UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
WASHINGTON, D.C. 20460

OFFICE OF
AIR AND RADIATION

June 10, 2010

**Memorandum**

**SUBJECT:** Peer Review of ADAGE and IGEM

**FROM:** Eric Smith,
Climate Economics Branch

**TO:** EPA Council for Regulatory Environmental Modeling

The Climate Change Division (CCD) of the U.S. EPA Office of Air and Radiation is responsible for economy-wide analysis of greenhouse gas mitigation bills and proposals for the Agency, the Administration and Congress. CCD uses two computable general equilibrium (CGE) models to conduct this analysis:

- "Applied Dynamics of the Global Economy" (ADAGE), developed and maintained by Resource Triangle Institute of Research Triangle Park, North Carolina.
  (See http://cfpub.epa.gov/crem/knowledge_base/crem_report.cfm?deid=198000 for additional information on the ADAGE model)

- "Intertemporal General Equilibrium Model" (IGME), developed and maintained by Dale Jorgenson Associates of Cambridge, Massachusetts.
  (See http://cfpub.epa.gov/crem/knowledge_base/crem_report.cfm?deid=198005 for additional information on the IGEM model)

In accordance with the Office of Management and Budget *Information Quality Bulletin for Peer Review* and the U.S. EPA *Peer Review Handbook*, CCD has undertaken a peer review of the models by a panel of external experts.

The Peer Review was coordinated by Industrial Economics, Incorporated, of Cambridge, Massachusetts. IEc selected the panel of experts in economic modeling who conducted the review. Please see the attached memo from IEc describing the process of the peer review.

The Review by the panel of external reviewers is attached. The Review Panel summarized their findings in the following paragraph:

> On balance, these are two excellent models that provide useful information to EPA as it goes about its work of evaluating climate policies. While we may have issues with elements of the models, in general we find these to be first-rate and state-of-the-art. These models are essential tools for the analysis of environmental policy in general and climate policy in particular.

The panel made a number of suggestions for improvement.  The IGEM and ADAGE modeling teams each prepared responses to the peer review report addressing the findings and discussing planned model improvements.  The responses are each attached.

Attachments:

1. IEc Peer Review Documentation Memorandum

2. Report of the Peer Review Panel: *"Peer Review of Computable General Equilibrium Models for Climate Change Analysis"*

3. Response to Peer Review Panel prepared by Dale Jorgenson Associates regarding IGEM

4. Response to Peer Review Panel prepared by Resource Triangle Institute regarding ADAGE

# Attachment 1

## IEc Peer Review Documentation Memorandum

IEc

**MEMORANDUM | June 9, 2010**

**TO** Eric Smith, USEPA/CCD/CEB

**FROM** James Neumann

**SUBJECT** Documentation of Peer Review Process for the IGEM and ADAGE Computable General Equilibrium Models for Climate Change Analysis

## 1. OVERVIEW

Industrial Economics, Inc. (IEc) was contracted to manage the external peer review of two economic tools currently being used by the Climate Economics Branch (CEB) of the Climate Change Division (CCD) of the Office of Atmospheric Programs, USEPA: 1) the Intertemporal General Equilibrium Model (IGEM) developed by Dale Jorgensen and Associates; and 2) the Applied Dynamic Analysis of the Global Economy (ADAGE) model developed by RTI International. This memorandum summarizes the results of the peer review. The first section provides a brief description of the process for selecting individuals to serve on the review panel. The second section provides a summary of information provided to reviewers to support their activities. The full text of the peer review panel's report is provided separately.

This independent, external peer review was conducted in compliance with EPA's Peer Review Guidelines. The peer review will assist CEB in supporting their analytical responsibilities to provide long-run economic and integrated assessment modeling support to CCD, EPA, and the US Government. These long-run analyses inform near-term policy development with feasible alternative projections that provide insights for policy making. For example, ADAGE and IGEM have been used extensively by EPA for the purpose of analyzing climate change bills in both the U.S. Senate and the House of Representatives.

Results of the peer review will be used to help CEB evaluate the insights that can be gleaned from the different models' results and their relative strengths and limitations. The review will also help to identify opportunities for improvements to the models and suggest research directions that strengthen the credibility of model results. Reviewers are being asked to comment on the economic methodology and utility of model results. While the models will be deployed to support policy decision-making, no specific policy questions were asked of the reviewers.

## 2. PROCESS FOR SELECTING PEER REVIEW PANELISTS

The peer review process began in April 2009 and is now complete. IEc recruited four reviewers for the panel; one of these reviewers was recruited to serve as chairperson for the panel. The work of the peer review panel began in October 2009 and ended in February 2010. The reviewers were compensated for approximately ten days of effort and provided with an honorarium sufficient to attract a high-quality review panel. The chair, who was also asked to oversee the review of the models and engage particularly in the technical and substantive nature of the economic model review, was compensated for approximately 11 days of time.

IEc initially provided to EPA a list of candidate peer reviewers – the list is provided in Attachment A to this memo. While we consulted with EPA staff to clarify the expertise necessary to perform this review, and ensure that candidates met the stated requirements, IEc independently selected all of the reviewers, consistent with the guidelines of the *EPA Peer Review Handbook*. (US EPA, 2006). IEc discussed conflict of interest and independence issues with each reviewer, and each signed a statement confirming that they had no financial or personal conflicts of interest (included as Attachment B). In addition all four reviewers signed a contract with IEc that included a requirement to immediately report any potential personal or organizational conflict of interest, should one arise during the course of completing the review.

IEc selected peer reviewers for independence, economic expertise and knowledge, and modeling expertise. Each of the four peer reviewers ultimately selected are nationally recognized experts in the field of CGE modeling and climate economics and have a general knowledge of environmental economics issues, as well as the specific knowledge, expertise and experience required to adequately and authoritatively respond to the charge for the review. One of the key features of the IGEM and ADAGE models that makes them useful for CEB is that they capture economy-wide and sector specific economic activity at a regional, national, or international level, and, as they capture the interactions among sectors (and over time) they have advantages in analyzing complex dynamic responses to climate policy that jointly affect energy use, economic growth, and greenhouse gas (GHG) emissions. Each of the reviewers has expertise at the interface of energy and economics, and each is expert at assessing the implications of market-based approaches to regulating GHG emissions.

Exhibit 1 below provides a brief description of the four reviewers and their relevant expertise. Full curriculum vitae (CVs) for each of the four reviewers are included in Attachment C to this memo.

**EXHIBIT 1. SUMMARY OF QUALIFICATIONS OF PEER REVIEW PANEL**

| PEER REVIEWER | BRIEF DESCRIPTION OF QUALIFICATIONS |
|---|---|
| Dr. Charles Kolstad, University of California – Santa Barbara | Economist with extensive background in energy and climate change modeling. Lead author for the Intergovernmental Panel on Climate Change and a member of the Academy of National Sciences committee charged with evaluating the U.S. Climate Change Research Program. Has published widely in peer-reviewed energy, climate, and science journals. |
| Dr. Gilbert Metcalf, Tufts University | Specializes in taxation, energy, and environmental economics, with a current research focus on policy evaluation and design in the area of energy and climate change. Member of the National Academy of Sciences Committee on Health, Environmental, and Other External Costs and Benefits of Energy Production and Consumption. |
| Dr. Ian Sue Wing, Boston University | Applied general equilibrium modeler who has studied induced technical change and the impact of carbon taxes, the energy intensity of U.S. production, accumulation of capital and knowledge in dynamic general equilibrium, energy technology detail in CGE simulations for energy and climate policy analysis, and the effect of uncertainty on the cost of U.S. climate policies |
| Dr. Roberton Williams, University of Maryland | Specializes in the general equilibrium effects of taxes in environmental policy, with a focus on energy taxation and optimal design of climate policies. Authored numerous publications examining the impact of climate policies on the US economy. |

## 3. MATERIALS PROVIDED TO PEER REVIEW PANELISTS

Exhibit 2 provides a copy of the cover letter sent to the peer reviewers. As indicated in the letter, peer reviewers were provided a list of charge questions developed by the EPA sponsors; detailed documentation of each of the models; and summaries of the results of recent EPA efforts to apply the models to proposed GHG regulatory policies. The charge provided to the panel is included as Attachment D, and Attachment E provides an inventory of the materials provided for the reviewers. Note that some materials were provided in response to questions of clarification from the panelists to the EPA sponsors. The panel conducted one group conference call, facilitated by IEc, on October 21, 2009, shortly after receipt of the review materials. A second call was conducted on November 6, 2009, also facilitated by IEc, where panelists asked clarifying questions of the EPA sponsors. Reviews were originally requested to be complete by December 10, 2009, but because of some delays in receipt of clarifying materials and in light of the volume of materials reviewers were requested to be familiar with, the deadline was extended. A completed draft review report was delivered to EPA on January 25, 2010. The EPA review of the draft review report was solely to assess and suggest correction to any potential factual errors or clarifications. No such errors were found, and the report was finalized in April 2010, with no substantive changes from the draft.

## EXHIBIT 2. COVER LETTER FOR PEER REVIEWERS

IEc

INDUSTRIAL ECONOMICS, INCORPORATED

October 13, 2009

Dr. Ian Sue Wing
Department of Geography and Environment
Boston University
675 Commonwealth Avenue, Room 461
Boston, MA 02215
[transmitted via Federal Express and electronic mail]

Dear Dr. Wing,

Thank you for agreeing to serve as a peer reviewer of EPA's application of computable general equilibrium models for climate policy. The sponsor of this review is the US Environmental Protection Agency's Office of Air and Radiation, Office of Atmospheric Programs, Climate Change Division, Climate Economics Branch (CEB). One of CEB's specific responsibilities is to provide long-run economic and integrated assessment modeling support to EPA and the US Government. These long-run analyses inform near-term policy development with feasible alternative forecasts that provide insights for policy making.

CEB uses computable general equilibrium (CGE) models to perform selected analytical tasks; two of these models are the subject of this review: 1) the Intertemporal General Equilibrium Model (IGEM) developed by Dale Jorgensen and Associates; and 2) the Applied Dynamic Analysis of the Global Economy (ADAGE) model developed by RTI International.

CEB has a need for independent external peer review of these two models. Results of the review will be used to help CEB evaluate the insights that can be gleaned from the different models' results and their relative strengths and limitations. The review will also help to identify opportunities for improvements to the models and suggest research directions that strengthen the credibility of model results.

Enclosed you will find a list of specific charge questions that we request you address in conducting your review, and use as a guide in organizing your response. You will also find the following items:

- *Analyzing Environmental Policies with IGEM, an Intertemporal General Equilibrium Model of U.S. Growth and the Environment.* Please quickly skim these volumes to determine if adequate information is provided to support your review. If the documentation is not adequate, please contact me immediately and we will attempt to augment it.

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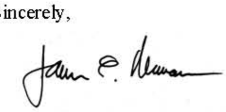
- *Documentation of the Applied Analysis of the Global Economy Model.* Please quickly skim this volume to determine if adequate information is provided to support your review. If the documentation is not adequate, please contact me immediately and we will attempt to augment it.
- *EPA Analysis of the American Clean Energy and Security Act of 2009 H.R. 2454 in the 111th Congress.* This document is example of a publicly available briefing CEB prepared based on application of the IGEM and ADAGE tools. It is provided to illustrate for you EPA's intended use of the model to evaluate greenhouse gas emissions reduction policies.
- *Conflict of Interest Certification.* I have previously sent you this under separate cover. If you have not yet review, signed, and returned to me, you must do so before you begin your review. If you have any doubts about whether a current or past engagement represents a conflict of interest for this review, don't hesitate to contact me to discuss.
- *Your contract with Industrial Economics.* I have previously sent this to you under separate cover. If you have not yet returned a signed copy to me please do so before you commence your review. .

If you would like to clarify further any aspect of the charge, the model, or the ultimate intended purpose of the model, please contact me and I can arrange a teleconference with the model developers, EPA, or both. Note that, in order to maintain the independence of the peer review, during your review I ask that you refrain from direct contact with the EPA sponsors of the review in the Office of Air and Radiation, Climate Change Division, Climate Economics Branch, except as arranged through me.

We request that you submit a written review no later than December 8, 2009. If this timeframe proves problematic for you, please contact me as soon as possible. You can e-mail the review to me at jneumann@indecon.com. Please organize the review in the form of a memorandum or a short report (preferably in MS Word), beginning with your general impressions of the tool and then moving to your more specific comments in response to each charge question.

Thanks again for your participation. If you have any questions, please feel free to contact me via e-mail, jneumann@indecon.com, or by phone at (617) 354-0074.

Sincerely,



James Neumann
Principal
Industrial Economics, Inc.

Enclosures

# Attachment 2

Report of the Peer Review Panel: *"Peer Review of Computable General Equilibrium Models for Climate Change Analysis"*

# Peer Review of Computable General Equilibrium Models for Climate Change Analysis

By:

Charles D. Kolstad+
Gilbert E. Metcalf
Ian Sue Wing
Robert C. Williams III

Work performed under contract from the U.S. Environmental Protection Agency

*through*

Industrial Economics, Incorporated
James E. Neumann, Program Manager

+ Review Panel Chair

April 2010

# I. INTRODUCTION

The EPA contracted with Industrial Economics, Incorporated to conduct an expert review of two computable general equilibrium (CGE) models in the context of EPA's work in evaluating proposed federal legislation for greenhouse gas mitigation. This is the result of that review. The EPA posed very specific charge questions to the expert panel and our review follows the structure of those questions. Furthermore, the EPA provided us with documentation of the models and several supplementary documents.[1]

The EPA uses two CGE models to evaluate prospective greenhouse gas policies: IGEM and ADAGE. IGEM (Intertemporal General Equilibrium Model) has been used for decades (though it is constantly being updated and refined) and was developed by Prof. Dale Jorgenson and colleagues. The ADAGE Model (Applied Dynamic Analysis of the Global Economy) is of more recent vintage, though it is adapted from MIT's EPPA model (in part).

