Draft Responses to Charge Questions

Contents

Question 1 – Alan Fox 2
Question 2 – Mun Ho 6
Question 3 – Dominique van der Mensbrugghe 17
Question 4 – Sergey Paltsev 18
Question 5 – Ron Sands 19
Question 6 – David Montgomery 21
Question 7 – Pete Wilcoxen 24
Question 8 – Peter Wilcoxen 25
Question 9 26
Question 10 – Peter Wilcoxen 27
Appendix to Charge Question 1 29
Typesetting Multi-Character Variable Names in LaTeX 29
Suggested Code Restructuring 31
Proxy Configuration Examples for R 49

Question 1 – Alan Fox

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 is broadly clear, transparent and accurate. EPA staff have produced an important document to guide the interpretation, use, and further development of the SAGE model and data framework. As it currently stands, the documentation is understandably targeted at the technical community. The documentation can be improved further 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 understanding. The recommended changes fall into the following broad categories:

1) additional material to aid less technical readers;
2) organization and presentation of the documentation;
3) and supplementary description to clarify certain points concerning the model and data.

Additional Material To Aid Less Technical Readers

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 model 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.

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 as simply CGE), and the model is stated to be an applied general equilibrium model (without clarifying that the authors treat AGE model being the same as CGE model). There are some passionate papers that make a distinction between AGE and CGE (e.g., Mitra-Kahn, Benjamin H. (2008) "Debunking the Myths of Computable General Equilibrium Models." Schwartz Center for Economic Policy Analysis, Working Paper 2008-1). We would encourage a fuller description of the general modeling approach.

Organization and Presentation in the Documentation

The SAB recommends that 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 approach. 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.

The SAB suggests that 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 perfect foresight model implementations. Starting with a simple framework and annual time steps and then expanding the simple 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.

The discussion in the Solution section (4) 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 EPA wish to retain them, be moved to a mathematical appendix.

The SAB suggests that EPA consider reorganizing the model description using the standard circular flow paradigm: (1) production; (2) income allocation; (3) final demand; (4) domestic and international trade; (5) market equilibrium; and (6) closure. A suggested restructuring of the model code that follows this paradigm is provided in the CQ1 Appendix. This version of the model code also keeps 'modules' together. This means that they can more readily be swapped out if model structural changes are made.

The typesetting of equations throughout the LaTeX document code can be made more legible by ensuring that all multi-character variable names (e.g., *pfx*, *bopdef*, *tl_refund*, etc.) should be typeset as \mathit{<variable_name>}, e.g., \mathit{tl_refund}_{t,r,h}. Using \mathit{} ensures that LaTeX properly sets *tl_refund* compactly and with appropriate kerning, rather than as "*tl_re f und"*. See the LaTeX code example in the CQ1 Appendix for more detail and an example.

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. EPA should also include the wealth accumulation equation that can be computed post-solution to facilitate confirmation values are adding up with capital gains.

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 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 EPA replaced the use of 's' and 'ss' for sector for another index, such as "*i*" for commodities and "*a*" for activities. GTAP and other global models frequently use "*s*" for source country or region.

The SAB recommends that 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, eq. 9:

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

would be cleaner with a variable for the producer (seller) price $py_{trs} = (1+ty_{trs})py^p_{trs}$. The current formulation without py^p_{trs} saves T×R×S endogenous variables in the GAMS code, and thus is reasonable in the program. In the documentation, however, the presentation would be clearer with distinct base and purchaser prices. In the post-solution code, the second price may be computed and stored. (If the modelers wish to implement it within the model code, this can be readily done using GAMS' MACRO feature).

Clarifications to the Text

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

Balanced Growth Path: EPA should make clear from the beginning that the model 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 p. 43, and then only obliquely.

Citation for Nested CES: In section 2.2.1 (p. 8) reference for nested CES is made to Brockway et al. Note that the first use of the multiple nested energy structure was in the OECD's GREEN model (see van der Mensbrugghe, OECD 1994). GREEN was subsequently transferred to MIT and morphed into the EPPA model.

Capital Remuneration: It appears that there is an implicit assumption that all capital remuneration is saved, plus or minus some adjustment. The SAB would like to see a formal development of the analytics of this (even in a simplified framework, i.e. where all other income is consolidated into a single variable).

Equation 23, Household Savings and Budget Constraint (p. 17): Equation 23, the household savings and budget constraint, should be clarified in line with NCEE's reply to questions submitted by the SAB. It is most accurate to say "household savings are used to finance the government deficit, the current account surplus and private investment (extant and new capital). The change in wealth is the sum of savings and capital gains." We recommend that EPA **not** use *kh* as a stock variable in an equation where it is treated in value terms, and say that it is multiplied by the price *pkt* elsewhere (see p. 23). Value variables and stock variables should be kept clearly separated.

Use of the Term "Clears" in the Goods Market (p. 21): The SAB suggests that care be taken in the use the word "clears" with respect to the goods market, for example for equation (36). The Armington price is a composite price and can be derived from the true 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).

Clarification of Choice of Numéraire (p. 22): The numéraire in the model is set equal to the price of foreign exchange in the initial period, pfx_0. Equation (42) is Walras' law in the benchmark year, where *pfx* is the numéraire and exogenous. In recursive dynamic models, often the numéraire is fixed in each period (discounting would be done post-simulation), and typically all prices are simply designated relative to base year prices. It is possible to re-price future years post- simulation with SAGE as well, so this decision has no implications for model results. EPA should elaborate the reasoning for this choice.

Regional Balance of Payments (p. 23): 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.

Time Steps and the Model Horizon: 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 (p. 42). This also relates to the organizational question above concerning presentation of dynamics within the model.

Role of Discount Rate: The discount rate is a critical parameter for dynamic models and there is a substantial literature on a choice of discount rates (e.g., Stern vs Nordhaus). The model documentation in Section 3.4 provides the assumed rate of time preference (and therefore the discount rate), but it does not refer to any of the debates about the choice of the discount rate. If the authors believe that the debate on proper discounting is settled or not relevant for their purposes, it should be explained in the model documentation.

The Production Function for the Investment Good: 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.

Relationship of fixed factors to resource depletion: 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, and possibly superior, and needs more discussion.

Productivity Shocks and regulatory phase-ins: The documentation does not illustrate how productivity shocks are implemented for regulations that are phased in over time.

Section 6, Using the Model (p. 59): It should be noted there is a public version available without the data, and a full version that is available to licensees of the IMPLAN data set. It is also worth including with the GAMS and R search path requirements that if the user is behind a proxy, .Renviron and .Rprofile configuration files must be populated to allow the R scripts as written to download the publicly available datasets. Sample configuration files are in Appendix to CQ1.

Question 2 – Mun Ho

Prelim note: For a number of comments listed under Question 2, they are more appropriately moved to Q1 and Q10, and have been sent to Alan Fox and Pete Wilcoxen. *The items in italics are the more important ones needing a Panel decision.*

CQ2. Are the model structure and assumptions reasonable and consistent with economic theory?

2.1 Dynamic structure of SAGE

2.1.1 Balanced growth path

[Ho]

The model assumes that the economy is in a balanced growth equilibrium, that all real exogenous variables grow at the steady state rate $(\gamma + \omega)$ in the base case (population growth rate + labor productivity growth). This is a common approach in macroeconomics using complicated stochastic models. This is an appropriate simplification for the analysis of many types of policies and may even be appropriate using a non-stochastic model like SAGE.

However, we should demonstrate that this is appropriate for the policies that EPA are most likely to analyze. The actual economy is not in a steady state and over the next few decades we are quite certain that the population will continue to age (growth of labor supply not equal to growth of population), the government and trade deficits are not sustainable (either tax rates or spending have to change over the 2050 horizon), and the sector composition and relative prices will keep changing.

(I am not sure how others define a balanced growth equilibrium. Textbooks say that the steady state is when all relative prices stop changing and real quantities growth at the rate of effective labor. Such textbook models have a simple capital input that is reproducible capital. In SAGE there are resource inputs that are fixed in supply, and the prices of resources (*pres*) diverge to infinity (e.g. *pres*(2061,enc,agr)=10.8 relative to cpi(2061) after starting at 1 in 2016). Is the equilibrium in SAGE well defined? Are equations 46 and 47 valid in this framework? Other models with fixed resources are myopic where there is no need to worry about steady states. ADAGE is a foresighted model and says explicitly that all endowments grow at the same rate; G-cubed also have infinite supply of resources. IGEM does not have fixed resources.)

Below in section 2.1.5 we suggest methods to allow for different growth rates for different industries. But the issue here is: in an infinite-lived model with positive productivity growth, then for the model to have a well-defined steady state with no diverging prices, it must eventually have (i) equal TFP growth across industries, (ii) unit income elasticities, (iii) no resource limits. An alternative is to eventually have zero TFP growth where income elastic demands and fixed resources do not matter.

(the Review cmmt may thus consider these options for recommendation:)

a) *We recommend that SAGE keep the current simplification and ignore these balanced path issues.*
b) *We recommend a longer horizon, where realistic current trends in productivity and output are included in the period of interest (say 2050) but zero TFP is imposed thereafter to allow convergence to a well-defined steady state.*
c) *We recommend an alternative resource supply specification.*

2.1.2 Government and CA deficit paths

[Paltsev] The balance of payments is exogenous, but the current profile in SAGE is not justifiable (running a deficit forever under an assumption of perfect foresight).

[Wilcoxen] The model currently requires that both the government's fiscal budget and the nation's international trade accounts balance, although both are far from it in practice. A good first step would be to specify each exogenously. The fiscal deficit could be based on CBO projections. (Mun: They are not, strictly speaking, in balance. Eq. 34 for the government budget has the variable *tran* which is linked to *incadj*, which is a lump sum transfer that is parallel to financing a deficit with compulsory lending to the government. The Current Account eq 42, has *bopdef* that includes the deficit, as noted in the Paltsev comment above.)

[v d Mensburgghe] Describe the government budget constraint explicitly using a government savings variable; the current closure assumes that this is set to 0. If you add this, you could simply exogenize government savings (or government savings wrt to nominal GDP) and then the lump sum transfers are endogenous to meet the fiscal target.

