EPA-SAB-20-xxx

The Honorable Andrew Wheeler
Administrator
U.S. Environmental Protection Agency
1200 Pennsylvania Avenue, N.W.
Washington, D.C. 20460

Subject: Transmittal of the Science Advisory Board report on its technical review of EPA's Computable General Equilibrium Model, SAGE, dated [TBD]

Dear Administrator Wheeler:

The EPA's National Center for Environmental Economics requested that the Science Advisory Board (SAB) review its computable general equilibrium (CGE) model known as SAGE. SAGE is intended to strengthen the regulatory process by capturing the social costs of environmental regulation through modeling important interactions between markets. Please find enclosed the final report from the SAB.

In response to the EPA's request, the SAB assembled a review panel with subject matter experts to conduct the review. The panel met in-person meeting on November 22, 2019 and held two teleconferences to deliberate on the agency's charge questions. Oral and written public comments were considered throughout the advisory process. This report is based on the work of that panel and conveys the consensus advice of the SAB.

Overall, the SAB commends the agency on its development of SAGE. The SAB recommended in 2017 that the agency begin developing an open-source CGE model for use in regulation. In the relatively short time since then, the agency has come a long way. On the whole, SAGE is a well-designed open-source model that will soon be suitable for use in regulatory analysis.

This report provides recommendations the agency may want to consider for refining the model. The suggestions are grouped into three categories: Tier 1 recommendations are very short-term changes the SAB thinks are necessary before the model is used as a formal component of the regulatory process. Tier 2 and Tier 3 recommendations are less crucial or are changes that the SAB recommends over the longer run. The key Tier 1 recommendations that go beyond improvements in the model's documentation are listed below and discussed in detail in the text.

Tier 1 Modeling Recommendations:

- Move away from the current exclusive use of a balanced growth baseline by allowing for projected changes over time in key variables that are exogenous to the model, such as the government's fiscal deficit;

- Improve modeling of consumer demand to avoid the current assumption that shares of different goods in overall spending are unaffected by changes in income;

- Revise the current assumption that the United States is a small open economy.

Those changes will address the top three respects in which the model departs from common practices in the field, and they will significantly improve its credibility. Although the SAB provides many additional suggestions and recommendations, these are clearly the highest priority in the near term. As the EPA continues developing SAGE further into the future, the SAB encourages the Agency to consider the remaining suggestions and recommendations.

The SAB appreciates this opportunity to review the SAGE model and looks forward to the EPA's response to these recommendations.

Sincerely,

Dr. Michael Honeycutt, Chair
Science Advisory Board

Dr. Peter Wilcoxen, Chair
Computable General Equilibrium Model Review Panel

Enclosure

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ACRONYMS AND ABBREVIATIONS

AEO	Annual Energy Outlook
AGE	Applied General Equilibrium model
CA	Current Account
CBO	Congressional Budget Office
CDE	Constant Difference of Elasticities
CES	Constant Elasticity of Substitution
CGE	Computable General Equilibrium
CPS	Current Population Survey
EIA	Energy Information Administration
EPPA	Emissions Prediction and Policy Analysis model
EV	Equivalent Variation
GAMS	General Algebraic Modeling System
GTAP	Global Trade Analysis Project
IMF	International Monetary Fund
IMPLAN	Economic Impact Analysis for Planning
LES	Linear Expenditure System
LP	Labor Productivity
NCEE	National Center for Environmental Economics
NIPA	National Income and Product Accounts
OECD	Organization for Economic Cooperation and Development
SAB	Science Advisory Board
SAM	Social Accounting Matrix
TFP	Total Factor Productivity
U.S. EPA	U.S. Environmental Protection Agency
WiNDC	Wisconsin National Data Consortium

1. INTRODUCTION

In September 2017, the Science Advisory Board (SAB) issued a report on the use of general equilibrium approaches to prospectively evaluate the costs, benefits, and economic impacts of environmental regulation (U.S. EPA SAB, 2017). The SAB affirmed the importance of using a computable general equilibrium (CGE) model to capture important interactions between markets when there are both significant cross-price effects and distortions in those markets. In contrast to partial equilibrium models, general equilibrium models are designed to capture the aggregate welfare or distributional impacts of a policy under consideration, taking cross-price and cross-market effects into account. To represent complex interactions in the economy, CGE models employ a framework of consumer and producer maximization with a large number of variables and parameters in a structurally complex framework.

Pursuant to the SAB's 2017 report, the National Center for Environmental Economics (NCEE) developed a new CGE model called SAGE. SAGE is an Applied General Equilibrium model intended to capture the social costs of environmental regulation by capturing important interactions between markets. SAGE is a dynamic intertemporal model of the U.S. economy with subnational resolution across both regions and households. It can be used to estimate the welfare effects of an environmental policy.

In response to a request from NCEE for SAGE to be reviewed by the SAB, the SAB Staff Office solicited nominations for the Computable General Equilibrium (CGE) Model Review Panel, which was to address ten charge questions regarding the model. Panelists were selected from a list of candidates over the summer of 2019. Dr. Peter Wilcoxen, who previously chaired the 2016-2017 SAB Economy-Wide Modeling Panel and was lead author of the 2017 SAB report, was asked to return as Chair of the CGE Model Review Panel. The other panelists were Alan Fox, Mun Ho, W. David Montgomery, Sergey Paltsev, Thomas Rutherford, Ron Sands, and Dominique van der Mensbrugghe, all of whom are distinguished experts on general equilibrium modeling. The review began with a teleconference on August 22, 2019, followed by a face-to-face meeting on November 22, 2019 and concluded with a final teleconference on January 31, 2020.

The CGE Model Review Panel was given the SAGE model along with model documentation, source code, a build stream and source data along with a list of ten charge questions all of which may be found posted on the SAB website (U.S. EPA SAB, 2019). The remainder of this report is organized by charge question. Each section includes a charge question followed by the SAB's consensus response and recommendations. The recommendations are grouped into three tiers to indicate their priority: tier 1 (T1) revisions are highest priority and should be made before the model is used for regulatory analysis; tier 2 (T2) revisions are middle priority and are suggestions offered to the EPA to strengthen the model over time; and tier 3 (T3) are lower priority and can be addressed further in the future.

2. RESPONSES TO CHARGE QUESTIONS

2.1 Charge Question 1: Model Documentation

Charge Question 1: Is the model documentation clear, accurate, and transparent? Do you have any specific suggestions for how to improve it?

The SAB finds that the SAGE model documentation (U.S. EPA NCEE, 2019a) is clear and accurate over all. EPA staff have produced an important document to guide the interpretation, use, and further development of the SAGE model and its underlying data framework. As it currently stands, the documentation is understandably targeted at the technical community. It can be enhanced by improving accessibility to less technical users of the model, reorganizing certain aspects of the documentation, and addressing issues enumerated below to improve overall readability and understandability. The recommended changes fall into the following broad categories: (1) additional material to aid less technical readers; (2) organization and presentation of the documentation; and (3) clarifications to the text at certain points. We provide the specific recommendations in corresponding sections below.

2.1.1 Additional Material To Aid Less Technical Readers

Recommendation CQ1-1: Define What is Meant by CGE (T1)

As part of this general overview, the term "CGE" should be defined and explored (it appears for the first time on page 5 of the documentation (U.S. EPA NCEE, 2019) as simply CGE), and the model is stated to be an applied general equilibrium model (without clarifying that the authors treat the term "AGE model" as equivalent to "CGE model"). Certain authors argue that there is an important distinction between AGE and CGE (Mitra-Kahn, 2008). We would encourage a fuller description of the general modeling approach.

Recommendation CQ1-2: Add a Section for Non-Modelers (T2)

The model documentation of SAGE is clear and transparent to an experienced computable general equilibrium (CGE) modeler. We recommend that the EPA add to the documentation a section targeted at non-CGE modelers that would explain the basic principles of CGE modeling and the dynamics represented in this particular version of the SAGE model.