Two recent and prominent analyses illustrate how these models are used by EPA. One is an analysis of the climate legislation which passed the US House of Representatives on June 26, 2009 (H.R. 2454 – the Waxman-Markey bill).[2] Another is an analysis of proposed senate legislation intended to parallel HR 2454 (Senate bill S. 1733—the Kerry-Boxer bill).[3]

In our review of the two models, we considered model documentation provided to us, these two analyses of legislation using the two models, as well as a number of other sources which are cited in this report.

# II. GENERAL COMMENTS

The EPA posed four general questions to the reviewers regarding the adequacy of the two CGE models. Before addressing these charge questions individually, it is appropriate to review our sense of the types of information EPA would want to obtain from the models, in order to be responsive to policymakers considering adopting legislation such as the two bills considered during 2009.

Energy is of course the source of most greenhouse gas emissions. One would expect to be able to forecast energy consumption and production as a consequence of legislation. In

[1] Primary documents reviewed: Ross (2009), Goettle et al. (2009), EPA (2009a,b).

[2] US EPA (June 23, 2009).

[3] US EPA (Oct. 23, 2009).

particular, one should be able to understand how electricity supply (by fuel) and use might be affected by legislation. How the use of low carbon fuels might change is also important. It is also important to be able to estimate the effect on electricity and other energy prices as a consequence of proposed legislation.

CGE models are particularly good in capturing the interconnectedness of the sectors of an economy and in tracing throughout the economy the indirect effects of a regulatory intervention. One should be able to measure the effect of proposed legislation on household consumption and aggregate consumption. And one should be able to measure the effect on specific narrow sectors of the economy which may bear a significant burden from proposed regulations (such as energy intensive industries). Furthermore, the competitiveness implications for these sectors (in terms of leakage or losing market to foreign producers) are politically important.

In the case of a cap and trade program (which appears to be central to most if not all proposed legislation), a model should be able to estimate a time-path for allowance prices, as well as a trajectory for emissions (and the extent to which allowances are banked or borrowed). With offsets (which are in both bills), it is important to estimate the use of international and domestic offsets.

For all of the issues mentioned above, it is important to understand the incidence of regulations, broadly defined. How are the various issues raised above manifest in different geographic regions of the country? How are different income classes of the population affected by regulations?

Generally, it is important that models be able to represent the wide variety of complex regulations which may need analyzing. Most legislation contains a set of complex rules, intended to address political dimensions of bill passage. There may be subsidies to certain sectors, free allocation of permits to certain consumers of electricity, incentives for R&D, and the list goes on. It is important that a model be flexible enough so that such diverse regulations can be analyzed.

Finally, it is important that any model be able to capture uncertainties in parameter values as well as the structure of the problem.

We now turn to the four general charge questions raised by EPA.

## 1. *Given the scope and intended purpose of the model, are the analytical framework, assumptions, and application of data appropriate?*

Both the ADAGE and IGEM models are sophisticated computable general equilibrium models in which great care has been taken to model aspects of the economy particularly important for analyzing environmental policy in general and climate policy in particular. Both the ADAGE and IGEM models are comparable to other top-tier economic models used to analyze climate policy (see, for example, the recent evaluation of models in Stanford University's Energy Modeling Forum 22 exercise).[4] Furthermore, in those comparisons with other models, ADAGE and IGEM are not outliers in the measures presented (emissions pathways and carbon prices). Although having results that are consistent with other models is in no way an indication that a model is correct, having a model which is always an outlier would be grounds for concern.

ADAGE and IGEM are complimentary models in a sense. ADAGE is an international model that uses GTAP data to calibrate to a base year and has particular strengths in considering the interaction of U.S. policy with policy actions in other countries. IGEM, in contrast, has no detail on other countries but has considerable detail on industry sectors in the United States. Also in contrast to ADAGE's non-statistical approach to calibrating their model, IGEM is an econometrically estimated model building on extensive high-quality statistical work over the years by Dale Jorgenson and numerous co-authors.

There are still major uncertainties even with the best models, so the models' predictions should be regarded as rough estimates, particularly when projecting far into the future. Estimates from large-scale dynamic CGE models such as these will still likely be much more accurate than those from other approaches. And having even a rough estimate of the economic effects of policy is far better than having no information at all. But it is important to recognize those uncertainties. And neither model's documentation does a particularly good job of identifying the key uncertainties.

For important parameters, it would be useful to know both how uncertain the parameter estimate is and how sensitive the model's results are to changes in that parameter. A quantitative assessment of the amount of uncertainty in a given parameter estimate is fundamentally very difficult; one can report an

[4] For more information on EMF 22 and comparisons of IGEM, ADAGE and four other CGE models applied to climate change policy, see http://emf.stanford.edu/research/emf22/ and in particular, documentation of the June 2009 workshop (available at the site).

estimated standard error (as the IGEM documentation does[5]), but that only expresses the uncertainty within a given estimation approach, not the additional uncertainty over what estimation approach is best. In general, neither model's documentation identifies how much disagreement there is in the literature over the value of any given parameter.

Identifying and quantifying the sensitivity of the model's results to changes in a given parameter is much easier, and such sensitivity analysis is commonly used to help evaluate CGE models. Neither model's documentation includes much sensitivity analysis (though presentations of the results from these models may well include much more sensitivity analysis).

One notable (and very useful) exception is Chapter 7 of the IGEM documentation, which focuses on the role of the consumption-leisure tradeoff in determining the model's results. This section clearly identifies the labor supply elasticity as a parameter that is relatively uncertain, and presents sensitivity analysis that shows it can have major effects on the model's results. Similar analyses for other key parameters would be very helpful in pointing out and assessing key uncertainties.

### 2. *Are the methods applied in this model appropriate for quantifying the economic impacts of climate policies for the US and global economies? If not, what methods would you recommend?*

Perhaps the biggest criticism of the two models for use in climate policy analysis is that they are generic models, for broad application, and for that reason do not necessarily adequately answer all of the climate-specific questions posed at the introduction to this section. For instance, the electricity sector is key in determining the allowance price as well as the effects on other sectors. In particular, fuel switching in electricity should be well represented. That is not a strength of either model.[6]

In addition, the price of allowances appears to be largely exogenous, dependent on assumptions about availability and cost of foreign offsets. That has been the reason offered for why the allowance price generated by both models is virtually identical

[5] Because ADAGE's parameters are generally calibrated based on values from the literature, rather than estimated as in IGEM, it doesn't have standard error estimates for parameters.

[6] In the EPA analysis of H.R. 2454 the differences between the CGE models and the more detailed electricity sector model (IPM) are clear: compare page 17 (ADAGE) with page 26 (IPM). The two models come up with strikingly different forecasts of fuel use in electric power under H.R. 2454. This is not to suggest IPM is more correct than ADAGE/IGEM, only that the differences are of concern.

through 2050 in the analysis of HR 2454.[7] This is due to the fact that the supply curve for international offsets is exogenous to the models and it is that supply that is very important in HR 2454. However, because of the significance of the allowance price to any analysis of climate policy, we would strongly suggest that the EPA consider developing a more sophisticated representation of the international allowance market so that the price information coming from these two models is more robust.

Incidence is also poorly represented in the models – how are different income classes and regions differentially affected by policies? IGEM is taking steps to be able to answer this question. For future model development, one fundamental structural aspect that might be worth changing about these models would be to move away from the representative-agent assumption and include more heterogeneous households. This would yield more realistic estimates of household-level economic responses, and would permit the models to examine the distribution of policy costs and benefits across different households.

In terms of specific recommendations for improvement for the two models, some of those are incorporated into our response to specific charge questions. With respect to IGEM, we suggest the developers evaluate the efficiency of their solution algorithm.[8] We also suggest remedying the lack of non-marginal GHG-saving technological change by incorporating discrete alternative energy supply and demand technologies, which come on line endogenously in response to price.

Due to the limitations of ADAGE's documentation we are not able to make as specific recommendations for improvements to this model. However, in the spirit of IGEM's econometric calibration, we suggest designing and conducting a program of testing to compare ADAGE's baseline with available economic data, with the objective of establishing the congruence between the model base year and reality, and identifying and implementing adjustments to calibration procedures that reduce the most serious errors. This is admittedly not a simple exercise given the way in which ADAGE is calibrated, but for this very reason it is appropriate in order to have confidence in the initial conditions that form the basis for its projections.

[7] Refer to page 12 of the EPA analysis of H.R. 2454.

[8] There are alternative solution methodologies available, such as replacing the current Fair-Taylor solution algorithm with Dirkse and Ferris' (1995) PATH algorithm based on Lau et al's (2002) formulation of the intertemporal pseudo-excess demand correspondence as a mixed complementarity problem.

**3.** ***What are the overall major strengths and weaknesses of the model for EPA's intended purpose?***

The main strength of both models is their internal consistency and ability to capture complex interactions among different sectors of the economy in response to climate policy. Both also have considerable detail about energy production and industry sectors that are particularly sensitive to higher energy prices from climate policy.

Both models only focus on the economic costs of climate policy and cannot measure policy benefits. In fact, it is not the purpose of these models to measure policy benefits. This is appropriate given the greater confidence that economists have in modeling economic outcomes in contrast to our more limited understanding of the economic impacts of climate change.[9]

Both models – like nearly all CGE models – are full employment models. This is probably a reasonable assumption as these models should be viewed as modeling scenarios out forty or more years for which economic fluctuations should be viewed as deviations around a full-employment trend.

As we discuss below, the IGEM model does not incorporate capital adjustment costs. Given the interest by policymakers in understanding the transitional costs of climate policy, this seems an important limitation and has the potential to significantly understate costs for particular subsections of the economy.

IGEM's strengths are its econometric calibration to historical data, ability to capture detailed sectoral impacts, and its sophisticated representation of endogenous incremental technological change. ADAGE's strength is its ability to consistently characterize the incidence of climate policy at the sub-national level, based on its formulation of the U.S. economy as a set of interacting regions through movements of goods and factors, set in an international framework. Both models have weaknesses in the representation of capital frictions, household transportation, and induced technological change.

**4.** ***Are all of the essential elements included in the model documentation? Is the document clear and well-written? What additional documentation, if any, do you feel is needed to ensure transparency?***

[9] Some integrated assessment models have made progress on measuring greenhouse gas concentrations and damages in response to climate policy (eg, DICE, RICE and MERGE). Credibly estimating the damage from climate change remains a difficult challenge that has yet to be successfully addressed in any model.

ADAGE's documentation is simple, clear, and well organized, so it is easy to find the relevant sections on any particular topic. And it provides at least basic detail on the entire model structure, so there are no major sections that need to be added. However, it could be improved by adding more detail throughout, particularly on the details of how particular aspects of the model are implemented. Some examples are provided below, in our response to specific charge questions.

Also, since ADAGE incorporates significant elements of MIT's EPPA model (e.g., much of the structure and parameterization of production and utility functions), it would be useful to add a summary of how those elements of the EPPA model are parameterized (e.g., where do the substitution elasticities come from?) in the ADAGE documentation itself, along with a reference to the EPPA documentation in case more detail is necessary. Furthermore, a discussion of how ADAGE differs from EPPA would be appropriate.

The documentation of IGEM is exactly the opposite of ADAGE. IGEM's documentation is exhaustive, but can make for difficult reading, even for a professional modeler attempting to get their arms around this model. When presenting that much information, it is important that the information be very well organized in order for users to be able to find the information they need. The IGEM documentation is not that well organized. It is spread across two volumes and a set of appendices and it's not always obvious even which volume to consult.

Moreover, some of the information provided was superfluous to establishing the quality of the methods employed by IGEM, even as important gaps remained. A key area for improvement is describing in detail the procedure by which non-$CO_2$ GHG emission inventories are constructed and the corresponding abatement costs are obtained.

IGEM's documentation, however, is generally quite complete, containing essentially all of the relevant detail about the model's structure and parameterization (though there seem to be a handful of exceptions; for example, the estimated value of , the elasticity of intertemporal substitution, doesn't seem to be reported anywhere in the documentation). However, the IGEM documentation isn't that well organized. And the clarity of the IGEM documentation varies widely. Many sections are very clearly written, but others are very difficult to follow (for example, the explanation on p. 8-5 of the rationale for targeting nominal government expenditures is nearly incomprehensible).

In short, the IGEM documentation contains (nearly) any detail of the model one might want to know, but finding that detail is often difficult, and understanding it once you've found it is sometimes much harder than it ought to be. This may be inevitable for a model that has been around as long as IGEM and has had so many contributors. But nonetheless, it would be worthwhile to put some effort into organizing the documentation better (even very simple changes such as putting page numbers in the table of contents would help) and into writing more clearly.

One other feature that would be nice to add to the documentation would be some sensitivity analysis of the model's results with respect to key parameters. Chapter 7 of IGEM's documentation does this for the labor supply elasticities, and it was quite helpful. But there is no similar analysis of other key parameters. As is, ADAGE's documentation doesn't include any such results, much less any sensitivity analysis. Both models would benefit from attention to this issue.[10]

## III. SPECIFIC COMMENTS

### 1. *Quality of the Data Inputs*

#### a) Are the underlying data used to benchmark the model (e.g. input-output table or Social Accounting Matrix) appropriate?