[Ho] The government budget is given by eq. 34:

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

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

The variable *tran0* is not clearly described in the documentation, it should consist of interest payments, social security payments, official transfers less imputation for gov capital depreciation. The *incadj* would be interpreted as the government borrowing requirement (net deficit taking into account trust fund surplus) and is the endogenous variable to meet this constraint. v.d.Mensburgghe's suggestion is to have

incadj = Deficit + lumpsum

where "Deficit" is the official projected deficit and "lumpsum" is the taxes required to hit the spending assumptions.

[Ho] I have not plotted the $tran_{t,r,h}$ variable, but would be very interested to see it (government consumption grows at $(\gamma + \omega)$ and tax rates stay at base year levels so *tran* should be a stable value, unlike actual CBO projections of the deficit, interest payments and official transfers). A policy that has a large impact on government revenues (e.g. carbon taxes) would play a big role in these deficit baselines. A more realistic base case path would have higher tax rates and thus bigger welfare effects of changing them due to, say, carbon revenues. In other words, eq. 34 may suffice for most EPA policies, but not good for policies with large revenue impacts.

A more complete accounting of the current account balance of region r and household h would include the international income and transfers in eq. 42:

$$\sum_{r,s} p^? x_{t,r,s,ftrd} - \sum_{r,s} p^? m_{t,r,s,ftrd} + \sum_r Inc_{tr}^{row} + TR_{tr}^{row} = CA_t = \sum_{r,h} bop_{t,r,h}$$

This equation should be recorded even if it is not used in the model solution. It clarifies what National

Account variables correspond to what model variables; in this case how *bop* is related to the trade deficit, net interest and dividends from rest-of-the-world, and net transfers. This gives a more accurate accounting of the actual savings since it makes the international income and transfers distinct from the CA surplus; right now these are mushed together into the variable *bopdef*. Note that the above equation is written with prices, *p?*, unlike eq. 42 that is in real quantities. I think eq 42 is misleading since the balance equation should be in nominal units. The *bop* above is in nominal terms, unlike *bopdef* in SAGE.

[*for committee consideration:*]

We recommend that the SAGE team write the elements of the government budget in greater detail; separating the deficit from actual transfers. The deficit paths should be set to those generated by CBO and other agencies for the medium term, and then converge to zero to allow for a well-defined steady state.

Similarly, a current account balance equation should spell out the elements that can be tied to the National Accounts, and allow a transparent link to projections of CA deficits. The path of CA deficit should converge to zero.

2.1.3 Dynamics of extant and new capital; partial putty clay model

[v d Mensburgghe and Rutherford]

The definition of 'extant' versus 'new' capital in SAGE is unusual. Capital installed in 2021 is still considered 'New' in 2061. In other myopic models such as 'GREEN' model (and subsequent derivatives such as ENVISAGE), the putty clay model's main distinction is between "fixed" and "mobile". "Fixed" capital is allowed to increase over time; at the start of each period, we add the old capital and the new mobile investment K_new:

$$K_fix(t) = (1-d)K_fix(t-1)+K_new(t-1)$$

'New' capital is determined by current rates of return and the CES substitution elasticity, and represents a relatively small share of total capital. The treatment in SAGE (eq 8 for new capital) means that all capital created after the benchmark year is mobile across sectors for all future periods. This partial-putty-clay model seems to have an intermediate degree of mobility between the K_fix defined above (putty-clay) and full mobility of all capital (putty-putty).

The SAGE document highlights of the transition dynamics provided by this partial putty-clay formulation. It would be helpful if the usefulness of this formulation could be demonstrated, that is, compared to the putty-clay model.

2.1.4 Labor mobility

[v d Mensburgghe] SAGE currently does not allow labor mobility across regions. This seems highly restrictive in a long-term model.

We recommend that the SAGE team consider allowing an alternative option where labor is allowed to respond gradually to wage gaps between regions.

2.1.5 Industry growth are different, contra model assumption

[Montgomery and Wilcoxen]

It is now assumed in SAGE that productivity growth is identical across industries. The historical record shows a wide range of TFP growth, from strong positive to negative[1]. Projections based on this historical record shows that relative prices will continue to change (much cheaper electrical equipment relative to services). On the demand side, given that income elasticities are different from 1 and that we expect sizable changes in demographic composition, there will be a shift in relative demand for the different commodities. The assumption of balanced growth will produce different magnitudes of impacts for sectoral policies than would the assumption that the affected industries will be growing or declining over time. These considerations enter into regulatory debates.

We recommend that the SAGE team consider a more general production function that allows for differentiated productivity and move away from the current labor-augmenting setup. See also 2.4.1 below. A simpler, short-run, improvement could be to calibrate sectoral growth rates to forecasts of secular change in the industry mix in the U.S. (other than the energy sectors already considered based on EIA forecasts).

2.1.6 Time-steps; fixed versus variable time steps

[v d Mensburgghe and Ho]

The 5-year time step is appropriate as a tradeoff point between accuracy and computational burden for long term policies such as carbon prices. Other regulations may have a shorter horizon. This model is designed with a distinction between extant capital and new capital, that is, built with short-run considerations very much in mind.

We recommend trying to implement uneven time spacing; e.g. every year for the first 5 years, then every 5 years. (Few models do this, but Peter Wilcoxen may be consulted about this).

2.1.7 Dynamic calibration

(This might perhaps be better classified under Charge Q1)

[Rutherford] I spent some time looking for a discussion of dynamic calibration in the model. It is not obvious how this is done -- the input-output table provides a snapshot of transactions in a given year, but there is typically a big discrepancy between the imputed capital stock and the requisite investment demand. I'd like to see how this is finessed in the baseline calculation.

2.2 Households, Consumption functions, welfare

[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*.

[Ho]

The consumption function is a CES function where the share parameters for energy is calibrated to AEO projections. The non-energy share parameters then undergo a small rescaling so that the shares for all 23 commodities add to 1. It would be better to project all share parameters based on models that have a richer set of income elasticities instead of assuming unit income elasticity. Right now, for example, the food share rises a bit due to the balancing of the declining energy shares. This is against the few widely accepted laws of empirical economics – Engel's Law. This is probably not an extremely important issue and may be done in future revisions.

The proposals for potential near-term updates include a suggestion to use a flexible demand system with non-unit income elasticities and cross-price elasticities. They also include the proposal to estimate such a demand system.

Rutherford feels that it would be risky and difficult to take on a demand system which is potentially non-convex at points on the price simplex far from the benchmark. He agrees that it is important to have a demand system which can be calibrated to own-price and income-elasticities. He suggest the consideration of the constant difference of elasticities (CDE) demand system (Hanoch, 1975) used in the GEMPACK GTAP model[2]. GTAPINGAMS includes both the CDE system and a linear expenditure system (LES), with code to parameterize the function to match income elasticities and average price elasticities. Mun Ho suggest also consulting a recent overview of consumption functions in CGE in Ho et al. (2019)[3].

There seems to be 3 options for the Review Committee to recommend:

1) *Support the SAGE team effort implement a flexible demand system and estimating it econometrically.*
2) *Recommend against trying to implement a flexible demand system now, do something simpler first. Suggest adding a LES and CDE alternatives to the current CES system.*
3) *Recommend against spending time on new demand systems now, merely adjust the CES share parameters to reflect expert forecasts. Defer work on consumption until other improvements are made.*

2.2.2 Specific commodity issues

[Montgomery] In the consumption CES function now, motor vehicles and petroleum as regarded as substitutes. Regulations that affect motor vehicles or petroleum costs would only get a simple treatment in this framework. There is a more complex relationship here, both US-REP and NewERA models have a nest that combines fuel, O&M, and vehicle services into a transportation aggregate that is consumed by the household. In this framework, an increase in fuel cost or vehicle cost will reduce transportation demand, and fuel economy can be improved

[2] See a comparison of different demand systems in Bruno Lanz and Rutherford, 2016, "GTAPinGAMS: Multiregional and small open economy models" Journal of Global Economic Analysis, 1(2).

[3] Ho, Mun, Ruth Delzeit, Florian Leblanc, Franziska Schuenemann, Matthias Weitzel. 2019. "Modelling consumption and constructing long-term baselines in final demand," GTAP conference June 2019 and revised.

by substituting vehicle services for fuel.

We recommend that the SAGE team consider such a framework in future versions.

2.2.3 Income distribution

[v d Mensburgghe] The income distribution aspects for 5 different types of households differentiated by incomes are a nice feature of the model. The structure of households, however, is static in this dynamic model — no migration, no significant change in sources of income, etc. We recommend that the SAGE team consider developing additional structural change for the households.

2.2.4 Welfare, discounting

[Wilcoxen] The definition of equivalent variation has an unconventional sign. The usual definition is the expenditure needed to get the new utility at the original prices less the original expenditure: $ee(pp_0, uu_1) - ee(pp_0, uu_0)$. Defined that way, a positive EV shows a gain in welfare. The definition in equation 134 is the reverse, consistent with model results that produce positive EVs for regulations that should reduce welfare based on the consumption measure. 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.

[Ho] We also note that the EV is defined over a finite time horizon. Since the model is an infinite horizon model (eq 21), if a low discount rate is chosen, then 2061 still carries significant weight. One can easily add in the discounted sum of a steady state value for the period beyond 2060. The model now use rbar=0.045 following CEA(2017); but given the discussions in Arrow, Cropper et al (2013) it may be useful to show the effects of using alternative discount rates in the cost-benefit assessments.

2.3 Investment and government demand functions

[v d Mensburgghe and Ho]

The function allocating total investment and total government purchases to the various commodities is of the Leontief form (eq. 20, 32). This is not reflective of past investment trends that show rising shares of, say, computer equipment. This is indeed a topic ignored by most models; but the cost of making it more flexible should be small. We recommend that one could start with a generic CES function which can allow for zero elasticities. A CES will also allow the option to set an exogenous trend in the share parameters to accommodate expert projections or other government agency projections. The modeling of investment allocation is also discussed in Ho, Delzeit et al. (2019).

