Response to Recommendations from the Science Advisory Board's Technical Review of EPA's Computable General Equilibrium Model, SAGE

March 22, 2021

In 2017, the EPA's Science Advisory Board (SAB, 2017) recommended that the Agency enhance its regulatory analyses using computable general equilibrium (CGE) models "to offer a more comprehensive assessment of the benefits and costs" of regulatory actions. In response, the EPA has invested in building capacity in this class of economy-wide modeling. A key outcome of this effort is the EPA's CGE model of the U.S. economy, called SAGE. SAGE is a forward-looking, intertemporal CGE model of the United States economy, with the flexibility of physical capital differentiated by age. SAGE includes subnational regional representation where each region contains multiple representative firms that vary by the commodity they produce and have region-specific production technologies. Each region also has multiple representative households that vary by income level and have region specific preferences. In addition to households and firms, there is a single government in SAGE that imposes taxes on capital earnings, labor earnings, and production and uses that revenue (in addition to deficit spending) to provide government services, make transfer payments to households, and pay interest on government debt. The Armington assumption is applied to both international and cross-regional trade within the United States. In addition, SAGE recognizes that the United States is a relatively large part of the global economy and shifts in its imports and exports have the potential to influence world prices.

The SAGE model provides an important complement to the analyses typically performed during rule development by evaluating a broader set of economic impacts and offering a more complete estimate of costs. To ensure that the SAGE model is consistent with economic theory and reflects the best available science prior to use in a regulatory context, the EPA undertook a peer review of its new CGE model. Specifically, the EPA submitted SAGE v1.2 to the Science Advisory Board's (SAB) Computable General Equilibrium (CGE) Review Panel for review.

On August 28, 2021 the SAB sent the EPA its report, "Technical Review of EPA's Computable General Equilibrium Model, SAGE" with recommendations for the Agency's consideration.[1] The report classified recommendations as tier 1, 2, or 3, where tier 1 recommendations were identified as those that should be addressed "before the model is used as a formal component of the regulatory process;" tier 2 recommendations were labeled as "less crucial;" and tier 3 recommendations were identified as "changes that the SAB recommends over the longer run."

After a careful review of the SAB's recommendations, the EPA has released a minor update of the SAGE model and accompanying documentation to incorporate revisions that address the SAB's top tier recommendations. This response to recommendations document also provides written responses to the SAB's tier 1 and 2 recommendations. In addition, the EPA greatly appreciates the SAB's longer term (tier 2 and tier 3) recommendations and will carefully consider them as it develops the role of CGE modeling in economic analysis at the Agency.

[1] https://yosemite.epa.gov/sab/sabproduct.nsf/0/511476D92CEF2AC7852585D6005D373C/$File/EPA-SAB-20-010.pdf

Tier 1 Recommendations

CQ1-1: The term "CGE" should be defined and explored (it appears for the first time on page 5 of the documentation 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).

Response: We have defined CGE in the text and discuss the distinction between AGE and CGE models in a footnote in the introduction to the model documentation.

CQ1-11: The SAB recommends that the agency 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 + g + w) throughout the baseline.

Response: The version of SAGE (v1.2) reviewed by the SAB did not rely purely on a balanced growth path baseline given exogenous changes to energy intensities in both production and consumption based on the Annual Energy Outlook and the presence of fixed factors. However, to address SAB recommendations we have made additional changes to the baseline that required further deviations from a balanced growth assumption. These improvements include updates to sector-specific labor productivity growth (CQ2-2) and to the international and government accounts (CQ2-1, CQ2-16, CQ2-18, CQ3-2). The model documentation has been revised to reflect these updates.

CQ1-12: In section 2.2.1, a reference for nested CES is made to Brockway et al. (2017). Note that the first use of the multiple nested energy structure was in the OECD GREEN model (van der Mensbrugghe, 1994). GREEN was subsequently transferred to MIT and later evolved into the EPPA model.

Response: We have added this citation.

CQ1-13: The implementation of the household's intertemporal budget constraint in Equation 23 on page 17 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. Finally, it would be good to state the savings-investment balance explicitly 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.

Response: The variable kh is now a quantity variable with a rental rate of prh and a purchase price of pkh. In addition, an explicit variable for household savings/investment has been added, invh. These changes have been made in both the model code and the documentation. This allows the household budget

constraint to explicitly include the returns to household capital holdings, prh * kh. Household wealth is then represented by pkh * kh.

We now explicitly model household investment, full investment returns, and capital stock. This makes the savings-investment-capital relationship for households more obvious and links it to regional capital markets through a market clearance condition between household capital investment in the national market and the capital installed in regions, which determines the returns on household capital holdings (prh). The documentation has been updated to reflect these changes. While addressing this, the closure rule for the household's terminal period capital stock was improved to reflect the national capital market for new capital. The share of the aggregate terminal capital stock for a household is now proportional to its share of aggregate capital in the last model period, and the price is the average terminal capital price similar to other periods.

CQ1-14: 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.