2.1.2 Organization and Presentation in the Documentation

Recommendation CQ1-3: Improve Typesetting of Variable Names (T2)

In the LaTeX file used to generate the documentation, EPA should use the \mathit{} instruction to ensure that multi-character variable names (e.g., *pfx*, *bopdef*, *tl_refund*, etc.) are typeset with appropriate ligatures and kerning. This is especially important for those variables that include the letter *f*. For example, in Equation 23, pfx_{t} and bopdef_{t,r,h} should be coded as \mathit{pfx}_{t} and \mathit{bopdef}_{t,r,h}. As it is, there is too much space preceding the "*f*" in those variable names. This is especially noticeable in the case of "*tfica*", where the "fi" should be a ligature but will not be without

\mathit{}. Making this change for all multi-character variables will significantly improve the legibility of the documentation.

Recommendation CQ1-4: Clarify Treatment of Taxes (T2)

The SAB recommends that the EPA make two changes with respect to prices in the model: (1) keep base and purchasers' prices as separate variables (at a minimum within the documentation) to make expressions more compact, and (2) apply taxes to the producer price, a more natural approach, and consistent with tax laws. For example, consider the definition of profits in Equation 9, which is defined in terms of the purchaser's price py_{trs}:

$$(1 - ty_{trs})py_{trs}y_{trs} - \sum_j pa_{trj}id_{trjs} - (1 + tk)pr_{tr}kd_{trs} - pl_{tr}ld_{trs}$$

It would be cleaner if a variable py^p_{trs} were added for the producer or seller price and the purchaser's price defined in terms of it:

$$py_{trs} = (1 + ty_{trs})py^p_{trs}$$

Doing so would allow the expression for profits to be rewritten more cleanly as:

$$py^p_{trs}y_{trs} - \sum_j pa_{trj}id_{trjs} - (1 + tk)pr_{tr}kd_{trs} - pl_{tr}ld_{trs}$$

By including only purchaser's prices and not producer's prices, the current formulation saves T×R×S endogenous variables in the General Algebraic Modeling System (GAMS) code. If that generates important savings in computational resources, EPA could continue to eliminate one of the variables by algebraic substitution (as it does now) but include both in the documentation for clarity. In that case, the second price could be computed and stored in post-solution code, or it could be implemented within the model code using GAMS' MACRO feature.

Recommendation CQ1-5: Use Separate Sections for Theory and Parameterization (T2)

The SAB recommends that the EPA consider reorganizing the documentation into two parts, one to lay out the theory of the SAGE model, followed by a second part illustrating the construction and sourcing of data and parameters. The documentation is already partway to this format. As part of this reorganization, the construction of the benchmark social accounting matrix (SAM) deserves more attention. This approach will also simplify maintenance of the documentation, allowing updates to the model section and to the data and parameters section to occur independently of one another.

Recommendation CQ1-6: Expand Discussion of Dynamics (T2)

The SAB suggests that the EPA describe first the comparative static model, followed by the introduction of dynamics. Doing so means the budget constraint can be described vis-à-vis household savings, and then the savings/investment dynamic can be illustrated in a separate section on dynamics. Model dynamics would benefit from more explanation, especially for readers less familiar with implementations of perfect foresight models. Beginning with a simple framework and annual time steps and then expanding the framework to encompass the structural features of the model (e.g. multiple households) and the passage from annual time steps to multi-year time steps would make the stock/flow dynamics more transparent.

Recommendation CQ1-7: Simplify the Section on the Solution Method (T2)

The discussion in section 4 (U.S. EPA NCEE, 2019a) describing the solution procedure appears more complicated than necessary. EPA has described most of the model equations earlier in the documentation. The model is a set of N non-linear equations that is solved using a Newton procedure. The model includes (presumably) a number of diagnostics that provide confidence in the resulting solution. The SAB recommends that this section be summarized, and that the proofs and mathematical details, should the EPA wish to retain them, be moved to a mathematical appendix.

Recommendation CQ1-8: Organize Documentation and Code into Modules (T2)

The SAB suggests that the EPA consider reorganizing the model description using the standard circular flow paradigm that includes: (1) production; (2) income allocation; (3) final demand; (4) domestic and international trade; (5) market equilibrium; and (6) closure. Grouping equations together into modules will make the code clearer and easier to maintain. For example, it allows the modules to be swapped out more easily if model structural changes are made.

Recommendation CQ1-9: Reorganize the Presentation of Equations and Variables (T2)

The SAB has a number of recommendations with respect to the mathematical presentation of the model. The presentation could be improved by moving the bulk of the model's mathematical presentation to an appendix, while relying on tree diagrams and more abbreviated mathematical notation in the body of the document. Within the mathematical presentation, we ask that the EPA include a full presentation of the equations of the SAGE model, including balance equations that explicitly show how prices and quantities are multiplied together. A consolidated table of all variable names and descriptions should also be provided. The current layout presents some challenges. For example, the variables *pa, pn, pd,* and *pfx* are listed immediately before Equation 2 on p. 7, but are only first used in Equation 88 on p. 47 (U.S. EPA NCEE, 2019a). EPA should also include the wealth accumulation equation that can be computed post-solution to facilitate confirmation values are adding up with capital gains.

Recommendation CQ1-10: Improve Naming of Some Variables (T2)

The current presentation denotes the domestic and foreign markets with the indices *dtrd* and *ftrd* respectively. The SAB recommends that these indices be dropped in favor of separate variable names for variables that indicate domestic and foreign markets. We also recommend that the EPA use more informative variable names where possible and avoid single-letter names, which should be reserved for sets (for example "*i"*). It would also help make the exposition clearer if the EPA replaced the use of "*s*" and "*ss*" for sector for another index, such as "*i*" for commodities and "*a*" for activities. The Global Trade Analysis Project (GTAP) and other global models frequently use "*s*" for source country or region.

2.1.3 Clarifications to the Text

The following individual issues should be addressed throughout the documentation. Pages and sections are listed as appropriate.

Recommendation CQ1-11: Discuss Balanced Growth Path (T1)

As will be discussed in more detail in section 2.2.1, the SAB recommends that the agency should move away from using a balanced growth equilibrium as the model's baseline. Until the baseline is revised, however, the agency should make clear from the beginning of the documentation that the model's baseline is a balanced growth path, i.e., it is assumed that the exogenous variables of the model are in

the steady state from the first year (2016), with real values growing at $(1 + \gamma + \omega)$ throughout the baseline. This point currently is not made until page 43 (U.S. EPA NCEE, 2019a), and then only obliquely.

Recommendation CQ1-12: Cite for Nested CES (T1)

In section 2.2.1 (U.S. EPA NCEE, 2019a) a reference for nested Constant Elasticity of Substitution (CES) is made to Brockway et al. (Brockway, P. E., Heun, M. K., Santos, J., and Barrett, J. R., 2017). Note that the first use of the multiple nested energy structure was in the Organization for Economic Cooperation and Development (OECD) GREEN model (van der Mensbrugghe, 1994). GREEN was subsequently transferred to the Massachusetts Institute of Technology (MIT) and later evolved into the Emissions Prediction and Policy Analysis (EPPA) model.

Recommendation CQ1-13: Household Savings and the Intertemporal Budget Constraint (T1)

The implementation of the household's intertemporal budget constraint in Equation 23 on page 17 (U.S. EPA NCEE, 2019a) should be clarified and explained in more detail. For example, *kh* is described in the text as household savings (a flow variable) but as it is used in the equation, it represents a component of the household's wealth (a stock variable). In addition, the nomenclature suggests it is a quantity variable but its role in the equation is as a value. There should be a sharper notational distinction between quantity and value variables, or the corresponding price should appear in the equation. The text should also clarify the relationship between the returns on *kh* and the rental payments on the corresponding capital stock, and the role of the price of new capital goods (which can lead to capital gains and losses). Finally, it would be good to state the savings-investment balance explicitly; i.e., the link between household savings (and business savings if any capital income is retained) and its use in financing the government deficit, the current account surplus, and private investment (extant and new capital), as well as to explain in terms of the model's variables how the change in wealth is the sum of savings and capital gains.