[Ho] The Government industry is included as part of the Services industry and this has some implications. Government capital input is now mixed in with private capital input; this K_{gov} is unlike regular private capital that consist of depreciation and profits, it is an imputed value just based on depreciation of the vast stock of government capital. The rental rate of this giant Services sector is thus a mixed bag of market return and imputed depreciation and may give a wrong idea of the marginal cost of capital to services. This may not be an important simplification for the likely policy simulations but the SAGE team should keep this in mind.

2.4 Industry and production function issues

2.4.1 Production function; productivity term

Productivity in SAGE is represented by a Harrod-neutral growth in effective labor at rate ω.

Effective time endowment: $te_{t,r,h} = te0_{r,h}(1+\gamma+\omega)^t$

Labor S=D: $\sum_h l_{t,r,h} = \sum_s ld_{t,r,s}$; $te_{t,r,h} = leis_{t,r,h} + l_{t,r,h}$

Production function: $kl_{t,r,s} = .[.(kd)^s + .(ld)^s]^{1/s}$

[v d Mensburgghe and Ho] Why is labor productivity implemented through effective time endowment? Why not put it directly into the model's production nest? That is, why not write the K-L aggregate in eq. 8 as:

$$kl_{t,r,s} = e^{\mu_{rs}t}[cs(kd_{t,r,s})^{\sigma-1/\sigma} + (1-cs)(ld_{t,r,s})^{\sigma-1/\sigma}]^{\sigma/\sigma-1}$$

(Or as an equivalent term in the gross output equation 3.) Writing in this form allow each industry to have its own TFP term ($e^{\mu_{rs}t}$). In the current effective labor form, all industries benefit equally from the extra labor.

2.4.1.1

[Ho]

There are various definitions of productivity and I like to first clarify how "labor productivity (LP)" is related to the ω and μ in the above equations.

LP at the aggregate level, in the BLS definition, is GDP/hoursworked. In growth accounting we have the growth rate formula:

LP growth = capital deepening + labor quality growth + TFP growth

Or, LP growth = capital stock deepening + cap composition(quality) + labor quality + TFP

(Labor quality is a compositional change index, a bigger share of total workers with higher skills over time. Capital quality is the compositional change with the changing ratio of equipment to structures.) If we use the concepts in Jorgenson, Ho and Samuels (2019)[4] then in the 1990-2014 sample period for the US, the 3 component contributions of LP are:

LP = 1.63 = 0.93 + 0.25 + 0.46.

Or, when we use the 4-component formula, approximately: 1.63=0.70+0.23+0.25+0.46

If we think of a simple aggregate Cobb-Douglas function in a typical macro model, then the Hicks-neutral

[4] Jorgenson, Ho and Samuels. 2019. Education Attainment and the Revival of US Economic Growth, in Hulten and Ramey (eds) Education, Skills and Technical Change. NBER Studies in Income and Wealth Vol. 77.

TFP of $\mu = 0.46\%$ per year is represented by:

$$Q_t = e^{\mu t} K_t^{\alpha} L_t^{1-\alpha}; \qquad L_t = e^{q_L t} N_t$$

In this formulation L is effective hours, and N is hours (number of workers); q_L is the rate of growth of labor quality and K is the effective capital input. Converting this to the Harrod-neutral form gives:

$$Q_t = K_t^{\alpha} (e^{\omega t} L_t)^{1-\alpha}$$

where $\omega(1-\alpha) = \mu$, or $\omega = 0.46/(1-0.4) = 0.77$

Other authors do not distinguish the labor quality and capital quality effects and these are lumped into the TFP term. In this case, historically, TFP_b = 0.23+0.25+0.46=0.94.

And converting to the omega form:

$$\omega = 0.94/(1-0.4) = 1.6$$

Thus, *by coincidence*, this is equal to the average 0.016 cited by the SAGE document from the AEO projection of the *nonfarm private* labor productivity growth rate. The correct rate to use is the economy-wide LP, not just the private LP; which would be about 10% lower than the NFP sector.

In the Jorgenson et al projections, we expect q_L growth to fall a lot and TFP fall a little in the coming decade, and thus the outlook for TFP_b is more like 0.8 or lower, or an omega of 1.33. This together with capital growth and workforce growth we get almost 2.0% GDP growth (close to the general consensus for US medium term outlook).

The base case growth is SAGE is about 2.1% with the assumed $\omega = 0.016$ and workforce growth (equal to population growth) of 0.006. This workforce assumption is slightly higher than the 0.003 outlook for 2030s in the CBO and Jorgenson et al., both of which distinguishes population from workforce. These small differences are not important, but it would be good to show in the base case description of the documentation the key values – capital growth, resource growth, labor growth and GDP growth – in a Table for diagnostic checks.

2.4.2 Capital modeling

[v d Mensburgghe] Could combine 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.

2.4.3 Sector specific issues

[Montgomery] Experience suggests that the CES specification for the electricity sector cannot adequately capture fuel choice for power generation. Substitution between coal and gas is good enough for the fossil energy input, but the lack of explicit treatment of energy inputs from nonfossil sources means that economic choices of such forms of energy has to be captured in the elasticity of substitution between value added and energy. Thus investing in nuclear increases capital and labor inputs so that more energy can be produced with the same amount of fossil

energy input. This may not be satisfactory for policies that impact the power sector and *we recommend that the SAGE team develop a plan to have a richer model of the electricity sector.*

[Montgomery] Adding more structural detail to the model in key sectors subject to repeated regulation – such as the electricity production function and transportation consumption (motor vehicles, fuel) – would have benefits. It would make it possible to include more of the margins on which decisions are made in response to regulations; a better recognition of the opportunity costs. These additional structures are often found in partial equilibrium models, for example those used to study the impact of emission standards on motor vehicles, and has been very useful to identify ways in which the fine detail of regulations leads to perverse behavioral changes.

2.4.4 Emissions modeling

[Rutherford] It would be useful to include emissions coefficients in the production function; it should not be too difficult to attribute emissions to fuel use or to processes. The model should be "driven" by engineering estimates of abatement costs, but if it is to be compared with conventional energy-economy-environment models, it should be able to compute permit prices and emission tax scenarios (at the very least). A key policy interest for EPA should involve the assessment of command-and-control as compared with tax instruments or quotas.

I like the idea of hooking the process abatement technologies to engineering studies, but I think that this is something which could incorporate endogenous adoption of specific measures. Abatement per unit output from a given mitigation measure has a cost and capacity. Taken together the abatement measures provide a staircase abatement cost curve.

2.4.5 SAGE implementation of unit costs

[v d Mensburgghe] Is there a reason to maintain both unit costs and the respective price variable for the CES composites? The only bundle where they might deviate in practice is for output prices where any type of non-competitive assumption or deviation from CRTS would introduce a wedge between the unit cost of production and the producer price. (Mun: Is it because of complementarity way of writing the model e.g. eq. 89?)

2.5 Natural resources

[v d Mensburgghe] i) Many models have a natural resource supply function, that is, the supply respond to prices. The SAGE team should consider this, and/or adding resource supply shifters. ii) Right now the tax on natural resource is the same as for capital (at rate tk); 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.

The resource supply issue should be discussed in relation to the issue in 2.1.1 above.

2.6 Regional issues

[Paltsev] There are nine regions now represented in SAGE. It would be good to discuss the

difficulties in trying to represent more regions, even all 50 states, so we have an idea of the tradeoffs between regional detail, tractability and computing time.

[Ho] The documentation should acknowledge explicitly that 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. There is no data on flow of incomes across states and no data on ownership at such a level of detail. I would think there is a substantial flow of dividend income from assets in *r* to households in New York, and a flow of investment by NY in k(r).

2.7 Government accounts, taxes

[Ho] The attention paid to the tax system is impressive, distinguishing between average and marginal rates; using the CPS data and Taxsim model to calculate marginal tax rates. Section 3.2 of the documentation states that *tk* is made up from the corp tax rate from 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. I think tax rates should be calibrated to replicate the NIPA revenues and it would be good if the *tran* variable in the base year can be related explicitly to items in the NIPA government accounts. Similarly, the production tax *ty* based on IMPLAN should be calibrated to produce the corresponding total revenues in the NIPA in the base year.

[Rutherford] It is important to bear in mind that introducing taxes on sales should probably go hand-in-hand with attribution of retail margins. This could involve a lot of work. I would guess that this is not worth the effort at this point.

2.7.2 Labor taxes

[v d Mensburgghe] On the labor tax schedule (eq 52), couldn't this be implemented with a single curve that allows for the marginal rate to differ from the average? [Mun: I think the implementation is the simplest method to allow tl_marginal to differ from tl_average.]

2.8 International trade specification

[Sands and Wilcoxen] The treatment of the US as a small open economy is undesirable in terms of both flows of goods and financial capital. This should really be relaxed and it is good that it is on the list of potential near-term updates.

[Sands] How does the current structure of SAGE, with its price of foreign exchange, compare to a global model with real exchange rates? Clarify if the international trade closure is different between the static and dynamic versions of SAGE.

[Rutherford] It is difficult to specify the appropriate elasticities for the downward sloping demand for US exports and an upward sloping supply of US imports. Rutherford and Tarr (2003)[5] demonstrated that by taking value shares and Armington elasticities from GTAP it is possible to incorporate the international trade responses of the multiregional trade model within a small open

[5] Thomas Rutherford and David Tarr. 2003. Regional trading arrangements for Chile: Do the results differ with a dynamic model?", Economie Internationale 94-95:261-282; and in Trade and Integration 18(6). Also GTAP Resource #1338.

economy model. I'm not so sure that the same can be done for the US; one can set up a multiregional GTAP model and see how it compares with a large open economy formulation based on the same data.

We encourage the prioritization of an improvement in the modeling of international trade. We recommend consulting Thomas Rutherford for advice about implementing international demand and supply functions. It would be useful if we can compare such a model with a 2-region global model, even if in a static setting.

Question 3 – Dominique van der Mensbrugghe

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

Preliminary comments of the Science Advisory Board on the model inputs were largely laudatory.