Response: We have included more explicit discussion of the numeraire choice in a footnote in the documentation. Specifically, the footnote states,

"SAGE solves for a set of relative prices through the selection of a numeraire, or a chosen price level used to denominate other prices in the model. Here, price changes are characterized relative to the foreign exchange rate in the initial period. A numeraire is required in this class of economic models to satisfy Walras' Law. A competitive general equilibrium is homogeneous of degree one in prices, meaning that the equilibrium level price vector scaled by a common factor is also a solution to the model. This indeterminacy is solved by fixing a single price to align the number of equations and variables in the model. In SAGE, we drop equation 141 for t = 0, though this condition is verified to hold post-solve. Notably, in intertemporal dynamic CGE models, only one price level in a single year is needed as a numeraire. For recursive dynamic formulations, a numeraire price can be assigned in every period if the model is homogeneous of degree one in prices within each period." Additionally, we've included a numeraire test in the model's diagnostics to accommodate CQ5-1 that illustrates the model's homogeneity assumptions.

CQ1-15: 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.

Response: We have revised the discussion of how we calibrate the pure rate of time preference in section 3.4 to explain our choice of this parameter and added appropriate citations. Specifically, the text states,

"The pure rate of time preference, ρ, for households is a determinant of their savings rate and therefore, important for defining the baseline. Based on the isoelastic form of the intra-temporal utility function, the pure rate of time preference, ρ, in (24) is calibrated via the Ramsey formula given the specification of η, *rbar*, and the expected labor productivity and population growth rates over the first four model periods. Based on these assumed parameter values, ρ is about 0.018. Opinions on the most appropriate value for ρ vary. Some argue on ethical grounds that it should be equal to or very near zero (e.g., Ramsey (1928), Stern (2007)). Others rely on descriptive approaches to backout the implied pure rate of time preference, which typically imply somewhat higher values between 0.02 and 0.03 (Nordhaus, 2007). See Arrow et al. (2013) for a summary of these different approaches."

CQ1-16: 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 topic.

Response: Section 2.3 of the model documentation discusses the structure of the partial putty-clay capital representation and in particular, the formation of the single regional investment good. We have changed the functional representation of the aggregate investment good to be a generic CES production function as opposed to what was initially represented as a Leontief production function. As discussed in section 3.3.5, we set the substitution elasticity on investment demands across commodities to be low (0.05) to approximate the Leontief technology, which is similar to what is assumed in other models (e.g. USREP (Yuan et al. 2019)). However, generalizing this structure to CES allows us to test the importance of this assumption in subsequent analyses as needed.

CQ1-17: 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.

Response: We have revised Section 2.2.2 in the model documentation to more explicitly state our assumption that the fixed factors in resource industries do not vary over time. This assumption will be the subject of further work to accommodate other SAB recommendations (CQ4-1 and CQ2-12).

CQ1-18: The documentation does not illustrate how productivity shocks are implemented for regulations that are phased in over time. The text should describe the process.

Response: We have included an example of a regulation where the requirements are phased in over time, described in Section 6.5.3 of the documentation.

CQ2-1: The SAB recommends that the transition path be explicitly modelled. That is, the EPA should not assume that tax rates and the government and current account deficits are constant over time at values that are arbitrarily set to be consistent with a steady state (such as assuming the government's budget is balanced at all times). Instead, the near-term path of tax rates and government spending and deficits could be taken from the 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 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.

Response: The SAGE transition path is now explicitly modeled. Government accounts are now calibrated to match Congressional Budget Office (CBO) projections when feasible. Government deficits follow the CBO forecast and then decline linearly to zero, per the SAB recommendation in CQ2-1. When the government accounts cannot be explicitly calibrated to CBO or when extending past the CBO forecast horizon, the model generally follows the calibration approach of Jorgenson, et al. (2013). Aggregate labor productivity and population growth rates follow the CBO forecasts and then decline linearly to zero, per the SAB recommendation in CQ2-1, to achieve a long-run steady state in the solution given the inclusion of fixed factors of production and non-homothetic consumer demand. The current account balance follows the CBO forecast and then declines linearly to zero, per the SAB recommendation in CQ2-18. Other exogenous international accounts follow GDP growth, which is relatively consistent with historic trends.

CQ2-4: The current consumption function is a CES function where the share parameters for energy are calibrated to AEO projections. The SAB 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 agency will need to obtain appropriate estimates from the literature. EPA may want to refer to GTAPinGAMS because it includes both the CDE and LES and has code to parameterize the functions to match income elasticities and average price elasticities.

Response: We have updated the model to use a nested CES/LES demand system. Non-leisure consumption demand is modeled as LES and calibrated to income elasticities estimated using the methodology of Aguiar, et al. (2015). We generate income elasticities based on recent CEX data and map the estimated elasticities to input-output accounts using the personal consumption expenditures (PCE) bridge from the Bureau of Economic Analysis (BEA). The calibration routine selects the parameters of the LES demand system to target these point estimates for the implied income elasticities. Additional diagnostics are included in the model package to verify that income elasticities internal to the model match those that are exogenously estimated.

CQ2-5: 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.

Response: We have corrected this error and have added the calculation of full consumption (leisure and commodity-based consumption) to the standard model output file so that one can calculate EV as a share of full consumption.