Recommendation CQ1-14: Improve Discussion of Prices that Clear Markets (T2)

Greater care should be taken when identifying the prices that clear markets, such as in the discussion of Equation 36 (U.S. EPA NCEE, 2019a). Strictly speaking, the Armington price index mentioned at that point does not, itself, clear any markets. Rather, it is a composite price derived from the true market-clearing equilibrium prices—which in the case of demand are *pd* (the equilibrium price for domestic goods), *pn* (the equilibrium price for national goods), and *pm* (the equilibrium—though exogenous—price for imported goods).

Recommendation CQ1-15: Clarification of Choice of Numéraire (T1)

The discussion of the model's numéraire should be expanded and clarified. The documentation currently states that numeraire is the price of foreign exchange in the initial period, pfx_0. However, there would normally be a numeraire price in every period, not just the first, since most general equilibrium models are homogeneous of degree one in prices within each period. Alternatively, an additional equation is sometimes added to describe how the numeraire price evolves over time. From the existing documentation it appears as though the price of foreign exchange is held constant in every year, not just the first, but if so that should be stated explicitly. Clarifying the treatment of the numeraire is particularly important since all prices and values reported by the model are relative to it. EPA should

clarify how the model's price level is set over time or, if the model is not homogeneous in prices, discuss that explicitly and clarify how it affects the model's results.

Recommendation CQ1-16: Correct Regional Balance of Payments (T2)

The imbalance between regions not only reflects investment flows, but also public expenditure flows—to the extent that the net public revenues in each region don't necessarily line up with public expenditures in each region: $S_r = I_r + DG_r + CA_r$. The text should reflect this.

Recommendation CQ1-17: Discuss Options for Time Steps and Model Horizon (T2)

The documentation does not specify time steps of the model and the model horizon. The model file `parameters.gms` provides a setting for a set t in 5-year steps from 2016 to 2061, but it is not clear from the documentation if the model can be run at different time intervals and for different time horizons. This should be clarified in the Dynamic Baseline section (U.S. EPA NCEE, 2019, p. 42). This also relates to the organizational question above concerning presentation of dynamics within the model.

Recommendation CQ1-18: Expand Discussion of the Discount Rate (T1)

The discount rate is a critical parameter for the analysis of long term policies and there is a substantial literature on the topic. EPA should provide one or more citations to the literature, such as the overview paper by Arrow, et al. (2013), and briefly explain its chosen discount rate for the model in that context.

Recommendation CQ1-19: Expand Discussion of the Investment Good (T1)

The importance of changes in the prices of inputs to producing the investment good is mentioned several times, but we could not find a specific discussion of the *production function* for the investment good. Since new capital is malleable and assigned to sectors by sharing based on values in the SAM, we assume that there is a single investment good, not one differentiated by sector. From the balance conditions, this implies that the investment good is made up of output of each sector not otherwise assigned to government and household consumption or net exports. Given the importance attached to changes in the cost of the investment good for sectoral and dynamic impacts, the SAB recommends a fuller discussion of this.

Recommendation CQ1-20: Discuss Fixed Factors and Resource Depletion (T1)

The assumption that resource industries have a fixed factor (land, resources in the ground) is valid and conventional. The documentation does not discuss whether the fixed factor varies over time to represent resource depletion and appears to suggest that whatever exhaustion occurs is due to decreasing returns in the presence of the fixed factor. That is different from the way some other models calibrate for depletion. Although it might be superior, it requires more discussion.

Recommendation CQ1-21: Describe Implementation of Productivity Shocks (T1)

The documentation does not illustrate how productivity shocks are implemented for regulations that are phased in over time. The text should describe the process.

Recommendation CQ1-22: Expand Section Six on Using the Model (T2)

The documentation currently discusses the process of building the model's input files from raw data before it discusses running the model. Although that order is logical in terms of the development of the model, the documentation would be more accessible to users if running the model and analyzing the

results were discussed first and rebuilding the dataset was presented later. Switching the order is useful since many users may want to run the model using EPA's prebuilt datasets, particularly if they don't have access to the proprietary IMPLAN data. The current ordering obscures the fact that that's possible. In addition, EPA may want to elaborate on alternative licensing options for the IMPLAN data. Finally, instructions should also be provided for R users who are behind proxy servers, since they will need to configure R correctly to be able to use the provided R scripts to download the publicly available components of the model's overall dataset.

Recommendation CQ1-23: Clarify Analysis of Capital Remuneration (T2)

Revise the discussion of the relation between capital remuneration and savings to make it clear that all income is consolidated into a single variable which the household then allocates among savings, consumption and taxes, using a tree diagram if possible.

2.2 Charge Question 2: Model Structure and Assumptions

Charge Question 2: Are the model structure and assumptions reasonable and consistent with economic theory?

Broadly speaking, the SAB found the model to be consistent with economic theory and common practices in general equilibrium modeling. However, there are several areas in which it could be strengthened. Recommendations for nine of the model's key characteristics are provided below. The first group focuses on the model's overall dynamic structure and the remainder address its treatments of household behavior, investment, production, emissions, natural resource use, regions, taxation and government accounts, and international trade.

2.2.1 Dynamic Structure

Recommendation CQ2-1: Transition Path and Exogenous Variables (T1)

The current version of SAGE is a foresighted model using a balanced growth approach, that is, it assumes that the economy is in a steady-state growth equilibrium in the base case where all real exogenous variables grow at the same rate (equal to population growth rate + labor productivity growth). While this is a common approach in macroeconomics using aggregate production functions, it is not so suitable for a multi-sector model like SAGE where it is used to analyze policies during a time of economic transition (i.e. when the economy is not in a steady state equilibrium).

The SAB recommends that the transition path be explicitly modelled. That is, do not assume that the current tax rates, government and current account deficits are arbitrarily consistent with a steady state. The near-term path of tax rates and government spending and deficits may be taken from the Congressional Budget Office (CBO). Beyond the period projected by the CBO, one should specify a path for the exogenous variables such as government spending and current account deficits in a way that is consistent with a steady state. The time frame in which the EPA may wish to analyze policies is usually limited, and beyond that horizon of interest the modeler may choose parameters that allow the most tractable solution of an infinite horizon model.

For example, the rate of productivity growth may be specified in a flexible manner – for the short-term, set at rates matching projections by industry experts and for the long-term, set at rates that allow a

convenient determination of the steady state. We note that setting the long-term productivity growth to zero allows several simplifications that avoid difficult solution problems: (i) there will be no more changes in relative productivity and prices for different industries; (ii) there will no steady state income effects in a consumption function that is non-homothetic; (iii) there will be no change in steady state factor inputs relative to a fixed resource supply

In terms of government variables, the more recent CBO work provides separate 10-year and 30-year projections, the first conforming to actual law, and the longer extended baseline "generally reflects current law … extending most of the concepts underlying" the 10-year baseline. This means that the long-term projection involves a rising debt to GDP ratio, and is not sustainable in a steady state modeling sense. Due care should be taken to specify parameters beyond the CBO horizon.

Finally, current account projections are delivered by macro-models focused on the short horizon of 1-3 years, an example being the International Monetary Fund (IMF) forecasts. There is no consensus on long term trends and the agency is free to make reasonable assumptions. The SAB recommends the construction of a projection of the current account deficit path in a way that delivers a convenient, but well specified, steady state without explosive foreign debt ratios.

Recommendation CQ2-2: Allow More Flexible Modeling of Productivity (T2)

Improvement in productivity in SAGE is now represented by a single economy-wide Harrod-neutral growth rate in effective labor input. This is a relatively inflexible way of specifying technical change because it constrains the rate of productivity growth to be the same across industries. As discussed in more detail in the next recommendation, historical productivity growth has varied a lot across industries and that is likely to continue. To allow for more nuanced treatment of productivity in the future, the SAB recommends that the agency include a productivity parameter in the production function for each industry, either in the value added nest or in the gross output nest.

Also, the rate of growth in effective labor has to be carefully related to labor productivity (LP) growth. LP is an endogenous term that depends on capital deepening and is distinct from the concept of an exogenous rate of labor augmentation. If the LP rate is to be used in the current version of SAGE, then the appropriate rate is the economy-wide LP growth rate, not the nonfarm private rate that is currently used.