As Donald Rumsfeld might have said, you develop a model based on the data you have, not what you might like to have. However, even given this caveat, economic data used in these models appears to be adequate and certainly the best that is readily available. ADAGE uses IMPLAN social accounting data, widely recognized as some of the best subregional economic data. ADAGE also used GTAP data for international information, similarly the best that is available.

The IGEM model is also closely tied to data. Given that the IGEM model has been developed over several decades, and has used the best national data that is available, IGEM cannot be faulted in terms of economic data used to estimate the model.

It is unclear what data are used by the models for carbon abatement costs. IGEM appears to adopt the reasonable assumption that it is only substitution away from carbon intensity

[10] As already indicated, the EPA does appear to be conducting sensitivity analysis though that work has not yet been made publically available, as far as we are aware.

that results in a reduction in emissions. Thus abatement is endogenous to the model, though there is a recognition that some abatement is exogenous (such as soil carbon sequestration and CCS). There is very little discussion of the source of abatement cost estimates in ADAGE. Furthermore, because ADAGE is calibrated, not estimated, it is unclear how confident we should be in the model's representation of energy substitution opportunities.

**b) Do the parameters of the model (eg, elasticities, emission coefficients, etc) have an appropriate basis (eg, econometric estimation, support from existing literature)?**

IGEM's parameters are very carefully estimated (econometrically). ADAGE's parameters are chosen so that the model behaves realistically. IGEM's estimation approach is much more sophisticated, but each approach has its advantages and disadvantages and neither is unambiguously better than the other. One suggestion, in the spirit of IGEM's econometric calibration, is to design and conduct a program of testing to compare the ADAGE benchmark with available economic data, with the objective of establishing the congruence between the model base year and reality, and identifying and implementing adjustments to calibration procedures that reduce the most serious errors. This is admittedly not a simple exercise given the way in which ADAGE is calibrated, but for this very reason it is absolutely necessary if we are to have confidence in the initial conditions that form the basis for its projections.

**c) Are the reference data used to construct the baseline (e.g., GDP and emissions baselines of EIA's 2009 Annual Energy Outlook) sound?**

The authors of both models appear to have used sound energy and economic data as the basis for their baseline.

## 2. *Theoretical and Analytical Quality*

### a) Activities Accounts

***i) Sectoral disaggregation.*** The degree of sectoral disaggregation of ADAGE and IGEM are both adequate. IGEM in particular incorporates many more industries than ADAGE, whose sectoral resolution is just about the minimum necessary to undertake detailed analyses of the effects of climate mitigation policies. Given the central cost-moderating role envisaged for domestic and international emission offsets under H.R. 2454, as well as the importance of the agriculture and forestry sectors as sources of such credits, disaggregation of these sectors in both the GTAP and IMPLAN data inputs to ADAGE is perhaps worthwhile.

***ii) Firm behavior.*** IGEM and ADAGE follow the standard approach of modeling each producing sector as a representative competitive firm. The zero- profit condition for production is a CRTS cost function, and the input demands derived by Shephard's Lemma are the building blocks of the models' commodity and factor market clearance conditions. Both models adopt fairly complicated nested production structures. In IGEM the structure of the nest is the same for all sectors and differs only in its parameterization, while in ADAGE both the structure and parameters of the nesting hierarchy differs from one sector to another.

***iii) Production functions (functional form and parameters).*** As is now standard CGE modeling practice, both IGEM and ADAGE are formulated and solved in terms of the dual, with sectors' production modeled as cost functions. In IGEM these take the form of a system of econometrically estimated hierarchical Translog cost share equations, while ADAGE employs a more traditional hierarchical CES production structure.

Each of these modeling choices has its pros and cons. The fact that IGEM's production structure is econometrically estimated on a sequence of input-output tables would seem to make it superior to traditional calibration techniques which rely on a single year of data and elasticities of substitution whose values are assumed, and tuned to the modeler's sense of plausibility or the general economic literature, as is the case with ADAGE. The somewhat ad-hoc character of the latter approach has long been the subject of criticism (e.g., Jorgenson, 1984; McKitrick, 1998). Nevertheless, the use of econometric calibration implicitly assumes that the future will be a continuation of past trends, which may not necessarily be the case with a policy such as climate change mitigation which is sectorally wide-ranging and capable of profoundly transforming the structure of the energy system and the economy. While it is undoubtedly good that one's model reproduces the historical record, this is no guarantee that the resulting calibrated numerical scheme is any better at projecting the far future than one that relies more heavily on assumptions.

A concern about IGEM is its exclusive reliance on a functional form which is flexible but not globally regular, in the sense that the estimated Translog share equations are not guaranteed to map an arbitrary vector of positive prices into a vector of positive input shares (e.g., Lutton and LeBlanc, 1984; Perroni and Rutherford, 1998). Ad-hoc numerical countermeasures have been developed to deal with this issue (Wilcoxen, 1988, p. 127—especially footnote 2), but there is no discussion of how much use IGEM makes of them—particularly in situations where a stringent policy regime is being modeled, with attendant energy prices that lie far outside the range of the historical record on which the econometrically estimated share equations are based. This problem does not arise with nested CES functions.

A possible solution is to develop an alternative specification of production for IGEM that is based on the type of nested CES functions employed by ADAGE, but parameterize the substitution elasticities, distribution parameters, and technical bias trends using nonlinear econometric estimation techniques.

***iv) Capital investment.*** Both models' representations of capital dynamics may lead to biased estimates of the transition costs associated with abatement of GHG emissions. Production in IGEM is perfectly reversible, with capital services being frictionlessly reallocated among sectors within each period so as to earn the highest possible return, and increments to the aggregate capital stock facing no adjustment costs from one period to the next. This would suggest a downward bias in welfare costs.

ADAGE's formulation is somewhat more realistic, specifying an intertemporal pure putty-clay scheme in which each sector initially has only fixed-proportions "clay" capital, but the latter depreciates away over time, replaced by reversible "putty" capital as investment proceeds over the simulation horizon. This scheme does not resolve retrofit or retirement of the existing capital stock—which would likely generate more rapid adjustment in the energy-using characteristics of the capital stock, and leads to an expansion of substitution possibilities over time as the aggregate capital stock becomes increasingly malleable. Since a higher aggregate elasticity of substitution lowers the welfare costs of a price or quantity distortion, in an intertemporal model this formulation will likely imply an unintended additional inducement (over and above discounting) for the simulated regional representative agents to postpone costly abatement to future periods.

These representations of capital dynamics are ostensibly employed because of the conceptual difficulty of calibrating intertemporal GE models with as many capital stocks as there are industries, and the computational difficulty of solving for the equilibrium of the resulting excess demand correspondence.

***v) Technologies.*** A key limitation of IGEM in comparison to other CGE models for climate policy analysis is that it does not include disaggregated representations of key energy supply and demand technologies that reasonably might be anticipated to become economically viable over the coming century. The latent technology trends in IGEM's cost functions do capture the long-run influence of run-of the-mill disembodied technical progress on economic growth and emissions. But there is no process within the model that is able to adequately reflect the potential impact of radical technical change as a result of, e.g., cost-reducing or performance-enhancing breakthroughs in "backstop" energy supply options that facilitate their rapid penetration once the costs of conventional fossil fuels rise sufficiently high.

This is not an issue for the analysis of policies such as H.R. 2454, in which the marginal cost of GHG abatement are significantly moderated by a large influx of low-cost emission offsets from abroad. But it is easy to envision more costly scenarios such as global GHG concentration stabilization in which allowance prices in the early periods would be much higher, creating incentives for energy suppliers to undertake substantial investments in alternative, low-carbon technologies such as carbon capture and sequestration in the 2040-2060 timeframe. The anticipated reductions in abatement costs from the operation of these technologies would then be missed by IGEM in its current form.

ADAGE does an adequate job of representing alternative electricity supply technologies within the nested CES cost function framework, though the input cost share and markup assumptions are subject to considerable uncertainty—especially if one takes into consideration the potential cost-reducing effects of learning by doing (as the authors imply on p. 27 of the documentation).

One technological arena in which both models fall short is the transport sector. IGEM and ADAGE appropriately distinguish between transportation that is purchased (i.e., transportation industries) versus supplied by households using purchased inputs of vehicle capital and fuel. But neither model seems to represent the potential for the substitution of electric vehicles and biofuels in the production of transport services. Given that these technologies currently exist only at negligibly small scale, it is a simple matter to include them as dormant cost functions that embody a premium over benchmark output prices which enables them to endogenously switch on and produce output once the relative price of conventional transport increase sufficiently. However, parameterizing the cost functions might be challenging.

***vi) Technological innovation.*** CGE models for climate policy analysis typically incorporate a mix of exogenous and endogenous technical progress. Typically, exogenous technological change of the "economy-growing" kind (labor productivity or TFP) is included in part as a way of compensating for diminishing returns to both capital and labor as the former accumulates and the supply of the latter saturates with slowing rates of population expansion. Exogenous technological change of the "emission-saving" kind applies a secular declining trend to the coefficients on fossil fuel commodities in industries' cost functions or households' expenditure functions, popularly dubbed autonomous energy efficiency improvement (AEEI). The AEEI progressively decouples GHG emissions from economic growth, proxying for the attenuating impact on $CO_2$ emissions of the non-price-induced declines in the energy-GDP ratios historically observed in many countries. Price-induced endogenous technological change is more difficult to represent. One approach is to incorporate backstop energy supply technologies, which remain dormant until climate policy-induced relative price changes enable them to be profitably operated.

ADAGE follows the foregoing conventional recipe, whose major limitations are (a) the lack of responsiveness of incremental energy-saving technical progress to emission limits—i.e., induced technological change (ITC), and, (b) uncertainty over the future rate of growth of the AEEI index.[11] ADAGE calibrates the time-path of AEEI to approximate EIA projections of baseline energy use and emissions to 2030. Given the importance of this parameter, the documentation needs to be much more specific about the rates of future decline in the energy-GDP ratio (regionally and nationally) thus implied, and how they compare to historical trends.

Against this backdrop, the procedure used by IGEM to estimate incremental energy-saving technical progress is nothing short of remarkable. The rate and biases of technical change are all modeled econometrically as latent variables in the sectoral cost functions, and structural parameters governing their evolution are estimated as the transition matrix in a vector auto regression (VAR). This last piece of information enables the latent trends in the rate and bias of technology to be propagated forward as

[11] There is a large literature on endogenous technological change, though less so in the case of CGE models. For a recent review of this literature, see Popp et al (2009).

functions of the equilibrium prices that are being solved for, effectively incorporating the state of technology as a variable within the determination of general equilibrium.

Despite the impressive methodological advance that this represents, we question the value of the results for climate policy analysis on two counts. The first is econometric: with so many parameters to be estimated for each industry from a mere 46 years of data, one worries about the capacity of the data to speak when so much structure has to be imposed to achieve identification, and about the standard errors given the degrees of freedom penalty that will likely attend latent variable estimation.

The second point is a philosophical one, namely, that the representation of technology through trends is something the modeling community should be doing *less*, not more, of. Notwithstanding the sophistication of the present approach, it would be intuitively attractive to represent ITC in a way that is more faithful to the process of cumulative investment in the creation of knowledge, followed by industries employment of the services from the resulting stock of intangible capital. This “stock of knowledge” approach has proved attractive in theory but elusive in empirical applications, though the papers of Popp (2001, 2004, 2006) are potentially useful in this context.  We would encourage research to develop this further, marrying hard data on innovation (e.g., R&D, patents) with empirical models of production in the IGEM mold to create climate policy simulations with endogenous invention and diffusion of the subsequent innovations. We feel the issue is sufficiently important that resources should be devoted to research on improving the representation of innovation in CGE models.

***vii) Greenhouse gas emissions calculation.*** $CO_2$ is handled in the standard way, which is straightforward given the stoichiometric relationship between emissions and the quantities of fossil fuel use. It is much more difficult to model non-$CO_2$ GHGs and their abatement possibilities, because there is no fixed stoichiometric linkage between these emissions and the economic activities resolved within the CGE model. The solution, developed by Hyman et al (2003) and incorporated within ADAGE, is to employ bottom-up non-$CO_2$ marginal abatement cost (MAC) curves from EPA (which are constructed from engineering estimates) to calibrate the parameters of a constant elasticity of substitution composite of the benchmark quantity of emissions and the benchmark value of the activity with which they are associated. Non-$CO_2$ GHGs are thereby transformed into an input to production for which purchases of labor, capital or intermediate inputs can substitute, depending on the price of allowances relative to the latter inputs.

Given IGEM's representation of the aggregate economy and the availability of EPA's detailed GHG emissions accounts for the US, it isn't apparent why the authors could not distribute emissions amongst sectors and sub-tiers of the production and consumption hierarchies, and directly model abatement possibilities using the aforementioned state-of-the-art technique, instead of the now dated method of using MAC curves directly as a side-constraint on the general equilibrium problem. Turning to ADAGE, while the approach to modeling non-$CO_2$ GHGs is adequate, the data are not. The dearth of state- and regional-level inventories of non-$CO_2$ GHG emissions has compelled the authors to impute emissions data at the regional level based on the geographic distribution of output and consumption. Remedying this data gap is therefore a priority for model development.