CQ2-16: Section 3.2 states that tk is made up of the corporate tax rate from the 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. The tran0 variable represents transfers to households but is actually made up of many different items. 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 CBO projections. 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 endogenizing tax rates, lump sum transfers, or 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 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.

Response: The tax rate on capital in the SAGE model, as described in Section 3.2, is a marginal rate. Therefore, the tax revenues will not match those reported in the National Accounts. The following footnote has been added to Section 3.2 to clarify this modeling assumption:

"Notably, because we assign a marginal tax rate on capital demands, resulting tax revenues will not match those reported in the National Accounts. Any revenue recycling associated with this assumption occurs within the net transfer payment between households and government."

The tran variable has been disaggregated into its underlying components: transfers, government interest payments, government deficit, in addition to an additional lumpsum adjustment. SAGE does not explicitly model inter-institutional transfers except for the one occurring between households and the government. Therefore, inter-institutional transfers between households are absorbed into the government transfer mechanism. This additional lumpsum adjustment represents those transfers on net in addition to other fees and taxes not explicitly modeled.

The exogenous government account pathways are now calibrated to match CBO forecasts when possible and government deficits follow the CBO forecast and then linearly decline to zero per the SAB recommendation in CQ2-1.

CQ2-17: The treatment of the U.S. 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 U.S. exports and an upward sloping supply of U.S. 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 and Zhai (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.

Response: We have updated the model to include the reduced form large open economy specification found in Yuan et al. (2019). We estimate export demand and import supply elasticities, based on the GTAPinGAMS package, that are then used to calibrate supply and demand responses in the SAGE model. Changes to the model structure are described in section 2.1, while calibration is discussed in section 3.3.4 of the model documentation. In addition, we include a regulatory scenario example in section 6.5.4 to illustrate potential differences in model results based on a small versus large open economy assumption.

CQ2-18: The 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.

Response: The variable, bopdef, has been broken up into its constituent components: net income from rest of world, net transfers from rest of world, government interest payments to rest of world, and the current account balance. The exogenous path for the current account balance now follows the CBO projection and then declines linearly to zero after a couple decades per the SAB recommendation.

CQ3-1: 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.

Response: This recommendation led to a review of the labor tax rates used in SAGE. We made two changes that lead to slightly lower labor and FICA tax rates. First, wages specified in the TAXSIM simulations were inclusive of employee paid health insurance premiums, even when they were for an employer sponsored plan, when in practice that would be treated the same as the employer payments and not subject to the income tax. Those payments are now subtracted from wages prior to running TAXSIM. Second, since both the employer and employee share of the FICA tax are collected on the household side in SAGE, the tax base upon which the marginal effective rates are applied was inclusive of the employer FICA tax payments causing the additional FICA and income tax to be collected on those employer contributions - which does

not match tax law in practice. To correct for this, the rates are scaled down to correct for the inclusion of employer FICA taxes in the base to which the tax rates are applied.

These changes bring the federal marginal effective tax rates on labor income in line with other published estimates. A remaining difference between the rates used in SAGE and those recently published by CBO is due to a difference in what is assumed about the share of marginal income that is non-taxable health benefits versus wages. In calculating its marginal rates, CBO assumes that the next dollar of compensation will be partly health benefits where that share matches healthcare's average share of labor compensation in the economy. In SAGE, we currently assume that the marginal labor compensation will be all wages. Moving from that assumption would require further evidence regarding the share of marginal compensation that is expected to be in the form of healthcare benefits.

CQ4-1: The SAB suggests the EPA perform additional testing of the model 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.

Response: We have updated the sensitivity scenarios to include sector-specific consumption tax simulations, which are described in section 6.5.5 of the model documentation. We intend to explore model sensitivity to assumptions about the supply of natural resources at a future date. The most recent version of the model includes example simulations that explore additional tests and scenarios that highlight key features of the model and help users build intuition regarding how the model operates and confirms that SAGE delivers expected results for well understood scenarios. Example simulations provided in the model package include a comparison of a small open economy formulation to a large open economy formulation, and comparisons between models formulated as national vs. regional, static vs. dynamic, putty-clay vs. putty-putty, and a comparison of a phased-in policy design with one that is not phased in. We intend to continue building this suite of simulations.

CQ4-2: The SAB 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 consistently interpret model output reliably.

Response: We have created functions for producing pivot tables from results files as well as graphs of the results. Function code is in R_utilities.R. We have also added a separate file in examples (plot_results.r) illustrating these functions, which are noted in the documentation. The plotting functions are flexible to aggregate and report all variables contained in the model output via line or bar graphs. The code allows the user to plot at most three dimensions at once (choosing between time steps, regions, sectors, households, and origin sectors) and plot the baseline and policy values as well as the percent change and absolute difference between the two. As we move forward with applying the model in practice, we will consider how to use this new functionality to produce consistent, user-friendly reports.

CQ5-1: 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.

Response: We have added a homogeneity test as a solution check in section 6.4.1. The documentation now states,

"The previous solution checks illustrated instances of hypothetical policy shocks that satisfied post equilibrium adding up conditions. One other form of model validation concerns test simulations where the outcome of the simulation is already known. One such test suggested by Dixon and Rimmer (2013) is to test the model's homogeneity assumptions. As described above, SAGE is homogeneous of degree one in prices and hence a numeraire is assigned to represent equilibrium prices as relative. The level of the numeraire is typically fixed to 1. Because the model relies on relative prices, perturbing the numeraire from 1 to (1+β) should adjust all baseline price and value variables by the same perturbation factor (β) while quantity variables remain unchanged.