When the production functions are modified to have industry-specific total factor productivity (TFP) growth parameters, these parameters should be set carefully. There are different accounting methods that generate very different estimates of TFP. Some studies distinguish between hours worked and labor input adjusted for the composition of the work force, and some distinguish between capital stock and a measure of capital input that takes the composition of the stock into account. That is, the concept of labor and capital input in the model must be consistent with the TFP method chosen. A source of TFP estimates for US industries is the Bureau of Labor Statistics, Multifactor productivity group (U.S. Bureau of Labor Statistics).

Recommendation CQ2-3: Industry Productivity (T2)

As noted above, SAGE now restricts productivity growth to be symmetric across industries, acting through effective labor input. The historical record, however, shows a wide range of total factor

productivity (TFP) growth, from strong positive to negative.[1] Projections based on this historical record shows that relative prices will continue to change in the short and medium term (e.g. much cheaper electrical equipment relative to services). Industry experts also project that U.S. industries will grow at quite different rates. The SAB recommends that SAGE allow a more flexible specification of productivity, allowing each industry to have its own TFP growth rate in the medium term. Such a feature will give the modeler a lever to calibrate the growth rate of particular industries to expert projections. It will also be easy to align with the Energy Information Administration (EIA) projections of energy prices.

2.2.2 Households, Consumption Functions, and Welfare Measurement

Recommendation CQ2-4: Improving the Consumption Function (T1)

The current consumption function is a CES function where the share parameters for energy are calibrated to Annual Energy Outlook (AEO) projections. While the CES is easy to implement, it has the unfortunate feature of imposing unit income elasticities on demand. This violates Engel's Law regarding food demand and is contrary to other empirical observations. It thus imposes a baseline growth path that will be at odds with historical experience. This is likely to be a significant concern since the model's baseline has growing household income.

The SAB thus agrees with the agency's proposed near-term project to reformulate the consumption function and recommends that the agency start with a simple linear expenditure system (LES) or the constant difference of elasticities (CDE) system used in the GTAP model. Moving to one of these demand models will require at a minimum a set of income elasticities—presumably household specific—and, depending on the functional form, may also require own-price elasticities. The LES, for example, requires income elasticities while the CDE demand system requires both income and price elasticities. The agency will need to obtain appropriate estimates from the literature in the short run. EPA may want to refer to GTAPinGAMS, a multiregional model written in GAMS but using GTAP data, because it includes both the CDE system and the LES and has code to parameterize the functions to match income elasticities and average price elasticities.

Recommendation CQ2-5: Using a Flexible Functional Form to Model Consumption (T3)

The agency has also proposed moving toward flexible functional forms for modeling consumption, including plans to estimate the parameters of the functions from historical data. The SAB strongly supports moving to econometric estimation over the longer run. However, adopting an approach based on a flexible functional form should be deferred until more urgent improvements are made. An additional cautionary note is that these functions may violate regularity conditions at prices far from the observed sample period prices, raising challenges in both modeling and interpretation of results.

Recommendation CQ2-6: Extend Demographic Modeling Underlying the Income Distribution (T3)

SAGE now distinguishes households by 5 different income groups. This is a useful feature. The structure of households, however, is static in this dynamic model — there is no migration, no significant

[1] The official productivity accounts are produced by the BLS, and described in https://www.bls.gov/opub/mlr/2018/article/multifactor-productivity-slowdown-in-us-manufacturing.htm . See also Figure 4.17 in Jorgenson et al. (2013) *Double Dividend*.

change in sources of income, etc. The SAB recommends that the agency consider developing additional structural change for the households, for example, incorporating expert projections of regional migration, and increasing government transfers due to aging.

Recommendation CQ2-7: Correct Definition of Equivalent Variation (T1)

The definition of equivalent variation (EV) has the wrong sign. The EV is the change in expenditure needed under baseline conditions to make a household just as well off as it would have been under the policy change. It should thus be the expenditure needed to get the policy-case utility at the base case prices less the baseline expenditure (i.e., positive if the policy-case utility would have been more expensive than the baseline utility). Equation 134 on page 53 (U.S. EPA NCEE, 2019a) is the reverse. In addition, it would be good to link the EV to wealth since the household's intertemporal expenditure should be consistent with its full wealth (including the imputed value of its leisure time). That is, express the EV as a share of the full wealth, both being present discounted values.

Recommendation CQ2-8: Examine Sensitivity to Alternative Time Preference Rates (T3)

The model currently sets the time preference rate to satisfy a balanced growth equilibrium condition, Equation 77, that connects two parameters, the time preference rate and the intertemporal elasticity of substitution, with three imposed variables: the rate of population growth, the rate of growth of the effective time endowment, and the real interest rate. Ordinarily, the equilibrium condition is regarded as determining the interest rate given the other parameters and variables. Here, however, the EPA sets the real interest rate by assumption to 0.045 following (Council of Economic Advisers, 2017) and calculates the time preference rate that would be necessary to achieve that. In the long run, the time preference rate should be determined empirically from household behavior. As discussed in charge questions 9 and 10, the SAB recommends that EPA move toward establishing a stronger empirical basis for key parameters in the model, especially those related to consumption. In the meantime, however, EPA should report the time preference rate that results from its current calculation and should conduct sensitivity analysis by varying the assumed steady-state interest rate.

2.2.3 Investment and Government Demand Functions

Recommendation CQ2-9: Improve Treatment of Investment and Government Spending (T2)

The function allocating total investment and total government purchases to the various commodities is of the Leontief form, which causes the ratios of individual investment goods in total investment to be fixed. This is not reflective of past investment trends that show rising shares of, say, computer equipment, due to changes in prices and technology. The SAB recommends that EPA move toward using a more flexible functional form that would allow the mix of investment goods to evolve over time and to respond to changes in relative prices. The latter would be particularly important when the model has been moved to a non-balanced-growth baseline, which will cause the prices of some goods, such as information technology, to change relative to other kinds of capital. An initial option might be to use a CES function with substitution elasticities set to zero to replicate the model's current structure. The substitution elasticities could then be revised over time as better estimates become available. Finally, the replacement function should have parameters that would allow an exogenous trend in the investment share parameters to be introduced to accommodate expert projections regarding trend changes in the composition of investment.

Recommendation CQ2-10: Improve Treatment of Government Capital (T3)

The government industry is now included as part of services, and this has some implications about the cost of capital. Government capital is unlike regular private capital that has returns consisting of depreciation and profits; rather, the returns to government capital are imputed based purely on depreciation of the government capital stock. As a result, the capital rental rate of SAGE's services sector is a mixed bag of market return and imputed depreciation and may give an incorrect picture of the marginal cost of capital to services. In a myopic version of SAGE it would not be costly to have more disaggregated industries and the SAB recommends a consideration of this aspect in future versions.

2.2.4 Capital and Natural Resources

Recommendation CQ2-11: Streamline Implementation of Capital Modeling (T2)

In the modeling of capital input, the agency can consider combining the 'extant' and 'new' nests in a single structure indexed by 'v'. This would add additional future flexibility, reduce code size and simplify the documentation.

Recommendation CQ2-12: Introduce Supply Curves for Resources (T2)

In the current formulation of SAGE, resources are in fixed supply. Under the model's current assumptions of persistent growth in the population and labor effectiveness, the fixed supply assumption implies that the relative price of the resources will eventually become arbitrarily large. The implied degree of inelasticity is implausible and at odds with the historical record. Many other long-run models address this issue by using a natural resource supply function to allow resource supply to respond to changes in prices. The SAB recommends that the EPA consider this. A simple initial option would be an isoelastic function. An important benefit of introducing explicit supply functions is that it would allow sensitivity analysis with respect to the elasticities used. In the near term, EPA could add exogenous resource supply shifters that could be used as an alternative.