### b) Household Sector (labor supply, consumption, and savings)

ADAGE and IGEM each model consumer behavior using fundamentally the same approach. Both assume an infinitely lived household whose decision-making can be divided into several stages. At the top level, the household allocates full consumption (consumption of leisure, goods and services) among different time periods to maximize an intertemporal utility function. Within each period, the household then makes a labor-leisure decision, deciding how much to work and how much to spend on goods and services to maximize utility within that period. And then the household divides that spending across the range of goods and services. This approach is theoretically very sound, and is very widely used in dynamic CGE models.

The differences come in how those utility functions are parameterized, and the resulting implications for household behavior. In IGEM, the utility function parameters are estimated using historical data and an estimation approach that is theoretically consistent with the structure of the model. This approach is different from the approach most CGE models take, and it has a number of advantages. The theoretical consistency is intellectually appealing, and avoids practical problems that can appear when parameters estimated under one set of assumptions are used in a model that makes different assumptions.

ADAGE uses the much more common approach of taking elasticity parameters from the prior literature. Indeed, it takes both those parameters and the form of the goods-and-services sub-utility function from MIT's EPPA model. This approach is much simpler and easier to implement than the estimation approach used in IGEM. It also has the advantage that the values for each key parameter can be taken from an empirical study specifically focused on that parameter, which may yield more accurate estimates: the ideal empirical setting for estimating labor supply elasticities is probably not the same as the ideal setting for estimating an intertemporal elasticity of substitution. But it may also introduce inconsistencies between those parameters because they were estimated in different ways. Each approach has its advantages, and it is not at all clear which is better overall.

The elasticity of labor supply is very important in determining the welfare effects of interactions between environmental policy and pre-existing distortions from taxes on labor. This elasticity comes out of the labor-leisure decision within a time period, and so it is determined largely by the parameters in that level of the utility function, and most importantly by the elasticity of substitution between consumption and leisure.

ADAGE takes the labor supply elasticities from a survey by Russek (1996), using a value of 0.4 for the compensated and 0.15 for the uncompensated labor supply elasticity. These values seem reasonable, and are consistent with those used in other CGE models. It might still be worthwhile for the ADAGE modelers also to consult other sources, such as the survey by Fuchs et al (1998) and the recent empirical literature on taxable income elasticities, but those more recent sources imply a very similar range of elasticities.

ADAGE then sets the household time endowment and elasticity of substitution between consumption and leisure in order to achieve those values of the labor supply elasticities. Given that ADAGE is using a CES functional form, this is the right way to calibrate those parameters (see Ballard, 1999, for details).

IGEM estimates values of the relevant utility function parameters as part of its larger estimation approach.[12] Those parameter estimates imply a compensated labor supply elasticity in the range of 0.8 to 1 and an uncompensated elasticity of roughly zero. That

[12] IGEM also sets the time endowment to 14 hours per day. In a homothetic utility function, the time endowment directly determines the income elasticity of labor supply, so choosing an arbitrary value can cause problems. But this is not generally true for a non-homothetic function and the translog function is not homothetic, so the time endowment assumption is unlikely to have any significant effect. Nonetheless, it might be useful to try changing that assumed time endowment in the estimation and see how this changes the labor supply elasticities.

uncompensated elasticity is lower than most studies use, but is still within the range of estimates from the labor literature. However, the compensated elasticity is much higher than the values typically used in other CGE work, and is substantially above the range of values found in the labor literature (even in studies that include labor force participation and labor effort choices, not just decisions about how many hours to work). Moreover, because the uncompensated elasticity is relatively low and the compensated quite high, that implies that the income elasticity of labor supply (which is closely related to the difference between the compensated and uncompensated elasticities) must be much higher than in other studies.

An empirical approach specifically designed to estimate labor supply elasticities seems likely to yield better estimates of those elasticities than an approach designed to estimate a broader range of utility function parameters. Moreover, the estimates in the prior literature come from a range of different data sets, time periods, and methodologies, and yet very few of them are as high as the estimate used in IGEM.

To their credit, the IGEM modelers have included some sensitivity analysis with respect to the labor supply elasticity in the IGEM documentation. That analysis indicates that using a lower labor supply elasticity (a compensated elasticity of 0.3 instead of 0.8) makes a big difference in the estimated cost of a carbon cap-and-trade regulation: the estimated cost under the lower elasticity is roughly half of the estimated cost under the higher elasticity. A bit more detail in this section would help in interpreting this result and evaluating its implications. In particular, when the compensated elasticity was lowered to 0.3, what did that imply for the uncompensated elasticity? Theoretical work in the environmental tax-interaction literature suggests that both the compensated and uncompensated elasticities are important. So the interpretation of this sensitivity analysis is very different if the uncompensated elasticity dropped by the same amount (i.e., from 0 to -0.5, very strongly backward-bending and well outside the range of prior estimates) than if the uncompensated elasticity remained constant.

Thus, without more information, it is difficult to know just how the use of more standard labor supply elasticities would affect IGEM's results. And one cannot say for sure that IGEM's elasticities are too high. Nonetheless, these results suggest that the labor supply elasticities used in IGEM will tend to overstate the costs of climate change policy. It would be good to run more sensitivity analyses (and provide more details on the current sensitivity analysis). And it might well be worth either changing the labor supply elasticity in IGEM's central case or including a disclaimer that IGEM's labor supply elasticities are substantially higher than in other studies, and that this will tend to yield higher cost estimates.

The key parameter for consumption and savings decisions is the elasticity of intertemporal substitution (the elasticity of substitution in the top level of the utility function), which controls how easy it is to substitute across different time periods. A higher elasticity means that consumption and savings will be more sensitive to changes in incentives to save. The elasticity of intertemporal substitution is notoriously difficult to estimate accurately, so estimates vary widely, but most credible estimates lie somewhere between zero and one.

ADAGE uses a value of 0.5 for this elasticity, which is quite reasonable. The ADAGE documentation doesn't explicitly say where this value came from, though it appears to have been taken from MIT's EPPA model.

IGEM estimates this elasticity using the standard Euler equation approach, which seems highly appropriate. But the documentation doesn't seem to report the estimated value anywhere, making it impossible to confirm that the resulting elasticity estimate is reasonable. Nonetheless, given the wide range of estimates in the literature, it seems quite likely that IGEM is using a value that falls within that range.

### c) Government Sector

***i) Government behavior (consumption and investment).*** In general, the way government is modeled in both ADAGE and IGEM is quite reasonable and appropriate, and fairly standard in CGE modeling. However, some of their modeling assumptions may yield misleading results in some cases.

The most important issue here is the assumption about the effects of government purchases (government spending used to purchase goods, as opposed to transfer spending), and how that assumption interacts with assumptions about what elements of government spending are held constant.

Both ADAGE and IGEM assume that government purchases do not have any effect on household utility, nor do they affect production (though the taxes used to finance those purchases impose costs on firms and households, and distort economic decisions). In other words, both models assume that government purchases provide nothing of value, and thus are completely wasteful.[13] This is clearly a simplifying assumption, not any attempt at realism (there is widespread disagreement over the magnitude of benefits from government purchases, which would make them very difficult to model, but those benefits are clearly greater than zero).

ADAGE assumes that government purchases of goods and services remain constant for any policy change. Under this assumption, any assumptions about the benefits from government purchases are irrelevant, and thus assuming that those benefits are zero causes no problem.

IGEM, in contrast, does not hold government purchases constant. Combined with the assumption that government purchases provide no benefit, this assumption can cause substantial problems. The model will overestimate the net cost of any policy change that increases real government purchases, because it recognizes the cost of such an increase, but ignores any potential benefits.

This problem shows up in the analysis in Chapter 8 of the IGEM documentation, which finds that using carbon permit revenues to reduce marginal tax rates on labor income actually *raises* the cost of the policy (relative to returning the revenue lump-sum to households), a result that is strongly at odds with the extensive literature on environmental tax interactions. That result arises because of an assumption that nominal government expenditures remain constant, and under the model's numeraire assumption, lowering the labor tax lowers prices throughout the economy, so holding nominal expenditures constant implies higher real government purchases. Thus, the anomalous result is an artifact created by the combination of the numeraire assumption, the assumption that government purchases provide no benefits, and the assumption that nominal government expenditures remain constant. This illustrates how these assumptions can combine to yield very misleading results.

One way to address this problem would be to allow benefits from government purchases (e.g., having those government purchases be used to provide a public good that would then enter the consumer utility function). But that would add substantial complexity, and would be very difficult to calibrate accurately. A simpler solution would be for IGEM to assume that (real) government purchases remain constant for policy changes (as ADAGE does).

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[13] IGEM may allow some government purchases to provide benefits, though the documentation is very unclear on this point. Page 1-31 of the IGEM documentation says "Government spending affects household welfare directly through transfer payments and public health spending and indirectly through public capital that improves private sector productivity." But there is no mention anywhere else in the documentation either of public health spending or of how public capital affects private sector productivity, and there do not appear to be any terms in the relevant equations that would represent those effects.

More generally, IGEM should avoid targeting any nominal variable (e.g., holding a variable constant in nominal terms, or assuming that it rises at a constant nominal rate). The value of any nominal variable depends on the choice of numeraire, which is inherently arbitrary.

In other respects, both models' treatment of government purchases seems appropriate and reasonable. Both have a solid basis for how they allocate government purchases across different goods and services, and for how these fit into the larger model.

A distinct but closely related issue is how the models assume that government responds to a change in revenue. Both models assume that tax rates remain constant (except for cases in which the policy being analyzed explicitly includes changes in taxes), so when the tax bases change in response to a policy, government revenue also changes. Thus, some other part of the government budget constraint must also change. IGEM holds the government budget deficit and government transfer payments fixed, which means that government purchases change to offset any change in revenue. ADAGE also holds the government budget deficit fixed (indeed, it appears to assume that the deficit is always zero, though the ADAGE documentation doesn't explicitly say this). But, as noted above, it keeps government purchases fixed, so government transfers adjust to offset changes in revenue.

As noted above, IGEM's assumption that government purchases change is clearly problematic when combined with other assumptions in the model. One could argue that ADAGE's assumption that government purchases are fixed and government transfers adjust is preferable. But it might be better still for both models to make the assumption that all government expenditures are fixed (in real terms), and thus that tax rates adjust to hold government revenue fixed (also in real terms). This issue is similar to the point above about holding government purchases constant. In a representative-agent model, there is no reason for government to make transfers to the household, but such transfers do have a cost (the distortionary cost of raising tax revenue). But in a more sophisticated model, there would be a reason for those transfers. Because these models assume a representative agent for simplicity, they ignore the reasons for government transfers, and thus will give somewhat misleading results for cases in which lump-sum transfers change. Alternatively, one could keep the assumption that tax rates stay constant and transfers adjust, which is simpler than adjusting tax rates, but explicitly note that when describing the results and add the caveat that this may have significant distributional effects.

In addition, both models would benefit from better documentation of how they model government. ADAGE's documentation on this issue is simple and well-organized, so it is easy to find and to understand the relevant sections, but more detail on implementation would be useful. For example, the documentation says that government purchases of goods and services are held constant. This suggests that the quantity of each good or service purchased by the government is held constant, not that the amount spent on each good is held constant, or that the total amount spent is held constant, but the description is so brief that one cannot be entirely sure.

IGEM provides much more information, which is very helpful, but the documentation is not well organized, and it is difficult to find the relevant sections. Moreover, different sections of the documentation sometimes seem inconsistent.[14] These may in fact be consistent, but not written clearly, or this may be the result of minor modifications to the model with different sections of the documentation being written at different times.

***ii) Taxes.*** ADAGE and IGEM each recognize and include the important distinction between marginal and average tax rates on labor, which differ substantially in a progressive tax system (IGEM, for example, uses a marginal labor tax rate of roughly 28% and an average rate of roughly 12%). The average tax rate is important for calculating tax revenue, whereas the marginal tax rate determines the size of the tax distortions in the labor market. Both models therefore include this distinction (though the ADAGE documentation could use a bit more detail on exactly how the two different rates are used in the model).

Both models calculate average tax rates in essentially the same way, by dividing labor tax revenue by pre-tax labor income from national accounting data. But they take marginal tax rates from different sources. ADAGE uses the National Bureau of Economic Research's TAXSIM model to calculate marginal tax rates. This model includes many details of the federal and state income tax systems, and is widely used for economic models that include income taxes. IGEM draws marginal tax rates from IRS data on income tax paid at different income levels. This approach is less precise and less detailed, but still sufficient for estimating a marginal tax rate for use in a representative-agent model. The two approaches yield very similar results for the marginal labor tax rate exclusive of FICA (Social Security) taxes: their estimated marginal rates differ by less than 1%, with both models using a rate of approximately 28%.

[14] For an example, refer to Footnote #13 of this report.

However, the two models differ in how they treat FICA taxes. ADAGE treats the FICA tax as a tax, which adds roughly 13% to the marginal labor tax rate (the full combined FICA tax rate is 15.3%, but applies only on earnings up to a cap, so its effect on the average marginal tax rate is smaller). IGEM treats the FICA tax as a combination of household saving (to the extent that contributions are going into the Social Security trust fund) and transfers within the household sector, and thus does not include the FICA tax when calculating the marginal tax rate on labor. Thus, even though both models use very similar marginal rates exclusive of FICA tax, the total marginal tax rates differ substantially, with ADAGE using a rate of roughly 41% and IGEM using a rate of roughly 28%.

