "carbon" tax by 2030, using 2005 as the base year. The energy "intensity" line in this figure illustrates the impact of additional energy efficiency improvements stimulated by the carbon tax throughout the economy. These incremental improvements in energy efficiency in the mitigation case relative to those implicit in the reference cases equal at most 0.5% per year (see page 3 — the change is about a cumulative 10 percentage point improvement over 25 years). An even smaller average level of incremental energy efficiency—namely, a cumulative 7 percentage point improvement over 25 years, or about 0.3% per year—appears for the residential sector in isolation in Fig. 10. When averaged over all the models, this figure hides the fact (illustrated in Fig. 10) that the individual model results range from a 2% to a 10 percentage point improvement due to the carbon tax, a factor of 5 difference, which is a very large range given that it involves only one sector (residential) of the economy in only one country (the United States). Note that Fig. 10 clearly identifies the energy efficiency improvement implicit in the reference case as a cumulative average of about 13 percentage points over 25 years, or only about 0.6% per year. Thus, the impact of the carbon tax seems to exhibit some degree of diminishing returns or increasing model-related constraints relative to actual historical trends for reasons that are not discussed.

Figs. 11, 12, and 13 show that the incremental energy efficiency improvements average somewhat less than 7 percentage points over 25 years for the commercial, industrial, and transportation sectors, respectively, because of the carbon tax.[11] Similarly, the variation in model results for each of these other sectors is as large as, if not larger than, the variation between results from different models for the residential sector. Interestingly, after the disaggregation of the average energy efficiency enhancement results into separate averages for the economic equilibrium models and the "process-economic" models, the efficiency improvements were clearly higher, on average, for the economic equilibrium sub-group.

What is the implication, then, of the results of the most intensive model comparison exercise ever to focus on energy efficiency for mitigating climate change, namely the EMF #25 study? The same modest carbon tax trajectory used in all the model runs was only sufficient to induce incremental efficiency improvements of about 0.5% per year through 2030, compared to the International Energy Agency recommended incremental target of about 1.2% per year.[12] This is a very big difference relative to the IEA recommended level, especially if it is projected far into the future. This 0.7 percentage points per year difference amounts to about a cumulative 50% reduction in energy use by 2100 relative to 2005. Such a 50% reduction would clearly make the total costs of mitigating climate change far lower.

More importantly, for our purposes of trying to assess the current state of art for the economic analysis of mitigating climate change, the results of EMF #25 suggest that since the net reduction in energy demand in the United States, by sector and in total, varied so significantly from model to model for the same carbon tax, either the variance in the other input assumptions besides the carbon tax must have also been significantly different from model to model. Or, the models have such fundamentally different structures, that most models must be highly flawed. This implies that the net long-run costs or benefits of mitigating climate change via implementation of the same carbon tax would also vary tremendously from model to model, though those results were not reported. In fact, there is no way to tell from the EMF #25 report whether the implementation of the very modest incremental levels of energy efficiency actually achieved in the mitigation scenarios run would yield net benefits or net costs to the economy. In summary, then, either the model structures, the many implicit input assumptions such as the costs of energy efficiency-enhancing technologies, or both were so different from model to model that the impact on GWP of mitigating climate change via this critical "tech fix" approach would itself be highly variable and indeterminate.

8. The other major determinant of net mitigation costs or benefits

As noted above, the other major component of the cost of mitigating climate change stems from de-carbonizing the energy supply sector. This includes the electricity, liquid fuel, solid fuel, and the gaseous fuel sectors. Examples on the cost side of the equation are the cost of new wind turbines or solar cells to generate electricity and the cost of advanced biofuels for jet aircraft. The savings of converting to renewable energy in these supply sectors come from the displacement of fossil fuel-based electricity and traditional kerosene for aircraft engines, respectively. Again, the net benefit of mitigation derives from the difference between these two sets of costs, though we must also consider the "rebound" effect when calculating the magnitude of the overall macro-economic benefits. (If the net benefits are negative (net costs), the rebound effect will tend to show lower energy demand in the remainder of the economy, and vice versa.) In theory, one of the virtues of having macroeconomic modules as part of IAMs is the ability to compute the impacts of trade-offs, such as the rebound effect, within the economy. But an unresolved issue is whether these existing macro-economic modules in IAMs are at all accurate when attempting to compute the size of rebound effects or similar economic trade-offs. The lack of knowledge of

[11] Most IAMs only disaggregate the economy into these three sectors in addition to the residential sector.