Recommendation CQ2-13: Refine Modeling of Resource Supply (T3)

In the long run, the SAB suggests that EPA further refine the resource supply curves, perhaps adding backstop resources that are available at high cost but in very elastic supply. In addition, it would be helpful to revise the tax treatment of resources. Right now the tax on natural resources is the same as for capital (at rate *tk*). However, the treatment of natural resource income in the US is quite distinct, particularly across states, and it would be good to allow a separate tax rate.

2.2.5 Regional Issues

Recommendation CQ2-14: Examine Feasibility of Increasing the Number of Regions (T3)

There are nine regions now represented in SAGE, which is typical for a foresighted dynamic model. It would be good to know the tradeoffs of having more disaggregated regions, i.e. what the additional computational burden is. As noted above, in a myopic model, it would be low cost to add more regions.

Recommendation CQ2-15: Improve Handling of Ownership of Capital (T3)

The current version of SAGE assumes that there are no holdings of capital in region r by households in region s, and hence no flows of capital income across regional boundaries. An alternative formulation would be to specify a national ownership of capital and allocate national capital income to all regional

households. Since we have no data on ownership it may be good to have these two options of specifying ownership and see how they might matter for particular policies.

2.2.6 Government Accounts and Taxes

Recommendation CQ2-16: Ensure Government Accounts are Consistent with Forecasts (T1)

The attention paid to the tax system is impressive, distinguishing between average and marginal rates and using Current Population Survey (CPS) data and the TAXSIM model to calculate marginal tax rates. Section 3.2 of U.S. EPA NCEE (2019) states that *tk* is made up from the corporate tax rate from the Congressional Budget Office (CBO) and personal income tax data. It would be good to clarify if the resulting tax revenues match the total revenues given in the National Accounts. Tax rates should be calibrated to replicate the National Income and Product Account (NIPA) revenues, including the production tax *ty* based on IMPLAN estimates. The *tran0* variable represents transfers to households but is actually made up of many different items (interest payments, social security payments, official transfers less imputation for gov capital depreciation). Such details do not matter much in a static model, but in constructing the base case transition path, the modelers should be careful that this total transfer is consistent with the CBO projections.

In particular, the government budget, simplified, is given by eq. 34 (U.S. EPA NCEE, 2019a):

$$\sum_{r} pgov_{t,r} gov_{t,r} + cpi_t \sum_{h} tran_{t,r,h} + [\sum_{rh} (tl_{t,r,h} + tfica_{t,r,h}) pl_{t,r,h} l_{t,r,h} - averagelabortax]$$
$$= outputtax + captax + restax + consumtax + \sum_{rh} (tl_{t,r,h} + tfica_{t,r,h}) pl_{t,r,h} l_{t,r,h}$$

where:

$$tran_{t,r,h} = tran0 + incadj$$

The SAB recommends that the government budget constraint have an explicit government savings (deficit) variable; the current closure confusingly buries this in the *tran* variable. With such a savings variable one could then simply exogenize government savings (or government savings as a share of nominal GDP) and then the closure to meet the fiscal target by any of the following methods: endogenous tax rates, endogenous lump sum transfers, or endogenous government final demand. In the base year, if tax rates are calibrated to actual revenues, then the required lump sum or government purchases should be equal to the actual data.

A transition path calibrated to official projections, such as the CBO's, would reflect rising debt and interest payments, and under the assumed tax rates, generate large deficits. A path set merely to mimic the base year values would miss this expected transition; hence missing the available household savings for investment.

2.2.7 International Trade Specification

Recommendation CQ2-17: Clarify Handling of the Current Account Balance (T1)

The current account (CA) balance Equation 42 has a complex variable, *bopdef*, that encompasses net capital and labor income from the rest-of-world, net transfers and the CA surplus (foreign savings). While this may be a simple representation of the net flows required to finance the trade deficit, it hides details needed to have a clear specification of the steady state foreign debt path. If these separate items of *bopdef* were made explicit then one would be able to specify the CA surplus and exogenize it (or as a share of GDP), and set it to zero in the long-term to be consistent with a well-defined steady state.

Recommendation CQ2-18: Relax the Small Open Economy Assumption (T1)

The treatment of the US as a small open economy is undesirable in terms of both flows of goods and financial capital. The SAB notes that the EPA has put relaxing this assumption on the list of potential near-term updates and supports that move. The SAB recognizes that doing so will be challenging as it will require EPA to specify the appropriate elasticities for the downward sloping demand for US exports and an upward sloping supply of US imports. It suggests that the EPA consult Jorgenson, et al., (Jorgenson, Goettle, Ho, & Wilcoxen, 2013) for an example showing how these elasticities were estimated for another model of the US, as well as Rutherford and Tarr (Rutherford & Tarr, 2003) and (Horridge & Zhai, 2005) for approaches that could be used to build single-country elasticities from multi-region models such as GTAP. An alternative approach EPA could consider over the longer run would be to set up a multiregional static model along the lines of GTAP itself and see how the results from it compare to those from a single-country large open economy model based on the same data.

2.3 Charge Question 3: Inputs in the Model

Charge Question 3: Are the inputs used in the model (e.g., elasticities, social accounting matrix) reasonable and reflective of the peer-reviewed literature?

Overall, the SAB finds that the agency has done an impressive job in assembling the inputs to the model. The agency is to be commended on its efforts to source production-based elasticities and to parameterize the pricing of natural resources. With that said, the SAB has a number of suggestions on how the parameters and input data could be strengthened going forward.

Recommendation CQ3-1: Review the Labor Tax Rate (T1)

The level of the effective tax rate on labor seems high relative to recent history. The agency should verify that it is correct for the model's specification.

Recommendation CQ3-2: Refine the Tax System (T3)

The agency should consider refining the representation of the tax system—notably sales taxes. It may eventually want to consider introducing trade and transportation margins but should not take that on in the near term.

Recommendation CQ3-3: Explicitly Track the Government's Fiscal Position (T2)

As discussed in section 2.2.8 (U.S. EPA NCEE, 2019a), it would be useful to improving the model's fiscal closure by introducing explicitly the government's net fiscal position. This would require tracking government debt and interest payments.

Recommendation CQ3-4: Assess the Feasibility of Moving to WiNDC (T3)

The agency's goal of producing a fully open-source model would be significantly strengthened by moving away from the proprietary IMPLAN database as its source of the SAM. The SAB recommends evaluating the feasibility of switching to the open-source Wisconsin National Data Consortium (WiNDC) database (Wisconsin National Data Consortium). Doing so would improve the accessibility and transparency of the model.

Recommendation CQ3-5: Clarify the Intertemporal Calibration (T2)

Calibrating an intertemporal model, particularly one that includes agents with foresight, presents particular challenges. It is hard to gauge from the existing documentation how well the model conforms to common practices in the literature. The agency should be clearer about how it handles the calibration of the model's intertemporal variables, including the specific variables that are targeted in the calibration and the exogenous adjustments made to achieve the targets. It should also explain what motivates the current choice of driving the baseline through shifts in the supply of effective labor.

2.4 Charge Question 4: Model Results

Charge Question 4: Does the model produce intuitive and expected results?

The charge question is very broad and the SAB was only able to examine a limited set of scenarios. In addition to the basic setting of the model provided by the EPA, Dominique van der Mensbrugghe of the CGE Model Review Panel tested a scenario where taxes on coal, natural gas, and oil are introduced. To complete the test, the SAGE model was modified to include commodity- and activity-specific taxes on intermediate demand and an upward sloping supply curve for natural resources. Dr. van der Mensbrugghe's results indicate the SAGE model produces intuitive and expected results for the explored scenarios. However, additional testing is needed before the model is used in production. Moreover, the EPA may wish to provide a standardized reporting tool for extracting and graphing commonly-used results from the model's output.

Recommendation CQ4-1: Add Several Initial Test Runs (T1)

Before the model is released, the SAB suggests the EPA perform additional testing of the model setting that includes commodity- and activity-specific taxes and supply curves for natural resources. Over the longer run (T2), the SAB recommends additional explorations for more extensive sets of scenarios.