The appropriate treatment of FICA taxes in calculating marginal tax rates remains something of an open question. The issue is that a marginal dollar of FICA-covered earnings is taxed, but may lead to a marginal increase in future Social Security benefits. Thus, the true effect on marginal labor tax rates is equal to the marginal FICA tax rate minus the expected discounted value of the marginal increase in future Social Security benefits. ADAGE, by treating the FICA tax purely as a tax, is ignoring the effect of future benefits. IGEM, in contrast, is effectively assuming that increase in benefits exactly offsets the tax. The truth is likely somewhere between those two assumptions: Feldstein and Samwick (1992) calculated effective marginal FICA tax rates taking into account changes in future benefits, and found that they vary widely, but in most (though not all) cases lie between zero and the full statutory tax rate. Some discussion of this issue in the documentation of both models would be useful so model consumers would understand what assumptions are being made in this context.

Both models contain a relatively detailed set of capital tax rates (though even that level of detail represents a vastly simplified version of the actual system of capital taxation in the US). In each case, these capital tax rates and other relevant variables are used to calculate a user cost of capital. This is conceptually the right way to put capital taxes into the model.

One key difference between the models, however, is that IGEM appears to be using the *average* effective tax rate on capital in its cost-of-capital calculations, whereas ADAGE is using the *marginal* effective tax rate. The roles of the two tax rates are analogous to their roles in the labor tax case: the average tax rate is important in calculating revenue, while the marginal tax rate determines the distortions in the capital market[15]

Of these two approaches, it is more important to get the marginal tax rate correct. Holding the marginal rate constant while the average rate changes (i.e., an inframarginal change in the tax), is equivalent to a lump-sum transfer between households and the government. This affects the accounting, but has no direct efficiency effect. In contrast, changing the marginal tax rate while holding the average rate constant (i.e., a compensated change in the tax rate) changes the magnitude of distortions in the capital market, and thus directly affects economic efficiency. Thus, if a model incorporates only a single capital tax rate, it is better to use the marginal rate than the average rate. However, it would be better still to explicitly represent both average and marginal rates in the model. ADAGE and IGEM both take this approach for labor taxes, but it appears that neither model takes this approach for capital taxes (though neither model's documentation is completely clear on this point).

### d) International trade

***i) Commodity flows.*** These are for the most part handled appropriately by both models. One area in which there might be concern is international energy trade in ADAGE, given that trade is modeled using the widely used Armington approach which represents the aggregate supply of each good as a CES composite of imported and domestic varieties. The CRTS CES aggregator function conserves value—the value of output equals the value of inputs—but not quantities, so that the exajoules of, say, coal used will generally differ from the sum of the exajoules of coal that are domestically-produced plus imported from each trade partner. This is a common problem for CGE models using the Armington approach.

A second issue is the ADAGE model's use of a gravity scheme to calibrate benchmark bilateral state-to-state trade flows, which are not part of the IMPLAN dataset and must be imputed. The dearth of this kind of trade data is a well documented problem.[16] This state of affairs raises two questions. First, how do ADAGE's data reconciliation procedures measure up to alternatives? Second, given the broader context of ADAGE's already heavily calibrated

[15] As in the labor tax case, the difference between the marginal and average rates appears to be substantial: the average effective capital tax rate in IGEM is given in Table G.1 as 13.44%, whereas the marginal effective capital tax rates in ADAGE (Table 4-7) for different industries range from 26.3% to 45.8%. There are many reasons why these rates differ between the models other than just the distinction between average and marginal rates, so it is not strictly correct to compare them, but the difference is illustrative nonetheless.

[16] Some recent work which addresses this issue include Canning and Wang (2005), Jackson et al. (2006), and Park et al., 2009).

base-year dataset and the considerable uncertainties involved in these imputation procedures, does all this effort really add up to an improvement in the accuracy of the simulations relative to a naive Armington formulation based on an aggregate supply pool?

***ii) Financial flows.*** The ADAGE model documentation yields few clues as to how international or interregional capital flows are handled. G-Cubed (McKibbin and Wilcoxen, 1998) appears to be the only CGE model that explicitly tracks flows of capital. The traditional scheme adopted by multiregional models based on the GTAP dataset is to specify a trade closure rule in which the current account balance moves toward zero at an exogenously-specified rate and the price of foreign exchange in each region adjusts endogenously in response, without regard to the origins and destinations of the underlying financial transfers among regions. Therefore, in an intertemporal GTAP model the only observable impact of such rules will be adjustments in the present value of aggregate income in each region.

This is essentially the same procedure employed by IGEM, whose authors' note the difficulty of pursuing the alternative approach of specifying the time path of the real exchange rate and allowing the import and export price indexes to adjust accordingly. However, the two approaches appear equally feasible. Trade-focused small open economy CGE models traditionally set the exchange rate as the numeraire price, and in an intertemporal setting it can be specified as declining at the steady-state rate of return on financial wealth, r*, for a reduction of 1 / (1 + r*) per annum. It is then a straightforward proposition to formulate a complementary slackness condition that allows the current account balance to adjust endogenously to satisfy this price path.

### e) Macroeconomic framework

These are handled appropriately by both models, as they generally must be in any CGE model.

### f) General

***i) Resolution:*** *are the model input and output scale resolutions appropriate and do they provide meaningful policy insights at these levels?*

The ADAGE model has an international module that is built on the GTAP Version 6 database of SAMS for 87 countries. This allows considerable flexibility for the model to consider a variety of international configurations with which the US model can interact. As the documentation indicates, a reasonable grouping of countries for a global analysis – essential for thinking about climate policy – would include the United States, Europe, Japan, Australia/New Zealand, China/India/Russia and the Rest of World.

ADAGE's clustering of countries is similar to other CGE models used for climate policy analysis including MIT's Emissions Policy and Prediction Analysis (EPPA) model. EPPA, for example, in a recent report focused on interactions between the United States and Canada, Japan, the European Union, Australia/New Zealand, the Former Soviet Union, Eastern European countries in transition, India, China, Indonesia, Higher Income East Asian countries, Mexico, Central and South American, the Middle East, Africa, and the Rest of World (Paltsev et al. (2009)). While this cited analysis using the EPPA model has greater detail in the countries, it appears that ADAGE has the capability to do comparably detailed modeling of international clusters of countries.

Within the United States, ADAGE's US Regional model allows for any configuration of states as is appropriate for modeling. The documentation included for this peer review in Ross (2009) shows an illustrative grouping in Figure 1-3 of the US broken down into five regions: West, Plains, Midwest, South and Northeast.

ADAGE's treatment of regions both internationally and within the United States is both appropriate and consistent with the regional resolution of other CGE models focusing on environmental issues including climate change. Other models that are in use to evaluate U.S. environmental and energy policy include CRA International's Multi-Region National (MRN) model, EPRI's MERGE model and Pacific Northwest National Lab's MiniCam model.

ADAGE breaks down each region's economy at the country level into five broad industrial groups (agriculture, energy-intensive manufacturing, other manufacturing, services, and transportation) and five primary energy industries (coal, crude oil, electricity, natural gas and refined petroleum). Electricity is further broken down into various sources of generation. Again this is consistent with the sectoral breakdown in other CGE models used for environmental and energy policy analysis. Given the importance of the electricity sector for climate change – over half the electricity in the United States is generated from coal – an important feature of the ADAGE model is its handling of renewable electricity sources (wind, solar, hydro, and biomass) as well as its inclusion of new fossil fuel technologies (IGCC with or without carbon capture and storage). The parameterization of these newer technologies is to some degree speculative. But given the importance of these new technologies for helping effect a shift to a carbon-free economy it is important to include them in any analysis of climate change policy.

ADAGE is a representative agent model. That means that in each country income is received by and consumption undertaken by a representative utility maximizing household. The advantages of this approach are that it is easier for ADAGE to compute a full forward looking intertemporal general equilibrium in which the representative agent in each country (or sub-region within the United States) maximizes its utility fully anticipating future policy impacts. Saving and investment is endogenous and consistent with economic theory. The drawback to this approach is that the ADAGE model cannot provide any information on heterogeneous policy impacts across different household types within the United States (other than across region). Elsewhere in this review we have discussed the shortcomings of using a representative agent and made suggestions for improvement.

Adding heterogeneity across income groups would be a valuable extension of the ADAGE model. With increased computing power it is becoming increasingly feasible to add this level of detail and keep the model tractable for computational purposes. MIT's EPPA model has recently been extended to allow for both regional and income heterogeneity in its US-REP model (see Rausch et al. (2009) for a discussion of this new model). That model is being extended in a dynamic-recursive framework along the lines of the standard EPPA model.

IGEM is a highly detailed CGE model of the U.S. economy with great sectoral and household detail. It's strengths are the detailed modeling of industries in the U.S. economy (35 industries listed in Goettle et al. (2009)). The benefit of the detailed sectoral groupings in the IGEM model is the ability to track specific industry impacts with great specificity. For example, IGEM is capable of providing analysis for specific industries – the chemicals and allied products industry, for example, while ADAGE groups this industry with other sectors into a single energy-intensive manufacturing sector.

One drawback of the IGEM model is its treatment of the energy sector. The model does an excellent job of treating existing energy production at a fairly high level: coal mining, oil and gas mining, petroleum refining, electric utilities, and gas utilities. This representation of energy precludes the model saying anything about the introduction of new technologies and will not easily represent the expansion of newer technologies (e.g. wind and solar). This is due to the model's econometric approach to constructing and parameterizing the model with data from the period 1960 to 2005. Wind and solar, for example, have been growing rapidly. Focusing on wind, it accounted for 0.1 percent of generation by 1991 and had grown in importance to 1.3 percent by 2008.[17] Using historic data to parameterize the model makes it difficult to add new technologies (or allow for more recent changes in technology for which a fundamental technological change has occurred that is not well represented by the translog functions).

This approach also means that new technologies such as carbon capture and storage (CCS) simply cannot be incorporated into the analysis. Goettle and Fawcett (forthcoming), for example, estimate a 44 percent reduction in the output of the coal mining industry by 2030 in response to a U.S. policy that limits GHG emissions to 203 billion metric tons (bmt) between now and 2050. The analysis by Paltsev et al. (2009) finds little growth of CCS by 2030 for a 203 bmt scenario but finds the growth of CCS sensitive to the relative cost differences between nuclear and CCS. Moreover the Paltsev et al analysis finds a greater role for CCS in the 167 bmt scenario.

IGEM handles this issue (as well as the issue of domestic and international offsets in climate policy) by incorporating external marginal abatement curves for different options into the analysis. Through an iterative approach, IGEM merges external marginal abatement costs with its internally computed marginal abatement cost schedule to arrive at a mix of emission reductions determined from IGEM's general equilibrium in the face of policy constraints along with a mix of externally generated emission reductions. In general, this approach is an appropriate grafting of new technologies and policy options onto a model that has been developed from econometrically derived relations.

IGEM is a domestic model. It uses an Armington (1969) assumption and treats imports as imperfect substitutes for domestic production. It is unclear how IGEM is able to handle different assumptions about climate policy by other countries in affecting US production, consumption and welfare outcomes, given this approach.

A new version of IGEM (Version 3) allows for household heterogeneity across family size, region of the country in which the household lives, race and gender of household head and type

[17] Table 8.2a in Energy Information Administration (2008).

of residence. The peer review team received this new documentation late in the review process and we have not done a detailed analysis of it. We found the reporting of household welfare effects in the documentation sent to us intriguing but difficult to interpret (e.g. Figure 9.9, Household Welfare Effects by Region). We would expect that as the new IGEM model is further developed the modelers will find more useful ways to report results taking household heterogeneity into account.

One issue for any analysis reporting results across regions is the treatment of household migration. It appears that implicit in the ADAGE and IGEM results is the assumption that households do not ever move to a new region. This is an assumption made by others including the MIT US-REP model, the U.S. regional variant of the EPPA model.

***ii) Sensitivity to alternate specifications or data.*** Neither the ADAGE nor the IGEM model reports results from alternative specifications or data. It is thus impossible for the Peer Review Team to assess the sensitivity of the models to alternative specifications or data.

***iii) Uncertainty: how does the representation of uncertainty compare with others in this class of models, and are there recommendations for better representation of uncertainty?*** Many environmental problems are associated with considerable uncertainty over the benefits and costs of policy response and/or inaction.

Considerable uncertainty exists over the likelihood of the development of new technologies to help shift the U.S. and other economies away from reliance on fossil fuels. Some sensitivity analysis of the ADAGE and IGEM marginal abatement cost curves for new technologies would be helpful for understanding how important assumptions about new technology development are in driving results. This can be done to a great extent by considering various scenarios about the availability of new technology as well as its cost.

As a class, CGE models for climate policy analysis generally do not have structural representations of uncertainty (as in, e.g., a dynamic programming simulation), nor do their outputs generally do a good job of capturing uncertainty, in terms of their input data, parameter values or random shocks. IGEM and ADAGE are as bad at this as their peers (e.g., MIT-EPPA). That said, there is enormous scope for conducting parametric uncertainty analysis with either of these models, but the key challenges are the size of the parameter space and the supports for the probability density functions (pdfs) of values for the various input parameters. A key advantage of IGEM is that the latter concern is automatically dealt with, at least to a certain extent, as every parameter of its cost, expenditure and demand functions has an associated standard error.

Computable general equilibrium models are complex systems of numerous equations that make detailed understanding of the drivers of results difficult to determine. Both the ADAGE and the IGEM model results are presented as scenario results rather than as predictions of the future. This is appropriate given the great deal of uncertainty of many key parameters embedded in the models. It would be valuable for EPA to fund analyses that explicitly account for our uncertainties about key parameters. Monte Carlo analyses with the ADAGE and IGEM models would improve our understanding of the economic impact of environmental policy to a great measure.[18]

The ADAGE model does not attempt to measure the benefits of improved environmental quality from policy action. Documentation for the IGEM model shows how IGEM can be used to model benefits from environmental policy – in particular improvements in morbidity and mortality effects. There is no discussion of the sensitivity of results to changes in assumptions of morbidity and mortality effects in its discussion of the costs and benefits of the Clean Air Act (Chapter 3 of IGEM documentation, part I).