The Science Advisory Board nonetheless has the following specific recommendations:

- Production and trade elasticities, the source of which is well documented, may require additional estimation, particularly to reflect the specificity of the SAGE model, rather than using rules-of-thumb. [This may allow, as well, for more spatial heterogeneity.] New estimates would also generate confidence intervals that could be used for probabilistic uncertainty analysis.
- The fiscal side of the SAGE database could be improved—notably the role of sales taxes. The latter may also require incorporating trade and transport margins.
- The SAGE model inputs could be usefully complemented with a set of emissions and energy balances based on official government databases.
- Dynamic assumptions may need to be reviewed, allowing for example for more heterogeneity in terms of growth (across households), separating labor growth from population growth, and labor productivity across activities and space.
- Is there a strategy to switch from IMPLAN to the open-source WiNDC database? What are the pros and cons?
- Proposed extensions of the model will create a need for additional key elasticities. Specifically, a non-homothetic consumer demand system is typically calibrated to a set of income and own- and cross price elasticities, that should reflect household heterogeneity and key stylized facts such as Engel's and Bennett's Law, energy shares as a function of income, etc. Relaxing the small country assumption will require estimates of import supply and export demand elasticities [and perhaps across sources/destination if trade is introduced on a bilateral basis].

Question 4 – Sergey Paltsev

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

The review panel has done an initial exploration of the results for a limited set of scenarios and the model produces intuitive and expected results for the basic cases. Additional explorations are warranted for more extensive sets of scenarios and reporting variables. Setting up additional reporting summary (including visualization) for major variables such as sectoral prices (including energy and agriculture), sectoral output, energy intensity, labor, capital and natural resources use and prices, GDP and equivalent variation (EV) would be useful.

Perfect foresight (forward looking) setting requires extra caution with interpretation of the results. With a dynamic, forward looking model and policies whose impacts vary over time, there is always a possibility that the model agents are anticipating future costs and rearranging consumption and investment over time in ways that lead to impacts on consumption and EV that are not simple to explain. In addition, there are some empirical studies that question the perfect foresight assumption (e.g., Li et al in Management Science (2014, 60, 9) evaluated air-travel industry and found that only 5.2% to 19.2% of population is strategic with perfect foresight).

Members of the panel request the following clarifications: 1) Is the initial equilibrium (i.e., for the baseyear of the model) affected by the simulations? 2) What is the rationale for setting pk (pk(2016,r) are all close to 1.0 except for r={mat, esc} with 1.25)? 3) For numerous scenarios, the analysis of changes in GDP and EV is needed and an intuition for their relationships should be provided; 4) Provide justification (including empirical evidence) for the perfect foresight setting of the model and clarify if the alternative settings (e.g., limited foresight, recursive-dynamics) are considered for implementation.

Question 5 – Ron Sands

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.

Numeraire Test

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.

Baseline Indicators

It would be useful to have more information about the base case, including more figures and tables in section 3.4. For example, a figure for GDP(t), the consumption and investment portions, agricultural and energy prices (with respect to CPI), energy intensity, agricultural and natural resource output growth, etc.

Model Sensitivity

A test to changing energy prices would be useful (e.g., West Texas Intermediate was $43/bbl in 2016, $51/bbl in 2017, and $65/bbl in 2018). With historical price shocks, would the model reproduce historical regional production and consumption changes?

The sensitivity to a choice of the time intervals and model horizon (e.g., if the model runs 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)?

A comparison of the baseline scenario to existing baselines: for example from the Shared Socio-economic (SSP) database, or other modeling efforts.

Energy Balance

Energy accounting matters for regulations or policies that involve emissions from fossil fuel consumption.

- This requires reconciliation of economic values in a SAM with energy quantities in an energy balance table.
- This suggests revising the benchmark SAM to better represent energy technologies.

A SAM ensures balance in terms of economic values, but there is also a need to maintain energy balance for analysis of environmental policy that involves use of fossil fuels. The SAGE model uses state-level energy data from the U.S. Energy Information Administration (EIA), but these data are not organized into an energy balance table.

Energy balance tables, such as those constructed by the International Energy Agency (IEA) may be useful. In fact, the Global Trade Analysis Project (GTAP), as well as other large modeling teams, have worked through the details of reconciling energy balance tables with input-output tables to maintain energy balance within a model over time. This is not easy and requires expert judgement. An energy balance table is essentially an energy input-output table. A diagnostic for energy balance would be helpful. One could generate an energy balance table for all model time steps, as part of model output.

There are several ways that the base-year SAM can be re-organized to better represent energy technologies. The electricity generation sector can be split into several production functions each representing a specific technology. Further, it can be recognized that energy is consumed indirectly through energy services, which can be represented by production functions with capital stocks for specific technologies (e.g., privately owned motor vehicles providing household transportation services).

Question 6 – David Montgomery

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?*

General framework:

The SAB concludes that the framework described in Figure 9 of SAGE documentation 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 allows consistency between SAGE and engineering descriptions of abatement technologies, fully incorporates abatement costs into the cost of production, and distributes the cost of abatement across inputs needed for operating the abatement technology.

Nonetheless, there will no doubt be cases in the future that call for novel approaches. The open-source nature of the model should ease the incorporation and vetting 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. These estimates should be obtained in separate studies and as much as possible be reflective of regional, sectoral, temporal heterogeneities. Addressing heterogeneities in the engineering analysis will provide useful data for differentiated assumptions about cost and elasticity parameters by region, sector or time.

[One reviewer suggests that it would be instructive to provide estimates of capital losses – the change in pk in the regulated sector.]

Recommendations for further development

The current examples of 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 tax regime (simple tax, cap and trade, etc.) for example the SO2 market.

The SAB also 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 to do this would be to define an implicit sectoral production function fi(yi,

xi1… xin, ei(yi), eij(xij)) where yi is output of good i, xij is input of good j in sector i, ei is emissions associated with output yi, and eij is emissions associated with input i in sector j.

The productivity shock approach applies a multiplier ai to output or multipliers bij to inputs j in sector i in order to alter their productivity in manner that produces a marginal cost of abatement (as a function of ∑i,jeij) consistent with engineering estimates.

Most commonly the explicit production function for sector i, yi(x1…xm) has associated emission factors such that emissions equal some constant times yi or a set of (different) constants applied to each input. That is, if x1 is coal input to electricity production, then CO2 emissions will be the relevant emission factor for the coal type times tonnes of coal burned. Then the abatement good can be defined with units of tonnes of CO2 that is produced by a second function ai1(xi1…xim) in which additional amounts of x1…xm are required to reduce emissions. Costs are then ∑ipj(xj – x0j) and a constraint is placed on the amount of ai to produce.]

The SAB believes that it would be valuable to develop an extended version of the explicit compliance approach where factor demands for abatement activities are linked to specific inputs and not only the overall level of output. As it stands, the demand for specific abatement inputs are separable from the demands for productive inputs. That would, for example, make it difficult to model the impact of fuel switching between coal and gas within electric power generation. The current structure would not be able to endogenously capture the reduction in scrubbing that would occur.

The productivity shock approach is much simpler 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 material inputs, the amount of substitutability among material inputs should have an effect on the equilibrium loss of output from a shock to the productivity of a single input. To maintain the simplicity of the productivity shock approach and avoid variation in cost estimates based on parameter choice, it might be better to assume that the productivity shock applies to the materials nest and not to individual material inputs.

The SAB understands that the productivity shock and abatement good approaches both envision a direct translation of cost estimates from engineering models to the economic model of an industry or consumer. In either a partial or a general equilibrium analysis, the purpose of the economic model is to estimate behavioral responses to the imposition of a regulation. To achieve this, the structure of the SAGE model should incorporate the important mechanisms by which a regulation is expected to affect behavior. As indicated above, there will be substitutions among consumption goods and factor inputs that depend on where the cost impact of a regulation is placed. These substitutions affect the overall cost of regulation. As in the case of electric

power regulation that causes fuel substitution, other regulations may have direct effects on input substitution that can only be captured endogenously if the relevant. If key margins on which decisions are made are not represented in the model, the welfare effects of regulations will be incomplete.

Since many regulations are phased in, it would be useful to have a capability to change the size of the shock over time.

Based on experience with the tax interaction effect, the SAB is concerned with the lack of discussion of 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 have to be addressed in the engineering analysis.

One of the conveniences of the productivity shock approach is that it is not necessary to calibrate the model to mimic the results of an engineering analysis – the production function is simply adjusted to incorporate the engineering analysis directly. The other side of this simplicity is that the cost per unit of output is constant for all levels of output of the regulated sector.

Adding more structural detail to the model in key sectors subject to repeated regulation – such as electricity generation and motor vehicles – would have some benefits. It would make it possible to include more of the margins on which decisions are made in response to regulations, and therefore opportunity costs are incurred. This additional structure is often found in partial equilibrium models, for example those used to study the impact of emission standards on motor vehicles, and has been very useful to identify ways in which the fine detail of regulations leads to perverse behavioral changes.

One challenge in moving from an engineering analysis to a structural PE model to a GE model with some structure is that each broader model must be calibrated to the narrower model, rather than just taking the results of the narrower model to alter productivity.

Question 7 – Pete Wilcoxen

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.

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.

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 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.

Question 8 – Peter Wilcoxen

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. 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.

Question 9

Question 10 – Peter Wilcoxen

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 highest priority would be to add supplementary accounting to allow the model to report energy inputs and emissions in physical units. Emissions, which are not included in the current model, could be added and reported in kilograms or metric tons. A good place to start would be to add greenhouse gases and a number of key conventional air pollutants such as sulfur dioxide, nitrogen dioxide, particulate matter, and volatile organic compounds. Fossil fuels, which are currently tracked using index numbers and dollars of expenditure, could also be reported 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. Account for emissions will be more challenging because it will require the agency 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 evaluating air rules.

Beyond this, the SAB suggests that the agency consider the following enhancements and extensions:

1. The model's baseline should be revised to avoid imposing the assumption that the economy is in a balanced growth equilibrium in the initial year of a simulation. Instead, the baseline should begin with divergent sectoral productivity growth rates that capture the state of the current economy, and it should converge to balanced growth gradually over time.
2. Modeling of the commodity composition of new investment goods should be made more flexible. At the moment, the model assumes that the ratios of individual investment goods in total investment are fixed. It would be better to move to a more flexible functional form that would allow the mix of goods to respond to relative prices. That 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.
3. More structural detail in household transportation would be useful. That would allow the model to capture important linkages between key variables that jointly determine vehicle emissions, including: the cost of new vehicles; the number of new and used vehicles in the overall fleet; vehicle miles traveled; fuel prices; and fuel use. Without that detail it will be impossible to fully account for the effects of policies such as fuel efficiency or greenhouse gas emission standards, which can slow the adoption of new vehicles.
4. More detail in electricity generation would also be useful. The structure for electricity production currently in the model will make it difficult for SAGE to produce reliable results on how regulations for different sources of emissions from powerplants will affect fuel choice for generation or investment in renewables.
5. Overall, moving toward stronger empirical parameterization 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 OMB Circular A-4.
6. 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 will cause the model to no longer have a 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.