Recommendation CQ4-2: Provide a User-Friendly Reporting Tool (T1)

The SAB also recommends setting up a user-friendly reporting and visualization of the major model outputs. Some variables EPA may want to consider reporting via the tool are regional and national GDP, equivalent variation, sectoral prices, sectoral outputs, energy intensity, sectoral, regional and national use of inputs and their prices (especially for labor, capital and natural resources). This will be particularly important in helping analysts outside the agency use the model reliably.

2.5 Charge Question 5: Verification Tests

Charge Question 5: Each model run is subjected to a series of tests to verify that the solution represents an equilibrium. Additional tests are performed to verify that implicit parameters (e.g.,

labor supply elasticity) match their calibration targets. Are there other verification tests that should be incorporated into the model?

The SAB recommends additional diagnostic tests in four general areas: economic integrity, baseline indicators, sensitivity tests, and energy balance. Further diagnostic tests would be useful to describe how the assumption of intertemporal perfect foresight affects model output, but specific tests are not identified at this time.

Recommendation CQ5-1: Numeraire Test (T1)

A good test for each build of the model (but not each individual simulation) is to check that it is appropriately homogeneous in the numeraire. For example, change the exogenous numeraire price from 1 to 2 and verify that all price and value variables double but no quantity variables change.

Recommendation CQ5-2: Provide Baseline Indicators (T2)

It would be useful for the agency to routinely provide more information about the base case, including more figures and tables similar to those in section 3.4 of its existing documentation. For example, it could include a figure showing GDP over time, as well as its consumption and investment components; a figure showing the evolution of agricultural and energy prices in real terms; and figures showing energy intensity, and agricultural and natural resource output growth.

Recommendation CQ5-3: Sensitivity Analysis of the Baseline (T2)

It is well established in the modeling literature that the costs and benefits of energy and climate policies can be strongly affected by a model's baseline trajectory. The SAB suggests that the agency plan to carry out sensitivity analysis regarding the factors that drive the baseline, ranging from projected trajectories of exogenous variables (energy prices being a particularly important category) to key parameters in the model's intertemporal equations. Comparing the model's baseline with those from other models, such as participants in the Energy Modeling Forum (EMF), would be useful as well.

Recommendation CQ5-4: Sensitivity to the Intertemporal Closure (T2)

It would be valuable to test the sensitivity of the model's near-term results to the period used between equilibria and to the model's long term horizon. For example, how do near term results change if the model were run at a shorter time interval (1 year instead of 5 year) and only up to 2031 (instead of 2061). Would the results of the policy be the same overall (e.g., in terms of EV), or the same in some particular year, say 2031 (e.g., for change in output)?

2.6 Charge Question 6: Framework for Capturing Compliance

Charge Question 6: While the most appropriate approach for modeling a policy will be regulation specific, is the general framework for capturing compliance requirements in the model reasonable? Are there other approaches that should be incorporated into the model?

The SAB concludes that the framework described in Figure 9 of the model documentation (U.S. EPA NCEE, 2019a) is very reasonable. The two suggested approaches, productivity shocks and production of an abatement good, are in common use and provide a good general framework.

Either of these approaches can achieve consistency between SAGE and engineering descriptions of abatement technologies, fully incorporate abatement costs into the cost of production, and distribute the cost of abatement across inputs utilized to reduce emissions.

Nonetheless, there will likely be cases in the future that call for novel approaches. The open-source nature of the model should ease the incorporation and peer review of any new methods.

The productivity shock and abatement good approaches both rely on engineering estimates of compliance cost to create or modify production functions in the regulated sectors to incorporate abatement costs. The need to parameterize these functions points to the need for detailed abatement cost data to support CGE modeling.

The SAB suggests that data inputs to the CGE model be obtained in separate studies and as much as possible be reflective of regional, sectoral, temporal heterogeneities. If the engineering analysis does not differentiate its estimates across these dimensions, it will be difficult to make data-driven assumptions about cost and elasticity parameters in the CGE model by region, sector or time.

Recommendation CQ6-1: Evaluate the Comparability of the Approaches (T3)

The SAB recognizes that although the two approaches – productivity shock and abatement good – are both reasonable, they will only produce identical results under special conditions and a reasoned decision will have to be made about which is more appropriate to a particular regulation. The examples confirm that for the special cases, results are quite similar for the outputs that each approach includes, but it would be worthwhile to ascertain more clearly under what conditions they will diverge.

The SAB recommends that some analytical effort be put into identifying the theoretical properties of the two approaches. One way of doing this analysis would be to determine the restrictions that each approach imposes on a general production function for output and emissions.

Recommendation CQ6-2: Support Cap and Trade or Emission Taxes (T2)

The examples provided in the SAGE documentation showing the use of these frameworks incorporate only quantity instruments that limit emissions or require specific controls. The only other obvious instrument would be some form of price-based regime (simple tax, cap and trade, etc.), such as the SO2 market. The SAB recommends inclusion of policy levers that allow cap and trade or emission taxes to be represented in a natural way, and comparison of the results of tax and quantity approaches as a model validation exercise.

Recommendation CQ6-3: Develop an Explicit Compliance Model (T3)

Over the longer run, the SAB suggests that the EPA develop an extended version of the explicit compliance (abatement good) approach where factor demands for abatement activities are linked to specific inputs and not only the overall level of output. As it stands, demands for specific abatement inputs are separable from demands for inputs to production of industry output. This limits the kinds of regulatory measures for which the abatement good approach could be used.

For example, the separability assumption makes it difficult to model the impact of fuel switching between coal and gas within electric power generation. Implicitly, the abatement good approach implies

in this example that the only means available to reduce emissions per unit of output is scrubbing. Thus the current structure would not be able to endogenously capture the joint decision about fuel switching and scrubbing that electric utilities actually face.

Recommendation CQ6-4: Check Substitution under Productivity Shocks (T2)

The productivity shock approach is straightforward to apply to individual inputs, requiring only an engineering cost analysis adequate to estimate unit factor requirements and assign the shock to labor, capital, energy or materials. In the case of materials, assigning the shock to particular materials would require the same data as determining input requirements for production of an abatement good.

If a shock is assigned to specific inputs, the amount of substitutability among material inputs will have an effect on the equilibrium loss of output from a shock to the productivity of any single input or multiple inputs. Thus, an emission option that has high capital costs relative to other factors of production will cause substitution away from capital into labor and other material inputs. The SAB recommends that the EPA examine such results carefully before adopting any model based on the productivity approach for regulatory purposes.

Returning to the example of electric power, the productivity shock approach in principle makes it possible to represent a joint decision about scrubbing and fuel switching. To do this, the nesting structure of the production function for electricity and related parameters must be calibrated to mimic the results of an engineering-economic study of electricity capacity choice and dispatch. This may or may not be possible in practice.

Achieving congruence between engineering studies and the CGE results is more likely when mechanisms by which a regulation is expected to affect behavior are included in the model. As in the case of electric power regulation that causes fuel substitution as well as installation of post-combustion controls, other regulations may have direct effects on input substitution that can only be captured endogenously if the relevant choices are represented explicitly. If key margins on which decisions are made are not represented in the model, the welfare effects of regulations will be incomplete.

Recommendation CQ6-5: Increase Detail in Electricity and Transportation (T2)

The SAB observes that the electric power sector and the transportation sector are the subject of repeated regulation by the EPA, and the SAB recommends that the agency make it a high priority to incorporate more detailed models of these sectors into SAGE. This could be done by incorporating greater structure into the production functions for these goods or by linking SAGE to more detailed engineering-economic models to be run in tandem with SAGE.

In the case of electric power, there are examples of both approaches in the literature. For example, the MIT EPPA model in one version represents electricity generation from each fuel type with a separate production function, and the outputs of the different flavors of electricity compete with each other as perfect substitutes. In this way cost of scrubbers, etc. can be incorporated for each fuel type and fuel switching takes place based on changes in the resulting cost of generation for each type. MIT's US-REP takes the other approach, linking the CGE model to a full, hourly capacity planning and dispatch model.