[12] Whether a much higher carbon tax trajectory would have achieved a result in the EMF #25 study much closer to 1.2% per year cannot be determined from the study's results.

the accuracy achieved in computing macro-economic trade-offs between reference case and mitigation case scenarios is another major source of uncertainty in attempts to determine the net mitigation costs.

9. "Pushing the Boundaries of Climate Economics" — a new analysis

Recently, a new article appeared in the literature on the economic modeling of mitigating climate change that also raises "critical issues to consider in climate policy analysis" [22]. Interestingly, one of the co-authors of this new article is Terry Barker, the lead author of the two meta-analyses that have been discussed above.[13] From the start, this article points out that "the 'cost' of climate policy is not an observable market price; rather, it is a construct shaped by the modeling apparatus and its explicit and implicit assumptions. … As in any economic modeling, the future macro-level assumptions driving the analysis have important implications for the costs and impacts of climate policy" (page 156).

The authors of this new article then proceed to make a controversial claim with which we agree: that "baseline assumptions employed in modeling studies are often arbitrary and inconsistent with each other, particularly when projections are taken off the shelf from different sources. A complete model of climate policy costs and impacts should, in theory, make some of these data endogenous; climate damages can affect the rate of (business as usual) growth of per capita incomes; climate policies can change the price of oil" (page 156). But, as this article points out, creating such a model is difficult because it would have to be very complex — in our view, far more complex than existing IAMs. The article likewise notes, "Beyond the universal dilemmas of modeling uncertain futures, the economics of climate change poses unique challenges to orthodox styles of economic analysis. There are four fundamental requirements for an adequate economic framework for climate policy [modeling]." We stress two of the requirements listed, namely the "incorporation of multi-dimensional, often un-monetisable impacts, rendering cost–benefit analysis problematical," and "recognition of the problems of catastrophic risks and irreducible uncertainty, leading to a precautionary approach to policy" (page 157). For example, in a baseline scenario, the world may run short of fossil fuels so quickly that fuel prices could skyrocket, causing the global economy to crash. No existing climate-related IAM can capture such an effect, despite its very real possibility.

In their discussion of risk and uncertainty, the authors further point out that trying to reduce the uncertainty in key inputs to IAMs "is not helpful in the face of catastrophic risks and deeply uncertain probabilities of worst-case scenarios. … Economies are highly complex non-linear systems and it is *impossible* [emphasis added] to accurately predict their future evolution" (page 157). The authors conclude that "climate economic analysis would need to cover the entire spectrum of uncertainty ranging from unknown uncertainty (variations around expected system behavior that cannot be quantified) to uncertainties that can be quantified" (page 157). We would add that it is not at all clear what kinds of uncertainties for input assumptions into IAMs could be quantified over the time periods as long as those assumed by our discussion, i.e. 50–100 years.

Finally, Scrieciu et al. [22] has a very interesting and useful discussion of induced technological change (ITC) in Section 3, which includes the modeling of enhanced energy efficiency. Here, the authors exactly echo several of our points in stating that some "economic models for climate policy may not include ITC at all, or include it with restrictive assumptions and in a partial form so that it has only weak effects. Furthermore, the models may not include all the policy instruments that affect ITC. In consequence, the results of the models exaggerate, from this perspective, the costs of mitigation and give the impression that stringent mitigation is not possible without economic collapse" [22, page 158]. The possibility of infeasibility might even apply to the existing economic system as it has behaved in the past, but it does not take into account the many positive impacts and flexibility that changing consumption, technology policies, and lifestyle patterns could provide to allow for the feasibility of the strictest mitigation of climate change.