7. It would be good to add alternative mechanisms for representing expectations beyond perfect foresight. Doing so would allow the agency to explore several important modeling questions, including: How important is the assumption of perfect foresight for the model's results? What would be the impact of having a mix of agents, some with perfect foresight and some with more myopic expectations or facing liquidity constraints? Would a recursive dynamic model run in parallel be useful and allow for greater flexibility?
8. 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.
9. The agency may also want to develop more the agricultural, forestry and land-use sides—there are important regulatory issues in these areas.
10. 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.

Appendix to Charge Question 1

Typesetting Multi-Character Variable Names in LaTeX

In cases where multi-character variable names are employed, EPA should use\mathit{} so they typeset properly. This is especially noticeable for those variables that include the letter *f* (e.g., in equation 23, *tfica*, *bopdef*, *refund*). For example, pfx_{t} bopdef_{t,r,h} should be set as \mathit{pfx}_{t}\mathit{bopdef}_{t,r,h}. As it is, there is too much space preceding the "*f*". This is especially noticeable in the case of "*tfica*", where the "fi" has a ligature when set using \mathit{} and none otherwise. If you do this for all multi-letter variables, it reads easier, because it signals LaTeX to tighten up the spacing within the variable name, but appropriately puts spacing between variables.

BEFORE:

```
\begin{equation}
 \begin{alignedat}{1}
  kh_{t+1,r,h}+pcl_{t,r,h}cl_{t,r,h} = &
   \left(1+r_{t}\right)kh_{t,r,h}+\left(1-tl_{t,r,h}-tfica_{t,r,h}\right)pl_{t,r}te_{t,r,h}\\
   & +pr\_ex\_agg_{t,r}kh\_ex_{t,r,h} +\sum_{s}{pres_{t,r,s}rese_{t,r,s,h}}\\
   & +pfx_{t}bopdef_{t,r,h}+cpi_{t}tran_{t,r,h}\\
   & +pl_{t,r}tl\_refund_{t,r,h}
 \end{alignedat}
 ,
 \label{eq:hh_budget}
\end{equation}
```

AFTER:

```
\begin{equation}
 \begin{alignedat}{1}
  \mathit{kh}_{t+1,r,h}+\mathit{pcl}_{t,r,h}\mathit{cl}_{t,r,h} = &
   \left(1+r_{t}\right)\mathit{kh}_{t,r,h}+\left(1-\mathit{tl}_{t,r,h}
   -\mathit{tfica}_{t,r,h}\right)\mathit{pl}_{t,r}\mathit{te}_{t,r,h}\\
   & +\mathit{pr\_ex\_agg}_{t,r}\mathit{kh\_ex}_{t,r,h}
   +\sum_{s}{\mathit{pres}_{t,r,s}\mathit{rese}_{t,r,s,h}}\\
   & +\mathit{pfx}_{t}\mathit{bopdef}_{t,r,h}+\mathit{cpi}_{t}\mathit{tran}_{t,r,h}\\
   & +\mathit{pl}_{t,r}\mathit{tl\_refund}_{t,r,h}
 \end{alignedat}
```

The following is the "before" and "after" of equation 23, interleaved to illustrate the difference made by employing \mathit{}:

$$
\begin{aligned}
kh_{t+1,r,h} + pcl_{t,r,h} cl_{t,r,h} &= (1 + r_t)\, kh_{t,r,h} + (1 - tl_{t,r,h} - tfica_{t,r,h})\, pl_{t,r} te_{t,r,h} \\
kh_{t+1,r,h} + pcl_{t,r,h} cl_{t,r,h} &= (1 + r_t)\, kh_{t,r,h} + \left(1 - tl_{t,r,h} - tfica_{t,r,h}\right) pl_{t,r} te_{t,r,h} \\
&\quad + pr_ex_agg_{t,r} kh_ex_{t,r,h} + \sum_s pres_{t,r,s} rese_{t,r,s,h} \\
&\quad + pr_ex_agg_{t,r} kh_ex_{t,r,h} + \sum_s pres_{t,r,s} rese_{t,r,s,h} \\
&\quad + pfx_t bopdef_{t,r,h} + cpi_t tran_{t,r,h} \\
&\quad + pfx_t bopdef_{t,r,h} + cpi_t tran_{t,r,h} \\
&\quad + pl_{t,r} tl_refund_{t,r,h} \\
&\quad + pl_{t,r} tl_refund_{t,r,h}
\end{aligned}
,
$$