To test that this assumption holds in SAGE, the "policy" file, diagnostics/numeraire test.gms, contains an adjustment to the numeraire by a perturbation factor of $\beta = 0.2$. "Policy" is written in quotes because the purpose of this test is to compare two separate baselines (not a policy case vs. a baseline) differed only by the magnitude of the numeraire but can be functionally implemented with a policy file. Notably, the chosen value of β is arbitrary. The example may be run from the command line in a similar fashion those already described or from the R script, diagnostics/numeraire test.R."

CQ7-1: 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. 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.

Response: Thank you for this recommendation. We have carefully considered the benefits and challenges associated with keeping the model and build stream in separate repositories and have determined that maintaining a single repository for SAGE is the preferred approach for organizing the code base. Below we list the rationale for maintain a single repository but also changes that we have implemented to increase transparency and reduce the risk of inadvertently overwriting the stock datasets.

1) The model code and data build code are developed in tandem – and similarly may be modified in tandem when preparing the model for a specific regulatory application. Maintaining these files in separate repositories would require extensive levels of due diligence to keep track of forward and backward compatibility between the repositories and could easily lead to confusion and errors.

2) The model package reports the version information of all underlying external datasets used to produce the benchmark data file. This report is pre-compiled and included with the distribution. This report (named build/data/satellite_data_versions.csv) is generated each time the build routine is run, and we will now prevent the pre-processed report from being over-written by naming it SAGE_release_data_versions.csv in the model release package. This distinguishes the underlying data versions in the released version of the model from those used when re-running the build code.
3) The model package already separates the build routine, model files and pre-compiled data files needed to run the model. Should the user have access to the state-level IMPLAN data and need to reconstruct the reference dataset, the meta data report indicated in (2) would provide the needed information to isolate the differences. To prevent a circumstance where an inexperienced user accidentally alters the build stream and produces a dataset at odds with the preprocessed file, we have added the following warning message to the primary script that launches the build routine:

   "WARNING: Rebuilding the SAGE database is for experienced users only. Note that by running this code, the resulting datafiles (in /data/) may differ from the ones included in the SAGE package. Exit the program if this is not intended. Please compare build/data/satellite_data_versions.csv to build/data/SAGE_release_data_versions.csv to isolate changes should they occur. The program will run in 20 seconds."

Tier 2 Recommendations

CQ1-2: We recommend that 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 the SAGE model. It would also be useful to enhance the graphics used to explain the model: the nested tree diagrams currently in the documentation will be opaque to readers outside the modeling community.

Response: We have added a summary for non-modelers at the beginning of the model documentation.

CQ1-3: 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. As it is, there is too much space preceding the "f" in those variable names. Making this change for all multi-character variables will significantly improve the legibility of the documentation.

Response: In math mode, Latex treats individual letters as separate variables and provides adequate spacing between them based on that assumption. As a result, the SAB is correct that some multi-letter variable names can have odd looking spacing between some letters. This is particularly prevalent with f's. To solve this problem, all multi-letter variable would need to be wrapped in \mathit{}. This includes subscripted set identifiers, such as "dtrd" and "ftrd".

Because this would be resource intensive to address, requiring well over a thousand variables to be wrapped in \mathit{}, we have not yet implemented the change but plan to do so at a future date. Note that when we elect to alter the typesetting of multi-character variable names, we will consider alternatives to \mathit{} to avoid hard coding. That way if we ever want to change the look of variables in the math environment it would only require adjusting the definition in the preamble of the .tex file. For instance, one possible option would be to wrap all variables, including single letter variables, in a single \var{} environment defined as \newcommand{\var}[1]{\mathit{#1}}.

CQ1-4: The SAB recommends that the EPA: (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. By including only purchaser's prices and not producer's prices, the current formulation saves T×R×S endogenous variables in the GAMS code.

Response: After careful consideration, we have decided to maintain the current pricing structure in both the documentation and the model. As the recommendation points out, introducing another set of prices outside of those already represented in the model would make no functional change to the solution and add extra variables that increase the dimensionality of the model along with the code footprint. However, we have added the following footnote to Section 2 of the documentation that clarifies this choice:

"We define all prices as purchaser prices to reduce the footprint of model code and documentation. This choice does not impact the model solution."

CQ1-5: 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 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.

Response: As the SAB notes, the documentation first lays out the theory and broad descriptions for each component of the model before turning to model calibration. We have read through the documentation to discern whether any additional adjustments to the organizational structure could better align the sections and have made some small changes. In addition, we have added more discussion of the benchmark SAM in Section 3.1. Specifically, we discuss the process we developed based on IMPLANinGAMS (Rausch and Rutherford, 2009) that extracts submatrices from the raw IMPLAN data files to construct SAGE parameters and the methodology used to recalibrate investment totals:

"The process for translating IMPLAN data from an input output data structure to model parameters is based on Rausch and Rutherford (2009). The input output matrix is partitioned into sub-matrices that include make and use matrices, vectors of factor and commodity demands by sectors and households respectively, transfer payments and trade accounts. Model parameters are created from these sub-matrices and run through a matrix balancing routine that minimizes the change in the data required to enforce accounting identities outlined in previous sections (specific options available in the matrix balancing routine are discussed in Section 6.5).