## 3. *Usefulness for Evaluating the Effectiveness of Policy Instruments*

### a) Are the model results reasonable and credible?

Given our limited understanding of important technological changes that climate policy (and other environmental policies) will engender and the considerable uncertainty about agricultural and land use impacts, the model results are reasonable and credible.

However, there are a few dimensions of the models which are less than totally satisfactory. One is the allowance price. One is always suspicious when two different models generate the exact same trajectory of prices over a half century for something as centrally important as the price of allowances. This is apparently because the price of allowances is effectively exogenous, at least in the context of HR2454 and S, 1733. What is exogenous is an estimate of the supply curve for international offsets (which is fairly elastic). If the constraint on international allowances is not

[18] Here we have in mind analyses along the lines of Webster et al. (2008).

binding, then the price of US allowances is set by the international market. This appears to be the case for HR 2454. Our recommendation is that this important component of the model determining allowance prices be documented more explicitly, including data inputs.

Another issue is the electricity sector. When the models are run in conjunction with the IPM (Integrated Planning Model), which is a very detailed model of the electric power sector, there are very significant differences between forecast fuel use in the sector between the CGE models and the IPM.[19] Working on merging a more detailed technology-based representation of electricity into the CGE framework would be useful.

One area where greater justification for modeling assumptions would be valuable – or perhaps greater sensitivity analysis presented – is the assumption in IGEM of perfect capital mobility. While this assumption might be valid for long-run general equilibrium models, it seems inappropriate for models that purport to measure impacts in both the short and long run. The assumption of perfect capital mobility should drive costs of climate policy down. A similarly high responsiveness occurs in labor supply with IGEM assuming a high compensated labor supply elasticity. Here again some sensitivity analysis and Monte Carlo analysis around these key assumptions would be valuable for policy assessment.

### b) Does the model produce forecasts that are meaningfully differentiated based upon the use of different policy instruments?

For climate policy, a key difference between price-based instruments (a carbon fee or tax) and quantity-based instruments (allowance system) is their operation under uncertainty (see Weitzman, 1974 and subsequent analysis by Newell and Pizer, 2003 and Karp and Zhang, 2005, among others, for discussion of instrument choice under uncertainty). In both the IGEM and ADAGE models the two policy approaches are functionally equivalent in the absence of uncertainty.

One way to address this issue would be to undertake Monte Carlo analyses to obtain stochastic variability in the marginal cost of abatement curves. This would actually be quite useful given the focus on cost containment in a number of the Senate and House climate policy bills that have been brought forward in the past year. We note however that Monte Carlo analyses are not the

[19] Compare pages 17 and 26 of the EPA analysis of HR 2454.

same as modeling explicitly under the assumption of uncertainty. In Monte Carlo, economic agents are not explicitly taking the uncertainty over future prices and policies into account when making decisions. Monte Carlo should best be thought of as sophisticated sensitivity analysis rather than a rigorous inclusion of uncertainty in a CGE model.

### c) Does the model have sufficient transparency to produce defensible forecast scenarios in the face of public criticism?

The model documentation appears sufficiently detailed to allow professional economists to assess and defend forecast scenarios in the face of public criticism. It is important for EPA to stress the limitations of any economic analysis extending out forty or more years in the face of considerable technological uncertainty. Models have great value for understanding the consequences of policy action (or inaction) but they are not forecasts of the future.

However, the models do remain as black boxes to many. It might be useful to both improve the clarity of the documentation of IGEM and the detail of the documentation of ADAGE. Furthermore, the EPA might consider developing small versions of each of these models that are more transparent.

### d) Does the model have enough flexibility to support the analysis of multiple types of regulatory regimes and input data sources?

Both the ADAGE and IGEM models are best suited to supporting the analysis of market-based policies. This follows from the simple fact that both these models are Arrow-Debreu general equilibrium models in which price adjustment to clear markets is central to the models' operation. Technology mandates and other command-and-control type regulation can be modeled by ADAGE and IGEM to the extent that reasonable constraints can be designed that capture the regulatory regime. But it is unclear that all of the nuances of actual legislation can actually be represented in either of these models.

## 4. *Conclusions*

We begin this summary by noting that both the ADAGE and IGEM models are extraordinarily sophisticated economic models with richness of detail in modeling various aspects of the U.S. economy. The model developers are to be commended for the excellent work that they have done in recent years to make these models useful for the EPA and other government agencies interested in modeling the impacts of policies to address greenhouse gas emissions and other environmental issues.

We have made a number of suggestions in the body of this report, none of which is vital for the validity of these models. Rather, we urge EPA to view the long-term improvement of these models as in the EPA's interest, so that future analyses may be improved. Some of these recommendations are listed below, though the list is not intended to be comprehensive (refer to the body of the report for other suggestions):

- Improve the Documentation of both IGEM and ADAGE
- Improve the documentation of the carbon abatement and allowance price determination in both models
- Work to reconcile electricity sector results from either model and bottom up electricity supply models such as IPM
- Improve the justification of perfect capital mobility in IGEM or consider alternative formulations
- Provide more documentation and justification for the parameterization in ADAGE
- Provide more publically available sensitivity analysis of both models
- Work to improve the representation of endogenous technological change

On balance, these are two excellent models that provide useful information to EPA as it goes about its work of evaluating climate policies. While we may have issues with elements of the models, in general we find these to be first-rate and state-of-the-art. These models are essential tools for the analysis of environmental policy in general and climate policy in particular.

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# Attachment 3

## Response to Peer Review Panel prepared by Dale Jorgenson Associates regarding IGEM

**Response to Charles D. Kolstad, Gilbert E. Metcalf, Ian Sue Wing, and Roberton C. Williams III, "Peer Review of Computable General Equilibrium Models for Climate Change Analysis," January 28, 2010.**

**by**

**Dale W. Jorgenson, Harvard University, Daniel T. Slesnick, University of Texas, Austin, Peter J. Wilcoxen, Syracuse University, Richard Goettle IV, Northeastern University, and Mun S. Ho, Resources for the Future, Inc., February 19, 2010.**

The conclusions of the Peer Review are presented on pages 31-32: "We begin this summary by noting that both the ADAGE and IGEM models are extraordinarily sophisticated economic models with richness of detail in modeling various aspects of the U.S. economy. The model developers are to be commended for the excellent work that they have done in recent years to make these models useful for the EPA and other government agencies interested in modeling the impact of policies to address greenhouse as emissions and other environmental issues."

We are very grateful to the reviewers for the care they have taken in preparing the Peer Review and we agree with their views about research priorities for the future. Here is a summary of our response, following the recommendations on page 32:

The documentation of IGEM discusses the current version used in policy evaluations for the Environmental Protection Agency, as well as a new version that will be implemented during the coming year. We will revise the documentation to focus on the new version. This will simplify the presentation and make it more user-friendly.

The documentation of carbon abatement and allowance price determination deserves special attention.

Integration of IPM and IGEM should be undertaken when this becomes a matter of priority in policy analysis.

The term "perfect capital mobility" used in the Peer Review does not convey the role in IGEM of external costs of adjustment along the transition path, as outlined below. We will try to frame this issue better in the documentation for the new version of IGEM.

We will provide standard measures of uncertainty for outcomes of IGEM, as well as the parameter estimates. Sensitivity analysis, recommended at several places in the Peer Review, cannot provide such measures. More detail is devoted to this central point below.

Pages 2-8 provide general comments and the reviewers' responses to general questions posed by EPA. The first conclusion, presented in page 3 is: "Both the ADAGE and IGEM models are sophisticated computable general equilibrium models in which great care has been taken to model aspects of the economy particularly important for analyzing environmental policy in general and climate policy in particular." Our response begins with the treatment of four major issues discussed in the Peer Review. The first is the representation of technology, the second is modeling household behavior, the third is the treatment of uncertainty, and the fourth is the solution of the model.

*Production Modeling.*

The approach to modeling the production sector in IGEM is based on recent research on induced technical change by Jin and Jorgenson (2010). This has been published in a refereed journal, the JOURNAL OF ECONOMETRICS. The principal achievement of this research is to integrate the estimation of the price elasticities that describe substitution with the rates and biases that describe technical change. The results are thoroughly discussed in the IGEM documentation.

The Jin-Jorgenson model of induced technical change provides an endogenous treatment of technical change. In fact, "induced" is a synonym for "endogenous". Furthermore, this model makes it possible to quantify the importance of policy-induced technical change in the evaluation of changes in policy. As in all the published literature on environmental and climate policy analysis, the role of policy-induced technical change in evaluation of policy outcomes is empirically very minor.

The representation of endogenous technical change in the Jin-Jorgenson model of is based on econometric estimates, fitted to historical data for each of 35 industries, five representing the energy sector. The vast bulk of economic activity relevant to environmental and climate policy evaluation is represented in the historical data. Econometric methods are essential for summarizing these data and introducing them into the simulations. An approach that ignores the historical data makes it impossible to evaluate the results using standard measures of uncertainty discussed below.

All econometric estimation involves imposing structure to achieve identification. IGEM imposes the structure required to use the economic theory of production that underlies concepts like price elasticities and technical change. On page 14 the reviewers make the "philosophical" point that indicators of innovation such as R&D expenditures should be integrated into econometric models. The data required to implement this approach for a model like IGEM are not available. However, these data are under construction by the Bureau of Economic Analysis and we will incorporate them into IGEM when they are released.

IGEM's estimation techniques impose concavity restrictions at all historical data points, following a technique first discussed in the econometric literature by Gallant and Golub (1984) and cited in the IGEM documentation. This is superior to "global" concavity restrictions that require a sacrifice of flexibility in representing substitution patterns. Although this point is well known to econometricians, it has been slow to penetrate the modeling literature. IGEM uses nonlinear econometric estimation techniques for both household and production models.

IGEM is unique among models of energy and environmental policy in using econometric methods to calibrate the unknown parameters. This is essential in providing the measures of uncertainty described below. However, the econometric approach leaves open the question of how to introduce technologies that are not represented in the historical data. Our solution to this problem is standard in the literature, namely, we use engineering representations in the form of marginal abatement cost (MAC) curves. This technique has been employed in previous versions of IGEM and in other models for evaluating energy and environmental policies.

On page 27 the reviewers assert that new technologies such as carbon capture and storage (CCS) "simply cannot be incorporated into the analysis." Actually, CCS and all of the technologies (except electric vehicles) discussed in the Peer Review are represented by the marginal abatement cost (MAC) curves in IGEM. These are introduced as endogenous responses to energy and environmental policies. Later on page 27 the reviewers point out that new technologies are introduced endogenously in response to price changes in IGEM and continue: "In general, this is an appropriate grafting of new technologies and policy options into a model that has been developed from econometrically derived relations."

On pages 14 and 15, the reviewers properly credit ADAGE for employing the "state-of-the art technique" developed by Hyman, *et al.*, (MIT – JCSPGC – Report No. 94, December 2002) for modeling non-$CO_2$ marginal abatement costs. The non-$CO_2$ MAC curves are supplied by the Environmental Protection Agency and are widely shared among the modeling community. In ADAGE these curves are used to calibrate the parameters of a constant elasticity of substitution (CES) composite production function, illustrated in Figure 1 below. Abatement depends on the price of allowances relative to the composite price of other inputs -- labor, capital and intermediate goods and services.

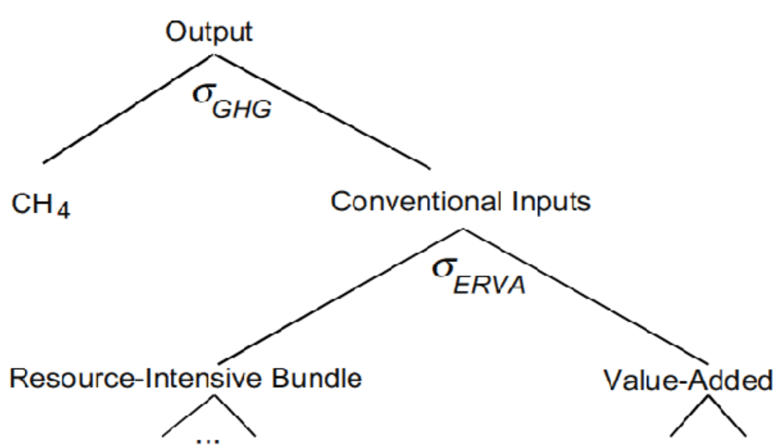



**Figure 1.** The Agriculture Production Structure with Methane as Input to Production

The reviewers go on to say, "Given IGEM's representation of the aggregate economy and the availability of EPA's detailed GHG emissions accounts for the US, it isn't apparent why the authors could not distribute emissions amongst sectors and sub-tiers of the production and consumption hierarchies, and directly model abatement possibilities using the aforementioned state-of-the-art technique, instead of the now dated method of using MAC curves directly as a side-constraint on the general equilibrium problem."