Suggested Code Restructuring

```
* hicksian demand equation - abatement with extant capital
hde_abate_ex(t,r,s,"extant")$(abate0(t,r,s,"extant")).
   abate(t,r,s,"extant") =e= y_ex(t,r,s);

* hicksian demand equation - intermediates for use with extant capital
hde_id_ex(t,r,ss,s)$(extant_share(r,s) and id0(r,ss,s)).
   id_ex(t,r,ss,s) =e= prod_ind(t,r,ss,s,"extant")*y_ex(t,r,s);

* hicksian demand equation - labor for use with extant capital
hde_ld_ex(t,r,s)$(extant_share(r,s) and ld0(r,s)).
   ld_ex(t,r,s) =e= prod_ind(t,r,"l",s,"extant")*y_ex(t,r,s);

* hicksian demand equation - sector specific extant capital
hde_kd_ex(t,r,s)$(extant_share(r,s) and kd0(r,s)).
   kd_ex(t,r,s) =e= prod_ind(t,r,"k",s,"extant")*y_ex(t,r,s);

* hicksian demand equation - fixed factor resources with extant capital
hde_res_ex(t,r,s)$(extant_share(r,s) and res0(r,s)).
   res_ex(t,r,s) =e= y_ex(t,r,s);

* unit cost equation - output with extant capital
uce_y_ex(t,r,s)$(extant_share(r,s) and y0(r,s)).
   uc_y_ex(t,r,s)
      =e= (sum(ss, cs_y_ex(t,r,ss,s)*prod_ind(t,r,ss,s,"extant")*pa(t,r,ss))
       +   cs_y_ex(t,r,"l",s)*prod_ind(t,r,"l",s,"extant")
       *    (1+tp(t,r))*pl(t,r)/(1+tp0(r))
       +   cs_y_ex(t,r,"k",s)*prod_ind(t,r,"k",s,"extant")*(1+tk(t,r))
       *    pr_ex(t,r,s)/((1+tk0(r))*pr0)
       +   cs_y_ex(t,r,"res",s)*(1+tk(t,r))*pres(t,r,s)/(1+tk0(r))
       +   cs_y_ex(t,r,"abate",s)*pabate(t,r,s,"extant"))
       /    (1-cs_y_ex(t,r,"abate",s))
       *  (1-ty0(r,s)) ;

* zero profit - output with extant capital
zp_y_ex(t,r,s)$(extant_share(r,s) and y0(r,s)).
  uc_y_ex(t,r,s) =e= py(t,r,s)*(1-ty(t,r,s));

*  ---------------------------------------------------------------------------
*
*     Production module -- new capital
*
*  ---------------------------------------------------------------------------

* hicksian demand equation - abatement with new capital
hde_abate(t,r,s,"new")$(abate0(t,r,s,"new")).
   abate(t,r,s,"new") =e= y(t,r,s) ;

* hicksian demand equation - resource(r)-capital(k)-labor(l)-energy(e)-
* materials(m) bundle
hde_rklem(t,r,s)$(y0(r,s)).
  rklem(t,r,s) =e= y(t,r,s) ;

* unit cost equation - output with abatement using new capital
uce_y(t,r,s)$(y0(r,s)).
   uc_y(t,r,s) =e= (cs_y(t,r,"abate",s)/cs_y(t,r,"rklem",s)*pabate(t,r,s,"new")
                +    prklem(t,r,s))*(1-ty0(r,s)) ;

* zero profit - output with new capital
zp_y(t,r,s)$(y0(r,s) and not (tfirst(t) and extant_share(r,s) eq 1)).
   uc_y(t,r,s) =e= py(t,r,s)*(1-ty(t,r,s)) ;
```

```
* hicksian demand equation - fixed factor resource
hde_res(t,r,s)$(res0(r,s))..
  res(t,r,s) =e= y(t,r,s)
              *  (uc_y(t,r,s)/(1-ty0(r,s))*(1+tk0(r))/((1+tk(t,r))*pres(t,r,s)))
              **se_rklem(t,r,s) ;

* hicksian demand equation - capital(k)-labor(l)-energy(e)-materials(m) bundle
hde_klem(t,r,s)$(y0(r,s))..
    klem(t,r,s) =e= y(t,r,s)
                 *  (uc_y(t,r,s)/(1-ty0(r,s))/pklem(t,r,s))
                 **se_rklem(t,r,s);

* unit cost equation - resource(r)-capital(k)-labor(l)-energy(e)-materials(m)
* bundle
uce_rklem(t,r,s)$(y0(r,s))..
   uc_rklem(t,r,s) =e=
         (cs_rklem(t,r,"res", s)*((1+tk(t,r))*pres(t,r,s)/(1+tk0(r)))
      **(1-se_rklem(t,r,s))
   +     cs_rklem(t,r,"klem",s)*pklem(t,r,s)**(1-se_rklem(t,r,s)))
      **(1/(1-se_rklem(t,r,s))) ;

* zero profit - resource(r)-capital(k)-labor(l)-energy(e)-materials(m) bundle
zp_rklem(t,r,s)$(y0(r,s) and not (tfirst(t) and extant_share(r,s) eq 1))..
   uc_rklem(t,r,s) =e= prklem(t,r,s);

* hicksian demand equation - capital(k)-labor(l)-energy(e) bundle
hde_kle(t,r,s)$(y0(r,s))..
   kle(t,r,s) =e= klem(t,r,s)*(uc_klem(t,r,s)/pkle(t,r,s))**se_klem(s) ;

* hicksian demand equation - materials(m) bundle
hde_mat(t,r,s)$(y0(r,s))..
   mat(t,r,s) =e= klem(t,r,s)*(uc_klem(t,r,s)/pmat(t,r,s))**se_klem(s) ;

* unit cost equation - capital(k)-labor(l)-energy(e)-materials(m) bundle
uce_klem(t,r,s)$(y0(r,s))..
   uc_klem(t,r,s) =e= (cs_klem(t,r,"mat",s)*pmat(t,r,s)**(1-se_klem(s))
                    +   cs_klem(t,r,"kle",s)*pkle(t,r,s)**(1-se_klem(s)))
                    **(1/(1-se_klem(s))) ;

* zero profit - capital(k)-labor(l)-energy(e)-materials(m) bundle
zp_klem(t,r,s)$(y0(r,s) and not (tfirst(t) and extant_share(r,s) eq 1))..
   uc_klem(t,r,s) =e= pklem(t,r,s);

* hicksian demand equation - capital(k)-labor(l) bundle
hde_kl(t,r,s)$(y0(r,s))..
   kl(t,r,s) =e= kle(t,r,s)*(uc_kle(t,r,s)/pkl(t,r,s))**se_kle(s);

* hicksian demand equation - primary energy(en)-electricity(e) bundle
hde_ene(t,r,s)$(y0(r,s))..
  ene(t,r,s) =e= kle(t,r,s)*(uc_kle(t,r,s)/pene(t,r,s))**se_kle(s);

* unit cost equation - capital(k)-labor(l)-energy(e) bundle
uce_kle(t,r,s)$(y0(r,s))..
  uc_kle(t,r,s) =e= (cs_kle(t,r,"ene",s)*pene(t,r,s)**(1-se_kle(s))
                 +   cs_kle(t,r,"kl",s) *pkl(t,r,s) **(1-se_kle(s)))
                 **(1/(1-se_kle(s))) ;

* zero profit - capital(k)-labor(l)-energy(e) bundle
zp_kle(t,r,s)$(y0(r,s) and not (tfirst(t) and extant_share(r,s) eq 1))..
  uc_kle(t,r,s) =e= pkle(t,r,s) ;
```

```
* hicksian demand equation - labor for use with new capital



hde_ld(t,r,s)$(y0(r,s))..
  ld(t,r,s) =e= kl(t,r,s)*prod_ind(t,r,"l",s,"new")**(1-se_kl(s))
             * (uc_kl(t,r,s)*(1+tp0(r))/((1+tp(t,r))*pl(t,r)))**se_kl(s) ;

* hicksian demand equation - new capital
hde_kd(t,r,s)$(y0(r,s))..
  kd(t,r,s) =e= kl(t,r,s)*prod_ind(t,r,"k",s,"new")**(1-se_kl(s))
             * (uc_kl(t,r,s)*(1+tk0(r))*pr0/((1+tk(t,r))*pr(t,r)))**se_kl(s) ;

* unit cost equation - capital(k)-labor(l) bundle
uce_kl(t,r,s)$(y0(r,s) and not (tfirst(t) and extant_share(r,s) eq 1))..
  uc_kl(t,r,s) =e=
      (cs_kl(t,r,"l",s)*(prod_ind(t,r,"l",s,"new")*(1+tp(t,r))
   *pl(t,r)/(1+tp0(r)))**(1-se_kl(s))
   +   cs_kl(t,r,"k",s)*(prod_ind(t,r,"k",s,"new")*(1+tk(t,r))
   *pr(t,r)/((1+tk0(r))*pr0))**(1-se_kl(s)))**(1/(1-se_kl(s))) ;

* zero profit - capital(k)-labor(l) bundle
zp_kl(t,r,s)$(y0(r,s) and not (tfirst(t) and extant_share(r,s) eq 1))..
   uc_kl(t,r,s) =e= pkl(t,r,s) ;

* hicksian demand equation - materials intermediates
hde_id_m(t,r,sm,s)$(y0(r,s))..
   id(t,r,sm,s) =e= prod_ind(t,r,sm,s,"new")*mat(t,r,s) ;

* unit cost equation - materials(m) bundle
uce_mat(t,r,s)$(y0(r,s))..
  uc_mat(t,r,s) =e= sum(sm, cs_mat(t,r,sm,s)*prod_ind(t,r,sm,s,"new")*pa(t,r,sm)) ;

* zero profit - materials(m) bundle
zp_mat(t,r,s)$(y0(r,s) and not (tfirst(t) and extant_share(r,s) eq 1))..
   uc_mat(t,r,s) =e= pmat(t,r,s);

* hicksian demand equation - primary energy(en) bundle
hde_en(t,r,s)$(y0(r,s))..
   en(t,r,s) =e= ene(t,r,s)*(uc_ene(t,r,s)/pen(t,r,s))**se_ene(s);

* hicksian demand equation - electricity intermediates
hde_id_ele(t,r,sel,s)$(y0(r,s))..
   id(t,r,sel,s) =e= ene(t,r,s)*prod_ind(t,r,sel,s,"new")**(1-se_ene(s))
                  *  (uc_ene(t,r,s)/pa(t,r,sel))**se_ene(s) ;

* unit cost equation - primary energy(en)-electricity(e) bundle
uce_ene(t,r,s)$(y0(r,s))..
  uc_ene(t,r,s)
   =e= (cs_ene(t,r,"ele",s)*(sum(ss$sel(ss), prod_ind(t,r,ss,s,"new")
    *    pa(t,r,ss)))**(1-se_ene(s))
    +   cs_ene(t,r,"en",s)*pen(t,r,s)**(1-se_ene(s)))**(1/(1-se_ene(s))) ;

* zero profit - primary energy(en)-electricity(e) bundle
zp_ene(t,r,s)$(y0(r,s) and not (tfirst(t) and extant_share(r,s) eq 1))..
  uc_ene(t,r,s) =e= pene(t,r,s) ;

* hicksian demand equation - primary energy
hde_id_en(t,r,sen,s)$(y0(r,s))..
  id(t,r,sen,s) =e= en(t,r,s)*prod_ind(t,r,sen,s,"new")**(1-se_en(s))
                 *   (uc_en(t,r,s)/pa(t,r,sen))**se_en(s);

* unit cost equation - primary energy(en) bundle
```

```
uce_en(t,r,s)$(y0(r,s))..
  uc_en(t,r,s) =e=
      sum(sen, cs_en(t,r,sen,s)*(prod_ind(t,r,sen,s,"new")
```

```
   *     pa(t,r,sen))**(1-se_en(s)))**(1/(1-se_en(s))) ;

* zero profit - primary energy(en) bundle
zp_en(t,r,s)$(y0(r,s) and not (tfirst(t) and extant_share(r,s) eq 1))..
   uc_en(t,r,s) =e= pen(t,r,s);

*  ---------------------------------------------------------------------------
*
*     Abatement module -- all vintages
*
*  ---------------------------------------------------------------------------

* hicksian demand equation - intermediates for abatement
hde_id_abate(t,r,ss,s,v)$(id_abate0(t,r,ss,s,v))..
   id_abate(t,r,ss,s,v) =e= abate(t,r,s,v) ;

* hicksian demand equation - labor for abatement
hde_ld_abate(t,r,s,v)$(ld_abate0(t,r,s,v))..
   ld_abate(t,r,s,v) =e= abate(t,r,s,v) ;

* hicksian demand equation - capital for abatement
hde_kd_abate(t,r,s,v)$(kd_abate0(t,r,s,v))..
   kd_abate(t,r,s,v) =e= abate(t,r,s,v) ;

* unit cost equation - abatement
uce_abate(t,r,s,v)$(abate0(t,r,s,v))..
  uc_abate(t,r,s,v) =e=
      sum(ss, cs_abate(t,r,ss,s,v)*pa(t,r,ss))
  +   cs_abate(t,r,"l",s,v)*(1+tp(t,r))*pl(t,r)/(1+tp0(r))
  +   cs_abate(t,r,"k",s,v)*(1+tk(t,r))*pr(t,r)/((1+tk0(r))*pr0) ;

* zero profit - abatement
zp_abate(t,r,s,v)$(abate0(t,r,s,v))..
   uc_abate(t,r,s,v) =e= pabate(t,r,s,v) ;

*  ---------------------------------------------------------------------------
*
*     Make module
*
*  ---------------------------------------------------------------------------

*  Aggregate output
*  ytot(t,r,s) = y_ex(t,r,s)+y(t,r,s) ;

*  ---------------------------------------------------------------------------
*
*     Income module
*
*  ---------------------------------------------------------------------------

* budget constraint - household
* the handling of the capital endowment using the conditionals based on the
* length of the t set is to correctly specify the budget constraint for the
* static model where the value of the endowment is defined by pr and not pk
* for the dynamic model need to account for the endogenous value of the initial
* period new capital stock in sensitivity analyses where the capital stock in
* the first period is not all extant

variables
   phikdist(t,r,h)      "National distribution of 'new' profits"
   savings(t,r,h)       "Savings equation"
```