While SAGE deviates from a balanced growth path assumption in a number of ways as illustrated throughout this documentation, the initial construction of the benchmark data relates investment demands and capital income through a standard Ramsey based formulation. Typically, input-output tables such as those from IMPLAN or BEA are constructed in a static framework meaning investment demand, i0, is determined as the residual that would lead the goods market clearance condition in (39) to hold. Doing so does not require investment demands to line up with assumptions about interest, growth and depreciation rates which are inherent in the dynamic context. The matrix balancing routine scales investment demands to align with assumed rates and minimally adjusts other parameters to maintain micro-consistency."

CQ1-6: 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.

Response: Thank you for this recommendation. We think that the documentation in its current form already does this to some extent. The documentation first builds the intra-temporal (static) choice structure on the production side of the model (trade, sectoral production functions). In these cases, the

difference between a static and dynamic framework is simply a *t* subscript. We then begin to discuss dynamics in the form of capital formation and intertemporal household choice. We think that discussing the intra-temporal consumer demand choice structure before capital dynamics and intertemporal utility may cause confusion due to the need to alternate between different segments of the model to discuss the time dimension.

CQ1-7: The discussion in section 4 describing the solution procedure should be shortened and clarified. The formal mathematical definition of the model should be omitted, or else moved to an appendix if the EPA wishes to retain them. The remainder of the section should focus on describing specific details that are important for understanding the model's implementation in GAMS, such as the section's current discussion of the switch from levels variables to indices relative to the base year. It would also be useful to include a brief discussion of the PATH solver. Finally, the section should note any strengths or weaknesses of the overall solution procedure, including key diagnostics provided by the software to indicate whether the model was correctly specified (e.g., that the counts of equations and endogenous variables match, or that the model is full rank, etc.) and whether or not a global optimum was found.

Response: We have added information on the model's implementation in GAMS and the PATH solver per the recommendation. However, for transparency we retain the model's formal mathematical definition as well. The model is described in previous sections in a primal (quantity based) formulation of general equilibrium. The actual solution of SAGE relies on the dual mixed complementarity formulation (price based). Therefore, including the detailed formulation provides transparency and important context for understanding the information on the solution algorithm.

We have added more information on the mixed complementarity framework, PATH solver, and model dimensions to the text in Section 4. On the mixed complementarity framework:

"The mixed complementarity formulation of SAGE arises from the Karush-Kuhn-Tucker conditions of the nonlinear programming formulation that maximizes household welfare. In what follows, we use the $\perp$ symbol to denote complementarity conditions. As an example, consider the condition: $xF(x) = 0$. For this to be true and assuming non-negativity, either x and/or F(x) must be 0. This problem can equivalently be written as: $F(x) \geq 0 \perp x \geq 0$. Here, if $F(x) = 0$, then $x \geq 0$, whereas if $F(x) > 0$, then $x = 0$. We apply this framework to the zero-profit, market clearance, and income balance constraints."

For more on PATH, we've added the following footnote:

"PATH is a solver designed for mixed complementarity problems, though it can be adapted to other problem formulations. Essentially, the solver is a variant of traditional Newton methods with added path generation procedures for non-smooth problems. The solver is shown to be globally convergent. The solver also requires that the number of model equations and variables match for it to begin its solution algorithm. See Dirkse and Ferris (1995) for more detail."

CQ1-8: 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.

Response: The model documentation is generally organized around this structure. We have added a circular flow diagram to the summary for non-modelers to make the connection between the overall structure of the model and the way the documentation is organized more apparent. See the response to CQ1-6.

CQ1-9: 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. EPA should also include the wealth accumulation equation so that a post-solution calculation can be used to verify that it holds (one of several tests that the model is functioning correctly; see section 2.5 for additional tests).

Response: Thank you for this recommendation. Because we have added an executive summary of model features, we have elected to keep the mathematical presentation of the model as-is throughout the rest of the documentation so that readers don't need to flip between the main body and an appendix to completely understand the model specification.

We have included a full representation of prices and quantities in the model documentation and code to help clarify model assumptions (also in response to other SAB recommendations). The wealth accumulation post-solve verification test is also included in the model code. Furthermore, we have added tables that includes model sets, parameters and variables and associated descriptions to the beginning of Section 2.

CQ1-10: 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. 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.

Response: Thank you for this recommendation. Because our naming conventions are consistent throughout the model and documentation, changes to sets and variable names are unlikely to make the exposition clearer. For instance, per our model naming convention, all data parameters are named with a trailing 0 to distinguish them from model variables. Variable, parameter and set notation in SAGE are also consistent with other CGE models in the literature and were initially selected for this reason. For these reasons, we have elected to maintain the existing variable, parameter and set notation. To make it easier for external analysts looking at the model we maintain all variable definitions, with descriptions, in one place in the GAMS code and have added tables with variable and set descriptions in the documentation in response to recommendation CQ1-9. Together, these features should make it is easier to navigate the documentation and code for folks unfamiliar with the model's naming conventions.