10. Conclusions and policy implications

We have suggested that there are numerous reasons to believe that the net cumulative benefits or costs of mitigating climate change are, in fact, unknowable for a period as long as 50–100 years, especially for the purpose of basing any climate change mitigation policy decisions on such calculations. In summary, those reasons are the following:

1. It is not possible to foretell the emissions trajectory of a reference or base case that assumes that no additional climate change mitigation policies are adopted, since forecasting the future of the energy/land-use economy over 50–100 years cannot be done to any relevant degree of accuracy. Thus, it is not at all clear what reference case costs one could validly compare to any mitigation scenario costs. In addition, the impact of climate change itself on the economy, land, ecosystems, and water is not typically modeled, yet these impacts would be significant.
2. The mathematical structure of most integrated assessment models is far too aggregate on the demand or energy-consumption side to forecast even a reference case with any reasonable accuracy. And such an aggregate structure cannot adequately quantify changes to the cost of new and existing technologies in a stringent mitigation scenario. The current structure of most, if not all, integrated assessment models (IAMs) is not even capable of forecasting changes in energy efficiency within the major sectors of the economy to any reasonable level of inter-model agreement, or agreement with "bottom-up" efficiency studies.
3. The neo-classical economic basis of most of the macro-economic modules contained within IAMs, as well as the micro-economic optimization methodology of many, has been strongly challenged by many economists as being inappropriate for forecasting the future of the world economy over long periods. In addition, these models do not even treat the financial sector of the economy explicitly and, thus, cannot predict financial problems caused by the

[13] Full disclosure: another co-author of this article used to work with Dr. Rosen at the Tellus Institute.

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energy sector and climate change, among other factors, that may impact long-term GDP growth.

4. It is impossible to forecast what kinds of low-carbon supply technologies may be invented in the future nor how the efficiencies and costs of current low- or no-carbon technologies may change over the next century in both a reference case and, separately, in a mitigation case. All these unknowable technology parameters will significantly affect net mitigation benefits and costs, especially for new technologies such as biomass-based carbon sequestration, on which many climate mitigation scenarios strongly rely. The same is true for forecasting fossil fuel prices and quantities available over the next 100 years.
5. No adequate inter-model comparison studies of either relevant reference cases or mitigation scenarios have been carried out with the quantitative input assumptions for the same scenario harmonized across all models to the extent allowed by their different structures. Because of differences in model structures, or in input assumptions, the IAM research community does not even know to what extent differences in economic results for the "same" mitigation or reference cases exist between models because of their differing structures alone. Thus far, the differences between results produced by different IAMs for the "same" scenarios reported in the literature have been substantial, even when a few key input parameters such as GDP and population growth have been harmonized in some inter-model comparison studies.
6. Many different model results for the "same" or similar mitigation scenarios appear to differ significantly because of the different climate mitigation policies modeled and different structural ways of modeling these policies. The IAM research community has not yet developed and agreed upon a uniform or harmonized way of modeling climate mitigation policies. In addition, most IAMs cannot even model many important climate change mitigation policies, such as mode shifting within the transportation sector, because the IAM structures are too aggregate.
7. Mitigation scenarios omit many types of costs, such as transaction costs, and most IAMs do not even include avoided climate-induced damage costs in mitigation scenarios as a benefit. This is inexcusable since both types of costs could be very substantial over 50–100 years [15]. In addition, there is substantial controversy over what discount rate is appropriate for long-run economic studies. While that issue has not been a focus of our analysis, the discount rate has a substantial effect on the numerical value of cumulative net economic benefits over the long run when expressed on a present value basis.
8. It is not appropriate to perform statistical meta-analyses on a database comprised of an arbitrary set of IAM model results, especially when the results are based on very restricted ranges of model input assumptions and structural parameters. In addition, it is not clear what one could learn from such an analysis, in part because each data point receives equal weight in the meta-analysis. Thus, whichever IAM produced the most scenario results included in the database will influence the results of the meta-analysis the most for no good reason.
9. Since the Western lifestyle can probably not serve as a role model for the life styles of the nine billion people likely to inhabit our planet by 2050, significant but unpredictable changes to consumption and production patterns not incorporated in existing IAMs are likely to occur, adding another layer of uncertainty to the economic calculations made by these IAMs for the net costs and benefits of mitigating climate change.