;

```
equations
   phikdisteq(t,r,h)    "National distribution of 'new' profits"
   saveq(t,r,h)         "Savings equation"
;

phikdisteq(t,r,h)$(not tfirst(t) and card(t) gt 1)..
   phikdist(t,r,h) =e= kh(t,r,h)*ke0(r,h)/sum((rr,hh), kh(t,rr,hh)*ke0(rr,hh)) ;

saveq(t,r,h)..
   0 =e= (kh(t+1,r,h)*ke0(r,h)  - (kh(t,r,h)*ke0(r,h) + savings(t,r,h)
      -     sum(rr, pr(t,rr)*k(t,rr)*k0(rr))*phikdist(t,r,h)))
      $(card(t) ne 1 and not tlast(t))
      +  (pkt(r)*kt(r)*ke0(r,h) - (kh(t,r,h)*ke0(r,h) + savings(t,r,h)
      -     sum(rr, pr(t,rr)*k(t,rr)*k0(rr))*phikdist(t,r,h)))
      $(card(t) ne 1 and tlast(t))
      +  (savings(t,r,h) - pkt(r)*invh0(r,h))
      $(card(t) eq 1)
      ;

bc_hh(t,r,h)..
   pcl(t,r,h)*cl(t,r,h)*cl0(r,h) + savings(t,r,h) =e=
*     Profits in comparative static model
      pr(t,r)*ke0(r,h)$(card(t) eq 1)
*     Profits from 'new' capital in dynamic model
  +   sum(rr, pr(t,rr)*k(t,rr)*k0(rr))*phikdist(t,r,h)
*     Profit from 'extant' capital
  +   pr_ex_agg(t,r)*k_ex(t,r)*ke0(r,h)
*     After tax labor income
  +   (1-tl(t,r,h)-tfica(t,r,h))*pl(t,r)*te(t,r,h)
*     Natural resource income
  +   sum(s, pres(t,r,s)*(res_ex(t,r,s)+res(t,r,s))*rese0(r,s,h))
*     Net balance of payment residual
  +   pfx(t)*bopdef(r,h)*q_base(t)
*     Government transfers
  +   cpi(t)*tran0(r,h)*q_base(t)
*     Adjustments to gross labor tax
  +   pl(t,r)*tl_refund(r,h)*q_base(t)
*     Lump sum taxes to close government accounts
  +   cpi(t)*incadj(t)*incadj_share(r,h)
*     Exogenous component
  +   inc_extra(t,r,h) ;

$ontext
bc_hh(t,r,h)..
  kh(t+1,r,h)*ke0(r,h)
  +   pkt(r)*kt(r)*ke0(r,h)$(tlast(t) and card(t) gt 1)
  +   pkt(r)*invh0(r,h)$(card(t) eq 1)
  +   pcl(t,r,h)*cl(t,r,h)*cl0(r,h)
 =e=
      kh(t,r,h)*ke0(r,h)$(ord(t) gt 1)
  +   pk(t,r)*kh(t,r,h)*ke0(r,h)$(ord(t) eq 1 and card(t) gt 1)
  +   pr(t,r)*ke0(r,h)$(card(t) eq 1)
  +   pr_ex_agg(t,r)*k_ex(t,r)*ke0(r,h)
  +   (1-tl(t,r,h)-tfica(t,r,h))*pl(t,r)*te(t,r,h)
  +   sum(s, pres(t,r,s)*(res_ex(t,r,s)+res(t,r,s))*rese0(r,s,h))
  +   pfx(t)*bopdef(r,h)*q_base(t)
  +   cpi(t)*tran0(r,h)*q_base(t)
  +   pl(t,r)*tl_refund(r,h)*q_base(t)
  +   cpi(t)*incadj(t)*incadj_share(r,h)
  +   inc_extra(t,r,h) ;
$offtext
```

```
* first order condition - consumption(c)-leisure(l) bundle
```

```
foc_cl(t,r,h)..
   (cl(t,r,h)*cl0(r,h)/n(t,r,h))**(-eta(r,h)) =e= lambda(t,r,h)*pcl(t,r,h) ;

* first order condition - savings
foc_lambda(t+1,r,h)..
   beta(t+1,r,h)*lambda(t+1,r,h) =e= beta(t,r,h)*lambda(t,r,h) ;

* market clearance - time
mc_time(t,r,h)..
   te(t,r,h) =e= leis(t,r,h)*leis0(r,h)+l(t,r,h)*l0(r,h) ;

*  ------------------------------------------------------------------------------
*
*     Demand module
*
*  ------------------------------------------------------------------------------

* hicksian demand equation - leisure
hde_leis(t,r,h)..
   leis(t,r,h) =e= cl(t,r,h)*(uc_cl(t,r,h)*(1-tl0(r,h)-tfica0(r,h))
                / ((1-tl(t,r,h)-tfica(t,r,h))*pl(t,r)))**se_cl(r,h);

* hicksian demand equation - consumption bundle
hde_c(t,r,h)..
   c(t,r,h) =e= cl(t,r,h)*(uc_cl(t,r,h)/pc(t,r,h))**se_cl(r,h);

* unit cost equation - consumption(c)-leisure(l) bundle
uce_cl(t,r,h)..
   uc_cl(t,r,h) =e= (cs_cl(r,h,"leis")*((1-tl(t,r,h)-tfica(t,r,h))*pl(t,r)
                 /   (1-tl0(r,h)-tfica0(r,h)))**(1-se_cl(r,h))
                 +   cs_cl(r,h,"c")*pc(t,r,h)**(1-se_cl(r,h)))
                 **(1/(1-se_cl(r,h)));

* zero profit - consumption-leisure bundle
zp_cl(t,r,h)$(cl0(r,h))..
   uc_cl(t,r,h) =e= pcl(t,r,h) ;

* hicksian demand equation - consumption materials bundle
hde_cm(t,r,h)..
   cm(t,r,h) =e= c(t,r,h)*(uc_c(t,r,h)/pcm(t,r,h))**se_c;

* hicksian demand equation - consumption electricity and energy bundle
hde_cene(t,r,h)..
   cene(t,r,h) =e= c(t,r,h)*(uc_c(t,r,h)/pcene(t,r,h))**se_c;

* unit cost equation - consumption bundle
uce_c(t,r,h)..
   uc_c(t,r,h) =e= (cs_c(t,r,h,"cm")*pcm(t,r,h)**(1-se_c)
                +   cs_c(t,r,h,"cene")*pcene(t,r,h)**(1-se_c))**(1/(1-se_c)) ;

* zero profit - consumption bundle
zp_c(t,r,h)$(c0(r,h))..
   uc_c(t,r,h) =e= pc(t,r,h) ;

* hicksian demand equation - consumption electricity
hde_cd_ele(t,r,sel,h)..
   cd(t,r,sel,h) =e= cene(t,r,h)*pref_ind(t,r,sel,h)**(1-se_cene)
                  * (uc_cene(t,r,h)*(1+tc0(r))/((1+tc(t,r))
                  *  pa(t,r,sel)))**se_cene;

* hicksian demand equation - consumption primary energy bundle
```

```
hde_cen(t,r,h)..
   cen(t,r,h) =e= cene(t,r,h)*(uc_cene(t,r,h)/pcen(t,r,h))**se_cene;
```

```
* unit cost equation - consumption electricity and energy bundle
uce_cene(t,r,h)..
  uc_cene(t,r,h) =e= (cs_cene(t,r,h,"ele")*((1+tc(t,r))
                  *  sum(s$sel(s), pref_ind(t,r,"ele",h)
                  *     pa(t,r,s)/(1+tc0(r))))**(1-se_cene)
                  +  cs_cene(t,r,h,"cen")
                  *     pcen(t,r,h)**(1-se_cene))**(1/(1-se_cene));

* zero profit - consumption electricity and energy bundle
zp_cene(t,r,h)$(cene0(t,r,h))..
   uc_cene(t,r,h) =e= pcene(t,r,h) ;

* hicksian demand equation - consumption energy
hde_cd_en(t,r,scen,h)..
   cd(t,r,scen,h) =e= cen(t,r,h)*pref_ind(t,r,scen,h)**(1-se_cen)
                   * (uc_cen(t,r,h)*(1+tc0(r))/((1+tc(t,r))
                   *    pa(t,r,scen)))**se_cen ;

* unit cost equation - consumption primary energy bundle
uce_cen(t,r,h)..
  uc_cen(t,r,h) =e= sum(scen, cs_cen(t,r,h,scen)
                 *   (pref_ind(t,r,scen,h)*(1+tc(t,r))*pa(t,r,scen)/(1+tc0(r)))
                 **     (1-se_cen))**(1/(1-se_cen));

* zero profit - consumption primary energy bundle
zp_cen(t,r,h)$(cen0(t,r,h))..
   uc_cen(t,r,h) =e= pcen(t,r,h) ;

* hicksian demand equation - consumption materials
hde_cd_m(t,r,scm,h)..
  cd(t,r,scm,h) =e= cm(t,r,h)*pref_ind(t,r,scm,h)**(1-se_cm)
                 *  (uc_cm(t,r,h)*(1+tc0(r))/((1+tc(t,r))*pa(t,r,scm)))**se_cm ;

* unit cost equation - consumption materials bundle
uce_cm(t,r,h)..
   uc_cm(t,r,h) =e=
      sum(scm, cs_cm(t,r,h,scm)*(pref_ind(t,r,scm,h)
         *  (1+tc(t,r))*pa(t,r,scm)/(1+tc0(r)))**(1-se_cm))**(1/(1-se_cm));

* zero profit - consumption materials bundle
zp_cm(t,r,h)$(cm0(t,r,h))..
   uc_cm(t,r,h) =e= pcm(t,r,h);

* hicksian demand equation - government
hde_g(t,r,s)..
   g(t,r,s) =e= gov(t,r) ;

* unit cost equation - government bundle
uce_gov(t,r)..
   uc_gov(t,r) =e= sum(s, cs_gov(t,r,s)*pa(t,r,s));

* zero profit - government bundle
zp_gov(t,r)$(gov0(r))..
   uc_gov(t,r) =e= pgov(t,r);

* hicksian demand equation - investment
hde_i(t,r,s)..
   i(t,r,s) =e= inv(t,r);

* unit cost equation - investment bundle
```

```
uce_inv(t,r)..
   uc_inv(t,r) =e= sum(s, cs_inv(r,s)*pa(t,r,s));
```

```
* zero profit - investment
zp_inv(t,r)$(inv0(r))..
   uc_inv(t,r) =e= pk(t+1,r) + pkt(r)$tlast(t);

* zero profit - capital stock
zp_k(t,r)$(card(t) gt 1 and not tfirst(t))..
  pk(t,r) =e= pr(t,r) + (pk(t+1,r) + pkt(r)$tlast(t))*(1-delta);

*  ---------------------------------------------------------------------------
*
*     Armington/CET module
*
*  ---------------------------------------------------------------------------

* market clearance - goods market
mc_a(t,r,s)$(a0(r,s))..
  a(t,r,s)*a0(r,s) =e= sum(ss, id(t,r,s,ss)*id_base(t,r,s,ss))
                    +  sum(ss, id_ex(t,r,s,ss)*id0(r,s,ss))
                    +  sum((ss,v), id_abate(t,r,s,ss,v)*id_abate0(t,r,s,ss,v))
                    +  sum(h, cd(t,r,s,h)*cd_base(t,r,s,h))
                    +  i(t,r,s)*i0(r,s) + g(t,r,s)*g_base(t,r,s);

* hicksian demand equation - imports
hde_m(t,r,s,trd)$(m0(r,s,trd))..
  m(t,r,s,trd) =e= (dn(t,r,s)*(uc_dn(t,r,s)/pn(t,s))**se_dn(s))$(dtrd(trd))
                +  (a(t,r,s)*(uc_a(t,r,s)/(pfx(t)*pm(t,s)))**se_nf(s))
                $(ftrd(trd)) ;

* hicksian demand equation - domestic-national armington aggregate
hde_dn(t,r,s)..
   dn(t,r,s) =e= a(t,r,s)*(uc_a(t,r,s)/pdn(t,r,s))**se_nf(s);

* unit cost equation - armington aggregate
uce_a(t,r,s)..
   uc_a(t,r,s) =e= (cs_nf(r,"n",s)*pdn(t,r,s)**(1-se_nf(s))
                +   cs_nf(r,"f",s)*(pfx(t)*pm(t,s))**(1-se_nf(s)))
                **(1/(1-se_nf(s))) ;

* zero profit - armington aggregate
zp_a(t,r,s)$(a0(r,s))..
   uc_a(t,r,s) =e= pa(t,r,s) ;

* unit cost equation - domestic-national armington aggregate
uce_dn(t,r,s)..
   uc_dn(t,r,s) =e= ((cs_dn(r,"d",s)*pd(t,r,s)**(1-se_dn(s)))$(cs_dn(r,"d",s))
                 +   (cs_dn(r,"n",s)*pn(t,s)**(1-se_dn(s)))$(cs_dn(r,"n",s)))
                 **  (1/(1-se_dn(s))) ;

* zero profit - domestic-national armington aggregate
zp_dn(t,r,s)$(dn0(r,s))..
  uc_dn(t,r,s) =e= pdn(t,r,s);

* hicksian demand equation - domestic supply
hde_d(t,r,s)$(d0(r,s))..
  d(t,r,s) =e= dn(t,r,s)*(uc_dn(t,r,s)/pd(t,r,s))**se_dn(s);

* market clearance - domestic output
mc_d(t,r,s)$(y0(r,s))..
   d(t,r,s) =e= (y_ex(t,r,s)+y(t,r,s))*(pd(t,r,s)/py(t,r,s))**te_dx(s) ;
```

```
* hicksian demand equation - exports
hde_x(t,r,s,trd)$(x0(r,s,trd))..
```

```
   x(t,r,s,trd) =e= (y_ex(t,r,s)+y(t,r,s))
                  *  (((pn(t,s)/py(t,r,s))**te_dx(s))$(dtrd(trd))
                  +   ((pfx(t)*px(t,s)/py(t,r,s))**te_dx(s))$(ftrd(trd)));

* unit cost equation - destination differentiated output cet
uce_dx(t,r,s)$(y0(r,s))..
  py(t,r,s) =e= (cs_dx(r,"d",s)*pd(t,r,s)**(1+te_dx(s))
             +   cs_dx(r,"n",s)*pn(t,s)         **(1+te_dx(s))
             +   cs_dx(r,"f",s)*(pfx(t)*px(t,s))**(1+te_dx(s)))
             **(1/(1+te_dx(s))) ;

* market clearance - national trade
mc_dtrd(t,s)..
   sum((r,dtrd), x(t,r,s,dtrd)*x0(r,s,dtrd))
      =e= sum((r,dtrd), m(t,r,s,dtrd)*m0(r,s,dtrd)) ;

*  ---------------------------------------------------------------------------
*
*     Factor markets
*
*  ---------------------------------------------------------------------------

* market clearance - labor
mc_l(t,r)..
  sum(h, l(t,r,h)*l0(r,h)) =e=  sum(s, ld_ex(t,r,s)*ld0(r,s))
                            +   sum(s, ld(t,r,s)*ld_base(t,r,s))
                            +   sum((s,v), ld_abate(t,r,s,v)*ld_abate0(t,r,s,v)) ;

*  Capital

* market clearance - rental rate for sector differentiated extant capital
mc_pr_ex(t,r,s)$(extant_share(r,s) and y0(r,s))..
  kd_ex(t,r,s) =e= k_ex(t,r)*extant_share(r,s)/extant_share_agg(r)
                * (pr_ex(t,r,s)/pr_ex_agg(t,r))**te_k_ex ;

* unit cost equation - sector differentiated extant capital
uce_k_ex(t,r)$(extant_share_agg(r))..
  pr_ex_agg(t,r)/pr0 =e= sum(s, cs_kd_ex(r,s)*(pr_ex(t,r,s)/pr0)**(1+te_k_ex))
                      **   (1/(1+te_k_ex)) ;


* market clearance - rental rate for new capital
mc_pr(t,r)..t
  k(t,r)*k0(r) =e= sum(s, kd(t,r,s)*kd_base(t,r,s))
                +  sum((s,v), kd_abate(t,r,s,v)*kd_abate0(t,r,s,v)) ;

* market clearance - price of new capital
mc_pk(t,r)..
  k(t,r)*k0(r) =e= k(t-1,r)*k0(r)*(1-delta) + inv(t-1,r)*inv0(r)
                +  ((1-extant_share_agg(r))*k0(r))$tfirst(t) ;

* market clearance - price of post-terminal capital
mc_pkt(r)..
  kt(r)*k0(r) =e= sum(t$tlast(t), k(t,r)*k0(r)*(1-delta) + inv(t,r)*inv0(r)) ;

*  Natural resources

* market clearnace - fixed factor resources
mc_pres(t,r,s)..
  res0(r,s) =g= (res_ex(t,r,s)+res(t,r,s))*res0(r,s) ;
```