CQ1-19: 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).

Response: We have clarified this text in Section 2.6 to include:

"The price of the Armington aggregate, pa, is a composite price index derived from three prices: the price for domestic output consumed regionally, pd, the price of commodities imported from the national market, pn, and the price for imported commodities from the foreign market, pm. pa clears the intermediary market for the aggregate demand of commodities, such that..."

CQ1-20: 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. The text should reflect this.

Response: We have added the following sentence to Section 2.5 clarifying this point:

"Because there is a single government agent in the model, regional public expenditures and tax revenues do not necessarily line up but are reconciled at the national level."

CQ1-21: 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.

Response: In response to other recommendations household capital accounts and returns to those accounts are now explicitly tracked thereby bringing an explicit savings variable into the household budget constraint, which is the difference between income and full consumption. This provides additional clarity regarding the full set of income sources and expenditure categories, including savings, for the household. Therefore, a tree diagram is unlikely to bring additional clarity to the documentation. However, to further demonstrate the relationship between income, savings, and consumption, both savings and full consumption are now placed on the left-hand side of the household budget constraint with income on the right-hand side (net of government transfers).

CQ1-22: 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.

Response: In response to this recommendation, as well as others, we have added a lengthy discussion of the calibration of the model's intertemporal variables to Section 3.4 of the model documentation.

CQ1-23: 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 (p. 42).

Response: The model documentation remains written in terms of annual time steps for simplicity, but we have added Section 4.1 to the model documentation describing a step function approach for handling multi-year time steps. The default version of the model is specified with five-year time steps due to computational limitations. This approach is operationalized in the model code by explicitly entering in the laws of motion for capital stocks and the inter-temporal no arbitrage condition. The choice of time steps can be changed either when rebuilding the database in build/build_default_datasets.R or directly in data/baseline.gms.

CQ1-24: 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. 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.

Response: The ordering of the "Using the Model" section has been changed to accommodate the first part of this recommendation. For IMPLAN licensing, the documentation references the version used to construct the underlying database. More information on licensing options for IMPLAN data can be acquired from IMPLAN Group, LLC.

EPA staff developing the SAGE model do not have to connect through a proxy server and are therefore unable to test such a configuration in the build system nor confirm that a single set of instructions would fit all use cases. Instead, we have included the following footnote in the documentation warning that additional configuration may be needed when a user is attempting to rebuild the database but is connecting through a proxy server:

"The build stream relies on the R package 'RCurl' to download external datasets. Functions in this package used in the build routine may require additional configuration if a user is attempting to rebuild the database but is connected to a proxy server."

CQ2-2: 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. 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. 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 TFP growth parameters, these parameters should be set carefully. 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.

Response: We have implemented an update to the model code and documentation (Section 3.4.1) that allows for sector-specific labor productivity growth rates. The economy-wide labor productivity growth rate is calibrated to the economy-wide labor productivity growth rate estimates in the CBO Long Term Budget Outlook to address the first part of the recommendation. The sector-specific growth rates are calibrated to target the economy-wide growth rate but with a heterogeneous distribution of productivity growth across sectors based upon historical estimates from BLS referenced in the recommendation. This is added to the model via a productivity parameter in the value-added nest of production. The model's baseline assumes long-run convergence in this distribution to a single economy-wide labor productivity growth rate.

CQ2-3: SAGE now restricts productivity growth to be symmetric across industries, acting through effective labor input. The historical record, however, shows a wide range of TFP growth, from strong positive to negative. 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 EIA projections of energy prices.

Response: See response to CQ2-2. Sector-specific labor productivity growth rates are implemented in the model. From Section 3.4.1:

"The Integrated Industry-level Production Account data from BEA and the U.S. Bureau of Labor Statistics (BLS), covering 1998 to 2017, provide estimates of historic integrated labor productivity growth by sector in addition to data on gross output. This information is used to developed output-weighted average labor productivity growth estimates for each of the SAGE sectors. Prior to 2050, the baseline assumes that these historic differences in productivity will persist. After that point, the variance across sectors is calibrated to linearly decline to zero by 2070 (i.e., the productivity growth rate in each sector converges to the mean growth rate)."

CQ2-9: The function allocating total investment and total government purchases to the various commodities is Leontief, which causes the ratios of individual investment goods in total investment to be fixed. This is not reflective of past investment trends. 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.

Response: We have implemented a CES aggregator function for the aggregate investment good with a small substitution elasticity to closely match the previous Leontief assumption. The cost shares in the CES aggregated function have been specified with a time index to allow for the possibility of accommodating projections on compositional changes in total investment. For more on the CES aggregator function, see response to CQ1-16.

CQ2-11: In the modeling of capital input, the agency can consider combining the 'extant' and 'new' nests in a single structure indexed by 'v'.

Response: Thank you for this recommendation. We think that this is a worthwhile addition to the model. While we have not yet implemented the change, we plan to do so in the future.

CQ2-12: 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. In the near term, EPA could add exogenous resource supply shifters that could be used as an alternative.