The emissions accounting in IGEM is precisely that recommended by the reviewers. The MAC curves are introduced endogenously in determining the allowance prices that clear markets under a cap-and-trade regime and do not serve as a "side constraint on the general equilibrium problem". While the mechanics differ, determination of allowance prices, abatement costs, and emissions reductions is identical between the IGEM and ADAGE. Moreover, the IGEM methodology recognizes the possibilities of irregularities, regions of "no regrets" and threshold pricing, which is impossible using the approach outlined in Figure 1. By way of example, the IGEM approach permits MAC curves like the "composite" shapes depicted below rather than relying on the CES approximation indicated by "sigma":

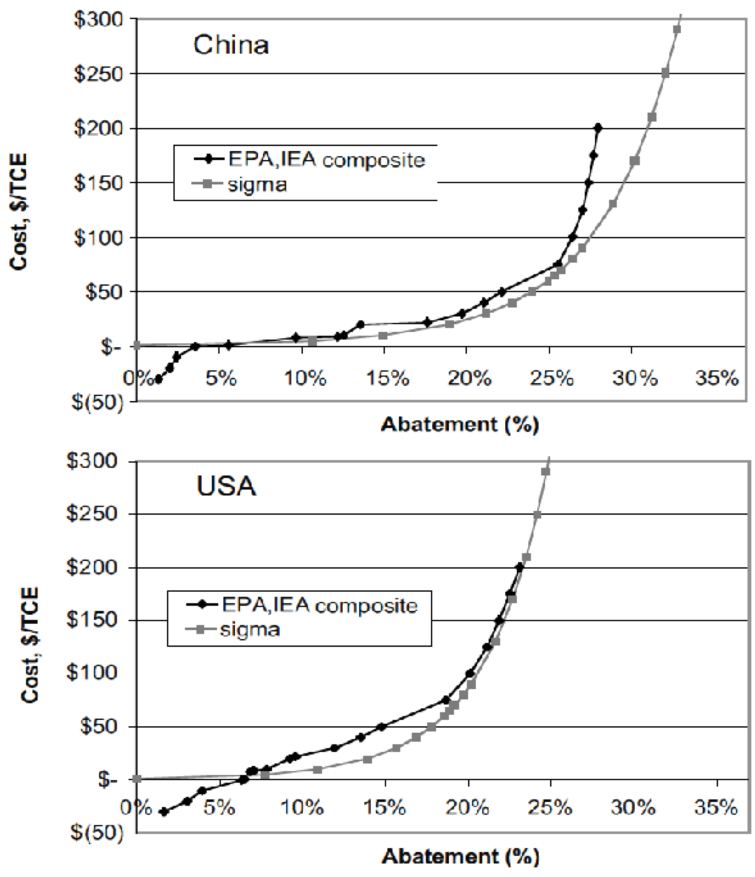


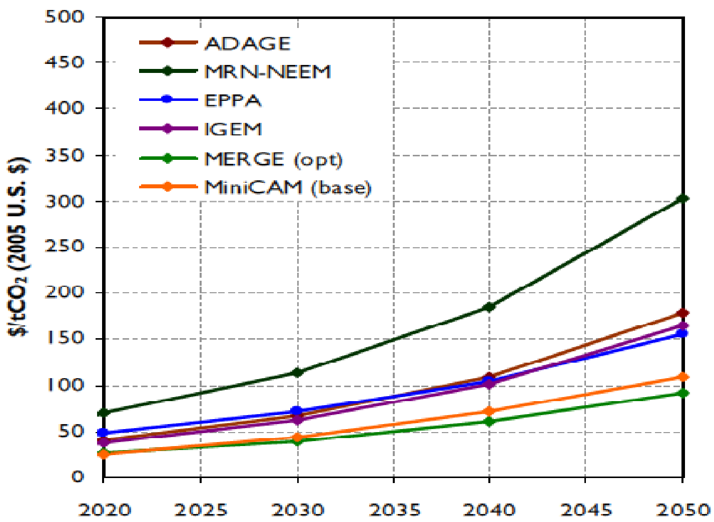

**Figure 2**. Comparison of EPPA parameterization (squares) with methane marginal abatement curves (diamonds) for China (top panel), and the USA (bottom panel) *Source:* Bottom-up abatement curves were derived by combining data from IEA (1998, 1999) and U.S. EPA (1999); for details, see Hyman (2001).

On page 5 the reviewers propose "…remedying the lack of non-marginal (GHG-saving) technological change by incorporating discrete alternative energy demand and supply technologies, which come on line endogenously in response to price." This is the purpose of the marginal abatement cost (MAC) curves used in IGEM. Given the exhaustive analysis of historical data on production by Jin and Jorgenson, the most important opportunity for improvement of models of technology is for EPA to obtain and utilize additional engineering studies. This is, of course, very resource-intensive.

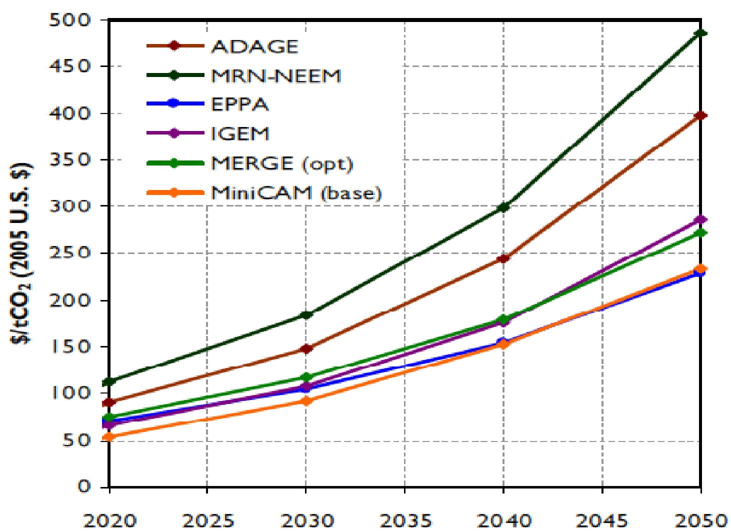
We must re-iterate that the time path of allowance prices is determined endogenously. This time path clears the market for a given time path of the cap on emissions. The abatement opportunities represented by econometric models of production in IGEM must compete with external abatement opportunities represented by MAC curves. These include capped non-CO2 sources, domestic offsets such as agricultural sequestration, international offsets, and new energy demand and supply technologies. The time path of allowance prices also recognizes provisions for banking and borrowing and the rules governing the use of domestic and international offsets.

The mix of abatement from IGEM and the external MAC schedules is also endogenous. We introduce the endogenous abatement costs from the external sources into IGEM, so that emissions accounting in IGEM and ADAGE is fully comparable. Pollution abatement results from output reductions, input and output substitution, and end-of-pipe treatments of pollutants. Price-induced substitution and technical change are based on observed behavior over the last half century. .

In conducting policy simulations for the EPA, a variety of scenarios involving the domestic and international offsets are considered. For example, in the EMF 22 exercise, the U.S. simulations were conducted with no international permit trading and, alternatively, no domestic offsets. In these simulations, the time paths of allowance prices between IGEM, ADAGE and the MIT-EPPA model are remarkably similar for the least restrictive caps on cumulative greenhouse gas emissions (287 and 203 $GtCO_2$-e). As the cumulative emissions constraint tightens to 167 $GtCO_2$-e, the price trajectories diverge with MIT-EPPA showing the lowest long-run allowance prices, ADAGE the highest and IGEM in between (the 203 and 167 $GtCO_2$-e EMF 22 results are reproduced below).




203 $GtCO_2$-e




167 $GtCO_2$-e

We conclude with a list of additional issues raised in the Peer Review about modeling production. IGEM has the capability to treat both real and nominal values of government purchases as fixed. The reviewers provide a very sophisticated discussion of modeling the impact of the government revenue structure on page 22. The IGEM modeling team will make use of this in its future work. Fuel switching is modeled in IGEM at the industry level. Fuel switching at the plant level is modeled in IPM; the results can be integrated with those in IGEM, if required for policy analysis. We agree that merging IPM and IGEM would be valuable for some purposes and should be undertaken when this has high priority and resources are available. The amount of capital available to the economy is the result of past investment. This limits production patterns in every period to those that are consistent with the initial stock of capital. We believe that imposing “ex post” fixed coefficients does not describe technologies actually available to the economy with any kind of accuracy.

*Modeling Household Behavior.*

We turn next to the modeling of household behavior in IGEM. It is not correct to say on page 5 of the Peer Review that "Incidence is also poorly represented in the models (IGEM and ADAGE) – how are different income classes and regions differentially affected by policies?" This is specifically addressed in the paper by Jorgenson, et al., "The Distributional Impact of Climate Policy," presented at the Energy Policy Symposium held on January 20-21, 2010, in Washington, DC. It is understandable that the reviewers did not discuss this paper, since the Peer Review was completed only a few days later. However, this is a critical omission.

The reviewers recommend to "… move away from the representative agent assumption and include more heterogeneous households. …" IGEM has never used a representative agent model. The model documentation demonstrates this and a peer-reviewed article published in the JOURNAL OF ECONOMETRICS by Jorgenson and Slesnick (2008), long before the Peer Review was initiated, presents the latest version of the household model. While previous versions of the model, discussed in Jorgenson's (1998) book, are based on heterogeneous households, the new version extends this treatment to labor supply.

As proposed on page 2 of the Peer Review, IGEM measures the effect of proposed legislation on both household consumption and aggregate consumption. This is possible within the exact aggregation framework introduced by Jorgenson, Lau, and Stoker (1980). This approach has generated a vast literature and is the subject of two review articles in the prestigious JOURNAL OF ECONOMIC LITERATURE, cited in the IGEM documentation. IGEM measures the impact on households for four different regions of the country and for subgroups of the population classified by urban vs. rural location, male versus female heads of household, white versus nonwhite heads of household, number of children, and number of adults – 244 groups in all. Within each group IGEM measures the impacts for different levels of living.

IGEM uses an econometric approach to modeling household behavior involving detailed individual data for 150,000 household units. The estimation process in IGEM is presented in the peer-reviewed article by Jorgenson and Slesnick (2008). IGEM bears no resemblance to the calibrated models discussed on page 15 of the Peer Review, which do not use data on individual households and ignore heterogeneity. The calibrated models described by the reviewers are based on a memo by Russek (1996) that has never been published, let alone refereed. The two approaches could not be more different.

The elasticities of labor supply used in IGEM differ by household and level of living. These elasticities are estimated econometrically. The econometric model combines commodity demand with labor supply, a first for empirical models of household behavior. One of the important features of the model is the incorporation of human capital or labor quality in the representation of labor supply. This is also a novel feature of the model.

Why does IGEM include human capital, when this is not the standard practice in much of the literature reviewed by Russek (1996)? This is because the demand for labor also takes human capital/labor quality into account and supply-demand balance in the labor market requires consistency. We do not agree with the reviewers that "… IGEM will tend to overstate the costs of climate change policy." IGEM provides the first model of household behavior that meets the needs of general equilibrium modeling for consistency in integrating demand and supply. Finally, the intertemporal elasticity of substitution estimated by Jorgenson and Slesnick (2008) is presented in the IGEM documentation.

*Representation of Uncertainty.*

We next consider a central issue introduced on pages 3 and 4 of the Peer Review, namely, the representation of uncertainty. IGEM is unique among models of environmental and climate policy in providing standard errors for the parameter estimates used in the household and production models. The current research objective for IGEM is to introduce a new version of the model. The next step will be to provide confidence intervals (and regions) for outcome variables, including impacts on households, regions, and industries, as well as measures of economic welfare. This requires estimated parameters as a point of departure, so that the econometric approach used for determining parameters in IGEM is essential.

It is important to distinguish between uncertainty and sensitivity analysis. In sensitivity analysis the parameter values are varied and the outcome variables corresponding to each value are calculated. This approach is valuable in providing measures of the change in outcomes with respect to the change in parameter values. However, sensitivity analysis does not provide measures of uncertainty in the form of confidence intervals with a stated level of confidence. An analysis of uncertainty involves transforming standard errors for the parameters into standard errors for the outcomes. Without standard errors for the parameters as a starting point, this is impossible.

Measures of uncertainty require standard errors. Sensitivity analysis produces measures of change in the outcomes with respect to changes in the parameter values, no standard errors. This simple point is usually overlooked in the literature on computable general equilibrium models because of the reliance of most models on calibration rather than estimation in determining parameter values. Calibrated models can produce measures of sensitivity (derivatives), but not measures of uncertainty (standard errors).

Monte Carlo analysis is not the best approach for dealing with uncertainty, as suggested on page 29 of the Peer Review, due to dimensionality of the parameter space in IGEM. Furthermore, models that capture the features of the economy relevant to climate policy will not be small for reasons outlined above. Standard statistical techniques based on transformations of random variables are appropriate and feasible for dealing with uncertainty. Unlike Monte Carlo methods, these techniques can deal with a large number of parameters. EPA has already developed methods "… that explicitly account for our uncertainties about key parameters." These methods should be extended to the outcome variables generated by IGEM.

*Model Solution Algorithms.*

Finally, we arrive at the solution of the model, an important issue in any application of computable general equilibrium modeling. The Fair-Taylor algorithm used in IGEM is a standard solution technique widely used for the solution of general equilibrium models. Determination of an equilibrium corresponding to a particular energy or environmental policy requires a matter of seconds in IGEM, using a standard desk-top computer running Windows XP. This is despite the large number of variables and equations in the model. The Path algorithm discussed on page 5, footnote 8, of the Peer Review is also a valid approach.

How can solutions to IGEM be carried out in a matter of seconds? This is due to the careful optimization of the computations described in detail in Appendix I of the IGEM documentation. Since IGEM is highly nonlinear, the calculation of the equilibrium involves an iterative process. Optimization of the computations involves a carefully designed sequence of calculations for each step in the iterative solution. The computational design is of great importance in reducing the time required for the calculations. Many of the standard algorithms recommended in the literature could be used, but Fair-Taylor is particularly economical in the use of information.