For the reasons cited above, not only do we not know the approximate *magnitude* of the net benefits or costs of mitigating climate change to any specific level of future global temperature increase over the next 50–100 years, but we also cannot even claim to know the *sign* of the mitigation impacts on GWP, or national GDPs, or any other economic metric commonly computed. Thus, the IPCC and other scientific bodies should no longer report attempts at calculating the net economic impacts of mitigating climate change to the public in their reports. Since most other aspects of reference and mitigation case scenario results depend entirely on the economic trade-offs modeled, they should not be reported either.

Contrary to the claims of scientists who are well aware of the many uncertainties in modeling the economic impact of mitigating climate change, reporting and analyzing the results of existing IAM Scenarios is not useful because even the simplest comparison of model results yields meaningless results — the uncertainties are too profound [12,16,17]. For example, Pearce et al. [12] list three ways in which IAM analyses over the long run are "valuable" (page 4) in spite of the paper's clear presentation of the uncertainties in model results: (1) internal consistency in any given model allows one to assess the relative implication of policy alternatives, (2) some "rough bounds" on mitigation costs are apparent, and (3) modeling can help estimate which policy architectures are likely to lead to lower versus higher costs. (Note that point #3 is basically the same as point #1.)

Our response to points #1 and #3 is twofold. First, it is usually clear just based on simple mathematical reasoning what the *qualitative* effect of various policy alternatives will be on climate change mitigation costs and benefits. Thus, no model runs are usually necessary at all. Secondly, most if not all currently existing IAM can analyze only one or two simple mitigation policies, e.g., a carbon tax, so policy analysis is usually impossible for most policy alternatives because of a lack of disaggregation in the models. Finally, our response to point #2 above is that learning the rough trends of costs is not credible given that we cannot even know the sign of the cumulative net costs over the long run, so there may be large net benefits rather than costs if realistic assumptions were input. One can also perform relatively simple spreadsheet analysis to get rough trends on cost, but doing so would not help to inform the world what to do if we cannot know just the sign of the likely outcome. We believe that Pearce et al. [12] wanted to water down their conclusions based on their own excellent analysis in order not to overly upset the IAM research community, with which they work closely.

The final question is, should these findings and conclusions about the inadequacies of current IAMs really matter to policymakers who are trying to figure out when, and to what extent, to implement effective climate change mitigation policies? Our answer is "no," because humanity would be wise to mitigate climate change as quickly as possible

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without being constrained by existing economic systems and institutions, or risk making the world uninhabitable. This conclusion is clear from a strictly physical and ecological perspective, independent of previously projected economic trade-offs over the long run, and it is well-documented in the climate change literature. As climate scientists constantly remind us, even if the world successfully implemented a substantial mitigation program today, a much warmer world is already built into the physical climate system. And since we can never know what the cost of a hypothetical reference case would be, and since we must proceed with a robust mitigation scenario, we will never be able to determine the net economic benefits of mitigating climate change, *even in hindsight*. Going forward, the key economic issue on which policymakers (and IAM research teams) should focus is how to implement as cost-effective and stringent a mitigation scenario as possible in the short to medium term, with periodic adjustments to such a plan. Making realistic plans to mitigate climate change decade by decade requires much more specialized and detailed sectoral planning models than the current IAMs to carry out least cost/maximum benefit planning in each sector of the economy in order to create hopeful, normative mitigation scenarios.

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