Response: Thank you for this recommendation. While we have elected to maintain the current fixed factor assumption in the near term, per our responses to CQ1-17, CQ2-12 and CQ4-1, the fixed factor resource supply will be the subject of future work.

CQ3-2: As discussed in section 2.2.8, 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.

Response: We have improved the exogenous government accounts in the baseline to include government deficits, debts, and interest and transfer payments in Section 3.4.3. In particular:

"The government agent in SAGE represents all federal, state, and local governments in the United States. Real government expenditures are exogenously specified, as is the level of deficit financing. The relevant expenditure variables are government consumption, gov, interest payments, gint and gint_row, and transfer payments, transfers. Where possible we calibrate the variables to CBO's budget projections. However, CBO's budget projections only cover the federal portion of the government expenditure variables and in many cases are only presented in the 10-year budget outlook, requiring extrapolation for the longer time horizon in SAGE."

More details about the extrapolation of exogenous forecasts beyond the CBO time horizon can be found in the responses to CQ2-1 and CQ2-16 along with Section 3.4.3 of the documentation. A graphical depiction of the government's fiscal position is plotted in Section 3.4.6.

Government debt and interest payments are now explicitly tracked in the model, though both are exogenous given the closure for government accounts that fixes real expenditures.

CQ5-2: 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.

Response: In response to this recommendation, we have added Section 3.4.6 to provide a comprehensive exposition of key intertemporal variables in the SAGE baseline. The figures are designed to be automatically updated and added to the documentation following any future changes to the baseline by running diagnostics/baseline_visualization.R. We include figures of growth rates (GDP, labor, capital), components of GDP via expenditures (e.g., consumption and investment), government accounts (per CQ3-2), foreign accounts, sectoral output growth, and national commodity price growth.

CQ5-3: 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 EMF, would be useful as well.

Response: We thank the SAB for this recommendation. Outside of explicitly tracking baseline variables via the visualization tools described in our response to CQ5-2, we will continue to monitor the importance of certain factors in characterizing the model's baseline. We also agree that inter-model comparison exercises such as the Energy Modeling Forum (EMF) would also provide a useful testing ground for alternative baseline assumptions and an opportunity to investigate whether specific factors such as energy prices are potentially influential when estimating policy impacts.

CQ5-4: 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 (e.g., 1 year) and only up to 2031. Would the results of the policy be the same overall (e.g., in terms of EV), or the same in some particular year (e.g., for change in output)?

Response: The model's results, particularly with the transition path updates in response to recommendations CQ2-1, CQ2-16, CQ2-2, and CQ2-3, can be sensitive to the terminal year, particularly for a 15 year time horizon ending in 2031. We would not recommend running the model with such a short time horizon. In fact, after initial testing with the updated baseline we have extended the model's time

horizon to 2081 to reduce the influence of terminal conditions on near-term results. The model has been updated to accommodate variable distance time steps so that we can introduce greater temporal resolution in the near term while maintaining a sufficiently distant terminal year in a computationally tractable manner. The impact of changing the time step at different points along the time horizon will, in part, depend on the details of the specific policy under consideration. Thus, we will carefully consider this on a case-by-case basis.

CQ6-1: 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 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.

Response: We thank the SAB for this recommendation. Similar to our response to recommendation CQ10-8, adding emissions is a priority for future model development efforts and will allow us to explore market-based approaches such as those discussed in the recommendation in SAGE.

CQ6-2: 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. 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. Achieving congruence between engineering studies and the CGE results is also more likely when mechanisms by which a regulation is expected to affect behavior are included in the model. If key margins on which decisions are made are not represented in the model, the welfare effects of regulations will be incomplete.

Response: The model package includes two alternative ways to introduce environmental regulations: via a productivity shock or an explicit abatement activity. In the latter case, Section 5.2 notes that:

"This is accomplished by extending the nesting structure of the production function depicted in Figures 4-6 to include a top-level Leontief nest that combines production of saleable goods and services with pollution abatement activities. For the standard manufacturing and services production functions with new capital, this extended production function is presented in Figure 21. Production then requires both the traditional production activity and an abatement activity, which is itself a Leontief function of inputs used in regulatory compliance."

The initial implementation of this abatement activity was purposefully implemented as a Leontief technology for the reasons outlined in the SAB's recommendation. The degree to which inputs into the abatement activity may be substitutable is case specific and will affect the results of modeling. From a programming perspective allowing for substitutability across inputs in the abatement activity is relatively straightforward for the analyst to implement if needed, but calibrating the function to represent the suite

of abatement activities available must be done carefully and be informed by the available engineering studies. However, this approach may not be well suited to modeling potential process changes pursued to comply with environmental policies. In these cases, the productivity shock or a hybrid approach may yield a more appropriate congruence with the engineering studies that represents more of the key margins along which firms will have to make compliance decisions. We thank the SAB for their insight and will heed their advice when selecting the appropriate representation of a regulation in the model, being sure to consider the potential substitution possibilities implicit in the modeling specification.

CQ6-3: 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.

Response: We thank the SAB for their suggestion. We are currently investigating opportunities for greater disaggregation of these sectors to allow for heterogeneity in the production structure.