Personal transportation has similar complexities, in that consumers make joint choices about purchasing and utilizing vehicles, so that, for example, regulations that affect the cost of new vehicles can lead to

substitution of driving older cars longer for purchasing new cars. This can lead to an older and less fuel-efficient fleet and therefore higher fuel consumption than would be implied by a model that separates auto purchase and fuel purchase decisions. There are again a number of approaches, the simplest being the replacement of fuel and auto purchases with a composite transportation services good composed of fuel consumption and use of the stock of vehicles. Combining this with a dynamic representation of the stock of vehicles in which new car purchases go into the depreciating stock can capture important interactions of regulations affecting fuels and vehicles. As in the case of electricity, this could be done by modifying the consumer's utility function to incorporate production of transportation services from vehicles and fuel, or by linking to a more detailed engineering-economic model of those (and other transportation-related) choices.

Recommendation CQ6-6: Improve Treatment of Existing Regulations (T2)

Based on experience with the tax interaction effect, the SAB also suggests that the EPA look into how existing regulations affecting a sector are included in the baseline. Since there are no structural representations of regulation in the model, it would appear that compliance costs with, for example, current air regulations on powerplants are just in the SAM data for unit costs in that industry. Any decreasing returns to emission control or interactions with controls already required would be missed in the CGE analysis unless the existing regulations are represented in SAGE, either explicitly or by obtaining a full marginal abatement cost curve from the engineering analysis.

2.7 Charge Question 7: Versioning System

Charge Question 7: Is the outlined versioning framework transparent and reasonable? Do you have any specific suggestions for how to improve it?

Overall, the SAB commends the agency on its proposed versioning framework. It is transparent, reasonable, broadly consistent with best practices in software development, and much better documented than the more ad-hoc processes used for many other economic models. Moreover, the approach anticipates the need for tracking the versions of the model used for different rules, as well as for tracking those used at different stages in the rulemaking for a single rule.

Although the versioning plan is strong, the SAB has two suggestions for improvement. The first is that the compiled input data and parameters for the model should be explicitly included in the versioning process and stored in the repository, while the scripts used for building the data should be tracked and stored separately. Second, the agency should consider an extended naming convention for model versions that would explicitly identify key features of important variants from the core model. Each point will be discussed briefly below.

Recommendation CQ7-1: Use a Separate Repository for Data Construction (T1)

The build process of the model envisions that new data will be drawn at build time from various data sources, such as the Current Population Survey from the Bureau of Labor Statistics. That helps model users keep the model up to date but it raises a serious complication for the versioning scheme. It should be possible for a user to get a snapshot of both the code and data for a particular version of the model, which is at odds with data being downloaded on the fly from sources outside the agency's control. This will eventually be very important when the agency needs to interact with outside groups running the model: quickly and unambiguously tying down exactly which inputs are being used will be important in

evaluating differences in results. To address this the SAB suggests: (1) including each version's fully-built input data in the main repository, and (2) using a separate repository for the scripts used to build the data. That would improve the integrity of the naming convention by ensuring that that someone running a freshly downloaded copy of SAGE version X.Y.Z will be using a known version of the code and input data. The separate repository of data-construction scripts would preserve the open-source nature of the build process for users who need it. However, it would reduce the chance that an unsophisticated user might inadvertently run the build scripts and cause their copy of the model to diverge from the downloaded one.

Recommendation CQ7-2: Extend the Model's Naming Convention (T2)

Extending the naming convention will be needed because a key goal for the SAGE project is to build a modeling framework that can be adapted for different regulatory needs. As a result, it is very likely that there will be a number of long-lived variants: for example, one with an extended treatment of electricity generation, another with more detail in motor vehicles, or a third with modeling of benefits. The current scheme appears to anticipate calling these branches something like SAGE X.Y.Z-rule_abc. However, in the long run it will be clearer to name the major branches by their core features rather than by the rules in which they were used. For example, a model with a more detailed electric sector could be SAGE electricity-X.Y.Z and when it is used in a particular rule it would become SAGE electricity-X.Y.Z-rule_abc. This would make the range and features of the variants clearer, especially to people outside the EPA, and the versions used for particular rules and papers would still be indicated with tagging them with a suffix. It would be straightforward for the agency to incorporate this into its plan: it is really just a suggestion to name the branches used for long-lived variants with slightly more user-friendly names.

2.8 Charge Question 8: Future Peer Reviews

Charge Question 8: Are the criteria in EPA's memo for the types of model changes that warrant subsequent peer review reasonable?

The SAB agrees with the agency that major revisions to SAGE's overall economic structure, or large-scale changes in its input parameters, or changes in its software implementation would warrant peer review of the full model. However, changes of that scale are likely to be fairly infrequent. Much more common will be substantial changes to components of the model, such as revisions to the modeling of electricity generation or consumer demand.

Recommendation CQ8-1: Plan for Reviews of Individual Components (T2)

To keep the quality of the model high without creating undue reviewing overhead, the SAB suggests that the agency develop a procedure for having specific components reviewed during the period between reviews of the full model.

These component reviews could be carried out by smaller teams of outside experts (two to four participants) than a full SAB review would require. As a concrete example, suppose the agency implements the consumer-side change it proposes as a near-term revision. If that were the only change from the current model, it would make sense to have the new consumer module reviewed but it would clearly not be necessary to review the entire model since the rest of it would have just gone through this review. A component-based approach may also be useful in addressing concerns about the validity of

changes made for a particular regulatory impact analysis. When such disputes arise, the agency would be on firmer ground if it has had the specific revisions peer reviewed.

In addition, the SAB notes that the agency's commitment to making the model and its data open-source is likely to provide it with extensive informal peer review. Indeed, creating an opportunity for that kind of review is the main benefit of building an open-source model. This kind of feedback has been a strength of the GTAP network.

Finally, the SAB suggests that the agency not establish a rigid rule that minor revisions other than feature branches be peer-reviewed: doing so would impede development and use of the model by making it cumbersome to use the middle tier of the versioning scheme. Rather, it should establish a clear record of peer reviews conducted and indicate the specific model or component version examined in each review.

2.9 Charge Question 9: Updates and Next Step Improvements

Charge Question 9: Are the anticipated updates outlined in EPA's memo sensible next step improvements to the model and its parameterization?

In its presentation to the CGE Model Review Panel on August 22, 2019, the agency proposed three broad areas of near-term work on the model: (1) improving the modeling of consumption decisions by households; (2) revising the model to eliminate the assumption that the United States is a small economy in world markets; and (3) refining the treatment of production, sales, and excise taxes (U.S. EPA NCEE, 2019b). To summarize points made in earlier sections, the SAB considers (1) and (2) very high priority: they are Tier 1 tasks and should be done before the model is used in production. The SAB regards (3) as lower priority (T3) and recommends instead that the agency work on improving the baseline (T1) and adding emissions coefficients, which will be discussed under charge question 10 (T2). The remainder of this section provides a brief summary of the SAB's suggestions for near term improvements in the model, and indicates where those suggestions may be found in responses to other charge questions.

As discussed in the response to charge question 2, the SAB agrees with the agency that improving the treatment of consumption should be a high priority. In the very short run, before the model is used for regulatory purposes, it is most important to move to a specification that avoids imposing homotheticity (response CQ2-4, T1). Over a somewhat longer period, the next priority is to move to econometric estimation of the parameters in the consumption model (CQ2-4, T2). Moving to a fully flexible demand system is not necessary in the short run but should be kept in mind for the model over the longer run (CQ2-5, T3).

In terms of the model's international closure, as discussed in the response to charge question 2, the agency should clarify the accounting used for international trade and financial flows (CQ2-17, T1) and then move away from the small open economy assumption in the near term (CQ2-18, T1).

High priority recommendations for improving the baseline include moving away from a balanced growth equilibrium by including better forecasts of exogenous variables (CQ2-1, T1). In addition, the agency should move toward using heterogeneous estimates of productivity growth at the sectoral level (CQ2-3, T2). Together, these changes would greatly strengthen the model's baseline.

Finally, an additional high priority for the near term is to include emissions coefficients in the production model (CQ10-1, T2).