On page 6 the reviewers argue that "costs of adjustment" must be modeled in order to capture transitional costs of climate policies. Although internal costs of adjustment are often used by macro-econometric modelers focusing on economy-wide aggregates, it has proved to be impossible to obtain a robust set of parameter estimates appropriate for intertemporal equilibrium modeling involving a large number of industries. In IGEM external costs of adjustment are captured in modeling the transition to long-run equilibrium. This avoids misleading simplifications often used by CGE modelers, including climate modelers, such as limiting policy comparisons to alternative steady states or even to alternative static equilibrium states.

IGEM models the transition from the initial configuration of outputs and inputs for the 35 sectors and initial consumption patterns of the thousands of different types of households along a transition path involving several decades. Relative prices change along the time path, resulting in costs of adjustment that are external to the producing units and the households. On page 11 the reviewers repeat their point about adjustment costs, ignoring the external adjustment costs employed in IGEM's modeling of transition paths. These paths are not reversible, since the initial conditions faced by the economy change as capital is accumulated and relative prices change.

Policy makers may be interested in features of the transition to a new policy regime over a much shorter period of time, such as the period of 12-18 months used in macro-econometric forecasting. As the reviewers point out IGEM (and ADAGE) are inappropriate for this purpose and could be replaced by a dynamic, stochastic, general equilibrium (DSGE) model like the one under development by the Federal Reserve Board. Integration of DSGE models with long-run intertemporal models like IGEM is beyond the scientific frontier at the moment, but is a worthwhile research objective. However, we would assign much lower priority to this than other research objectives described above.

*Summary and Conclusion.*

To conclude: The Peer Review covers the four major points in EPA's original request to the panel and provides a well-informed overview of the issues to be considered in the selection among different approaches to climate policy modeling. We have tried to clarify points that arise in the review's characterization of our approach to household modeling, the treatment of technological change through the introduction of MAC curves, and the important distinction between confidence intervals and sensitivity analysis. We will concentrate attention on providing confidence intervals and regions for outcome measures during the transition to a new version of IGEM. The econometric estimation approach employed in IGEM is essential for this purpose.

When the new version of IGEM has been successfully introduced, we will simplify the documentation by focusing attention on the new version of the model. This should help to dispel some of the ambiguity that is inevitable in the documentation for a complex modeling project like IGEM. However, we should emphasize in closing that we are in basic agreement with the reviewers on the central points of modeling production, analyzing consumer behavior, characterizing uncertainty, and choosing an appropriate solution algorithm. The Peer Review will be of great value in setting priorities for future research. This will add to the usefulness of IGEM in evaluating alternative environmental and energy policies, including the policies for mitigating climate change described on EPA's Climate Economics website.

# Attachment 4

## Response to Peer Review Panel prepared by Resource Triangle Institute regarding ADAGE

**RTI ADAGE Model**

**Peer Review of Computable General Equilibrium Models for Climate Change Analysis Response to Comments**

We are grateful to the reviewers for the thoughtful Peer Review they have put together, and we expect their recommendations will be very useful as we continue researching ways to improve the ADAGE model. We are pleased they have concluded the review by noting that "both the ADAGE and IGEM models are extraordinarily sophisticated economic models with richness of detail in modeling various aspects of the U.S. economy. The model developers are to be commended for the excellent work that they have done in recent years to make these models useful for the EPA and other government agencies interested in modeling the impact of policies to address greenhouse as emissions and other environmental issues."

The reviews raise a number of important points for consideration. Our comments below discuss options for addressing these points, whether through additional documentation of features already in the ADAGE model that may require clarification or through changes to the existing model structure. We are currently engaged in the process of revising and improving the model, and we expect the reviewers' comments to be particularly helpful in guiding this effort. Specific points from the peer review along these lines are highlighted in the following discussion. We will expand the model documentation to cover new features in ADAGE, in addition to clarifying any ambiguous descriptions of features in the current documentation.

On page 7, the review notes that "ADAGE's documentation is simple, clear, and well organized... However, it could be improved by adding more detail throughout, particularly on the details of how particular aspects of the model are implemented." Specific suggestions for the documentation include:

- Identifying key uncertainties (pages 3-4): We can expand the discussion of the model structure to contrast it with other computable general equilibrium (CGE) models. One similar model is the CRA MRN-NEEM model, although the publicly-available documentation does not provide the opportunity for a detailed comparison of important parameters and assumptions. However, since ADAGE is a "calibrated" model that uses nested constant-elasticity-of-substitution (CES) functions, generally based on the MIT EPPA model, it is hard to characterize "disagreement" in the literature over specific parameters, beyond a comparison of various models. As noted in the review, this makes sensitivity analyses important when evaluating these types of models. Another option may be to present information on the general-equilibrium elasticities of energy demand that are implied by particular choices of CES equations in the model.

- Additional details (page 7): Since parts of ADAGE are based on the MIT EPPA model, a discussion of how the EPPA model is parameterized can be included in the ADAGE documentation, to the extent that the EPPA documentation provides additional details not already covered. Differences between ADAGE and EPPA can be highlighted. One specific review question asks if the intertemporal elasticity of substitution in ADAGE comes from the EPPA model – it does, which can be highlighted in the documentation.

- Policy results and sensitivity analyses (page 8): The ADAGE documentation does not currently include information on policy results and sensitivity analyses. Given how dependent specific policy results are to a wide range of assumptions about policy implementation, the most practical option is to refer readers to the detailed policy analyses conducted for EPA, which are publicly available. These results contain additional information on input assumptions, model results, and several types of sensitivity analyses regarding technology and offset assumptions. In addition, we can refer readers to ADAGE modeling of a domestic climate policy for the Pew Center on Global Climate Change, which includes sensitivity analyses on the most important parameter assumptions regarding energy consumption and efficiency improvements.

- Information on future energy consumption in baseline forecasts (page 13): As noted in the review, ADAGE uses autonomous energy-efficiency improvements (AEEI) to match baseline energy consumption forecasts from the U.S. Energy Information Administration (EIA), similar to other CGE models. We can expand the model documentation to clarify how baseline forecasts are established after the EIA forecasts end in 2035. The current documentation provides tables of energy consumption through 2050, but a graphical presentation may also be helpful.

- Government actions (pages 20-21): As noted in the review, in accordance with standard modeling practice, ADAGE holds the government budget deficit fixed during policy analyses to avoid confusing policy results with changes in government spending. The documentation can be expanded to clarify how and why this is done. Unlike what is postulated in the review, ADAGE holds the deficit fixed at baseline levels (determined by historical information on tax collections and government spending, along with forecasts of economic activity), rather than forcing the deficit to always be zero. We can also consider the implications of maintaining government expenditures (in real terms), rather than the current approach of maintaining a specific pattern of government purchases (again in real terms). ADAGE adopts the usual approach to this by adjusting government revenues in a non-distortionary, lump-sum way. It is possible in ADAGE to adjust specific tax rates instead to maintain the government expenditures (see work by Goulder for implications of this, as discussed in the ADAGE documentation), however, this complicates significantly the interpretation of model results and is usually not part of proposed climate policies.
- Tax rates (pages 21 and 23): The documentation can be expanded to clarify that ADAGE considers both average and marginal tax rates for labor and capital taxes, although the focus is on marginal rates as these are what distort economic decisions in a CGE model.
- Financial flows (page 24): The ADAGE documentation can be expanded to describe how international and interregional financial flows are handled. As part of this effort, we are also working on describing more formally the equations used in ADAGE, especially those related to dynamics and investment decisions.

Along with these points that are largely related to clarifying and expanding the current documentation, the reviewers have several important suggestions for model improvements:

- Transportation modeling (pages 12-13): The reviewers note that, although ADAGE models some details regarding the provision of public and personal transportation (again based on the MIT EPPA model - see Figure 4 in their documentation), there are additional options for modeling advanced transportation technologies. Because changes in transportation are an important part of the response to climate policies, we hope to expand the modeling of various alternatives in the next version of ADAGE. As noted by the reviewers, the techniques for modeling new transportation options are relatively straight-forward. To handle advanced electricity generation, ADAGE already employs the suggested technique of including dormant technologies at a premium over existing technologies, which can then enter endogenously depending on changes in fuel prices and costs of conventional technologies. One of the reasons such transportation options have not already been included in ADAGE are the difficulties noted in the review associated with parameterizing the technology functions; i.e., determining what assumptions to use about technology costs and availability.

- Electricity modeling (pages 4, 12 and 30): We feel that modeling of electricity technologies is a particular strength of ADAGE, compared with many other CGE models, although any CGE model by necessity will have far less detail than detailed electricity dispatch models such as EPA's Integrated Planning Model (IPM). ADAGE explicitly models specific advanced generation options such as IGCC with carbon capture and storage (CCS). The modeling techniques used are similar to those suggested in the review for transportation modeling, and are the same techniques as those used in the MIT EPPA model. Currently, assumptions about costs and efficiency of these advanced electricity options, and any learning-by-doing as new capacity expands, are conservatively based on the reference case from EIA's Annual Energy Outlook. The reviewers point out that there are differences between results for the electricity sector from ADAGE and IPM. To some extent, this is a function of their being very different types of models, however, additional steps are being taken to coordinate their responses for consistency. Beginning with EPA's January 2010 supplement to the H.R. 2454 analysis, ADAGE is using additional information from the IPM model regarding feasible nuclear and CCS construction to help calibrate responses between the two models. Longer term, we hope to pursue additional methods for linking the two models, although calibration of responses between a CGE model and a model such as IPM that uses a linear-programming structure can be challenging.

- Households (page 5 and 26): Regarding income classes and the incidence of policies – in the next version of ADAGE, we hope to include multiple household classes in each region of the model, similar to the recent MIT US-REP modeling.  The IMPLAN economic data used in ADAGE for the U.S. distinguish nine types of households based on annual income.  While this is not a first-best solution (such as an overlapping generations model, perhaps), it would improve the model's ability to examine incidence.

- Agriculture (pages 9-10): The reviewers note that domestic and international emissions offsets from agriculture play an important role in climate policy analyses and suggest disaggregating the agricultural industry in ADAGE.  Although most dynamic CGE models used in climate analyses have a single, aggregated agriculture sector, we hope to expand this sector in the revised version of ADAGE to distinguish crops, livestock, and forestry so that sources of offsets could be modeled more explicitly.  Whether this proves to be feasible depends on computational limitations of dynamically-optimizing CGE models and competing needs for additional sectoral detail in other areas of the economy.

- Interstate trade in goods (page 23-24): The reviewers suggest considering alternatives to the current model structure that has explicit modeling of state-to-state trade flows, given a lack of good data on which to base this formulation.  We are considering adopting a more aggregate, or national, supply pool for goods, which would be easier to represent than the current formulation.  It is not entirely clear *ex ante* how this would alter estimated policy results, if at all.  An aggregate supply pool is currently used for crude oil (without the Armington specification) to represent it as a homogeneous good.

- Environmental benefits (page 29): The reviewers note that the ADAGE model does not attempt to measure the benefits of improved environmental quality from policy action. Preliminary work with ADAGE has examined how to include benefits associated with preventing climate change (see Copenhagen presentation summary), however, these estimates are not a part of the standard analyses for EPA.

Finally, we would like to clarify how the ADAGE model addresses a few specific points raised by the reviewers:

- $CO_2$ abatement costs (page 9): The reviewers mention that there is little discussion of the source of abatement costs estimates in ADAGE.  This is because estimated $CO_2$

abatement costs realized in policy analyses are a result of the production equations shown in the documentation. No external estimates of these costs are imposed on ADAGE.

- Non-$CO_2$ abatement costs and emissions (pages 14-15): The reviewers also mention that it is much more difficult to model non-$CO_2$ abatement costs. ADAGE employs the solution proposed in Hyman et al. (2003), which allows calibration of model responses to bottom-up marginal abatement cost (MAC) curves from EPA (constructed from engineering estimates). We agree that this approach provides advantages over the use of exogenous MAC curves in the modeling. We have been forced to estimate U.S. regional baselines for non-$CO_2$ emissions and would be pleased to update our information if better data are available, but we are not aware of any potential sources for such information. The exact distribution of interstate emissions will not likely have a great influence on overall U.S. climate policy results based on national cap-and-trade policies since we are using the most recent EPA GHG emissions inventory data for total U.S. GHG emissions.

- ADAGE benchmark, or baseline, data (page 9): The reviewers suggest conducting a program of testing to compare the ADAGE benchmark with available economic data in order to establish differences between the model base year and reality, and subsequently adjusting calibration procedures reduce the most serious errors. While these experiments sound valuable, it is unclear how to proceed with them due to the way a baseline is established. In ADAGE, assumed economic conditions in the base year of 2010 are imposed upon the model (based on the most recently available economic data), rather than allowing the model to make any specific predictions about reality. Similarly, economic growth and energy consumption into the future are imposed upon ADAGE based on external forecasts from EIA, rather than allowing the model to predict how the future will unfold. Some policy analyses conducted for EPA have taken the next-best step of altering these future forecasts and examining the changes in policy predictions.

- Labor supply elasticities (page 16): As the reviews note, ADAGE uses labor supply elasticities that are consistent with the empirical literature and those used in other CGE models. Among the literature considered was the survey by Fuchs et al. (1998), suggested by the reviewers. Unfortunately, all of the empirical literature tends to give a relatively wide range of estimates.