CQ6-4: 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.

Response: We thank the SAB for this recommendation. The cost of existing compliance activities in the benchmark year are represented in the SAM, and some future activities will be picked up in the calibration of the baseline. However, the SAB is correct that the default version of the model does not explicitly model margins along which those compliance activities have responded to regulatory changes in the past or will respond to a new regulation being analyzed. While the latter may be, to some degree, implicitly captured by the empirically informed substitution possibilities allowed for in the model, we agree this warrants careful consideration as it may inform the appropriate modeling approach for a given regulation or the interpretation of the results. We have added the following footnote in Section 3.4 to the documentation to elaborate on this point:

"We note that there is no explicit characterization of existing regulations in the constructed baseline for SAGE. While the costs of complying with existing regulations are included in the social accounting matrix used to calibrate the model, they are not distinguished from non-regulatory related costs. Therefore, interactions that potential policy scenarios may have with existing regulatory compliance activities are not captured using the default version of SAGE. Any decreasing returns to emission control or interactions with existing controls need to be carefully considered when calibrating the policy representation in SAGE and in conjunction with the default specification of the model."

CQ7-2: The current naming convention 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.

Response: We thank the SAB for this recommendation. We will consider this advice as we build additional model features that may not be included in the core SAGE framework to clearly distinguish between versions of the model.

CQ8-1: 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.

Response: The EPA will consider this recommendation as it moves forward with further development of the SAGE model. The EPA remains committed to peer reviewing the SAGE model as new components are developed. The EPA has at its disposal several avenues for peer review short of a full SAB review, including letter review, which can be utilized as warranted to review specific aspects of the model.

CQ10-1: Over the longer run, moving toward stronger empirical parameterization for the model is a very 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 Circular A-4. The SAB strongly recommends that the EPA move in that direction, as it is a significant improvement over sensitivity analysis. 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 to undertake probabilistic uncertainty analysis and report confidence intervals for modeling results. 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. As the EPA strengthens the model's parameterization it should also begin planning for future steps toward validating the model. Dixon and Rimmer (2013) and van Dijk, et al. (2016) provide two overviews of the process. The agency should also anticipate carrying out retrospective reviews of the model's performance.

Response: We thank the SAB for this recommendation and have taken this advice into consideration when implementing other SAB recommendations and as we pursue future development of SAGE. For example, in addressing recommendation CQ2-4 we elected to conduct new econometric estimation following methods available in the literature to improve our specification of the consumer demand system.

CQ10-2: In addition to accounting for emissions, the SAB suggests that EPA extend the model to track physical energy units. 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. Also, it is worth noting that the revisions to electricity generation and transportation suggested in response CQ6-3 would facilitate this reconciliation by providing finer detail on two of the key uses of energy in the economy.

Response: We thank the SAB for this recommendation. We will take this recommendation into consideration as we review the recommendations in CQ6-3 and CQ10-8, as tracking physical energy flows may also allow us to better capture the emissions impacts of policy scenarios.

CQ10-5: The agency may want to move toward an activity basis for the model by decomposing key sectors into a handful of heterogeneous activities that all produce a single commodity but have different cost functions.

Response: We thank the SAB for this recommendation. Moving forward, we will consider this alternative among others to disaggregate key sectors (such as electricity generation or transportation) in SAGE.

CQ10-6: 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. 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, 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. 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 in the G-Cubed model (McKibbin & Wilcoxen, 2013).

Response: We agree that incorporating agent foresight in SAGE captures an important aspect of economic behavior and allows the model to capture anticipatory changes in behavior due to forthcoming environmental regulations. We will review the trade-offs associated with capturing that aspect of economic behavior with the additional detail that could be incorporated in a recursive dynamic version of the model as we continue to develop the SAGE model.

CQ10-8: An additional step EPA could consider be to add supplementary accounting to allow the model to report emissions of one or more key pollutants. Doing so 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. However, accounting for emissions of many pollutants will be challenging because it will require EPA to be explicit about the links between inputs to production, production processes, abatement activities, and emissions. Therefore, the SAB recommends that over the long run the agency consider adding emissions of selected pollutants for which it is: (1) possible to incorporate an appropriate sub-model representing the process generating the emissions; and (2) the policy to be examined depends explicitly on the quantity of emissions.

Response: The SAB identifies both the utility and challenge of incorporating emissions into the SAGE model. We are investigating ways to represent emissions in SAGE, leveraging EPA and other sources of data that are publicly available.

CQ10-9: Many 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 was initially described by Lau, et al. (Lau, Pahlke, & Rutherford, 1997) has been used in various forms in models including ADAGE, NewERA, MRN, USREP, DIEM and EPPA-4. Because it may be important in determining the social cost of environmental policies that affect investment, the SAB suggests that the agency carry out sensitivity analysis with respect to this formulation.

Response: The current version of SAGE includes an option to run the model in the putty-putty framework. Using this functionality, we have included multiple examples that allow one to examine the sensitivity of the model's results to a partial putty-clay vs. a putty-putty specification. We will continue to monitor the literature on the implications of using a full vintaging structure in a forward-looking model and will also consider this recommendation as we continue to develop the SAGE model.