* ----------

```
*  Model closure
* ------------------------------------------------------------------------------

* market clearnace - foreign
trade mc_fx(t)$(not
tfirst(t))..
  sum((r,s,ftrd), px(t,s)*x(t,r,s,ftrd)*x0(r,s,ftrd))
    +  sum((r,h), bopdef(r,h)*q_base(t))
   =e= sum((r,s,ftrd), pm(t,s)*m(t,r,s,ftrd)*m0(r,s,ftrd)) ;

* budget constraint -
government bc_gov(t)..
  sum(r, pgov(t,r)*gov(t,r)*gov0(r))
    =e= sum(r, sum(s, tp(t,r)*pl(t,r)*ld(t,r,s)*ld_base(t,r,s)
     +                tp(t,r)*pl(t,r)*ld_ex(t,r,s)*ld0(r,s)
     +                tp(t,r)*pl(t,r)*sum(v, ld_abate(t,r,s,v)*ld_abate0(t,r,s,v))
     +                tk(t,r)*pres(t,r,s)*(res_ex(t,r,s)+res(t,r,s))*res0(r,s)
     +                tk(t,r)*pr(t,r)*kd(t,r,s)*kd_base(t,r,s)
     +                tk(t,r)*pr_ex(t,r,s)*kd_ex(t,r,s)*kd0(r,s)
     +                tk(t,r)*pr(t,r)*sum(v, kd_abate(t,r,s,v)*kd_abate0(t,r,s,v))
     +                ty(t,r,s)*py(t,r,s)*y_ex(t,r,s)*y0(r,s)
     +                ty(t,r,s)*py(t,r,s)*y(t,r,s)*y0(r,s)
     +                sum(h, tc(t,r)*pa(t,r,s)*cd(t,r,s,h)*cd_base(t,r,s,h)))
     +                sum(h, tl(t,r,h)*pl(t,r)*l(t,r,h)*l0(r,h)
     +                       tfica(t,r,h)*pl(t,r)*l(t,r,h)*l0(r,h))
     -                sum(h, cpi(t)*tran0(r,h)*q_base(t)
     +                pl(t,r)*tl_refund(r,h)*q_base(t)))
     -                cpi(t)*incadj(t) ;

* closure rule - real government expenditures per capita are
fixed cr_gov(t,r)..
   gov(t,r)*gov0(r) =e= q_base(t)*gov0(r) + gov_extra(t,r);

* closure rule - terminal capital
* scale the level of the terminal capital stock to achieve steady-state growth
* in last period
investment. cr_kt(r)..
   sum(tlast(t), inv(t,r)*sum(h, c(t-1,r,h)))
    =e= sum(tlast(t), sum(h, c(t,r,h))*inv(t-1,r)) ;

* ------------------------------------------------------------------------------
* auxilary
* ------------------------------------------------------------------------------

* auxilary - extant capital
aux_k_ex(t,r)$(extant_share_agg(r)
)..
   k_ex(t,r) =e= extant_share_agg(r)*(1-delta)**(ord(t)-1);

* auxilary -
welfare
aux_w(r,h)..
   w(r,h) =e= sum(t,  n(t,r,h)*beta(t,r,h)
           *   (cl(t,r,h)*cl0(r,h)/n(t,r,h))**(1-eta(r,h))/(1-eta(r,h))) ;

* auxilary - consumer price
```

```
index aux_cpi(t)..
  cpi(t) =e= sum((rr,hh), pc(t,rr,hh)*c0(rr,hh))/sum((rr,hh), c0(rr,hh)) ;
```

Proxy Configuration Examples for R

Users behind a proxy must be sure to include appropriate proxy configuration lines in your .Renviron file and .Rprofile file. The scripts as currently written do not necessarily report proxy communication errors. Text in <> should be replaced with appropriate values below:

```
# Proxy settings in .Renviron file

http_proxy=http://<ProxyAddress>:<ProxyPort>/
http_proxy_user=<UserName>:<UserPassword>

https_proxy=https://<ProxyAdress>:<ProxyPort>/
https_proxy_user=<UserName>:<UserPassword>

# Proxy settings in .Rprofile file:

library(httr)

httr::set_config(config(proxy="<ProxyAddress:<ProxyPort>",
proxyuserpwd = "<UserName>:<UserPassword"))
```