2.10 Charge Question 10: Near-Term Updates

Charge Question 10: Does the SAB recommend additional near-term updates to the SAGE modeling framework or parameterization?

A number of extensions to SAGE would be valuable. The most important, which has been discussed under response CQ2-1, is to move away from a balanced growth baseline. However, a number of additional changes would also be useful in the longer run. Most have been mentioned earlier but are repeated here for clarity.

Recommendation CQ10-1: Include Emissions of Key Pollutants (T2)

An important near-term step would be to add supplementary accounting to allow the model to report emissions of one or more key pollutants. Accounting for emissions will be challenging because it will require EPA to be explicit about the links between inputs to production, production processes, abatement activities, and emissions. Doing so, however, would significantly enhance the model's usefulness, especially for use in evaluating air rules. In particular, it would allow the model to be used to evaluate policies that depend explicitly on the quantity of emissions, such as emissions taxes or cap and trade systems.

A good place to start would be to add carbon dioxide and possibly one or more conventional air pollutants such as sulfur dioxide, nitrogen dioxide, particulate matter, and volatile organic compounds. Additional pollutants could be added over time. In the near term, emissions could be linked to fuel use, or to industry output, using fixed factors. Doing so would be a natural extension of the model's existing architecture for representing explicit compliance requirements, where abatement is assumed to be proportional to output.

Recommendation CQ10-2: Add Accounting for Physical Quantities of Energy (T2)

In addition to accounting for emissions, the SAB suggests that EPA extend the model to track physical energy units. Fuels are currently tracked using index numbers and dollars of expenditure, but it would be very useful to report them as well in either conventional quantity units (such as kilograms, tons or barrels) or by energy content (such as gigajoules or megawatt hours). Accounting for fuel use is fairly straightforward and can be done, at least initially, with fixed coefficients linking the model's output to physical units.

Implementing this form of energy accounting requires reconciliation of the economic values in the model's social accounting matrix with energy quantities in an energy balance table. The International Energy Agency (IEA) routinely produces energy balance tables and a recent version for the US may be a useful starting point. In addition, EPA may want to draw on the expertise of the GTAP project, which has experience reconciling energy balance tables with input-output tables over time and has built consistent sets of economic and energy accounts for a number of countries. Also, it is worth noting that the revisions to electricity generation and transportation suggested in response CQ6-5 would facilitate this reconciliation by providing finer detail on two of the key uses of energy in the economy.

Recommendation CQ10-3: Strengthen the Empirical Basis of the Model's Parameters (T2)

Over the longer run, moving toward stronger empirical parameterization for the model is a high priority. Doing so will tighten the conceptual link between the model and the underlying economy, which will strengthen the justification for using it in rulemaking that may be highly contested. It will also allow the agency to move in the direction of formal probabilistic uncertainty analysis, as is recommended in Office of Management and Budget (OMB) Circular A-4 (Office of Management and Budget, 2003).

Specifically, the agency could improve on the model's elasticities by estimating them with time series data at the model's level of aggregation. Moreover, the estimation procedure would produce standard errors for the parameters, as well as covariances between them, which would allow EPA could undertake probabilistic uncertainty analysis and report confidence intervals for modeling results. Moreover, the covariance relationships between the parameters would allow the agency better insight into the robustness of its results since it would be possible to trace the uncertainty in model results back to that of the individual underlying elasticities. Finally, in addition to estimating consumption and production parameters, emphasis should be placed on estimating the trade elasticities, which are also often a key to driving simulation results.

Recommendation CQ10-4: Explore Moving to an Activity Basis for Some Parts of the Model (T2)

The agency may want to move toward an activity basis for the model by decomposing key sectors, such as steel or electricity, into a handful of heterogeneous activities that all produce a single commodity but have different cost functions. This approach introduces a new source of complexity because it will break the model's existing one-to-one correspondence between producing sectors and commodities. However, that is already a feature of other models in the literature and the approach is used extensively in integrated assessment models for modeling the power sector. Moreover, breaking that correspondence would be necessary if EPA were to adopt the WiNDC database discussed in response CQ3-4, which has a non-diagonal make matrix (that is, some commodities are produced by multiple industries), or if it were to undertake the revisions to electricity and transportation discussed in response CQ6-5.

Recommendation CQ10-5: Add Alternative Mechanisms for Specifying Expectations (T2)

Including agents with foresight captures a very important aspect of economic behavior – that investment decisions are made today based on expected future regulations and trends. The cost of this option is to make the computation burden of solving the model at least an order of magnitude larger by converting the task from an initial-value problem to a two-point boundary value problem. To keep the model's solution time reasonable, this means that the number of regions, sectors, and time periods that can be included must be kept relatively small. Because those limits can sometimes present challenges when modeling environmental regulations, the SAB believes that it would be worthwhile for EPA to develop a version of SAGE with agents having myopic or adaptive expectations. Under that formulation, which does away with foresight, solving the model becomes an initial-value problem and the number of regions, sectors, or time-steps could be greatly increased. Such a model would allow those constraints to be relaxed, when appropriate, and could be developed at relatively low cost from the existing version of SAGE. It would permit, for example, disaggregation of the country into 50 separate states. Moreover, comparing models with different degrees of foresight would be a valuable check on the robustness of the model's results. Finally, in the long run the agency may want to move to a hybrid approach that includes a mix of agents, some with foresight and some with adaptive expectations, as is used in the G-Cubed model (McKibbin & Wilcoxen, 2013).

Recommendation CQ10-6: Assess the Impact of the Partial Putty-Clay Investment Model

Most CGE models employ either a mobile capital assumption, where capital goods can be moved from one sector to another as conditions change (putty-putty), or a putty-clay approach where investment, once installed, is costly to move to another industry. SAGE employs an intermediate approach, described in the documentation as a partial putty-clay model, where 'extant' capital is the stock at the beginning of the simulation period, and 'new' capital is any subsequent investment. The extant capital is fixed in the sector where it is installed at the start of the simulation but the new capital is assumed to be mobile across industries in all future periods. This approach is new to the literature and may have strong implications for the social cost of environmental policies that affect investment. The SAB suggest that the agency carry out sensitivity analysis with respect to this formulation to make clear how it influences the model's results.

Recommendation CQ10-7: Develop a Tool for Expanding or Collapsing Industry Detail (T3)

Adding a mechanism to facilitate collapsing or expanding the level of industry detail would be helpful. SAGE will be one of many tools used in analysis of a given environmental policy or regulation. This may require that SAGE be very flexible in the number and type of production sectors, to better match an abatement technology or output from detailed life-cycle or engineering models.

Recommendation CQ10-8: Expand the Treatment of Agriculture, Forestry, and Land Use (T3)

The agency may also want to develop more the agricultural, forestry and land-use sides—there are important regulatory issues in these areas.

Recommendation CQ10-9: Allow Imperfect Competition (T3)

The agency may want to consider adding one or more features that depart from the usual assumption of constant returns to scale and perfect competition, such as: increasing returns to scale, monopolistic competition or other price-setting behavior, or slow adjustments of prices over time, especially in labor markets.

Recommendation CQ10-10: Treatment of Labor Mobility (T3)

SAGE currently does not allow labor mobility across regions, which would seem highly restrictive over a longer horizon. The SAB recommends that an alternative option be developed where labor is allowed to respond to wage gaps between regions; such an option would be more suited for policies that have a long effect.

Recommendation CQ10-11: Treatment of Time Steps (T2)

The 5-year time step in the current SAGE implementation is appropriate as a tradeoff point between accuracy and computational burden for long term policies. Some regulations have a short horizon and the distinction between extant capital and new capital is built with short-run considerations in mind. The SAB recommends that alternative versions be tested to give the modeling team a better sense of the accuracy-computation trade-off. Alternatives may be 2-year time steps for a shorter horizon; or uneven time-steps with annual periods in the beginning and 5-years further out. These shorter time steps may need a smaller number of industries or regions to be tractable. That is, if the regulation concerns one particular industry then we may want to have the dynamics of investment in that industry well modeled and tolerate a less precise accounting of detailed inter-industry effects.

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